Automated Highway System (AHS)

WBS C1 Final Report Appendices

Develop Initial Suite of Concepts & Workshop #2

June 10, 1996

National Automated Highway System Consortium
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NAHSC

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APPENDIX A – DISTRIBUTION OF INTELLIGENCE TABLE

The following table shows the allocations of each of the functions for each of an early set of eleven alternative AHS Concepts. Note that these alternatives are quite generic, and there are different allocations shown in many cases. The following notation is used:

P	person
V	vehicle
Vs	vehicle in concert with other vehicles
R	roadway
C	centralized

[option]

(Alternatives)

{set within list of alternatives)

	Baseline	**ACC and Lane-keeping**	**Auto-nomous**	**locally Cooper-ative**	**Distrib-uted Across Region**	**Infra-structure Supported**
Sense relative longitudinal position	P,[V]	[P],[V]	V	Vs	Vs	(Vs,V)
Adjust relative longitudinal position	P	[P],[V]	V	Vs	Vs	(Vs,V)
Sense lateral position relative to lane	P,[V]	[P],[V]	V	Vs	Vs	(Vs,V)
Adjust lateral position relative to lane	P	[P],[V]	V	Vs	Vs	(Vs,V)
Determine lateral position/ velocity relative to other vehicles	P	P,[V]	V	Vs	Vs	(Vs,V)
Determine safety of lane change	P	P, [V—warning?]	V	Vs	Vs	(Vs,V)
Adjust longitudinal position/speed for lane change	P	P	V	Vs	Vs	(Vs,V)
Direct other vehicles to accommodate lane change	N	N	N	Vs	Vs	(Vs,N)
Command execute lane change	P	P	V	Vs	Vs	(Vs,V)
Sense potential hazard due to other vehicle	P	P,[V]	V	Vs	Vs	(Vs,V), [R]
Sense obstacle hazard	P	[P],[V]	V	Vs	Vs	(Vs,V), [R]
React to hazard	P	[P],[V]	V	Vs	Vs	(Vs,V)
Adjust traffic to optimize flow	(C,N)	(C,N)	(C,N)	(C,N)	({[C], [Vs]},N)	Vs,[C,R]

	Baseline	ACC and Lane-keeping	Auto-nomous	locally Cooper-ative	Distrib-uted Across Region	Infra-structure Supported
Determine route	P	P	[P],[V]	[P], [V]	[P],[V]	[P],[V]
Modify route	P	P	[P],[V]	[P], [V]	[P],[V], [Vs]	[P],[V], [Vs]
Determine lane	P	P	[P],V	[P],V, [Vs]	Vs	(V,Vs), [R]
Monitor traffic	[R],[C],[V],[N]	[R],[C],[V],[N]	[R],[C],[V],[N]	[R],[C],[V],[Vs],[N]	[R],[C], [V],Vs	[R],[C], [V],[Vs], [N]
Determine traffic management strategy	(C,N)	(C,N)	(C,N)	(C,N)	[C],Vs	[C],[Vs], [N]
Determine optimal traffic flow parameters	(C,N)	(C,N)	(C,N)	(C,N)	[C],[Vs]	[R],[C], [Vs],[N]
Sense incident/ malfunction	P,[V], [R],[C]	P,[V], [R],[C]	V,[P], [R],[C]	V,Vs, [P],[R],[C]	V,Vs, [P], [C]	V,[R],[C], [Vs],[P]
React to incident/ malfunction	P, C	P,C,[V]	V,[P], [R],[C]	V,Vs, [P],[R],[C]	V,Vs, [P],[R], [C]	V,[R],[C], [Vs],[P]
Test for entry	P	P, [V]	P,V	Vs,[P]	Vs,[P]	V,[R], [Vs],[P]
Manage entry	P	P, [V]	[P],V	Vs	Vs	(Vs,V), [R]
Test for exit	P	P	[P],[V]	Vs,[V],[P]	Vs	(Vs,V), [R],[P]
Manage exit	P	P, [V]	[P],[V]	Vs	Vs	(Vs,V), [R],[P]
Command vehicle actuators	P	[P],[V]	[P],V	[P],V	[P],V	V,[P],[R]
Tell vehicles about road geometry	R—exists	R	R	Vs,R, [R—active]	Vs,R	R,[Vs]

	Directed Platoons	Medium-Term Goal Control	Short-term Goal Control	Throttle, Steering Control	GPS-based
Sense relative longitudinal position	Vs	V,[Vs]	R,[V]	R	Vs using C-GPS
Adjust relative longitudinal position	Vs	V,[Vs]	V under R direction	R	Vs
Sense lateral position relative to lane	Vs	V,[Vs]	R,[V]	R	Vs using C-GPS
Adjust lateral position relative to lane	Vs	V,[Vs]	V under R direction	R	Vs

	Directed Platoons	**Medium-Term Goal Control**	**Short-term Goal Control**	**Throttle, Steering Control**	**GPS-based**
Determine lateral position/ velocity relative to other vehicles	Vs	V,[Vs,[R]]	R	R	Vs using C-GPS
Determine safety of lane change	Vs	R,[Vs]	R	R	Vs
Adjust longitudinal position/speed for lane change	Vs	R,[Vs]	R	R	Vs
Direct other vehicles to accommodate lane change	Vs	R	R	R	Vs
Command execute lane change	Vs	R	R	R	Vs
Sense potential hazard due to other vehicle	Vs	R,[V],[Vs]	R,[V], [Vs]	R	Vs
Sense obstacle hazard	Vs	R,[V],[Vs]	R,[V]	R	Vs
React to hazard	Vs,R	R,V, [Vs]	R,[V]	R	Vs
Adjust traffic to optimize flow	Vs,R, [C]	R,[C], [Vs]	({R, [C]},N)	({R, [C]},N)	({[C], [Vs]},N)
Determine route	[P],[V], [R,[C]]	[P],[V], [R,[C]]	[P],[V], [R,[C]]	[P],[V], [R,[C]]	[P],[V]
Modify route	[P],[V], [Vs], [R,[C]]	[P],[V], [R,[C]]	[P],[V], [R,[C]]	[P],[V], [R,[C]]	[P],[V], [Vs]
Determine lane	[R],[Vs]	R,[V]	R	R	[P],V, [Vs]
Monitor traffic	R,[Vs], [C]	R,[C]	R,[C]	R,[C]	[R],[C], [V],[Vs],[N]
Determine traffic management strategy	R,[C], [Vs]	R,[C]	R,[C]	R,[C]	({[C], [Vs]},N)
Determine optimal traffic flow parameters	R,[C], [Vs]	[R],[C]	[R],[C]	[R],[C]	({[C], [Vs]},N)
Sense incident/ malfunction	V,R,Vs, [C],[P]	R,[V], [C],[P]	R,[V], [C],[P]	R,[V], [C],[P]	V,Vs, [P],[R], [C]
React to incident/ malfunction	V,R,Vs, [C],[P]	R,V, [C],[P]	R,V, [C],[P]	R,V, [C],[P]	V,Vs, [P],[R], [C]
Test for entry	Vs,[V], [R],[P]	R,[V],[P]	R,[V], [P]	R,[V], [P]	Vs,[P]
Manage entry	Vs,[R]	R,[V]	R	R	Vs using C-GPS
Test for exit	Vs,[R]	R,[V]	R,[V]	R	Vs
Manage exit	Vs,R	R,[V]	R,[V]	R,[V]	Vs
Command vehicle actuators	V,[P]	V	V	R	V
Tell vehicles about road geometry	Vs,[R]	R	N	N	C-Maps, [R]

APPENDIX B – SPACING AND CAPACITY EVALUATIONS FOR DIFFERENT AHS CONCEPTS

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B. ABSTRACT

In Automated Highway Systems (AHS), vehicles will be able to follow each other automatically by using their own sensing and control systems, effectively reducing the role of the human driver in the operation of the vehicle. Such systems are therefore capable of reducing one source of error, human error, that diminishes the potential capacity of the highways and in the worst case becomes the cause of accidents. The inter-vehicle separation during* vehicle following is one of the most critical parameters of the AHS system, as it affects both safety and highway capacity. To achieve the goal of improved highway capacity, the inter-vehicle separation should be as small as possible. On the other hand, to achieve the goal of improved safety and elimination of rear end collisions, the inter-vehicle separation should be large enough that even under a worst case stopping scenario, no vehicle collisions will take place. These two requirements demand diametrically opposing solutions and they have to be traded off. Since safety cannot be compromised for the sake of capacity, it becomes a serious constraint in most AHS design decisions. The trade-off between capacity and safety gives rise to a variety of different AHS concepts and architectures.

In this study we consider a family of six AHS operational concepts. For each concept we calculate the minimum inter-vehicle spacing that could be used for collision-free vehicle following, under different road conditions. The minimum spacing in turn, is used to calculate the maximum possible capacity that could be achieved for each operational concept.

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* This work was performed as past of the California PATH Program of the University of California, in cooperation with the State of California Business, Transportation and Housing Agency, Department of Transportation; and the United States Department of Transportation, Federal Highway Administration.

B.1 INTRODUCTION

Urban highways in many major cities are congested and need additional capacity. Historically, capacity has been added by building additional lanes and new highways. Scarcity of land and escalating construction costs make it increasingly difficult to add capacity this way. One possible way to improve capacity is to use current highways more efficiently. The concept of Automated Highway Systems (AHS) was introduced to improve the capacity of the current transportation systems by using automation and intelligence.

Highway capacity depends on two variables: The velocity of the vehicles and the distance between them. Clearly, the higher the velocity of the vehicles, the higher the number of vehicles per lane per hour will be. But the vehicles need to maintain a certain amount of "safety distance" between them, to accommodate for the case that the flow of vehicles has to be slowed down or stopped, by applying the brakes. The moment that each vehicle starts applying its brakes typically involves a couple of seconds of delay in relation to the onset of braking of the vehicle in front, due to the fact that the human drivers need some time to process the information they perceive[22], plus an additional time delay to react and a delay for the mechanical and hydraulic systems of the vehicle to respond. During this time, the vehicle continues moving forward at practically the same speed and if there is not sufficient space between the leading and the following vehicle at the moment the leading vehicle applies the brakes and begins to decelerate, a collision would be inevitable. Even if the follower begins to apply its brakes at exactly the same time as the leader, the deceleration of the leading and the following vehicle may not match[9,10] and this generates the need for additional inter-vehicle distance during the cruising stage in order to accommodate for the difference in braking performance.

Heavy vehicles travel a significantly longer distance from the moment they apply their brakes until they come to a complete stop. This has to be accommodated for by allowing a significantly larger inter-vehicle spacing. On the other hand, when a light vehicle follows a heavy vehicle, the braking distance is not the limiting factor because typically the light vehicle will be able to come to a stop in a much shorter time and distance. In this case, the limiting factors are the initial conditions and the total delay between the time that the leader starts decelerating and the time that the follower starts decelerating at the maximum possible deceleration.

The delay in detecting and in reacting to the leading vehicle's deceleration can be reduced significantly, by taking the human driver out of the "control loop"[1,12,13,16]. With advances in technology and vehicle electronics, systems that were previously considered impossible to implement or too costly are becoming feasible and available. One such system is a functional extension of the classic cruise control[12]. The cruise control which is widely available on luxury cars today, is a controller that controls a throttle actuator in order to maintain constant vehicle speed. The next step in functionality, is a controller that uses a sensor to measure the relative distance and the relative speed to any vehicle ahead and controls a throttle and a brake actuator in order to follow at the same speed and maintain a fixed relative distance[12,14,15]. Such vehicles can follow each other in the same lane automatically by relying on their own sensors and controls. Vehicles that rely on their own sensors, controls and intelligence to operate in a highway environment are referred to as autonomous vehicles.

Advances in communications made it possible for vehicles to communicate with each other exchanging information about braking intentions and capabilities, acceleration, lane changing etc. The infrastructure may also support vehicle following and maneuvers by providing desired speed and spacing commands in addition to traveler information. This distribution of intelligence gives rise to the operating concept referred to as infrastructure supported free agent.

When the infrastructure becomes actively involved by sending braking commands for emergency stops and lane changing maneuvers, we have an operating concept referred to as infrastructure managed free agent.

Another concept is to organize free agent vehicles in platoons of a certain size where the intra-platoon spacing is very small and the inter-platoon spacing could be larger for safety purposes. In this case each platoon appears to the infrastructure as a single unit and therefore can be managed more efficiently. Each platoon is now responsible for the control of its vehicles so that a collision free environment is guaranteed.

In another concept, a high level of synchronization is introduced where each vehicle is allocated a slot in time and space. The infrastructure manages the slot distribution by issuing the appropriate commands for each vehicle.

The degree of infrastructure involvement and distribution of intelligence lead to different operational concepts and architectures for AHS. The purpose of this paper is to study the Minimum Safety Spacing (MSS) for a number of different AHS concepts and architectures and to obtain capacity estimates.

The paper is organized as follows: Section 2 presents the fundamental equations used in computing the MSS. Section 3 describes the candidate Vehicle Following Concept options. Section 4 presents the Spacing and Capacity calculations for each concept. Section 5 contains some discussion and further explanation of the results.

B.2 MINIMUM SAFETY SPACING

Inter-vehicle spacing during vehicle following is a very critical parameter of highway traffic. Insufficient spacing is usually the cause of rear-end collisions. In principle, the possibility of having a rear-end collision can be reduced by increasing the inter-vehicle spacing. However, the spacing that guarantees collision-free vehicle following can be characterized only when the braking scenario is known and well defined.

A braking scenario, which describes exactly how the vehicles brake, is usually specified by the deceleration profiles of the vehicles as a function of time. For each scenario there is a minimum spacing which must be maintained during steady state traffic flow, if collision-free vehicle following must be guaranteed. In this section we develop the basic equations that can be used to calculate the minimum spacing for collision free vehicle following, given the deceleration response information for both the leading and the following vehicle.

B.2.1 Safe Intervehicle Spacing Analysis

Consider two vehicles following each other, as shown in Figure B.2.1-1. Assume that at t=0 the leading vehicle begins to brake according to the deceleration profile defined by $a_l(t)$ and the following vehicle brakes according to the deceleration profile defined by $a_f(t)$. Assume that L_l and L_f are the lengths of the leading and following vehicles respectively. At t=0 the leading vehicle has a velocity $V_l(0)=V_{l0}$ and a position $S_l(0)=S_{l0}$ and the following vehicle has a velocity $V_f(0)=V_{f0}$ and a position $S_f(0)=S_{f0}$. If the spacing between the two vehicles at t=0, $S_r(0) = S_{l0} - S_{f0} - L_l$ is large enough, then there would be no collision during braking maneuvers.

For a given braking scenario we would like to calculate the minimum value of the initial intervehicle spacing $S_r(0)$ for which there will be no collision. We refer to this value as the Minimum Safety Spacing (*MSS*).

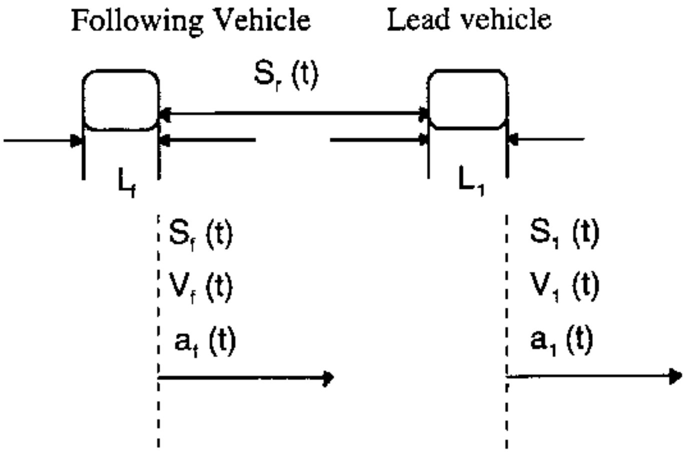

Figure B.2.1-1. Vehicle Following

The spacing between the two vehicles measured from the front of the following vehicle to the rear of the lead vehicle is given by

Eq. 1

$$S_r(t) = S_l(t) - L_l - S_f(t)$$

where

Eq. 2

$$S_l(t) = S_l(0) + \int_0^t V_l(\tau)d(\tau)$$

Eq. 3

$$S_f(t) = S_f(0) + \int_0^t V_f(\tau)d\tau$$

and

Eq. 4

$$V_l(t) = V_l(0) + \int_0^t a_l(\tau)d\tau$$

Eq. 5

$$V_f(t) = V_f(0) + \int_0^t a_f(\tau)d\tau$$

If the decelerations $a_l(t)$ and $a_f(t)$ and initial positions and velocities are specified, the MSS can be calculated as follows:

Assume that the two vehicles travel in the same direction but in two separate lanes. The position of the vehicles at time t = 0 is shown in Figure B.2.1-2.

Let t_s be the stopping time of the following vehicle. Then

Eq. 6

$$V_f(0) + \int_0^{t_s} a_f(\tau)d(\tau) = 0$$

Eq. 7

$$S_f(t) = S_f(0) + \int_0^t V_f(\tau)d(\tau), \forall t \le t_s$$

and Eq. 8

$$S_f(t) = S_f(t_s), \forall t > t_s$$

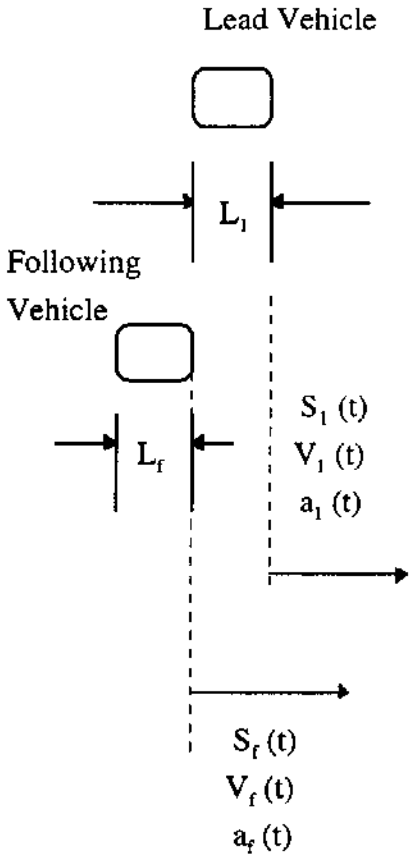

Figure B.2.1-2. Hypothetical Vehicle Motion

The position of the leading vehicle at each time t is given by

Eq. 9

$$S_l(t) = S_l(0) + \int_0^t V_l(\tau)d(\tau), \forall t \le t_s$$

The relative spacing at each time t is given by

Eq. 10

$$S_r(t) = S_l(t) - L_l - S_f(t)$$

If both the leading and following vehicle are in the same lane, then $S_r(t) > 0$ for all $t \in (0,t_s]$ will imply no collision, whereas $S_r(t) < 0$ at some $t = t_c \in (0,t_s]$ will imply collision.

The MSS value denoted by S_{min} is given as $S_{min} = -\min S_r(t)$, " $t \in (0,t_s]$

In other words S_{min} is equal to the maximum distance by which the following vehicle would overtake the leading vehicle at any time t in the interval $[0,t_s]$ in the scenario shown in Figure B.2.1-2.

Based on the above analysis, we adopt a numerical method to calculate S_{min}. Assume that the following vehicle brakes and it does so by following the given deceleration profile, and comes to a full stop at $t=t_s$. We divide the interval $[0,t_s]$ into small time steps and consider the time instants $t = 0, T_s, 2T_s, ..., kT_s$ where T_s is the length of the time step and k is an integer with the property $kT_s \leq (k+1)T_s$. The method of calculation of S_{min} is shown in the flowchart of Figure B.2.1-3.

B.3 VEHICLE FOLLOWING CONCEPTS

B.3.1 Motivation

With advances in technology and in particular in vehicle electronics, systems that were previously considered impossible to implement or toocostly are becoming feasible and available. One such system is a functional extension of the classic cruise control. It consists of a controller that uses a sensor to measure the relative distance and the relative speed to any vehicle ahead and controls a throttle and a brake actuator in order to follow at the same speed and maintain a desired relative distance. The relative distance may be characterized in terms of a constant length or it may be a function of the speed. If the majority of vehicles have such a controller on board, we can have an environment where vehicles follow each other automatically, in the same highway lane, without any other kind of interaction such as communication between them. The highway may provide a level of support to the vehicles by transmitting information about road conditions, congestion, routing suggestions and possibly recommended speeds. If the vehicles do not communicate and do not require any infrastructure support they are said to operate autonomously. A system like that, may provide a capacity increase by smoothing out traffic flow and eliminating the mistake that human drivers tend to do, that is to follow at short and unsafe distances and then overcorrecting by slowing down too much when a vehicle ahead starts to decelerate.

A further functionality enhancement comes by allowing the vehicles to communicate and notify each other about their braking intentions. Also the infrastructure may become involved in setting the desired velocity for each section of the highway communicating to vehicles about the need for emergency braking and coordinating the flow of the traffic. Such systems may achieve significant improvements in flow rates and capacity increases of the existing highways. In this section we describe a number of operating AHS concepts for automatic vehicle following.

B.3.2 Autonomous Vehicles

The simplest architecture is when the vehicles operate independently i.e., autonomously, using their own sensors. Each vehicle senses its environment, including lane position, adjacent vehicles and obstacles. The infrastructure may provide basic traveler information services, i.e., road conditions and routing information. The infrastructure may also provide some means to assist the vehicle in sensing its lane position. Many different systems have been proposed to help the vehicle sense its position, such as implanted magnetic nails, magnetic stripes, radar reflective stripes, RF cables, or GPS satellites[23].

In an autonomous environment, the vehicle does not rely on communication with other vehicles or the infrastructure in order to make vehicle following decisions. Each autonomous vehicle maintains a safe distance from the vehicle it is following or if a vehicle is not present within the sensing distance it travels at a constant speed in accordance with the posted speed limits and regional safety regulations and of course road conditions. In other words, if there is no vehicle ahead within the maximum safety distance, the vehicle travels at the speed limit or at a lower speed depending on the conditions.

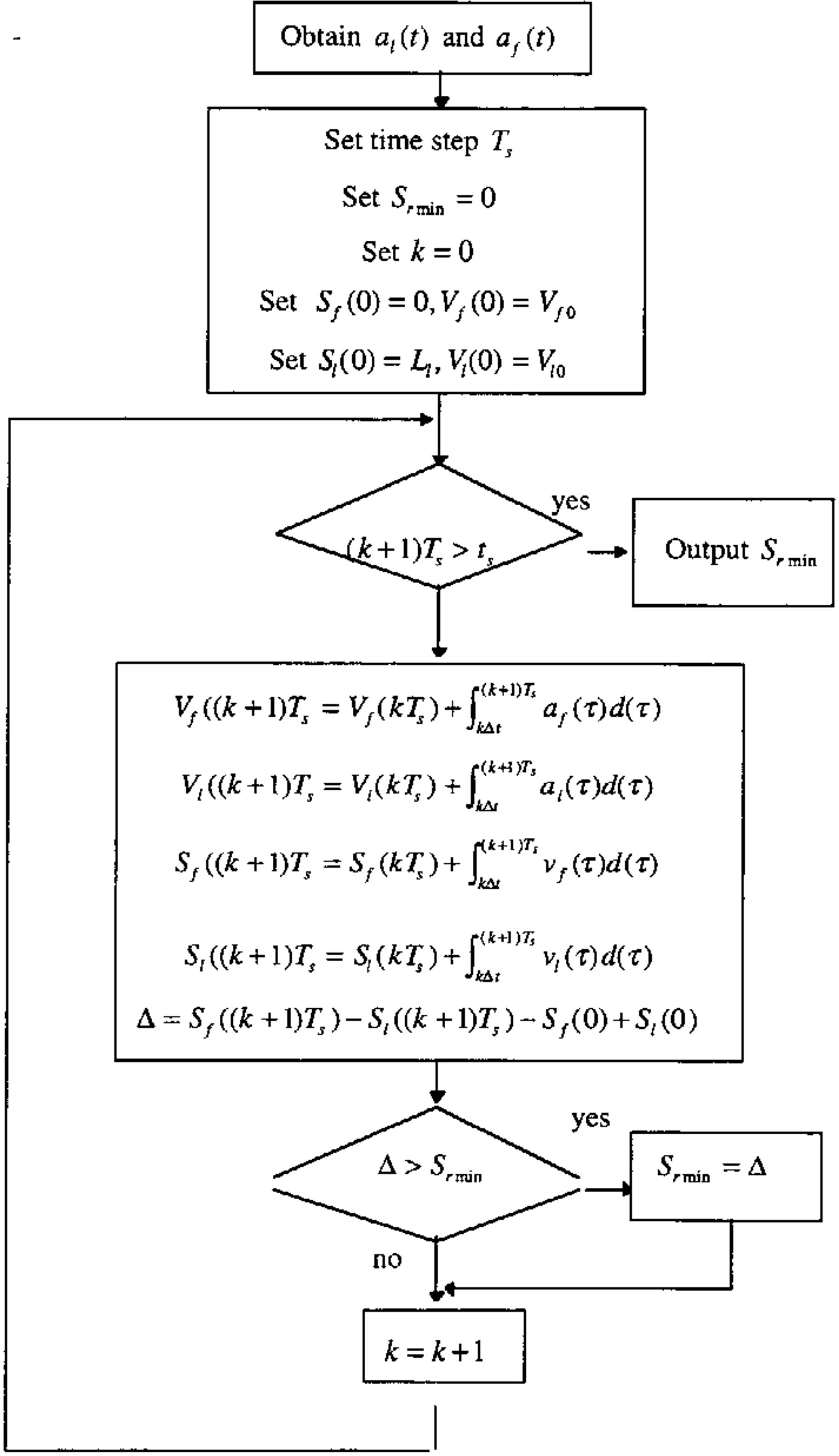

Figure B.2.1-3. Flowchart for MSS Calculation

Since there is no communication between vehicles for separation control, each vehicle senses the relative spacing and speed to the vehicle ahead and decides and selects a headway based on its own braking capabilities. The technology that allows the vehicle to sense the relative position and speed to the vehicle ahead can also be adapted to allow the vehicle to estimate the size and indirectly the vehicle class and braking capabilities of the vehicle ahead. The availability of this technology is not required but it will affect the capacity when there is mixing of vehicle classes, i.e., mixing of autonomous passenger vehicles, buses and heavy trucks as we will show in section 4.

B.3.3 Free Agent Vehicles - Infrastructure Supported

A vehicle is considered a Free Agent if it has the capability to operate autonomously but it is also able to receive communications from other vehicles and from the infrastructure. This implies that the infrastructure may get involved in a supporting role, by issuing warnings and recommendations for desired speed and headways but the infrastructure will not have the authority to issue direct control commands. Therefore this concept has been named "Infrastructure Supported". The fundamental difference between this concept and that described in subsection B.3.2 is that there is vehicle to vehicle and vehicle to infrastructure communication. Each vehicle communicates to the vehicle behind its braking capabilities and its braking intentions. This allows the vehicle behind to choose its headway. For example a shorter headway can be selected by a passenger vehicle if the vehicle ahead is a heavy truck or a bus. A larger headway must be selected by a heavy vehicle if the vehicle ahead is a passenger vehicle. A free agent vehicle uses its own sensors to sense its position and environment, including lane position, adjacent vehicles and obstacles.

The MSS between vehicles is expected to be smaller than that on conventional highways because of the intelligent longitudinal control system and vehicle to vehicle and infrastructure to vehicle communications. Each vehicle senses the relative spacing and speed to the vehicle ahead and decides and selects a headway based on its own braking capability, the braking capability of the vehicle ahead and the road surface conditions which are either sensed by the vehicle or are broadcasted from the infrastructure. When a vehicle starts to brake, it notifies the vehicle behind about the magnitude of its braking force. Even if we assumed a relatively primitive form of communication between vehicles like a line of sight communication that transmits the applied braking force, we can achieve better separation control as we eliminate the delay in deciding if the vehicle ahead is performing emergency braking.

B.3.4 Free Agent Vehicles - Infrastructure Managed

The Free Agent vehicles with Infrastructure Management is based on the assumption that the traffic is composed of vehicles acting as free agents while the infrastructure assumes a more active and more complex role in the coordination of the traffic flow and control of vehicles. Each vehicle is able to operate autonomously and uses its own sensors to sense its position and environment, including lane position, adjacent vehicles and obstacles. The difference in this centrally managed architecture is that the infrastructure has the ability to send commands to individual vehicles.

This is envisioned to be a "request-response" type architecture, in which individual vehicles ask permission from the infrastructure to perform certain activities and the infrastructure responds by sending commands back to the requesting vehicle and to other vehicles in the neighborhood.

It is expected and assumed that the infrastructure is able to detect emergency situations and whenever it detects such emergency, the infrastructure will have the responsibility to send an emergency braking command to all vehicles affected. This concept minimizes the delay in performing emergency braking. This allows for some further reduction of the minimum headway, compared to the other architectures presented so far. On the other side, the accurate timing of the emergency and stopping commands for each vehicle that must be issued by the infrastructure, requires accurate tracking of individual vehicles as well as extensive and frequent communications between individual vehicles and the infrastructure.

B.3.5 Platooning Without Coordinated Braking

This concept represents the possibility that the safest and possibly most cost-effective way of achieving maximum throughput is by making platoons of vehicles the basic controlling unit. This will boost road capacity by expanding on the concept of infrastructure managed control[17,18,19].

Platoons are clusters of vehicles with short spacing between individual vehicles in each group and longer spacing between platoons. The characterizing differentiation is that the platoon is to be treated by the infrastructure as an "entity" thereby minimizing some of the need for communicating with and coordinating individual vehicles. The infrastructure does not attempt to control any individual vehicle under normal circumstances, keeping the cost and necessary bandwidth low. The infrastructure is expected to be an intelligent agent which monitors and coordinates the operation of the platoons.

Tight coordination is required within the platoon in order to maintain a close spacing and this requires that the vehicles must be communicating with each other, constantly. The significantly longer inter-platoon spacing is required to guarantee no inter-platoon collisions.

Each vehicle is expected to be equipped with the sensors and intelligence to maintain its lane position, sense its immediate surroundings, and perform the functions of merging into and splitting off a platoon. It is not expected to accomplish lane changes, or merging and splitting without the infrastructure's or the platoon entity's help.

The main mode of operation of the infrastructure would be of a request-response type. Each vehicle's requests are processed and appropriate commands are sent to the appropriate vehicles/platoons to respond to that request. The infrastructure takes a more pro-active role in monitoring traffic flow, broadcasting traffic flow messages, advising lane changes to individual vehicles and platoons in addition to the usual information provider functions.

Once a vehicle has merged into a platoon, the headway maintenance controller must take into account the braking capabilities of each vehicle in the platoon in order to set an optimal separation distance that minimizes the possibility of collision.

Mixing of vehicle classes, although an implicit feature of the present highway system, creates a major complication because of the dissimilar braking characteristics of each vehicle class. Therefore it makes sense to form platoons of vehicles belonging to the same class, exclusively.

B.3.6 Platooning with Coordinated Braking

The Platooning architecture with Coordinated Braking is based on the concept of maximizing capacity by carefully coordinating the timing and degree of braking among the vehicles participating in a platoon entity. This allows the minimization of the spacing between vehicles without compromising safety.

The distinguishing feature of this concept is the minimization of intra-platoon spacing and the promise of higher capacity. Platooning, complete vehicle automation, global traffic flow management and controlled routing of different vehicle classes are important factors in achieving that goal. However, infrastructure investment and the complexity of the communication system that is required will be an important cost factor.

The intelligence will reside both on the vehicles and on the infrastructure. The vehicle uses the on-board intelligent control systems mainly for longitudinal control and platooning functions and also for lateral control.

The bulk of the communication will probably take place between vehicles. Vehicles that are at some distance apart are not likely to have a need to communicate as their dynamics and trajectories do not affect each other. At the same time it is desirable to minimize the transmitting power and range of vehicle to vehicle communication to minimize interference to other vehicles and to allow for efficient spectrum reuse.

B.3.7 Infrastructure Managed Slotting

Under the Infrastructure Managed Slotting concept, an infrastructure based control system creates and maintains vehicle "slots" in space and time. Slots can be thought of as moving roadway segments, each of which holds at most one vehicle at any time. The vehicles are identified and managed only by association with these slots. For simplicity in management i.e., to achieve slots of uniform length, vehicles that need more space may be assigned multiple slots. Heavy loaded light trucks may be assigned two slots, unloaded semis may be assigned three slots, loaded heavy trucks may be assigned four slots etc.

The basic slotting concept it that the slots should be of fixed length. The virtual leading edge of each slot can be thought of as a moving point that the vehicle assigned to the slot has to follow. Thus the controller on the vehicle is assigned to follow this virtual moving point, not another vehicle. In essence this relieves the requirement of using headway sensors on the vehicle and of sensing the relative distance and speed to any other vehicle. Under no circumstances is a vehicle allowed to violate the edges of its assigned slot.

The distinguishing feature of this concept is that the sensing requirements are theoretically simplified. At least, the vehicle does not need to sense the relative position and speed of other vehicles. Yet the vehicle must be able to sense its position relative to the edge of the slot and the virtual point it tries to follow. A global and accurate longitudinal position sensing system is required.

In terms of separation policy, the slotting method is bounded by the limitations of the inherently "synchronous" architecture. This means that the size of each slot must be sufficient such that the spacing between individual vehicles occupying a single slot is sufficient to avoid collisions under the worst case scenario. Thus the weakest link in the chain is the vehicle with the worst braking performance that the system tries to accommodate in a single slot. Once the spacing is set to accommodate such a vehicle, every other vehicle which has better braking performance will not be able to utilize this capability to shorten the spacing to the vehicle in front. There will be "dead space" in between them. Similarly, a vehicle that does not meet the minimum braking requirement to occupy a single slot will be assigned two (or more) consecutive slots, with the resulting inefficiency of wasting even more space than is really needed.

By comparison, an architecture where each vehicle optimizes the headway between itself and the vehicle in front based only on the braking capabilities of the two vehicles involved is inherently an "asynchronous" architecture, which results in true minimization of the unused space between vehicles.

The relative merits of a "synchronous" versus and "asynchronous" architecture have been intriguing the designers of computers and communications systems ever since digital systems became a reality. The typical tradeoff is complexity versus performance. It has been well established through extensive research in other fields that asynchronous architectures provide the potential for maximizing performance at the cost of increased complexity[24]. It is almost obvious that the same is true on the subject of the AHS separation policy architecture.

B.4 SPACING AND CAPACITY EVALUATIONS

In this section we present briefly the fundamental factors that affect traction during vehicle acceleration and braking.

Traction is what ultimately defines the braking capabilities of any kind of vehicle, under any kind of whether and road conditions. Then we develop likely emergency stopping scenarios for each AHS concept under consideration which we then use to calculate intervehicle spacing and capacity.

B.4.1 Adhesion and Friction

The friction force between two surfaces is defined as the force opposing the relative displacement of the two surfaces when a force is applied as shown in Figure B.4.1-1. In the context of vehicle traction this force is referred to as adhesion. Adhesion (attraction between two surfaces) and friction (resistance to relative motion of adjacent surfaces) are very complex physical phenomena. But for practical purposes it is common to use the approximation that the magnitude of the friction force F depends on two factors only: The normal force G between the two surfaces and a dimensionless coefficient of friction μ, such that:

Eq. 11

$$F = \mu G$$

The value of the coefficient of friction m depends on the characteristics of the two surfaces, primarily their smoothness and their hardness, and on the relative speed V_r between them. For most surfaces, as V_r increases, μ decreases. When the two surfaces do not move μ assumes a considerably higher value, referred to as the static friction coefficient.

Applying the general concept to the problem of vehicle traction, it is clear that the maximum Tractive or Braking Effort TE_{max} which can be utilized is limited by the tire to road surface adhesion.

Eq. 12

$$TE_{max} = \mu G_a$$

where G_a is the weight on the wheels which apply the force. For propulsion G_a is the weight on the powered axle while for braking Ga represents the total vehicle weight G since the brakes act on all wheels. The actual weight distribution between front and rear axles depends on vehicle design and furthermore varies as a function of the actual deceleration due to the mass transfer phenomenon.

The change of μ with speed is very important in traction and friction. It makes braking at high speeds more difficult than at low speeds because it increases the possibility of skidding. Any spinning or skidding of the wheels results in a rapid increase of the relative speed V_r between the

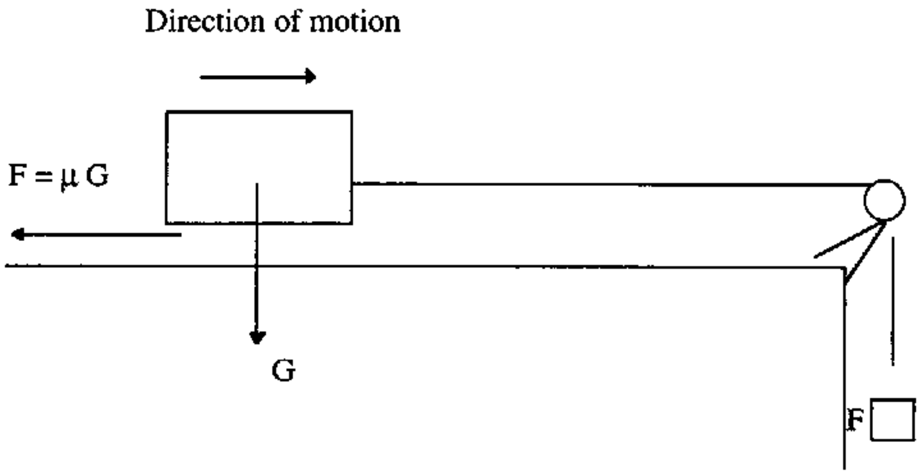

Figure B.4.1-1. Physical Representation of Friction Force F

wheels and the road surface and therefore a sudden reduction of μ. As a result, traction is lost. To restore the friction coefficient spinning or skidding must be terminated by reducing the tractive or braking effort. This is the principle of operation of the so called Antilock Braking Systems (ABS).

The value of μ for highway vehicles depends on the type and condition of the surface. A range of values for most classes of vehicles is shown in Figure B.4.1-2[8].

The braking ability of all vehicles is best on dry pavement. It degrades substantially on wet pavement and braking ability is virtually lost on snow.

In our analysis, we use data from vehicle tests performed by established authorities. For passenger vehicles, we use information from the "Consumer Reports" publication[9] and the consumer oriented "Road and Track" magazine[10]. For heavy vehicles like buses and trucks, we obtained information from actual tests[11]. Based on these data, we have estimated the braking capabilities of a range of passenger and heavy vehicles on dry, wet and snowed road pavement. In a more or less expected fashion, we found that sports cars can achieve the best braking distances (highest deceleration), followed by middle and upper class medium size vehicles (such as in the "sports sedan" category), followed by small or economy class vehicles. The last finding is a little counter intuitive, based on the fact that small vehicles are light weight thus require less energy dissipation to achieve braking and are less demanding of good tire performance. Yet there is an obvious trend for auto manufacturers to try to match the braking capabilities with the acceleration capabilities of a given vehicle. We found that the trend is to offer approximately double the deceleration (in g's) to the available acceleration (also in g's) in low gear. That's a ball park figure, of course, and deviations do exist.

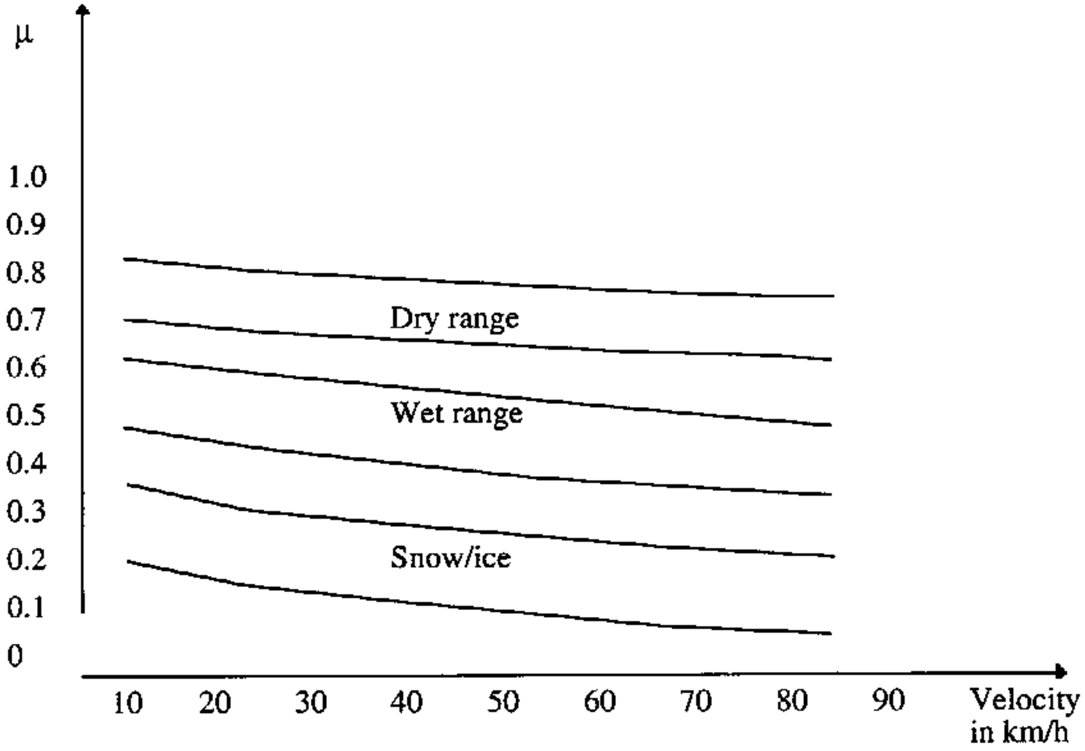

Figure B.4.1-2. Friction Coefficient of Vehicles with Rubber Tires

The braking capability of any vehicle degrades on wet pavement by a factor determined by the texture of the pavement and the type of tires used. We represent that as a change in the friction coefficient m. The data collected give a quantitative estimate of the friction coefficient on dry, wet and snowed pavement. The numbers of course vary depending on the vehicle, its tires and the presence of ABS. A typical vehicle that can achieve 0.8g deceleration on dry pavement can go down to 0.55g in wet conditions and to as low as 0.15g in snow conditions. The collected braking test results are presented in Appendix A.

In our study, we simplified somewhat our assumptions regarding the friction coefficient μ. Instead of assuming a maximum deceleration of 1g and scaling it by the typical value of μ, i.e., 0.8 for passenger vehicles, we used the value 0.8g for maximum deceleration and assumed that μ is 1.0. This does not affect the results for braking on dry road pavement. Then for wet road conditions we assumed a worst case scenario where the friction coefficient becomes half, i.e., μ becomes 0.5 while the maximum deceleration remains at 0.8g for passenger vehicles. Similarly, instead of assuming different values of μ for buses and for heavy trucks, we used the same value for all of them, but we used a different value of maximum deceleration for each class. We used 0.4g maximum deceleration for buses and 0.3g maximum deceleration for heavy trucks. These numbers are based on measurements on actual vehicles, and the data can be found in Appendix A.

The maximum deceleration that each vehicle can achieve depends on many factors and therefore it cannot be predicted exactly. It depends mostly on the tires of course, like the quality and type of tread, hardness, temperature, inflation pressure and the age of the tire. It also depends on the size and type of friction materials in the brakes, the mass distribution of the vehicle, the presence of ABS and many other factors. In our analysis we simplify these complex dependencies by using the abstraction of uniform value of μ and assuming appropriate values for maximum deceleration for different classes of vehicles, without affecting the accuracy of the results.

During the emergency braking phase the jerk is not intentionally limited and the maximum deceleration is allowed to be as large as the vehicle can achieve. The jerk clearly depends on the mass of the vehicle first and on the hydraulic brake system second. It clearly depends on the rate of change of the force that the driver applies on the brake pedal in the case of manually driven vehicles. For automated vehicles it will depend on the dynamics of the brake actuator. It would simply be inversely proportional to the mass of the vehicle if all the vehicles had exactly the same actuators and hydraulic systems, but this is certainly not going to be the case.

Based on our experience with an actual brake system which is in use in a prototype automated passenger class vehicle, we made an educated guess for other classes of vehicles. We assumed that the maximum jerk is limited to 50 $meters/sec^3$ for passenger vehicles, 40 $meters/sec^3$ for buses and 30 $meters/sec^3$ for heavy loaded trucks.

B.4.2 Uniform Versus Non-uniform Braking

For a realistic estimation of the theoretical capacity, we have assumed a "typical" maximum deceleration level for each class of vehicles, based on actual test data. Since discrepancies of 10% or more can be clearly seen in the braking capabilities among vehicles of the same class, we have made the assumption of a 10% discrepancy in maximum deceleration between the leader and the follower in the sense that the follower has inferior maximum deceleration capability, an assumption which inevitably generates the need for more spacing.

To be realistic, this discrepancy exists mostly at the limit of the braking capability of the vehicles, when braking occurs in the unstable region where the slope of μ versus wheel slip is negative as seen in Figure B.4.2-1[7]. At that point, demanding slightly higher deceleration results in skidding of the tires and in a sharp reduction in the μ and in overall deceleration. In our effort to

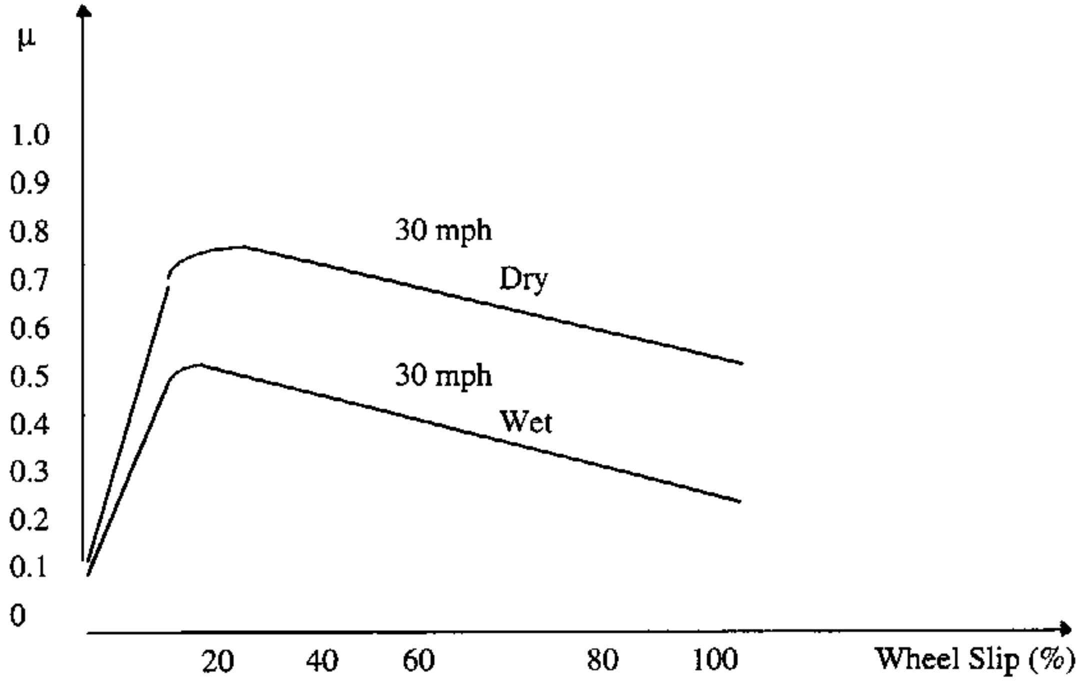

Figure B.4.2-1. Braking Coefficient Versus Slip

represent a realistic worst case scenario, we assumed 10% deviation from the maximum braking capability for the following vehicle in all cases of unrestricted braking, i.e., when the traction of the tires is pushed to the limits. On the other hand, braking by applying less than the maximum deceleration is easier because we can stay away from the unstable region of the μ curve. This can be used to our benefit if we impose a limit in deceleration for all vehicles. This limit is a common denominator that all vehicles should be able to meet by a proper design of their control system. This is the definition of the concept we will henceforth call "uniform braking". By staying away from the unstable braking region we can almost guarantee a better control of the magnitude of the deceleration. This justifies using only 5% deviation from the nominal braking capability for the follower in the case of uniform braking. Uniform braking is more crucial in platooning where, in the interest of efficiency, vehicles within each platoon have to have similar performance. For completeness and for the sake of comparison, we analyzed the effects of uniform braking both in platooning and non-platooning environments.

The concept that all vehicles should be restricted to a closely matched (i.e. uniform) degree of deceleration is clearly an architectural decision. We assumed that the braking deceleration on a dry road can be restricted to 0.5g for all passenger vehicles, 0.3g for all buses and 0.2g for all heavy trucks. The idea here is to use a number that every vehicle in its respective class can comfortably achieve. This helps guarantee that the deviation from one vehicle to another will be less than 5% in the worst case. So we used a 5% discrepancy in the deceleration of the leading and following vehicle to represent the worst case mismatch in the case of uniform braking.

B.4.3 Mixing of Vehicle Classes

The mixing of different classes of vehicles on the same AHS will affect capacity due to the different braking capabilities of the different classes of vehicles. In out analysis we consider three different vehicle classes, possessing fundamentally different characteristics: Passenger vehicles (P), buses (B) and heavy trucks (T).

This leads to the following possible combinations:

(a) PP: A Passenger vehicle leading a Passenger vehicle

(b) PB: A Passenger vehicle leading a Bus

(c) PT: A Passenger vehicle leading a Truck

(d) BP: A Bus leading a Passenger vehicle

(e) BB: A Bus leading a Bus

(f) BT: A Bus leading a Truck

(g) TP: A Truck leading a Passenger vehicle

(h) TB: A Truck leading a Bus

(i) TT: A Truck leading a Truck

We made the following distinctions in mixing possibilities:

a) No mixing.

Traffic consisting of passenger vehicles only, with 0% mixing of other vehicle classes among the passenger vehicles. In this case, the passenger vehicle to passenger vehicle (PP) minimum headway was assumed between all vehicles.

b) Allowed mixing of vehicle classes.

All cases of mixing assume uniform mixing, i.e., the minority vehicles are uniformly distributed among the population of passenger cars. This is a realistic assumption as long as the percentage of mixing is fairly low.

Case 1:

Traffic consisting of passenger vehicles with 5% mixing of buses. In this case, the passenger vehicle to passenger vehicle (PP) minimum headway was assumed between 90% of the vehicles, passenger vehicle to bus (PB) minimum headway between 5% of the vehicles and bus to passenger vehicle (BP) between 5% of the vehicles.

Case 2:

Traffic consisting of passenger vehicles with 5% mixing of trucks. In this case, the passenger vehicle to passenger vehicle (PP) minimum headway was assumed between 90% of the vehicles, passenger vehicle to truck (PT) minimum headway between 5% of the vehicles and truck to passenger vehicle (TP) between 5% of the vehicles.

Case 3:

Traffic consisting of passenger vehicles with 2.5% mixing of buses and 2.5% mixing of trucks. In this case, the passenger vehicle to passenger vehicle (PP) minimum headway was assumed between 90% of the vehicles, passenger vehicle to bus (PB) minimum headway between 2.5% of the vehicles passenger vehicle to truck (PT) minimum headway between 2.5% of the vehicles bus to passenger vehicle (BP) between 2.5% of the vehicles. and truck to passenger vehicle (TP) between 2.5% of the vehicles.

Case 4:

Traffic consisting of passenger vehicles with 5% mixing of buses. and 5% mixing of trucks. In this case, the passenger vehicle to passenger vehicle (PP) minimum headway was assumed between 80% of the vehicles, passenger vehicle to bus (PB) minimum headway between 5% of the vehicles passenger vehicle to truck (PT) minimum headway between 5% of the vehicles bus to passenger vehicle (BP) between 5% of the vehicles. and truck to passenger vehicle (TP) between 5% of the vehicles.

B.4.4 Autonomous Vehicles

In the case of autonomous vehicles, each vehicle relies on its own sensors to determine the motion intentions of the leading vehicle. Since there is no vehicle to vehicle communication, each vehicle has to use relative speed and spacing measurements to determine the intentions of the vehicle ahead. Therefore, in calculating a safe intervehicle spacing we consider the following worst case stopping scenario.

The acceleration (actually deceleration) profile of the leading and following vehicles involved in a braking maneuver is assumed to follow the trajectories shown in Figure B.4.4-1.

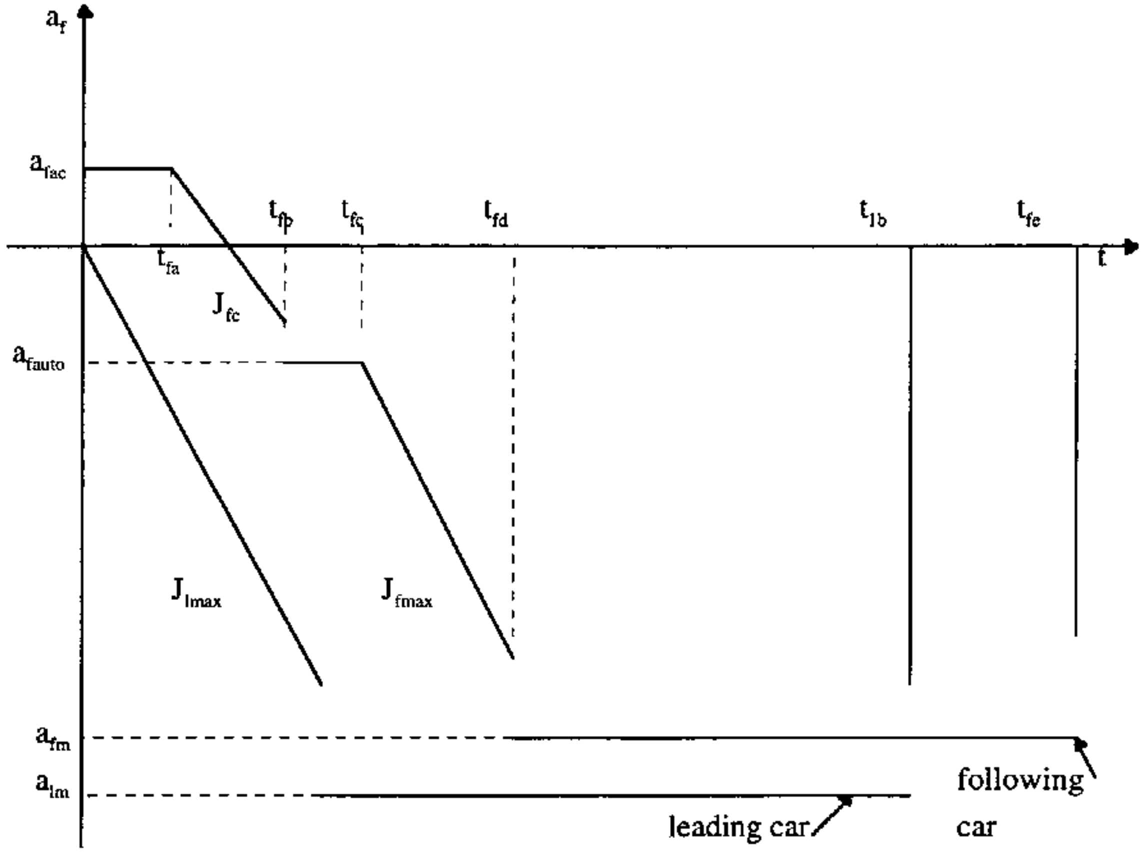

Figure B.4.4-1. Autonomous Vehicles

The leading vehicle performs emergency braking at time t = 0, at a maximum rate of change (jerk) equal to J_{lmax} until it reaches a maximum deceleration of a_{lm}. The follower, which might have been accelerating initially, at a_{fac} starts decelerating after a detection and brake actuation delay equal to t_{fa} in an effort to maintain the desired spacing. Since initially the follower is not aware that the leader is performing emergency braking, it limits its jerk and deceleration to J_{fc} and a_{fauto} respectively, in an effort to meet the vehicle control objective and at the same time maintain passenger comfort. The follower initiates emergency braking at $t = t_{fc}$. At this time passenger comfort is no longer a crucial issue and braking is done with maximum jerk J_{fmax} and maximum deceleration a_{fm}.

In this paper we use the above stopping scenario to calculate the minimum time headway for collision free vehicle following by substituting appropriate numerical values for all the above parameters.

In evaluating the above scenario we adopted a set of likely initial conditions at the onset of braking. The assumptions regarding the initial conditions are the following: The leader has been traveling at a speed of

60 miles per hour while the follower has an instantaneous velocity 5% higher, i.e. 63 miles per hour and an instantaneous acceleration $a_{fac} = 0.15g$. These conditions represent the realistic scenario that the follower had been performing a position adjustment as in trying to catch up with the leader. Therefore the vehicle is accelerating just before it has to start braking. When the vehicle detects that the leader is braking (which involves a 0.1 sec delay for detection and a 0.1 sec delay in the actuator) it starts braking until it reaches the maximum allowable deceleration $a_{fauto} = -0.1g$ for passenger comfort.

The vehicle initially applies a limited amount of braking because at the onset of braking it is not known if the leader is simply slowing down or performing emergency braking. If the follower applies emergency braking every time it detects the leader slowing down it would be detrimental to the stability of the traffic flow. Therefore the follower applies limited braking at first, with the objective of not upsetting the quality of the ride of the passengers or the position and velocity error of any vehicles behind. For this reason, the Jerk is limited to 5 meters/sec^3 during this phase.

Eventually, the follower will detect that the headway is diminishing rapidly and therefore the leader is performing an emergency braking maneuver. We assumed that the detection of emergency braking involves 0.3 seconds of delay.

Using these parameter values, we computed the necessary headways different road conditions and levels of mixing of classes of vehicles. The spacing results are presented in Table B-1 for the case of dry road surface. The spacing results for the case of wet road surface are presented in Table B-2.

The spacing calculations in Tables 1 and 2 are based on the assumption that vehicles can brake with maximum possible deceleration depending on their capabilities. Another possible scenario is to use the concept of uniform braking that limits the maximum deceleration and maximum jerk to values that could be met and used by all vehicles of the same class. These limits will make the braking performance of the vehicles very similar. Using this scenario we calculated spacings based on the vehicle values shown in Table B-3. In this case due to uniformity we assume 5% deviation between decelerations of vehicles of the same class. This 5% deviation accounts for inaccuracies in measuring acceleration/deceleration and maintaining the desired one using the on board vehicle controller.

Based on the above spacings the maximum possible throughput referred to as the capacity C measured as the number of vehicles per hour per lane is given by the formula

Eq. 13

$$\begin{gathered}C = (360000V)[(100-2W_T-2W_B)(L_P+h_{PP}V) \\ + W_T(L_P+h_{PT}V+h_{TP}V+L_T) \\ + W_B(L_P+h_{PB}V+h_{BP}V+L_B)]^{-1}\end{gathered}$$

where V is the speed of flow measured in meters/sec, L_p is the length of passenger cars, L_B is the length of buses and L_T is the length of trucks with trailers, in meters. The parameter h_{PP} is the minimum time headway between passenger cars, h_{PT} is the minimum time headway between a passenger car and a truck that follows it, h_{TP} is the minimum time headway between a truck and a passenger car that follows it, h_{PB} is the minimum time headway between a passenger car and a bus that follows it and h_{BP} is the minimum time headway between a bus and a passenger car that follows it, in seconds. W_B is the percentage of buses and W_T is the percentage of trucks in the mix. We use eq. (13) and the numerical results of Tables B-1, B-2 and B-3 to calculate the capacity values which are presented in Table B-4A.

In eq. 13 we assumed that a bus or a truck is always between two passenger vehicles and the passenger vehicle recognizes when its leader is a truck or a bus. This is a reasonable assumption because the radar sensors used for ranging measurements can be equipped with the feature of being able to distinguish different classes of vehicles. Without this assumption each vehicle has to assume the worst possible situation which is the one where each vehicle treats its leader as a passenger vehicle i.e., a vehicle with the highest possible braking capability. In this case eq. 13 is modified to

Eq. 14

$$C = (360000V)[(100-2W_T-2W_B)(L_P+h_{PP}V) + W_T(L_P+h_{PT}V+h_{PP}V+L_T) + W_B(L_P+h_{PB}V+h_{PP}V+L_B)]^{-1}$$

The capacity results for this case are listed in Table B-4B.

B.4.5 Free Agent Vehicles - Infrastructure Supported

In the case of Free Agent Vehicles we assumed the braking scenario shown in Figure B.4.5-1. The use of vehicle to vehicle communication simplifies the task of determining when the leading vehicle is performing emergency braking. The leader at t = 0 starts performing emergency braking. At t = 0 it communicates its intention to the following vehicle. The following vehicle receives the information from the leader and verifies using its own sensors that it has to perform an emergency braking as well.

The assumptions regarding the initial conditions are the same as in the previous case: We assume the leader has been traveling at a speed of 60 miles per hour while the follower has an instantaneous velocity of 63 miles per hour and an instantaneous acceleration of 0.15g, as if the follower had been trying to catch up with the leader.

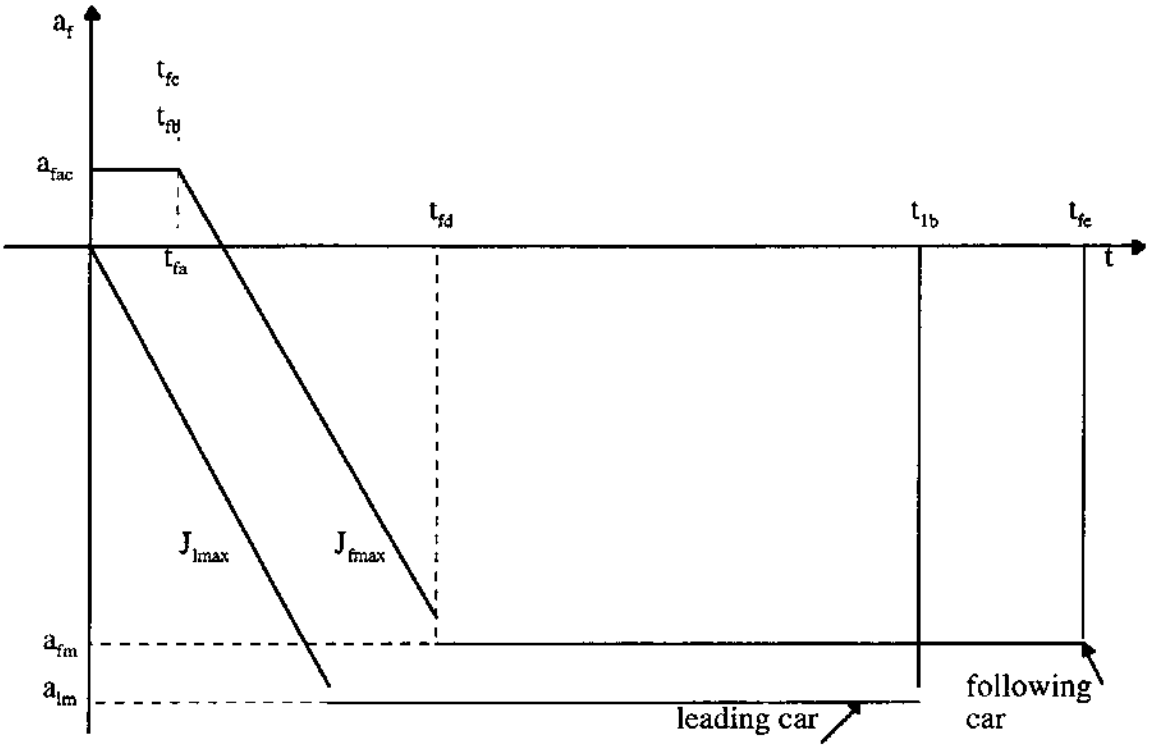

Figure B.4.5-1. Infrastructure Supported Free Agent Vehicles

When the vehicle detects the leader is braking and at the same time receives the information that this is emergency braking, it bypasses the limited jerk/limited braking stage shown in Figure B.4.5-1 in the previous section. In Figure B.4.4-1, we have clustered the detection and the actuation delay into a single 0.1 seconds delay before the follower applies emergency braking. In effect, the actuation delay is compensated for by the fact that the vehicle knows in advance it will have to apply the brakes, and the brake actuator may be preloaded. Therefore in Figure B.4.5-1 we assume t_{fa} = 0.1 sec and t_{fc} = 0.1 sec. The minimum headway results together with the numerical values of the variables shown in Figure B.4.5-1 are presented in Tables B-5, B-6 and B-7. Equation (13) is used to calculate capacity for different levels of mixing of different classes of vehicles. The results are shown in Table B-8.

B.4.6 Free Agent Vehicles - Infrastructure Managed

In the case of Free Agent Vehicles with infrastructure management we have assumed that the infrastructure has the primary responsibility of detecting the presence of emergencies and synchronizing the onset of emergency braking of all vehicles involved. This results in the most favorable timing for braking delays.

The infrastructure may simply issue the command "Begin emergency braking now" and all vehicles receiving this will have to apply maximum braking without further delay. This, not only simplifies the task of determining when the leading vehicle is performing emergency braking but also minimizes the relative delay in propagating the onset of emergency braking from each vehicle to the vehicle behind, effectively down to zero.

We have listed the actuation delay as a single 0.1 seconds delay before each vehicle applies emergency braking, but since all the vehicles receive the command at the same time the relative delay is zero and this is reflected in the value of the parameter t_{fc}. The time t_{fc} represents the total delay between the onset of emergency braking between the leader and the follower and in this case $t_{fc} = 0$.

The assumptions regarding the initial conditions are the same as before: The leader has been traveling at a speed of 60 miles per hour while the follower has an instantaneous velocity of 63 miles per hour and an instantaneous acceleration of 0.15g, as if the follower had been trying to catch up with the leader. The minimum headway results together with the numerical values of the variables shown in Figure B.4.6-1 are presented in Tables B-9, B-10 and B-11. Equation (13) is used to calculate capacity for different levels of mixing of different classes of vehicles. The results are shown in Table B-12.

B.4.7 Vehicles Platoons Without Coordinated Braking

In the platooning without coordinated braking case, we have assumed that each vehicle notifies the vehicle behind about its braking capabilities and the magnitude and timing of the braking force used.

When the platoon leader detects an emergency, it immediately notifies the vehicle that follows. There will be a delay while the message propagates from each vehicle to the vehicle behind, as well as an actuation delay. But the actuation delay is not affecting the scenario as long as it is approximately the same for each vehicle. We have assumed that the total delay is 0.1 seconds for every vehicle and it is represented by the parameter t_{fa}. Therefore we have accounted for only a 0.1 seconds total delay in propagating the message from each vehicle to the vehicle behind and this becomes the value of the parameter t_{fc}, which represents the delay of the onset of emergency braking.

The assumptions regarding initial conditions are as follows: The leader has been traveling at a speed of 60 miles per hour while the follower has an instantaneous velocity of 61.5 miles per hour. Since the platoon protocol involves a much tighter control of individual vehicle velocity than in the case of free agents, only a 2.5% difference is assumed in the initial vehicle velocities. The instantaneous acceleration was also taken to be 0g as it would be impossible for a vehicle in a platoon to be accelerating while the vehicle ahead is maintaining constant speed. Both the velocities and the accelerations of vehicles

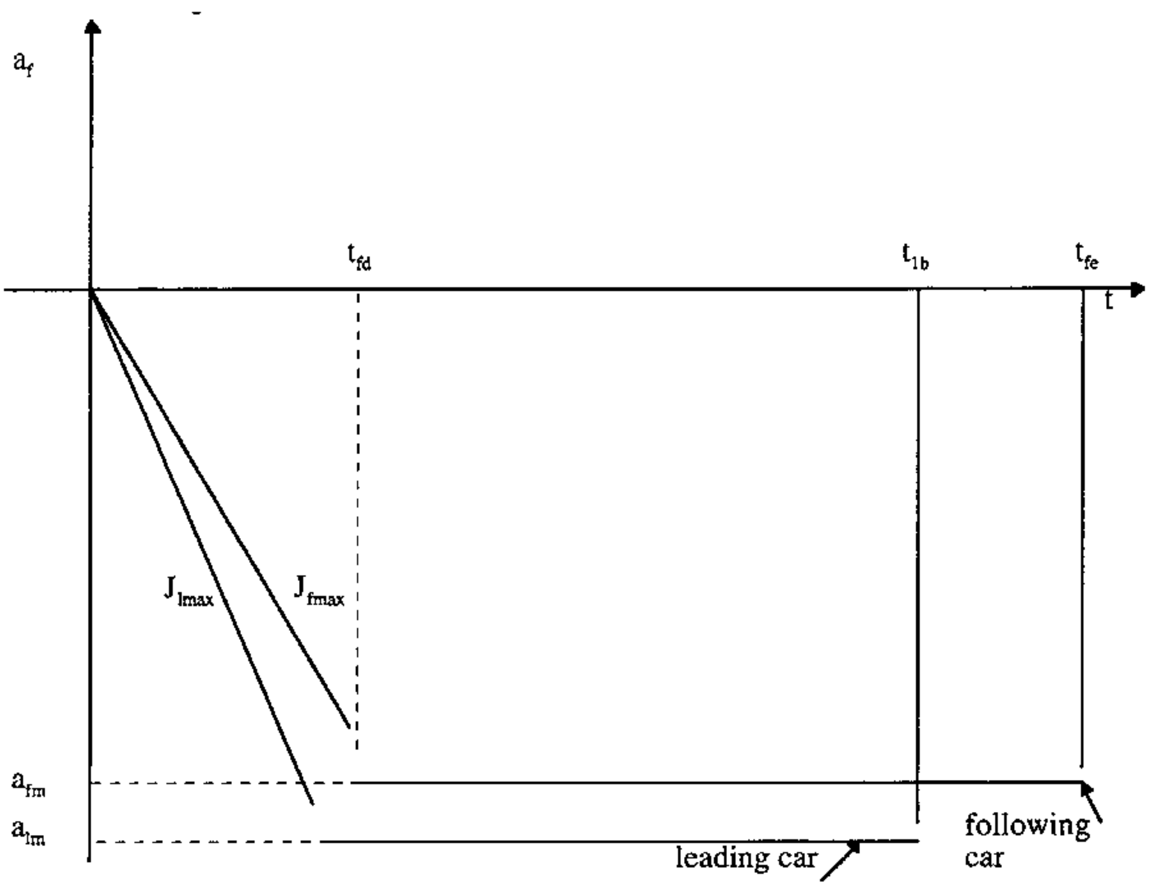

Figure B.4.6-1. Infrastructure Managed Free Agent Vehicles

in platoons are expected to be closely coordinated. In addition, for reasons explained earlier we assumed no mixing of vehicle classes.

The inter-platoon spacing depends on the concept used for platoon following. We compared three different concepts.

a) Autonomous platoons, where platoons do not communicate with each other and each platoon relies on its own sensors to detect the motion of a leading platoon. In this case, the inter-platoon spacing is calculated as in the case of autonomous vehicles. Therefore, each vehicle assumes t_{fc} = 0.1 seconds and each platoon entity assumes the parameters of autonomous vehicles: t_{fc} = 0.3 seconds for 10 car platoons and again t_{fc} = 0.3 seconds for 20 car platoons.

b) Free agent platoons supported by the infrastructure where the inter-platoon spacing is calculated as in the case of free agent vehicles with infrastructure support. Each vehicle in the platoon assumes t_{fc} = 0.1 seconds. Each platoon entity assumes the parameters of free agent infrastructure supported vehicles: t_{fc} = 0.1 seconds for 10 car platoons and t_{fc} = 0.1 seconds for 20 car platoons.

c) Free agent platoons managed by the infrastructure where the inter-platoon spacing is calculated as in the case of free agent vehicles with infrastructure management. Each vehicle in the platoon assumes t_{fc} = 0.1 seconds. Each platoon entity assumes the parameters of free agent infrastructure managed vehicles: t_{fc} = 0 seconds for

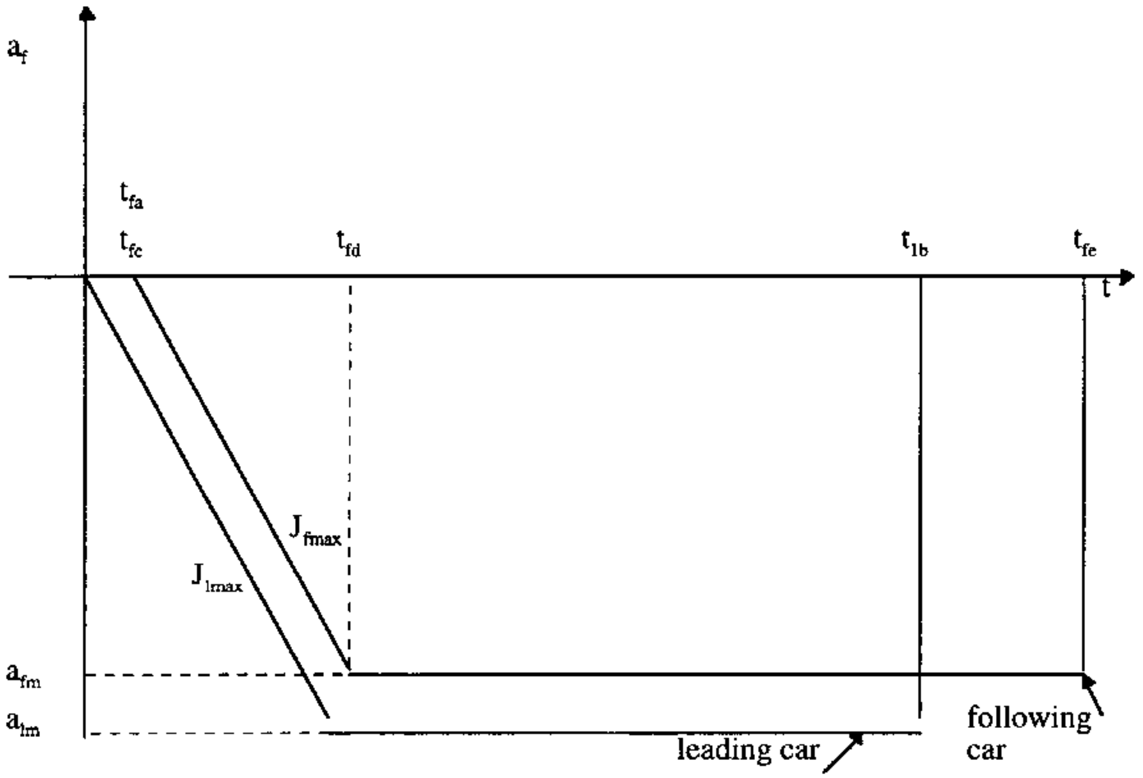

Figure B.4.6-1. Platoons Without Coordinated Braking

10 car platoons and $t_{fc} = 0$ seconds for 20 car platoons.

The capacity is calculated in each case using the equation:

Eq. 15

$$C = (3600\ V\ N)/((h_{pp}\ V + L_p)\ (N-1) + H_{pp}\ V + L_p)$$

where L_p is the length of each vehicle in the platoon (we have assumed vehicles of same length), h_{pp} is the intra-platoon time headway, H_{pp} is the inter-platoon time headway and N is the number of vehicles in the platoon. The resulting intra-platoon spacing for platoons without coordinated braking can be found in Table B-13. The capacity results are presented in Table B-14.

B.4.8 Vehicle Platoons With Coordinated Braking No Delay

In platooning with coordinated braking we assume that the vehicle in the platoon leader position assumes the primary responsibility of detecting emergencies and notifying each and every vehicle in the platoon. This notification takes place through a network style vehicle to vehicle communications system that minimizes the communication delays. The platoon leader notifies all the vehicle in the platoon about the magnitude of the braking force that is to be applied and also the exact time this is to be applied. This architecture, not only eliminates the need for each vehicle to detect the magnitude of braking and if the braking should be limited or emergency braking, but also can adjust the onset of emergency braking for an effective 0 seconds relative delay, or even to an artificial negative relative delay.

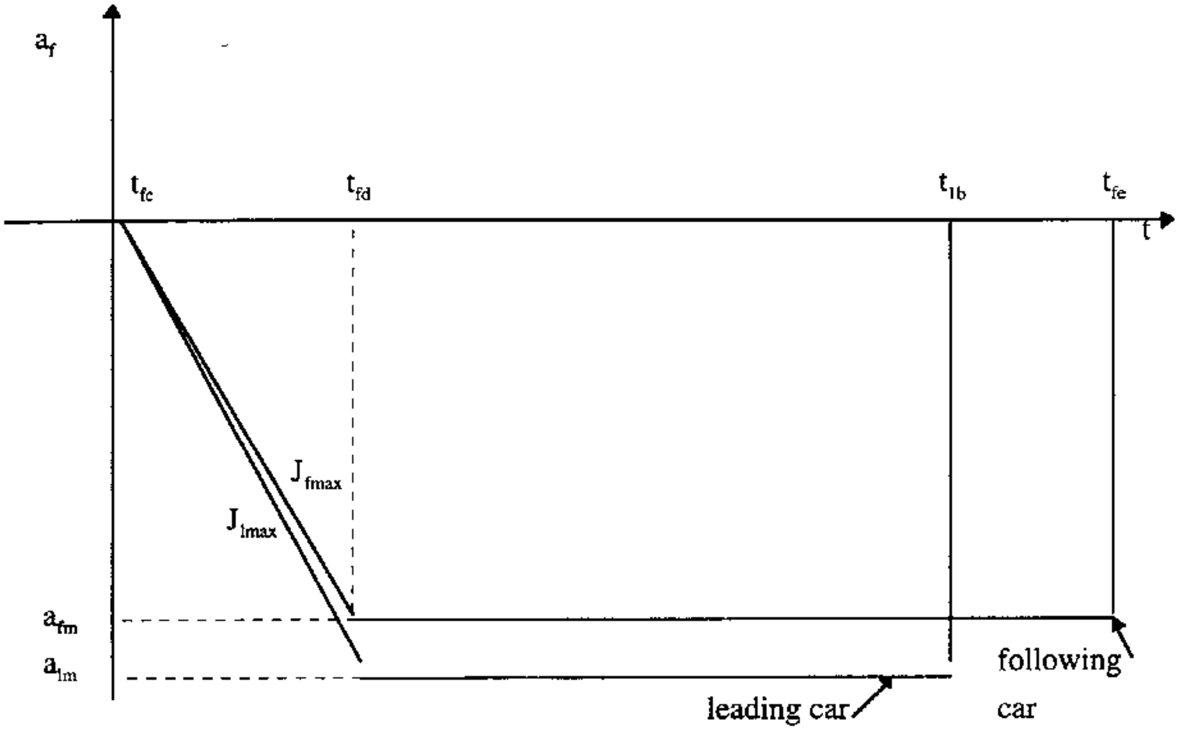

Figure B.4.7-1. Platoons with Coordinated Braking and No Delay

The brake actuation delay can be completely compensated for and it is not affecting the scenario as long as it is approximately the same for each vehicle. We have assumed it is 0.1 seconds on every vehicle. Therefore we have made the assumption of exactly 0 seconds total delay for the onset of braking for each vehicle in the platoon and this is the value of the parameter t_{fc} which represents this delay.

The other assumptions regarding the initial conditions are the same as in all architectures involving platoons. The leader has been traveling at a speed of 60 miles per hour while the follower has an instantaneous velocity of 61.5 miles per hour. The instantaneous acceleration was also take to be 0g as it would be impossible for a vehicle in a platoon to be accelerating while the vehicle ahead is maintaining constant speed. Both the velocities and the accelerations of vehicles in platoons are expected to be closely coordinated.

For the inter-platoon spacing we used and compared three different concepts.

a) Autonomous platoons where the inter-platoon spacing is calculated as in the case of autonomous vehicles. Therefore, each vehicle assumes $t_{fc} = 0$ seconds and each platoon entity assumes the parameters of autonomous vehicles: $t_{fc} = 0.3$ seconds for 10 car platoons and again $t_{fc} = 0.3$ seconds for 20 car platoons.

b) Free agent platoons supported by the infrastructure where the inter-platoon spacing is calculated as in the case of free agent vehicles with infrastructure support. Each vehicle in the platoon assumes $t_{fc} = 0$ seconds. Each platoon entity assumes the parameters of free agent infrastructure supported vehicles: $t_{fc} = 0.1$ seconds for 10 car platoons and $t_{fc} = 0.1$ seconds for 20 car platoons.

c) Free agent platoons managed by the infrastructure where the inter-platoon

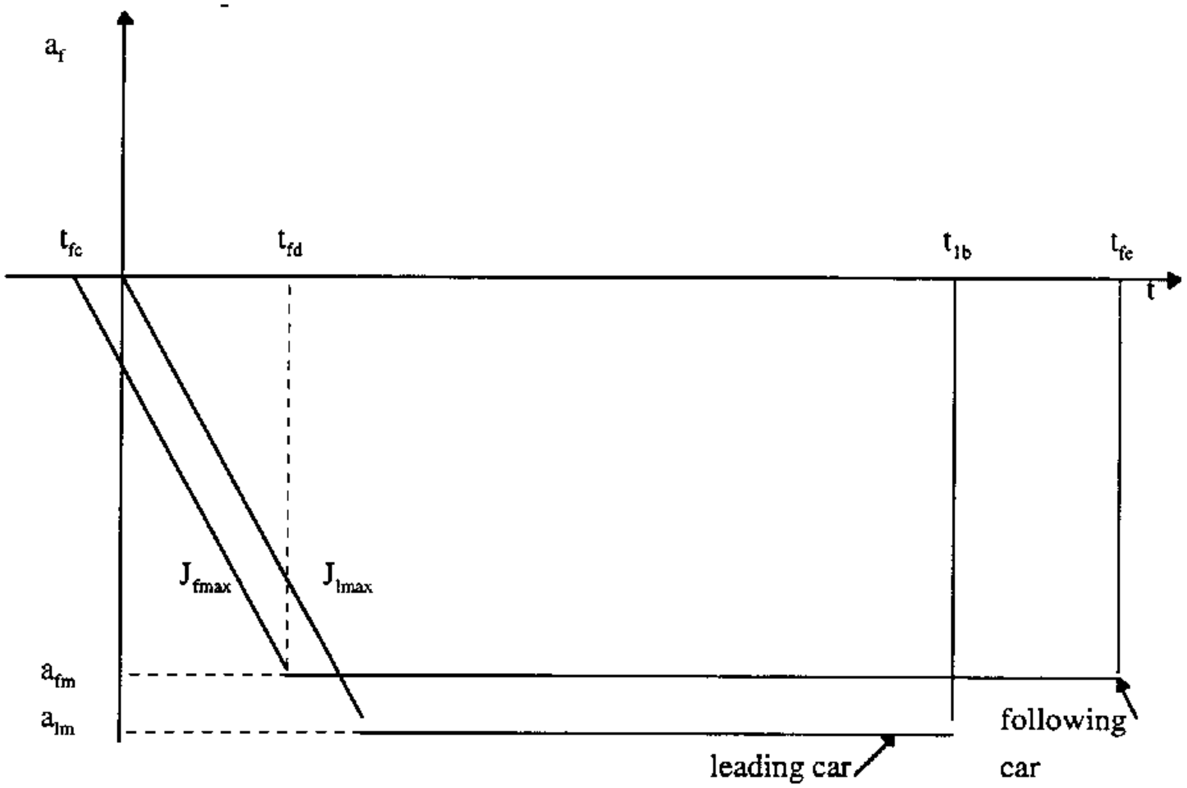

Figure B.4.8-1. Platoons with Coordinated Braking with Staggered Delay

spacing is calculated as in the case of free agent vehicles with infrastructure management. Each vehicle in the platoon assumes $t_{fc} = 0$ seconds. Each platoon entity assumes the parameters of free agent infrastructure managedvehicles: $t_{fc} = 0$ seconds for 10 car platoons and $t_{fc} = 0$ seconds for 20 car platoons.

The inter-platoon spacing results for platoons with coordinated braking are calculated using equation (15), based on the intra-platoon spacings presented in Table B-15. The capacity results are presented in Table B-16.

B.4.9 Vehicle Platoons with Coordinated Braking and Staggered Timing

This case is identical to the previous one except for the purposeful timing of the onset of emergency braking. In the platooning with coordinated braking case we have assumed the vehicle in the platoon leader position assumes the primary responsibility of detecting emergencies and notifying each and every vehicle in the platoon. This notification takes place through a network style vehicle to vehicle communications system that minimizes the communication delays. The platoon leader notifies all the vehicle in the platoon about the magnitude of the braking force that is to be applied and also the exact time this is to be applied. This architecture, not only eliminates the need for each vehicle to detect the magnitude of braking and if the braking should be limited or emergency braking, but also can adjust the onset of emergency braking to an artificial negative relative delay.

Therefore we have made the choice of using a 0.1 seconds total delay for the onset of braking for each vehicle in the platoon going from the tail to the head, in the sense that the tail of the platoon is requested to brake first, then the vehicle ahead after a delay of 0.1 seconds, until the command to begin braking becomes effective for the platoon leader. Therefore we used a negative value, -0.1 seconds, as the value of the parameter t_{fc} which represents the relative delay for two consecutive vehicles within the platoon.

We cannot omit mentioning the fact that the platoon leader which detects the presence of emergency is subsequently restrained from braking until every other vehicle in the platoon has begun braking. Therefore, while this architecture allows to minimize the necessary spacing between vehicles in the platoon, it increases the inter-platoon spacing requirement.

The other assumptions regarding the initial conditions are the same for all architectures involving platoons. For the inter-platoon spacing we used and compared several different concepts.

a) Autonomous platoons where the inter-platoon spacing is calculated as the sum of the inter-vehicle spacing used in the case of autonomous vehicles and the product of the coordinated braking delay with the number of vehicles in a platoon. Each vehicle in the platoon assumes t_{fc} = -0.1 seconds. Each platoon entity assumes t_{fc} = 1.3 seconds for 10 car platoons and t_{fc} = 2.3 seconds for 20 car platoons.

b) Free agent platoons supported by the infrastructure where the inter-platoon spacing is calculated as the sum of the inter-vehicle spacing used in the case of free agent vehicles with infrastructure support and the product of the coordinated braking delay with the number of vehicles in a platoon. Each vehicle in the platoon assumes t_{fc} = -0.1 seconds. Each platoon entity assumes tfc = 1.1 seconds for 10 car platoons and tfc = 2.1 seconds for 20 car platoons.

c) Free agent platoons managed by the infrastructure where the inter-platoon spacing is calculated as the sum of the inter-vehicle spacing used in the case of free agent vehicles with infrastructure management and the product of the coordinated braking delay with the number of vehicles in a platoon. Each vehicle in the platoon assumes t_{fc} = -0.1 seconds.

Each platoon entity assumes t_{fc} = 1.0 seconds for 10 car platoons and t_{fc} = 2.0 seconds for 20 car platoons.

The capacity is calculated using the following formula:

Eq. 16

$$C = (3600\ V\ N)/[(h_{pp}\ V + L_p)\ (N-1) + L_p + (H_{pp} + N\ t_b)\ V]$$

where L_p is the length of each vehicle in the platoon (we have assumed vehicles of same length), h_{pp} is the intra-platoon time headway, H_{pp} is the inter-platoon time headway, N is the number of vehicles in the platoon and t_b is the coordinated braking delay. The spacing is calculated using equation (16) based on the intra-platoon spacings given in Table B-17. The capacity results are presented in Table B-18.

B.4.10 Infrastructure Managed Slotting

The infrastructure managed slotting concept involves a different set of assumptions and parameters. We have not presented it in detail in the tables, except one table which shows capacity estimates under this architecture concept. We used the spacing data for passenger cars by assuming a doubling of all communication delays with an additional 3 meters to account for position inaccuracy, due to the inability to utilize space effectively by using the exact slot size for each vehicle. We also assumed that the follower has no initial acceleration. The capacities computed under these assumptions can be found in Table B-19.

B.5 DISCUSSION AND CONCLUSIONS

The capacity estimates for each concept considered are summarized in Table B-20. These results indicate that the capacity is reduced by 30% to 40% by going from dry road to wet road conditions under each concept. The capacity is also reduced by about 10% if all vehicles are required to use lower but similar braking force during emergency stopping. Mixing of different classes of vehicles reduces capacity by about 11% for 2.5% buses and 2.5% trucks and by about 23% for 5% buses and 5% trucks. Platooning with coordinated braking gives the highest capacities. infrastructure managed slotting gives the lowest. The use of vehicle to vehicle communication for notifying vehicles about the onset of braking used in the Free Agent and Platooning based concepts helps increase capacity considerably.

B.6 SYMBOLS AND NOTATION

PP: Passenger car leader, Passenger car follower

PB: Passenger car leader, Bus follower

PT: Passenger car leader, Truck follower

BP: Bus leader, Passenger car follower

BB: Bus leader, Bus follower

BT: Bus leader, Truck follower

TP: Truck leader, Passenger car follower

TB: Truck leader, Bus follower

TT: Truck leader, Truck follower

L_P: Length of a passenger vehicle, in meters

L_B: Length of a bus, in meters

L_T: Length of a truck with trailer, in meters

h_{PP}: Minimum time headway between Passenger car leader Passenger car follower, in sec.

h_{PB}: Minimum time headway between Passenger car leader, Bus follower, in seconds

h_{PT}: Minimum time headway between Passenger car leader, Truck follower, in seconds

h_{BP}: Minimum time headway between Bus leader, Passenger car follower, in seconds

h_{BB}: Minimum time headway between Bus leader, Bus follower, in seconds

h_{BT}: Minimum time headway between Bus leader, Truck follower, in seconds

h_{TP}: Minimum time headway between Truck leader, Passenger car follower, in seconds

h_{TB}: Minimum time headway between Truck leader, Bus follower, in seconds

h_{TT}: Minimum time headway between Truck leader, Truck follower, in seconds

V_{lo}: Leading Vehicle initial Velocity, in miles per hour.

V_{fo}: Following Vehicle initial Velocity, in miles per hour.

A_{lm}: The maximum achievable deceleration of the leading vehicle in g

A_{fm}: The maximum achievable deceleration of the leading vehicle in g

J_{lmax}: The maximum achievable jerk of the leading vehicle in meters/sec^3

J_{fmax}: The maximum achievable jerk of the following vehicle in meters/sec^3

μ_{lmax}: The maximum road-tire friction coefficient (dimensionless)

μ_{fmax}: The maximum road-tire friction coefficient (dimensionless)

A_{fauto}: The acceleration value under automatic brake control during soft braking, in g

A_{fac}: The initial acceleration value during vehicle following, in g

J_{fc}: The jerk value under automatic brake control during soft braking, in meters/sec^3

t_{fa} : Detection and brake actuation delay applicable to the following vehicle, in seconds.

t_{fc}: The time at which the following vehicle starts the emergency braking maneuver, in seconds

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APPENDIX B.1 VEHICULAR DATA REFERENCES

Braking performance comparisons of popular passenger vehicles on dry and wet roads.
(from Consumer Reports, March 1995) (Family sedans)

	Dry			Wet		
	Initial Velocity	**Stopping Distance**	**Deceler/n (avg. g)**	**Initial Velocity**	**Stopping Distance**	**Deceler/n (avg. g)**
Chrysler Cirrus Lxi	60 mph	145 ft	0.83 g	60 mph	167 ft	0.72 g
Mercury Mystique LS	60 mph	140 ft	0.86 g	60 mph	165 ft	0.73 g
Ford Contour GL	60 mph	148 ft	0.81 g	60 mph	158 ft	0.76 g
Honda Accord LX	60 mph	143 ft	0.84 g	60 mph	175 ft	0.69 g

Braking performance comparisons on Dry and Wet roads of popular passenger vehicles
(from Consumer Reports, May 1995) (Upscale sedans)

	Dry			Wet		
	Initial Velocity	**Stopping Distance**	**Deceler/n (avg. g)**	**Initial Velocity**	**Stopping Distance**	**Deceler/n (avg. g)**
Toyota Avalon XLS	60 mph	129 ft	0.93 g	60 mph	146 ft	0.82 g
Mazda Millenia S	60 mph	136 ft	0.88 g	60 mph	157 ft	0.77 g
Lexus ES300	60 mph	133 ft	0.90 g	60 mph	167 ft	0.72 g
Oldsmobile Aurora	60 mph	136 ft	0.88 g	60 mph	155 ft	0.78 g

Braking performance comparisons on Dry and Wet roads of popular passenger vehicles
(from Consumer Reports, June 1995) (Low-Priced Sedans)

	Dry			Wet		
	Initial Velocity	**Stopping Distance**	**Deceler/n (avg. g)**	**Initial Velocity**	**Stopping Distance**	**Deceler/n (avg. g)**
Mazda Protege ES	60 mph	135 ft	0.89 g	60 mph	167 ft	0.72 g
Chevrolet Cavalier LS	60 mph	133 ft	0.90 g	60 mph	165 ft	0.73 g
Nissan Sentra GXE	60 mph	142 ft	0.85 g	60 mph	158 ft	0.76 g
Saturn SL2	60 mph	138 ft	0.87 g	60 mph	157 ft	0.77 g

Braking performance comparisons on Dry and Wet roads of popular passenger vehicles
(from Consumer Reports, July 1995) (Mid-Sized Coupes)

	Dry			Wet		
	Initial Velocity	**Stopping Distance**	**Deceler/n (avg. g)**	**Initial Velocity**	**Stopping Distance**	**Deceler/n (avg. g)**
Dodge Avenger ES	60 mph	129 ft	0.93 g	60 mph	157 ft	0.77 g
Ford Thunderbird LX	60 mph	131 ft	0.92 g	60 mph	153 ft	0.79 g
Chevrolet Monte Carlo Z34	60 mph	139 ft	0.87 g	60 mph	165 ft	0.73 g
Buick Riviera	60 mph	133 ft	0.90 g	60 mph	147 ft	0.82 g

Braking performance comparisons on Dry and Wet roads of popular passenger vehicles (from Consumer Reports, August 1995) (Sport-utility vehicles)

	Dry			Wet		
	Initial Velocity	**Stopping Distance**	**Deceler/n (avg. g)**	**Initial Velocity**	**Stopping Distance**	**Deceler/n (avg. g)**
Ford Explorer	60 mph	148 ft	0.81 g	60 mph	181 ft	0.66 g
Jeep Grand Cherokee	60 mph	144 ft	0.84 g	60 mph	159 ft	0.76 g
Chevrolet Blazer	60 mph	156 ft	0.77 g	60 mph	172 ft	0.70 g
Land Rover Discovery	60 mph	143 ft	0.84 g	60 mph	202 ft	0.60 g

Braking performance comparisons on Dry and Wet roads of popular passenger vehicles (from Consumer Reports, September 1995) (Small, Cheap Cars)

	Dry			Wet		
	Initial Velocity	**Stopping Distance**	**Deceler/n (avg. g)**	**Initial Velocity**	**Stopping Distance**	**Deceler/n (avg. g)**
Hyundai Accent 4-door	60 mph	137 ft	0.88 g	60 mph	172 ft	0.70 g
Hyundai Accent 2-door L	60 mph	145 ft	0.83 g	60 mph	204 ft	0.59 g
Toyota Tercel 4-door DX	60 mph	156 ft	0.77 g	60 mph	195 ft	0.62 g
Toyota Tercel 2-door base	60 mph	153 ft	0.79 g	60 mph	193 ft	0.62 g
Geo Metro 4-door LSi	60 mph	151 ft	0.80 g	60 mph	172 ft	0.70 g
Geo Metro 2-door LSi	60 mph	152 ft	0.79 g	60 mph	199 ft	0.60 g

Braking performance comparisons of seven 4-wheel drive vehicles on dry roads and on snow. (from Road and Track, April 1989)

	Dry			Wet		
	Initial Velocity	**Stopping Distance**	**Deceler/n (avg. g)**	**Initial Velocity**	**Stopping Distance**	**Deceler/n (avg. g)**
BMW 325iX	60 mph	142 ft	0.85 g	20 mph	75 ft	0.18 g
Audi 90 Quatro	60 mph	143 ft	0.84 g	20 mph	99 ft	0.14 g
VW Quantum GL5	60 mph	145 ft	0.83 g	20 mph	59 ft	0.23 g
Toyota Celica All-Trac	60 mph	146 ft	0.82 g	20 mph	80 ft	0.17 g
Subaru Justy 4WD GL	60 mph	151 ft	0.80 g	20 mph	63 ft	0.21 g
Subaru XT6 4WD	60 mph	153 ft	0.79 g	20 mph	49 ft	0.27 g
Pontiac 6000 STE 4WD	60 mph	N/A	N/A	20 mph	56 ft	0.24 g

Braking performance comparisons on dry roads of passenger vehicles representing extremes (from Road and Track, October 1995)

	Dry			Wet		
	Initial Velocity	**Stopping Distance**	**Deceler/n (avg. g)**	**Initial Velocity**	**Stopping Distance**	**Deceler/n (avg. g)**
BMW 325i	60 mph	126 ft	0.95 g	80 mph	212 ft	1.01 g
Chevrolet Corvette LT1	60 mph	123 ft	0.98 g	80 mph	225 ft	0.95 g
Ford Mustang Cobra	60 mph	123 ft	0.98 g	80 mph	214 ft	1.00 g
Toyota Supra Turbo	60 mph	122 ft	0.99 g	80 mph	208 ft	1.03 g
Porsche 911 Turbo	60 mph	116 ft	1.04 g	80 mph	199 ft	1.07 g
BMW 740i	60 mph	144 ft	0.84 g	80 mph	255 ft	0.84 g
Chevrolet Camaro V6	60 mph	162 ft	0.74 g	80 mph	282 ft	0.76 g
Mercury Villager	60 mph	178 ft	0.68 g	80 mph	293 ft	0.73 g
Toyota Corolla DX	60 mph	186 ft	0.65 g	80 mph	319 ft	0.67 g
VW Golf III GL	60 mph	175 ft	0.69 g	80 mph	301 ft	0.71 g

Braking performance comparisons on dry roads of air braked heavy duty vehicles (From NHTSA test data)

	Initial Velocity	**Stopping Distance**	**Deceler/n (avg. g)**	**Initial Velocity**	**Stopping Distance**	**Deceler/n (avg. g)**
IH School Bus	20 mph	28 ft	0.48 g	60 mph	310 ft	0.34 g
Ford/IH Short School Bus	20 mph	36 ft	0.37 g	60 mph	375 ft	0.32 g
Thomas Transit Bus	20 mph	36 ft	0.37 g	60 mph	292 ft	0.41 g
Ford 4 by 2 Truck	20 mph	36 ft	0.37 g	60 mph	331 ft	0.36 g
GMC 6 by 4 Truck	20 mph	54 ft	0.25 g	60 mph	528 ft	0.23 g
Mack 6 by 4 Truck	20 mph	44 ft	0.30 g	60 mph	363 ft	0.33 g
Peterbilt 4 by 2 Tractor	20 mph	39 ft	0.34 g	60 mph	407 ft	0.30 g
Ford 4 by 2 Tractor	20 mph	30 ft	0.45 g	60 mph	289 ft	0.42 g
White 4 by 2 Tractor	20 mph	42 ft	0.32 g	60 mph	366 ft	0.33 g
IH 6 by 4 Tractor	20 mph	51 ft	0.26 g	60 mph	475 ft	0.25 g
Western Star 6 by 4 tractor	20 mph	46 ft	0.29 g	60 mph	431 ft	0.28 g
Stuart Conv. auto hauler	20 mph	43 ft	0.31 g	60 mph	434 ft	0.28 g
Stuart Stringer auto hauler	20 mph	39 ft	0.34 g	60 mph	354 ft	0.34 g

APPENDIX B.2 TABLES OF RESULTS

B.1 Symbols and Notation

PP: Passenger car leader, Passenger car follower

PB: Passenger car leader, Bus follower

PT: Passenger car leader, Truck follower

BP: Bus leader, Passenger car follower

BB: Bus leader, Bus follower

BT: Bus leader, Truck follower

TP: Truck leader, Passenger car follower

TB: Truck leader, Bus follower

TT: Truck leader, Truck follower

$L_{P:}$ Length of a passenger vehicle, in meters

$L_{B:}$ Length of a bus, in meters

$L_{T:}$ Length of a truck with trailer, in meters

$h_{PP:}$ Minimum time headway between Passenger car leader Passenger car follower, in sec.

$h_{PB:}$ Minimum time headway between Passenger car leader, Bus follower, in seconds

$h_{PT:}$ Minimum time headway between Passenger car leader, Truck follower, in seconds

$h_{BP:}$ Minimum time headway between Bus leader, Passenger car follower, in seconds

$h_{BB:}$ Minimum time headway between Bus leader, Bus follower, in seconds

$h_{BT:}$ Minimum time headway between Bus leader, Truck follower, in seconds

$h_{TP:}$ Minimum time headway between Truck leader, Passenger car follower, in seconds

$h_{TB:}$ Minimum time headway between Truck leader, Bus follower, in seconds

$h_{TT:}$ Minimum time headway between Truck leader, Truck follower, in seconds

V_{lo}: Leading Vehicle initial Velocity, in miles per hour.

V_{fo}: Following Vehicle initial Velocity, in miles per hour.

A_{lm}: The maximum achievable deceleration of the leading vehicle in g

A_{fm}: The maximum achievable deceleration of the leading vehicle in g

J_{lmax}: The maximum achievable jerk of the leading vehicle in meters/sec^3

J_{fmax}: The maximum achievable jerk of the following vehicle in meters/sec^3

m_{lmax}: The maximum road-tire friction coefficient (dimensionless)

m_{fmax}: The maximum road-tire friction coefficient (dimensionless)

A_{fauto}: The acceleration value under automatic brake control during soft braking, in g

A_{fac}: The initial acceleration value during vehicle following, in g

J_{fc}: The jerk value under automatic brake control during soft braking, in meters/sec^3

t_{fa} : Detection and brake actuation delay applicable to the following vehicle, in seconds.

t_{fc}: The time at which the following vehicle starts the emergency braking maneuver, in seconds

Table B2-1. Autonomous Vehicles, Dry Road Surface

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
m_{lmax}		1	1	1	1	1	1	1	1	1
m_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	5	5	5	5	5	5	5	5	5
t_{fa}	sec	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
t_{fc}	sec	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
min headway	sec	**0.66**	**2.63**	**3.97**	**0.08**	**1.04**	**2.37**	**0.06**	**0.25**	**1.28**
min headway	m	18.71	74.2	111.7	2.37	29.15	66.63	1.71	6.94	36.07

Table B2-2. Autonomous Vehicles, Wet Road Surface

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
m_{lmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
m_{fmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	5	5	5	5	5	5	5	5	5
t_{fa}	sec	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
t_{fc}	sec	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
min headway	sec	**1.03**	**4.99**	**7.65**	**0.09**	**1.77**	**4.43**	**0.07**	**0.32**	**2.26**
min headway	m	29.01	140.7	215.6	2.514	49.77	124.7	1.865	9.111	63.57

Table B2-3. Autonomous Vehicles - Uniform Braking - Dry Road

		P P	**P B**	**P T**	**B P**	**B B**	**B T**	**T P**	**T B**	**T T**
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.5	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.2
A_{fmax}	g	0.475	0.285	0.19	0.475	0.285	0.19	0.475	0.285	0.19
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
m_{lmax}		1	1	1	1	1	1	1	1	1
m_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	5	5	5	5	5	5	5	5	5
t_{fa}	sec	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
t_{lc}	sec	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
min headway	sec	**0.72**	**2.73**	**5.25**	**0.10**	**1.00**	**3.52**	**0.06**	**0.15**	**1.36**
min headway	m	20.33	76.83	147.7	2.908	28.27	99.15	1.768	4.134	38.19

Table B2-4. Autonomous Vehicles. Capacity Estimates Under Different Road Conditions Assumptions

A With identification of different vehicle classes	**Dry Road Surface**	**Wet Road Surface**	**Uniform Braking**
0% mixing	4116	2860	3850
5% buses	3746	2516	3525
5% trucks	3458	2278	3096
2.5% buses + 2.5% trucks	3596	2391	3297
5% buses + 5% trucks	3193	2054	2882
B. No identification of different vehicle classes	**Dry Road Surface**	**Wet Road Surface**	**Uniform Braking**
0% mixing	4116	2860	3850
5% buses	3631	2432	3416
5% trucks	3356	2207	3007
2.5% buses + 2.5% trucks	3488	2314	3198
5% buses + 5% trucks	3026	1943	2735

Table B2-5. Free Agent Vehicles - Infrastructure Supported - Dry Road

		P P	P B	P T	B P	B B	B T	T P	T B	T T
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
m_{lmax}		1	1	1	1	1	1	1	1	1
m_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	10	10	10	10	10	10	10	10	10
t_{fa}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
t_{fc}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
min headway	sec	**0.47**	**2.44**	**3.77**	**0.04**	**0.84**	**2.17**	**0.03**	**0.12**	**1.09**
min headway	m	13.13	68.7	106.2	1.03	23.64	61.17	0.779	3.34	30.61

Table B2-6. Free Agent Vehicles - Infrastructure Supported - Wet Road

		P P	P B	P T	B P	B B	B T	T P	T B	T T
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
m_{lmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
m_{fmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	10	10	10	10	10	10	10	10	10
t_{fa}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
t_{fc}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
min headway	sec	**0.83**	**4.80**	**7.46**	**0.04**	**1.57**	**4.23**	**0.03**	**0.18**	**2.06**
min headway	m	23.44	135.2	210.1	1.263	44.27	119.2	0.96	5.183	58.11

Table B2-7. Free Agent Vehicles - Infrastructure Supported - Uniform Braking - Dry Road

		P P	**P B**	**P T**	**B P**	**B B**	**B T**	**T P**	**T B**	**T T**
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.5	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.2
A_{fmax}	g	0.475	0.285	0.19	0.475	0.285	0.19	0.475	0.285	0.19
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
m_{lmax}		1	1	1	1	1	1	1	1	1
m_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	10	10	10	10	10	10	10	10	10
t_{la}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
t_{fc}	sec	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
min headway	sec	**0.53**	**2.53**	**5.06**	**0.05**	**0.81**	**3.33**	**0.03**	**0.08**	**1.16**
min headway	m	14.79	71.36	142.4	1.347	22.8	93.81	0.863	2.167	32.81

Table B2-8. Free Agent Vehicles - Infrastructure Supported. Capacity Estimates

	Dry Road Surface	**Wet Road Surface**	**Uniform Braking**
0% mixing	5400	3425	4942
5% buses	4730	2923	4377
5% trucks	4276	2605	3730
2.5% buses + 2.5% trucks	4492	2755	4025
5% buses + 5% trucks	3845	2304	3400

Table B2-9. Free Agent Vehicles - Infrastructure Managed - Dry Road

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
m_{lmax}		1	1	1	1	1	1	1	1	1
m_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	20	20	20	20	20	20	20	20	20
t_{fa}	sec	0	0	0	0	0	0	0	0	0
t_{fc}	sec	0	0	0	0	0	0	0	0	0
min headway	sec	**0.36**	**2.33**	**3.67**	**0.01**	**0.73**	**2.07**	**0.01**	**0.05**	**0.98**
min headway	m	10.25	65.75	103.2	0.411	20.7	58.18	0.327	1.536	27.62

Table B2-10. Free Agent Vehicles - Infrastructure Managed - Wet Road

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.8	0.8	0.8	0.4	0.4	0.4	0.3	0.3	0.3
A_{fmax}	g	0.72	0.36	0.27	0.72	0.36	0.27	0.72	0.36	0.27
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
m_{lmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
m_{fmax}		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{lc}	m/s^3	20	20	20	20	20	20	20	20	20
t_{la}	sec	0	0	0	0	0	0	0	0	0
t_{fc}	sec	0	0	0	0	0	0	0	0	0
min headway	sec	**0.73**	**4.69**	**7.35**	**0.02**	**1.46**	**4.12**	**0.02**	**0.11**	**1.95**
min headway	m	20.51	132.1	206.9	0.631	41.18	116.0	0.488	3.033	54.93

Table B2-11. Free Agent Vehicles - Infrastructure Managed - Uniform Braking - Dry Road

		PP	PB	PT	BP	BB	BT	TP	TB	TT
V_{lo}	mph	60	60	60	60	60	60	60	60	60
V_{fo}	mph	63	63	63	63	63	63	63	63	63
A_{lmax}	g	0.5	0.5	0.5	0.3	0.3	0.3	0.2	0.2	0.2
A_{fmax}	g	0.475	0.285	0.19	0.475	0.285	0.19	0.475	0.285	0.19
J_{lmax}	m/s^3	50	50	50	40	40	40	30	30	30
J_{fmax}	m/s^3	50	40	30	50	40	30	50	40	30
m_{lmax}		1	1	1	1	1	1	1	1	1
m_{fmax}		1	1	1	1	1	1	1	1	1
A_{fauto}	g	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
A_{fac}	g	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
J_{fc}	m/s^3	20	20	20	20	20	20	20	20	20
t_{fa}	sec	0	0	0	0	0	0	0	0	0
t_{fc}	sec	0	0	0	0	0	0	0	0	0
min headway	sec	**0.42**	**2.43**	**4.95**	**0.02**	**0.70**	**3.22**	**0.01**	**0.04**	**1.06**
min headway	m	11.87	68.38	139.3	0.602	19.82	90.74	0.404	1.119	29.74

Table B2-12. Free Agent Vehicles - Infrastructure Managed. Capacity Estimates

	Dry Road Surface	Wet Road Surface	Uniform Braking
0% mixing	6437	3823	5810
5% buses	5472	3197	5018
5% trucks	4873	2820	4184
2.5% buses + 2.5% trucks	5155	2997	4563
5% buses + 5% trucks	4299	2464	3756

Table B2-13. Platoons Without Coordinated Braking

		Dry	Wet	Uniform
V_{lo}	mph	60	60	60
V_{fo}	mph	61.5	61.5	61.5
A_{lmax}	g	0.8	0.8	0.5
A_{fmax}	g	0.72	0.72	0.475
J_{lmax}	m/s^3	50	50	50
J_{fmax}	m/s^3	50	50	50
m_{lmax}		1	0.5	1
m_{fmax}		1	0.5	1
A_{fauto}	g	0	0	0
A_{fac}	g	0	0	0
J_{fc}	m/s^3	20	20	20
t_{fa}	sec	0.1	0.1	0.1
t_{fc}	sec	0.1	0.1	0.1
min headway	sec	**0.37**	**0.65**	**0.38**
min headway	m	10.26	17.93	10.48

Table B2-14. Platoons of Passenger Vehicles Without Coordinated Braking (tfc= 0.1 sec). Capacity Estimates

A. Autonomous Platoons	**Dry Road Surface**	**Wet Road Surface**	**Uniform Braking**
10 car platoons	6090	5652	5955
20 car platoons	6257	5977	6142
B. Free Agent Infrastructure Supported Platoons			
10 car platoons	6312	5843	6166
20 car platoons	6372	6081	6252
C. Free Agent Infrastructure Managed Platoons			
10 car platoons	6434	5947	6283
20 car platoons	6433	6137	6311

Table B2-15. Platoons with Coordinated Braking - No Delay

		Dry	Wet	Uniform
V_{lo}	mph	60	60	60
V_{fo}	mph	61.5	61.5	61.5
A_{lmax}	g	0.8	0.8	0.5
A_{fmax}	g	0.72	0.72	0.475
J_{lmax}	m/s^3	50	50	50
J_{fmax}	m/s^3	50	50	50
m_{lmax}		1	0.5	1
m_{fmax}		1	0.5	1
A_{fauto}	g	0	0	0
A_{fac}	g	0	0	0
J_{fc}	m/s^3	20	20	20
t_{fa}	sec	0	0	0
t_{fc}	sec	0	0	0
min headway	sec	**0.27**	**0.55**	**0.28**
min headway	m	7.51	15.18	7.73

Table B2-16. Platoons of Passenger Vehicles with Coordinated Braking (tfc= 0 sec). Capacity Estimates

A. Autonomous Platoons	**Dry Road Surface**	**Wet Road Surface**	**Uniform Braking**
10 car platoons	7217	4531	7028
20 car platoons	7532	4683	7365
B. Free Agent Infrastructure Supported Platoons			
10 car platoons	7531	4652	7323
20 car platoons	7700	4747	7524
C. Free Agent Infrastructure Managed Platoons			
10 car platoons	7704	4718	7489
20 car platoons	7789	4780	7611

Table B2-17. Platoons with Coordinated Braking. (Delay of 0.1 sec from tail to head)

		Dry	Wet	Uniform
V_{lo}	mph	60	60	60
V_{fo}	mph	61.5	61.5	61.5
A_{lmax}	g	0.8	0.8	0.5
A_{fmax}	g	0.72	0.72	0.475
J_{lmax}	m/s^3	50	50	50
J_{fmax}	m/s^3	50	50	50
m_{lmax}		1	0.5	1
m_{fmax}		1	0.5	1
A_{fauto}	g	0	0	0
A_{fac}	g	0	0	0
J_{fc}	m/s^3	20	20	20
t_{fa}	sec	0	0	0
t_{fc}	sec	-0.1	-0.1	-0.1
min headway	sec	**0.17**	**0.45**	**0.18**
min headway	m	4.76	12.431	4.98

Table B2-18. Platoons of Passenger Vehicles with Coordinated Braking (tfc= -0.1 sec). Capacity Estimates

A. Autonomous Platoons	**Dry Road Surface**	**Wet Road Surface**	**Uniform Braking**
10 car platoons	7060	4468	6889
20 car platoons	7442	4646	7291
B. Free Agent Infrastructure Supported Platoons			
10 car platoons	7359	4586	7171
20 car platoons	7604	4709	7445
C. Free Agent Infrastructure Managed Platoons			
10 car platoons	7525	4649	7330
20 car platoons	7692	4743	7530

Table B2-19. Infrastructure Managed Slotting. Capacity Estimates

	Dry Road Surface	**Wet Road Surface**	**Uniform Braking**
0% mixing	4047	2826	3773

Table B2-20. Capacity Comparisons

Capacity without platooning	**0% mixing of vehicles**			**5% mixing of buses**			**5% mixing of trucks**		
	Dry	**Wet**	**Uniform**	**Dry**	**Wet**	**Uniform**	**Dry**	**Wet**	**Uniform**
Autonomous Vehicles with class identification	4116	2860	3850	3746	2516	3525	3458	2278	3096
Autonomous Vehicles without class identification	4116	2860	3850	3631	2432	3416	3356	2207	3007
Free Agents - Infrastructure Supported with class identification	5400	3425	4942	4730	2923	4377	4276	2605	3730
Free Agents - Infrastructure Managed with class identification	6437	3823	5810	5472	3197	5018	4873	2820	4184
Infrastructure Managed Slotting	4047	2826	3773						
				2.5% buses + 2.5% trucks			**5% buses + 5% trucks**		
				Dry	**Wet**	**Uniform**	**Dry**	**Wet**	**Uniform**
Autonomous Vehicles with class identification				3596	2391	3297	3193	2054	2882
Autonomous Vehicles without class identification				3488	2314	3198	3026	1943	2735
Free Agents - Infrastructure Supported with class identification				4492	2755	4025	3845	2304	3400
Free Agents - Infrastructure Managed with class identification				5155	2997	4563	4299	2464	3756
Capacity with platooning	**10 car platoons**			**20 car platoons**					
	Dry	**Wet**	**Uniform**	**Dry**	**Wet**	**Uniform**			
Autonomous platoons without coordinated braking	6090	5652	5955	6257	5977	6142			
Infrastructure supported platoons without coordinated braking	6312	5843	6166	6372	6081	6252			
Infrastructure managed platoons without coordinated braking	6434	5947	6283	6433	6137	6311			
Autonomous platoons with coordinated braking	7217	4531	7028	7532	4683	7365			
Infrastructure supported platoons with coordinated braking	7531	4652	7323	7700	4747	7524			
Infrastructure managed platoons with coordinated braking	7704	4718	7489	7789	4780	7611			
Autonomous platoons with delayed braking	7060	4468	6889	7442	4646	7291			
Infrastructure supported platoons with delayed braking	7359	4586	7171	7604	4709	7445			
Infrastructure managed platoons with delayed braking	7525	4649	7330	7692	4743	7530			

APPENDIX C - SAFETY EVALUATION RESULTS

The various concept dimensions were weighted, and concept characteristics scored, as follows:

- Intelligence Distribution (5=weight)
  - Autonomous - 1 (= score for this option)
  - Cooperative - 2
  - Infrastructure Supported - 3
  - Infrastructure Managed - 10
  - Infrastructure Controlled - 0

(This is based on a belief that only infrastructure managed systems will be able to effectively maintain contingency plans on the fly, and implement them if necessary.)

- Separation Policy (4.5)
  - Free Agent - 7
  - Platooning - 7

(There is insufficient evidence to make a safety determination on free agent versus plattooing. Both should be implemented in a "safe" manner, whatever that ultimately means in each case.)

- Mixing of AHS with Non-AHS (3)
  - Physical Barriers - 8
  - Barriers with Gaps - 6
  - Virtual Barriers - 3
  - Full Mixing - 2
- Mixing of AHS Vehicle Classes (3)
  - Mixed - 2
  - Not Mixed - 9
- Entry/Exit (3)
  - Dedicated - 6
  - Transition - 4
- Obstacle Avoidance (3.5)
  - Manual - 5
  - Auto/Manual - 5
  - Full Auto - 5

Concept #	Intel Dist	5	Seperation Policy	4.5	AHS/Non	3	Veh Cls	3	Entry/Exit	1	Obstacle	3.5	Safety Composite	Safety Scored	Safety Normalized
1a	Auto	1	Free Agt	7	Full Mix	2	Mixed	2	Transition	4	Manual	5	70	35%	0%
1b	Auto	1	Free Agt	7	Full Mix	2	Mixed	2	Transition	4	Full Auto	5	70	35%	0%
2	Infra Cntrl	0	Free Agt	7	Phys Bar	8	Mixed	2	Dedicated	6	Full Auto	5	85	43%	17%
3	Infra Mng	10	Slot	1	Phys Bar	8	Not Mixed	9	Dedicated	6	Full Auto	5	129	65%	69%
4	Coop	2	Free Agt	7	Bar w/ Gap	6	Mixed	2	Transition	4	Full Auto	5	87	44%	20%
5	Coop	2	Platoon	7	Bar w/ Gap	6	Mixed	2	Transition	4	Full Auto	5	87	44%	20%
6	Infra Spt	3	Free Agt	7	Bar w/ Gap	6	Mixed	2	Transition	4	Full Auto	5	92	46%	26%
8a	Infra Spt	3	Free Agt	7	Phys Bar	8	Mixed	2	Dedicated	6	Full Auto	5	100	50%	35%
8b	Infra Spt	3	Free Agt	7	Phys Bar	8	Not Mixed	9	Dedicated	6	Full Auto	5	121	61%	59%
9	Infra Spt	3	Platoon	7	Phys Bar	8	Mixed	2	Dedicated	6	Full Auto	5	100	50%	35%
10	Infra Mng	10	Free Agt	7	Bar w/ Gap	6	Mixed	2	Transition	4	Full Auto	5	127	64%	66%
11	Infra Mng	10	Platoon	7	Bar w/ Gap	6	Mixed	2	Transition	4	Full Auto	5	127	64%	66%
12a	Infra Mng	10	Free Agt	7	Phys Bar	8	Mixed	2	Dedicated	6	Full Auto	5	135	68%	76%
12b	Infra Mng	10	Free Agt	7	Phys Bar	8	Not Mixed	9	Dedicated	6	Full Auto	5	156	78%	100%
13	Infra Mng	10	Platoon	7	Phys Bar	8	Not Mixed	9	Dedicated	6	Full Auto	5	156	78%	100%
14	Infra Spt	3	Platoon	7	Bar w/ Gap	6	Mixed	2	Transition	4	Full Auto	5	92	46%	26%
15	Infra Mng	10	Free Agt	7	Full Mix	2	Mixed	2	Transition	4	Full Auto	5	115	58%	52%
16	Infra Spt	3	Free Agt	7	Virt Bar	3	Mixed	2	Transition	4	Full Auto	5	83	42%	15%
17	Coop	2	Platoon	7	Virt Bar	3	Mixed	2	Transition	4	Full Auto	5	78	39%	9%
18	Coop	2	Free Agt	7	Phys Bar	8	Mixed	2	Dedicated	6	Auto/Man	5	95	48%	29%
19	Infra Mng	10	Platoon	7	Phys Bar	8	Mixed	2	Dedicated	6	Auto/Man	5	135	68%	76%
20	Infra Spt	3	Free Agt	7	Phys Bar	8	Not Mixed	9	Dedicated	6	Auto/Man	5	121	61%	59%

APPENDIX D - COST EVALUATION DATA

D.1 RANGE OF POSSIBILITIES

A review of Cost Element 1 (Infrastructure Capital Costs – Civil/Structural) offers a prime example of the range of possibilities that exists for each option. A dedicated AHS facility with continuous barriers has been assigned a score of *10* based on the maximum level of complexity. However, this aspect of the system can be instituted several different ways, as dramatized in Figures D.1-1 through D.1-4.

Figure D.1-1 details a typical freeway and has been included to provide a point of reference when examining the AHS alternatives for a standard freeway configuration. Figure D.1-2 identifies a possible method of incorporating a single dedicated AHS lane while maintaining the existing paved area. The separation wall could be as simple as a jersey barrier, and the paved surface would require very few modifications. Right-of-way acquisition becomes an issue in this configuration only when constructing the AHS points of entry and exit. The scenario is simplified in this layout, but it is apparent from the sketch that the ramp work becomes extensive when applied to an interstate highway interchange.

Figures D.1-3 and D.1-4 display the two more-extensive efforts that produce a dedicated AHS facility. Most of the costs associated with the elevated highway option would be due to construction materials and labor. Right-of-way purchases would again be necessary only to supply access ramps. This option could become necessary in an urban environment, where widening the existing highway is not possible.

Right-of-way acquisition becomes the major cost attribute when considering the wide, single-elevation version of the AHS facility. The direct construction costs for the roadway in this scenario will be much lower when compared with those for the elevated highway, but available space may become a concern when applied to an urban environment.

The values applied in the scoring tables reflect potential cost and, as noted, should be reevaluated as the Concepts become more clearly defined. The preceding example is intended to identify alternatives for one specific dimensional option, as well as acknowledge the range of alternatives that exist for other dimensional options.

D.2 COST ELEMENT 1

Cost element 1 addresses the costs associated with building or modifying the physical portion of the highway. Two Dimensions were considered to envelop the costs associated with this element, as identified in Table D.2-I. The Dimension entitled "AHS and Non-AHS Mixing" identifies the requirements for interconnecting an AHS freeway with a non-AHS freeway. This Dimension was regarded as the major civil/structural cost element due to direct association with the physical infrastructure, and is weighted accordingly. The Dimension entitled "Class Mixing" outlines the necessity for class-specific lanes on the AHS freeway. This Dimension was considered to affect selective portions of the infrastructure only and, as a result, was weighted much lower. Table D.2-I defines the relative scores assigned to each of the dimensional options, as well as the relative weights applied to each Dimension when calculating the cost element rating. Table D.2-II summarizes the scoring for Cost Element 1 and calculates the relative ratings. Figure D.2-1 displays the results of this rating in bar graph format.

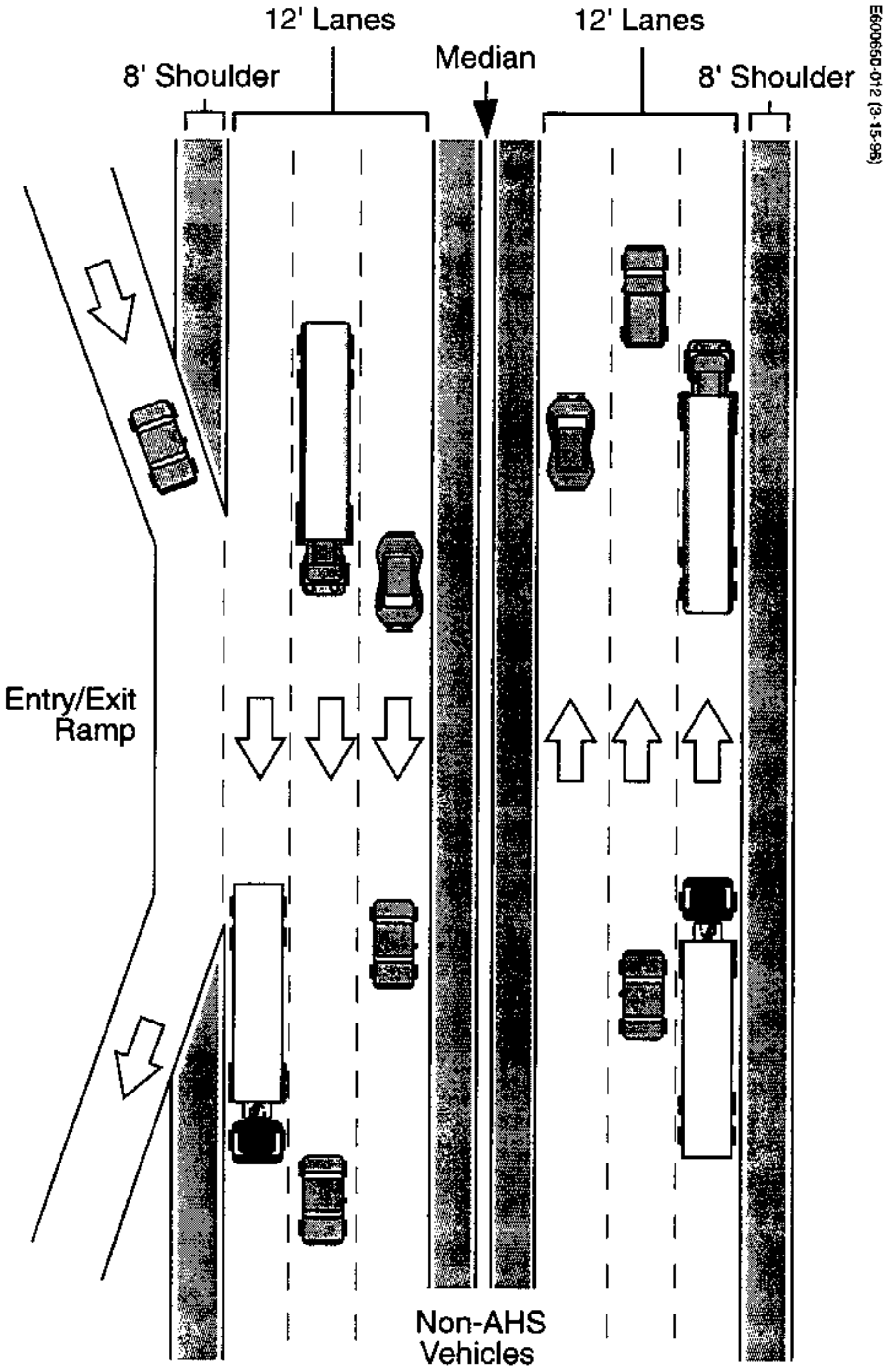

Figure D.1-1. Typical Freeway

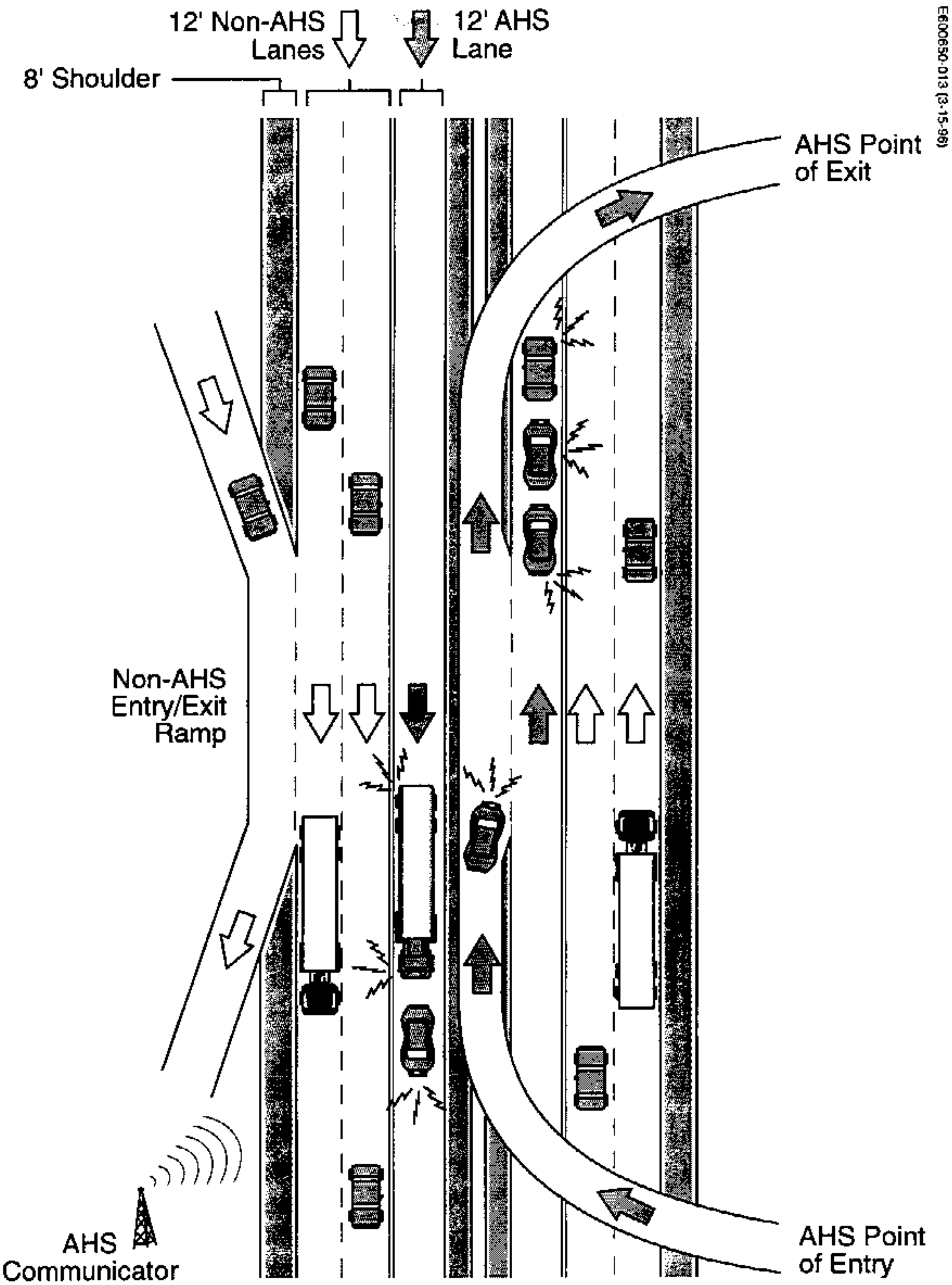

Figure D.1-2. Maintain Paved Area of Existing Highway and Reduce Number of Non-AHS Lanes

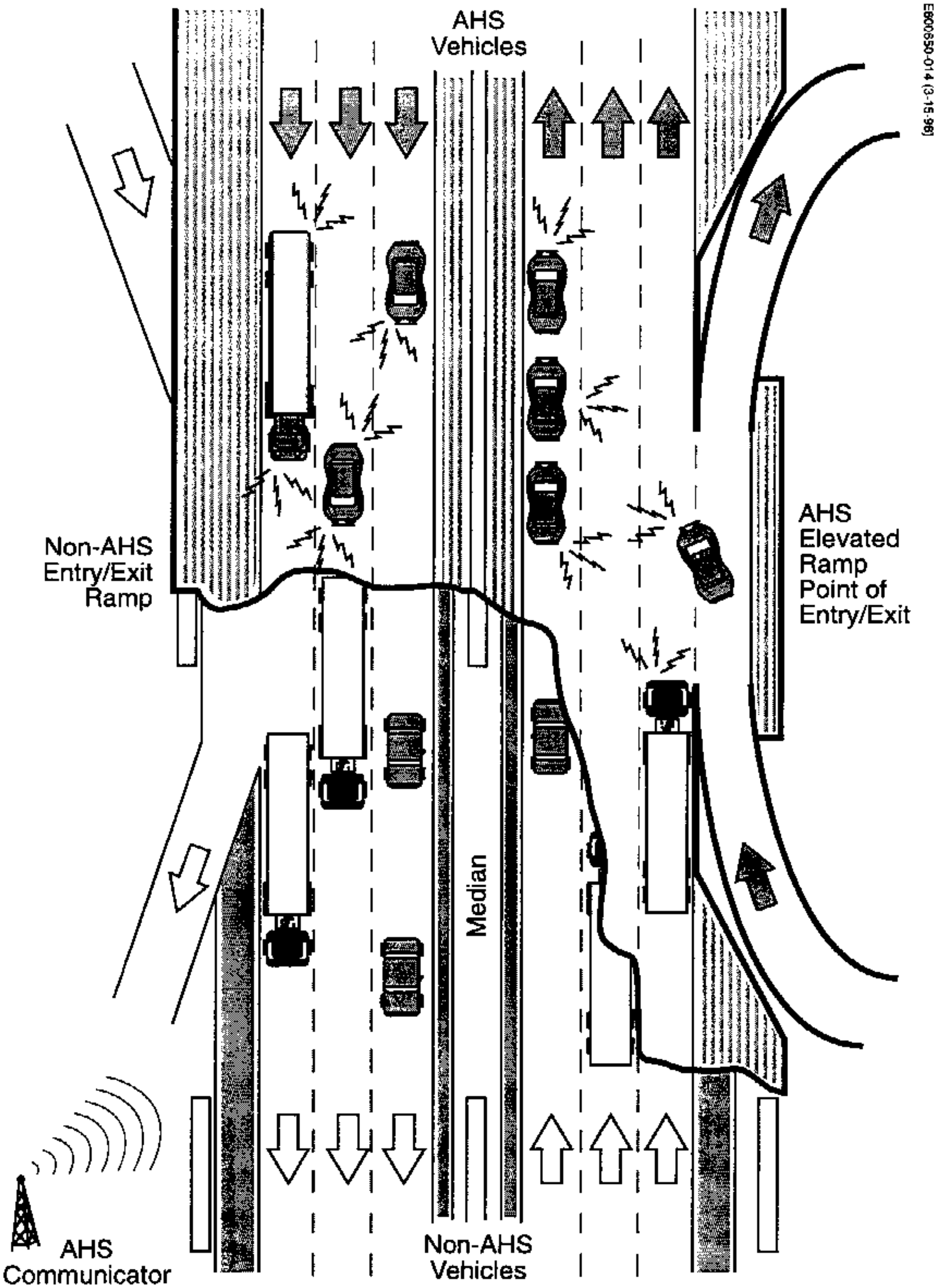

Figure D.1-3. AHS Lanes Elevated (Within Existing Width)

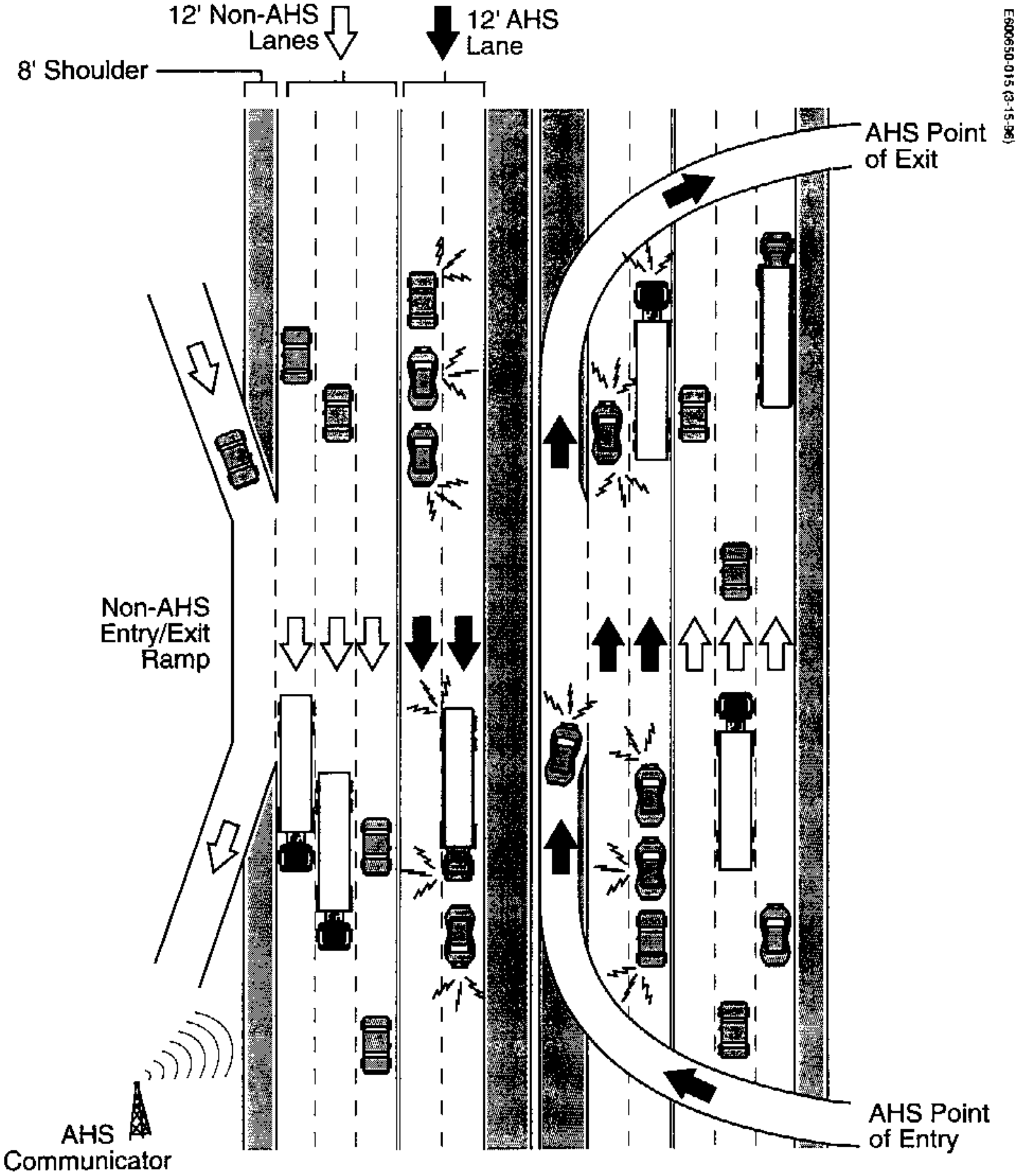

Figure D.1-4. Use More Highway Width
(Right-of-Way Acquisition)

Table D.2-I. Cost Element 1–Infrastructure Civil/Structural Applicable Dimensions and Relative Scores

Weight	Dimension	Relative Score	Assumptions and Rationale
80%	AHS and non-AHS Mixing		
	• Dedicated with Continuous Barriers	10	Requires dedicated entry/exit interchanges Roadway is separated and segregated New/improved connections to local roadway network Addition of new lanes, possibility elevated
	• Dedicated with Gaps in Barriers	5	Allows use of existing interchanges for entry/exit Requires constructing physical barriers Likely utilization of existing/expanded right-of-way
	• Dedicated with Visual Barriers	4	Similar to above without need for physical barriers
	• Full Mixing	1	Potential requirement to upgrade pavement
20%	Class Mixing		
	• Mixed	0	No impact
	• Not Mixed	10	Additional lanes must be built to accommodate each class of AHS vehicles in a "non-mixed" environment Count require highly complex interchanges for entry/exit to independent "non-mixed" lane

Table D.2-II. Automated Highway System–Cost Evaluation Matrix Cost Element 1–Infrastructure and Support Capital Cost, Civil/Structural

	I. Distribution of Intelligence Weight = 0					II. Separation Policy Weight = 0			III. AHS and non-AHS Mixing Weight = 8				IV. Class Mixing Weight = 2		V. Obstacle Detection Weight = 0			
Concept No.	Autonomous	Cooperative	Infrastructure Supported	Infrastructure Managed	Infrastructure Control	Free Agent	Platooning	Slot	Dedicated with continuous barriers	Dedicated with gaps in barriers	Dedicated with virtual barriers	Full mixing	Mixed	Not mixed	Manual sensing and avoidance	Automatic sensing, stop or manually avoid	Automatic sensing and avoidance	Element Rating
1a												1	0					8
1b												1	0					8
2									10				0					80
3a									10					10				100
4										5			0					40
5										5			0					40
6										5			0					40
8a									10				0					80
8b									10					10				100
9									10				0					80
10										5			0					40
11										5			0					40
12a									10				0					80
12b									10					10				100
13									10					10				100
14										5			0					40
15												1	0					8
16											4		0					32
17											4		0					32
18									10				0					80
19									10				0					80
20									10					10				100

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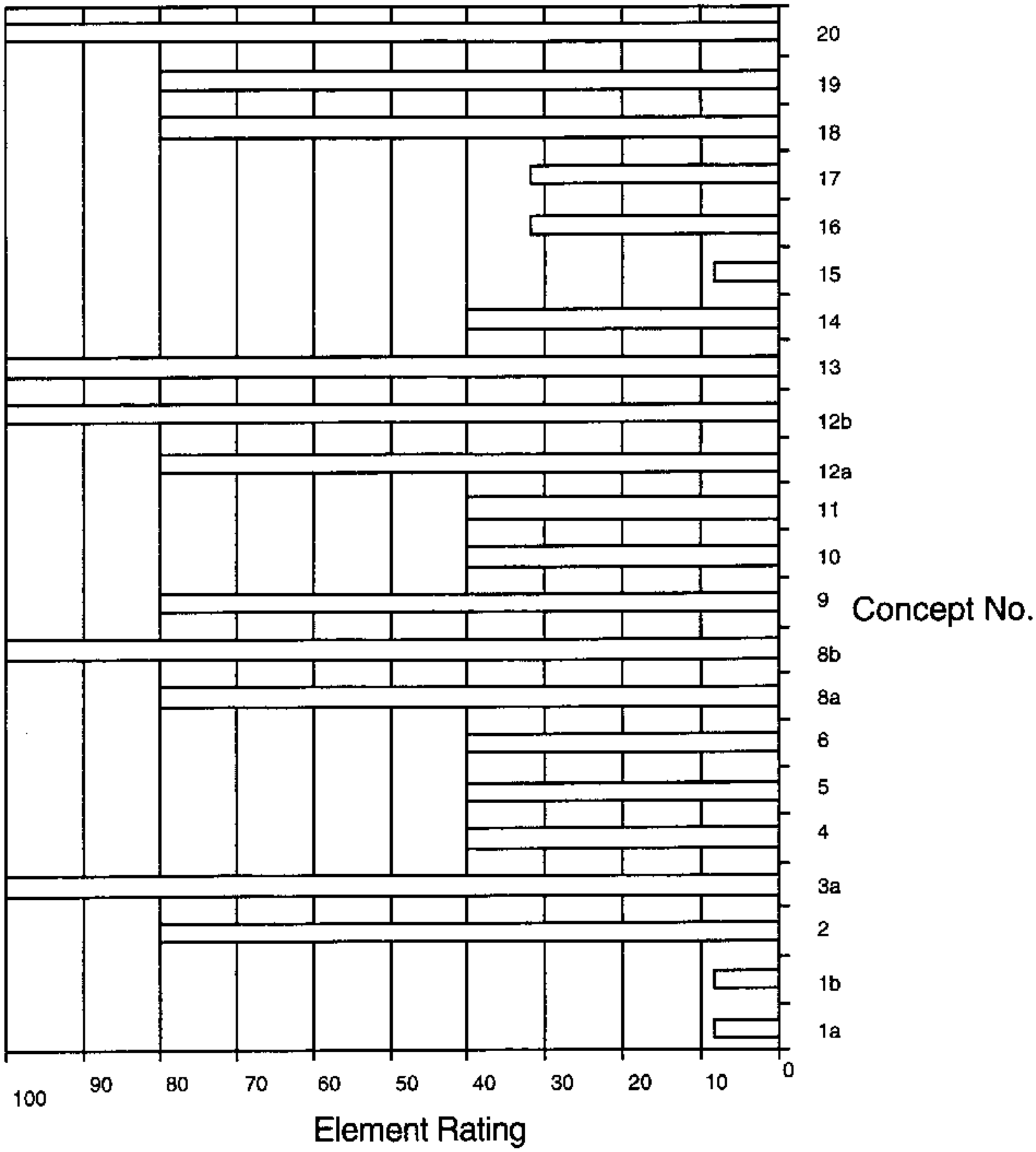

Figure D.2-1. Cost Element 1 Rating

D.3 COST ELEMENT 2

Cost Element 2 addresses the cost of instituting the systems and instrumentation network necessary to control the AHS environment. Three Dimensions were considered to envelop this cost element, as identified in Table D.3-I. The Dimension entitled "Distribution of Intelligence" identifies the level of participation the infrastructure has in controlling the operation of the AHS facility. This Dimension outlines the basic system functions of the infrastructure and, as a result, was weighted heavily. The Dimensions entitled "Obstacle Detection" and "Separation Policy" were considered to define specific parameters that enhance the system. These Dimensions were weighted lower, since the impact on the system cost depends entirely on the role of the infrastructure. The complexity required to adequately detect roadway obstacles warranted a slightly heavier weighting between these two Dimensions. Table D.3-I defines the relative scores assigned to each of the dimensional options, as well as the relative weights applied to each Dimension when calculating the cost element rating. Table D.3-II summarizes the scoring for Cost Element 2 and calculates the relative ratings. Figure D.3-1 displays the results of this rating in bar graph format.

D.4 COST ELEMENT 3

Cost element 3 addresses the cost of adding AHS-related sensors and intelligence to a vehicle. Two Dimensions were considered to envelop this cost element, as identified in Table D.4-I. The Dimension entitled "Obstacle Detection" specifies the most sophisticated sensor requirements on an AHS vehicle. This was weighted heavily due to the wide field of view required onboard the vehicle to adequately detect obstacles, plus the extensive coordination required to support automated evasive action. The Dimension entitled "Distribution of Intelligence" defines a much broader range of sensor requirements, but none as complicated as avoiding and detecting obstacles; thus, the lower weighting. Table D.4-I defines the relative scores assigned to each dimensional option, as well as the relative weights applied to each Dimension when calculating the cost element rating. Table D.4-II summarizes the scoring for Cost Element 3 and calculates the relative ratings. Figure D.4-1 displays the results of this rating in bar graph format.

D.5 COST ELEMENT 4

Cost element 4 addresses the relative costs attributed to infrastructure and vehicle O&M. By definition, these costs depend on the first three cost elements; therefore, three Dimensions were considered to envelop this cost element, as identified in Table D.5-I. The most dominant Dimension from each of Cost Elements 1, 2, and 3 was assumed to represent the O&M for that cost element. The dimensional scoring mirrors that applied to the Dimension in the previous ratings, for each respective cost element. The O&M for the infrastructure system was weighted the heaviest to reflect the relatively short service life of an electronic-based system and the extensive network of personnel required to prevent extended down times. The O&M for the physical infrastructure was weighted marginal to reflect the resources required for snow removal and other maintenance tasks along the extensive highway system. The O&M of the vehicle was weighted low, since the AHS-specific maintenance required for the vehicle will be minimal. Table D.5-I defines the relative scores assigned to each of the dimensional options, as well as the relative weights applied to each Dimension when calculating the cost element rating. Table D.5-II summarizes the scoring for Cost Element 4 and calculates the relative ratings. Figure D.5-1 displays the results of this rating in bar graph format.

Table D.3-I. Cost Element 2–Infrastructure Systems and Instrumentation Applicable Dimensions and Relative Scores

Weight	Dimension	Relative Score	Assumptions and Rationale
70%	Distribution of Intelligence		
	• Autonomous	1	Requires lateral sensing reference
	• Cooperative	1	Identical to Autonomous
	• Infrastructure Supported	4	Adds roadside capability to monitor traffic flow and broadcast traffic information to all AHS vehicles
	• Infrastructure Managed	7	Adds roadside responsibility for vehicle information and communicating traffic flow information to vehicles
	• Infrastructure Controlled	10	Requires infrastructure to control individual vehicles
10%	Separation Policy		
	• Free Agent	0	No impact
	• Platoon	0 10	Increase in roadside processing to coordinate maneuvering when maintained by infrastructure
	• Slot	10	Update slot offsets and maintain vehicle position database
20%	Obstacle Detection		
	• Manual Sense/ Manual Avoid	0	No impact
	• Auto Sense/Manual Avoid	0	No impact
	• Auto Sense/Auto Avoid	0	Infra-supported: sensing as an ITS feature - no impact
		5	Infra-managed: support emergency maneuver requests
		10	Infra-controlled: sense objects and coordinate maneuvers

Table D.3-II. Automated Highway System–Cost Evaluation Matrix Cost Element 2–Infrastructure and Support Capital Cost, Systems and Instrumentation Concept Scoring Matrix

	I. Distribution of Intelligence Weight = 7					II. Separation Policy Weight = 1			III. AHS and non-AHS Mixing Weight = 0				IV. Class Mixing Weight = 0		V. Obstacle Detection Weight = 2			
Concept No.	Autonomous	Cooperative	Infrastructure Supported	Infrastructure Managed	Infrastructure Control	Free Agent	Platooning	Slot	Dedicated with continuous barriers	Dedicated with gaps in barriers	Dedicated with virtual barriers	Full mixing	Mixed	Not mixed	Manual sensing and avoidance	Automatic sensing, stop or manually avoid	Automatic sensing and avoidance	Element Rating
1a	1					0									0			7
1b	1					0											0	7
2					10	0											10	90
3a				7				10									10	79
4		1				0											0	7
5		1					0										0	7
6			4			0											0	28
8a			4			0											0	28
8b			4			0											0	28
9			4				10										0	38
10				7		0											5	59
11				7			10										5	69
12a				7		0											5	59
12b				7		0											5	59
13				7			10										5	69
14			4				10										0	38
15				7		0											5	59
16			4			0											0	28
17		1					0										0	7
18		1				0										0		7
19				7			10									0		59
20			4			0										0		28

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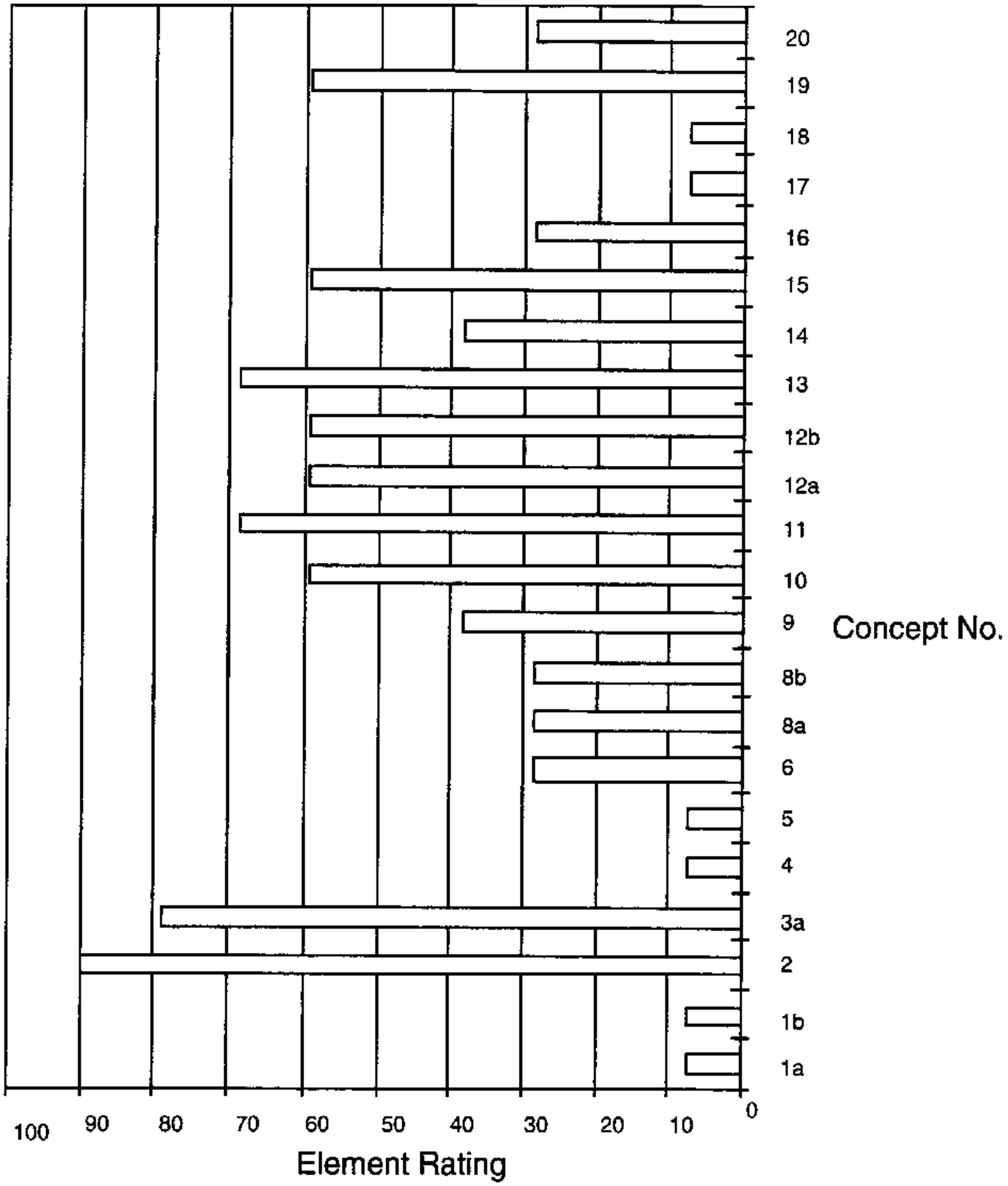

Figure D.3-1. Cost Element 2 Rating

Table D.4-I. Cost Element 3–Vehicle-Based Instrumentation Applicable Dimensions and Relative Scores

Weight	Dimension	Relative Score	Assumptions and Rationale
30%	Distribution of Intelligence		
	• Autonomous	10	All intelligence and sensing is required from the vehicle when coupled with automatic obstacle sensing
		3	Reduced functionality and significantly lower cost when associated with manual obstacle sensing
	• Cooperative	6	Maneuver coordination can be shared between vehicles
	• Infrastructure Supported	3	Vehicle intelligence and sensing aided by infrastructure
	• Infrastructure Managed	3	Identical to Infrastructure Supported
	• Infrastructure Controlled	1	High bandwidth communication required, but majority of functions are relegated to the infrastructure
70%	Obstacle Detection		
	• Manual Sense/Manual Avoid	0	No impact
	• Auto Sense/Manual Avoid	6	Forward obstacle detection sensors required
	• Auto Sense/Auto Avoid	5	Majority of sensory functions relegated to infrastructure when intelligence is infrastructure controlled
		10	Otherwise, sophisticated communication and intelligence, plus a wide field of view, is required for obstacle sensors

Table D.4-II. Automated Highway System–Cost Evaluation Matrix Cost Element 3–Vehicle-Based Capital Cost Concept Scoring Matrix

Concept No.	I. Distribution of Intelligence Weight = 3					II. Separation Policy Weight = 0			III. AHS and non-AHS Mixing Weight = 0				IV. Class Mixing Weight = 0		V. Obstacle Detection Weight = 7			Element Rating
	Autonomous	Cooperative	Infrastructure Supported	Infrastructure Managed	Infrastructure Control	Free Agent	Platooning	Slot	Dedicated with continuous barriers	Dedicated with gaps in barriers	Dedicated with virtual barriers	Full mixing	Mixed	Not mixed	Manual sensing and avoidance	Automatic sensing, stop or manually avoid	Automatic sensing and avoidance	
1a	3														0			9
1b	10																10	100
2	1				1												5	38
3a				3													10	79
4		6															10	88
5		6															10	88
6			3														10	79
8a			3														10	79
8b			3														10	79
9			3														10	79
10				3													10	79
11				3													10	79
12a				3													10	79
12b				3													10	79
13				3													10	79
14			3														10	79
15				3													10	79
16			3														10	79
17		6															10	88
18		6														6		60
19				3												6		51
20			3													6		51

E-600650-3 (2-28-96)

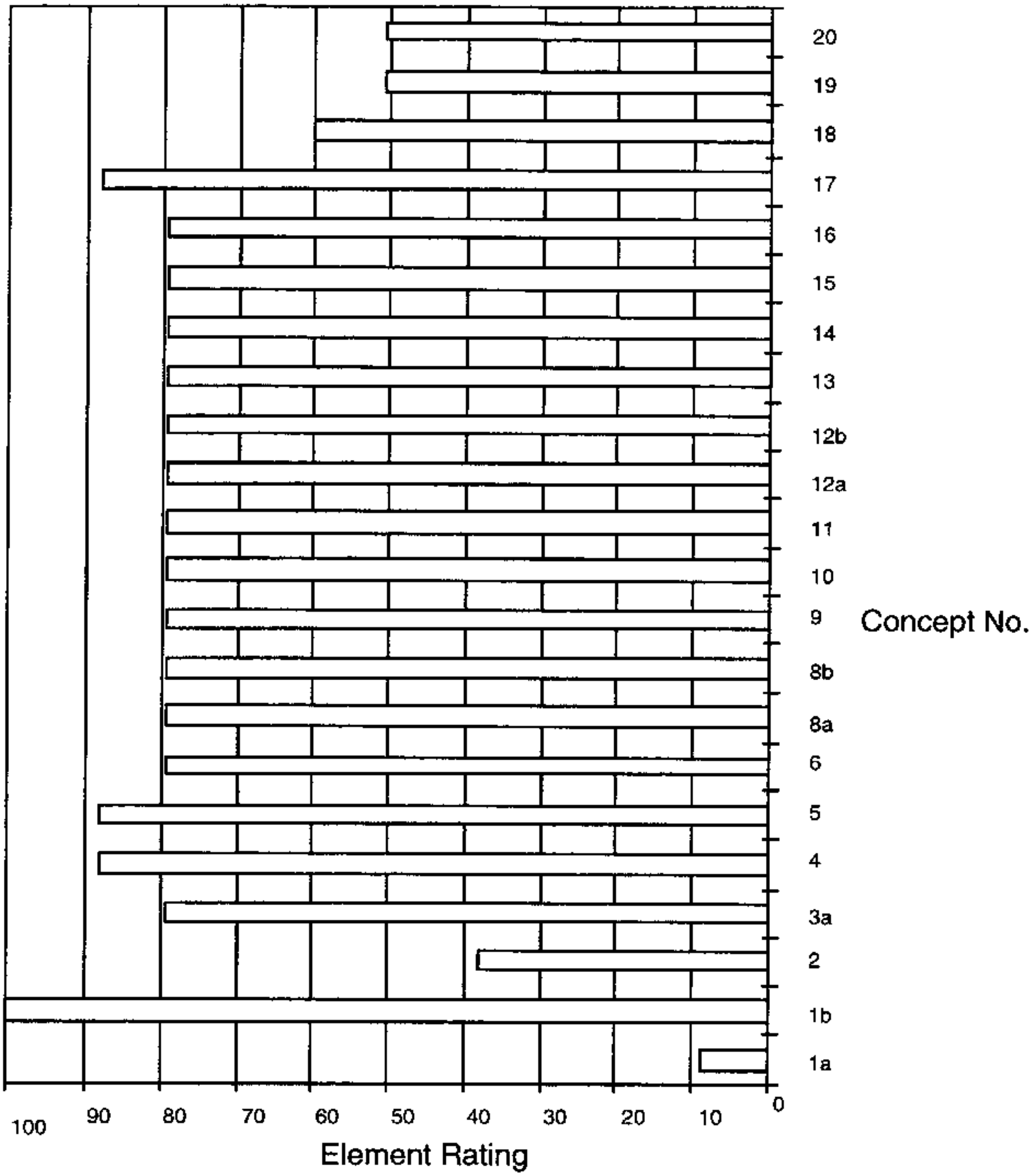

Figure D.4-1. Cost Element 3 Rating

Table D.5-1. Cost Element 4–Operation and Maintenance Applicable Dimensions and Relative Scores

Weight	Dimension	Relative Score	Assumptions and Rationale
60%	Distribution of Intelligence		Assumed to be a proxy for maintenance costs of the Infrastructure Systems and Instrumentation. Relative scoring mirrors that of Cost Element No. 2.
	• Autonomous	1	
	• Cooperative	1	
	• Infrastructure Supported	4	
	• Infrastructure Managed	7	Weighting reflects high relative O & M costs of electronic-based infrastructure system compared to O & M costs of physical infrastructure and AHS-equipped vehicles.
	• Infrastructure Controlled	10	
30%	AHS and non-AHS Mixing		Assumed to be a proxy for maintenance costs of the Infrastructure Civil/Structural. Relative scoring mirrors that of Cost Element No. 1.
	• Dedicated with Cont. Barriers	10	
	• Dedicated with Gaps in Barriers	5	
	• Dedicated with Virtual Barriers	4	Weighting reflects mid-range impact of O & M costs of the physical infrastructure.
	• Full Mixing	1	
10%	Obstacle Detection		Assumed to be a proxy for maintenance costs of the AHS-equipped vehicle. Relative scoring mirrors that of Cost Element No. 3.
	• Manual Sense/Manual Avoid	0	
	• Auto Sense/Manual Avoid	6	Weighting reflects low relative O & M costs of vehicles compared to the net O & M costs of a freeway system.
	• Auto Sense/Auto Avoid	5 10	

Table D.5-II. Automated Highway System–Cost Evaluation Matrix Cost Element 4–Operation and Maintenance Costs Concept Scoring Matrix

	I. Distribution of Intelligence Weight = 6					II. Separation Policy Weight = 0			III. AHS and non-AHS Mixing Weight = 3				IV. Class Mixing Weight = 0		V. Obstacle Detection Weight = 1			
Concept No.	Autonomous	Cooperative	Infrastructure Supported	Infrastructure Managed	Infrastructure Control	Free Agent	Platooning	Slot	Dedicated with continuous barriers	Dedicated with gaps in barriers	Dedicated with virtual barriers	Full mixing	Mixed	Not mixed	Manual sensing and avoidance	Automatic sensing, stop or manually avoid	Automatic sensing and avoidance	Element Rating
1a	1											1			0			9
1b	1											1					10	19
2					10				10								5	95
3a				7					10								10	82
4		1								5							10	31
5		1								5							10	31
6			4							5							10	49
8a			4						10								10	64
8b			4						10								10	64
9			4						10								10	64
10				7						5							10	67
11				7						5							10	67
12a				7					10								10	82
12b				7					10								10	82
13				7					10								10	82
14			4							5							10	49
15				7								1					10	55
16			4								4						10	46
17		1									4						10	28
18		1							10							6		42
19				7					10							6		78
20			4						10							6		60

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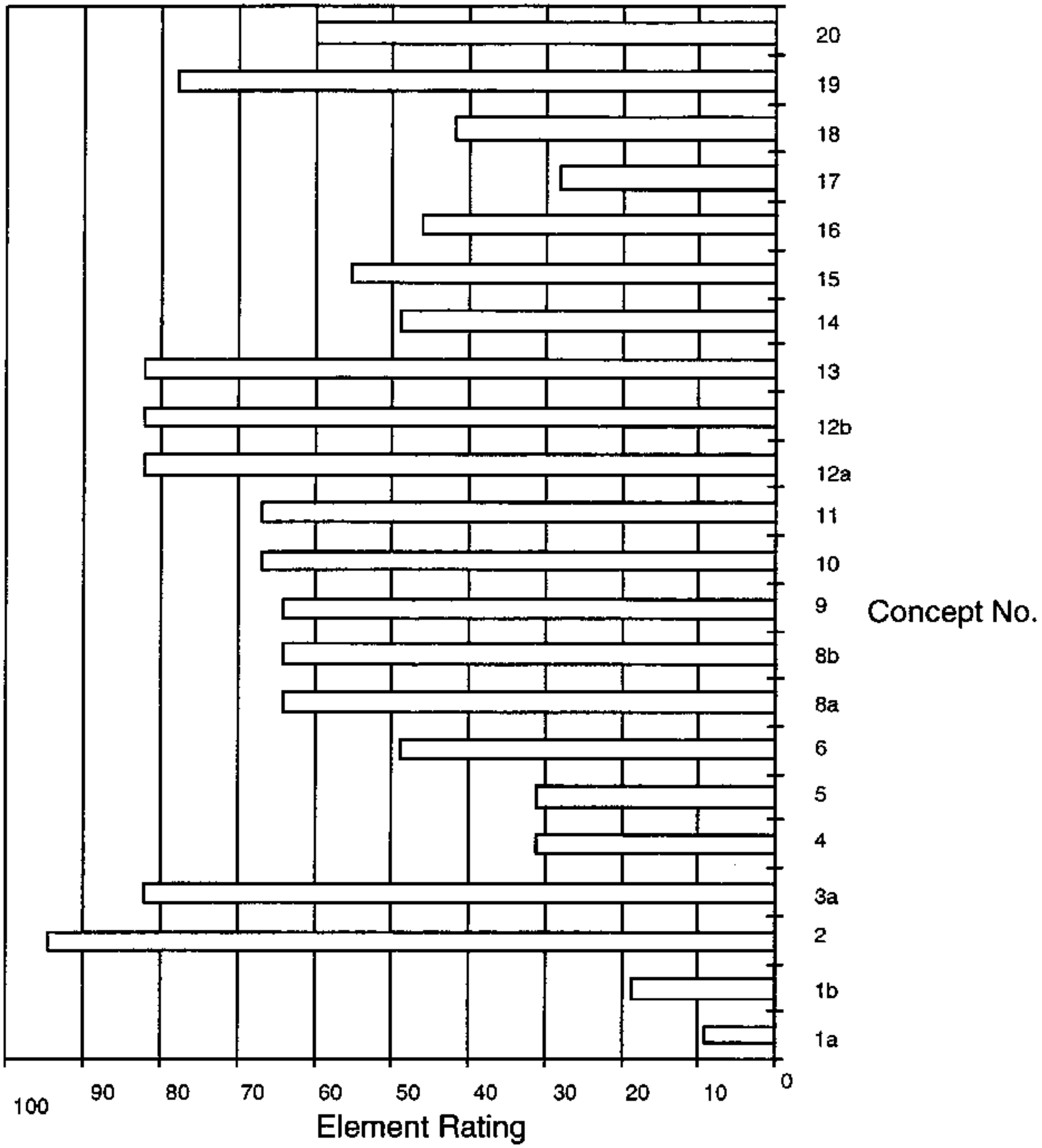

Figure D.5-1. Cost Element 4 Rating

D.6 SENSITIVITY ANALYSES

The sensitivity analyses were considered essential in determining the consistency of the evaluation results. The weights applied when rating each of the cost elements, as well as when performing the composite ranking, were the focus of these analyses. Various composite percentages were applied to recalculate the rankings and these results were compared with the original data. A similar comparison was made with each of the four cost elements. The goal of these analyses was to identify common results that would support a reasonable conclusion. The ranking of individual Concepts from high to low with respect to cost was not intended to identify the single most-expensive Concept. It is impossible to accurately perform this task given the current high level of the Concepts. Instead, grouping the Concepts into high-, medium-, and low-cost groups would be possible if the results were consistent throughout these sensitivity analyses. This grouping could then be used to identify the AHS characteristics with the highest potential cost and possibly to support a cost-benefit analysis.

The first step in determining sensitivity involved modifying the percentages that were applied in the composite ranking. This process could be used to determine if one cost element is able to control the results. Table D.6-I identifies the seven alternate ratios used to recalculate the composite rankings and summarizes the results of this effort. The original composite distribution and the associated ranking are also included in this table for comparison purposes. It is clear that Concept positions fluctuate for each composite ranking, but not excessively. In fact, the basis for cost-related groupings can begin with this comparison. It is apparent, after reviewing this table, that specific Concepts remain on the higher end of the cost ranking regardless of the composite percentages; the same also holds true at the lower end. This consistency indicated that cost groupings exist, but it was necessary to determine the divisions between each of the groupings. More data was necessary to make this determination, and this data could be generated by exploring the internal cost element weightings.

Independently modifying the applied weights from each cost element formed the basis of the next step of the analysis. Adjusting the composite percentages did not significantly affect the results; therefore, the original percentages were considered to be acceptable or ,as a minimum, representative. Changing the internal weights of a cost element without modifying any other parameters isolated the direct impact of this change and more clearly defined the significance of each cost element in the composite ranking. This also generated more data to support the creation of cost-groups and help define their alignments. Four alternative weighting schemes were generated for each cost element, and their direct impact on the composite rankings was evaluated. Tables D.6-II through D.6-V summarize this exercise for cost elements 1 through 4, respectively. The original weightings and the associated composite rankings from Table D.6-I are included in each table for ease of comparison. Reviewing each of these tables indicates that the original composite ranking does not fluctuate excessively and that the Concepts at the high and low end of the spectrum remain fairly uniform.

Table D.6-I. Sensitivity Comparison–Composites*

Composite Rankings	Alternate Composite Percentages							
	Cost Element No. 1 = 30% Cost Element No. 2 = 30% Cost Element No. 3 = 20% Cost Element No. 4 = 20%	Cost Element No. 1 = 40% Cost Element No. 2 = 40% Cost Element No. 3 = 10% Cost Element No. 4 = 10%	Cost Element No. 1 = 40% Cost Element No. 2 = 30% Cost Element No. 3 = 20% Cost Element No. 4 = 10%	Cost Element No. 1 = 40% Cost Element No. 2 = 30% Cost Element No. 3 = 10% Cost Element No. 4 = 20%	Cost Element No. 1 = 30% Cost Element No. 2 = 40% Cost Element No. 3 = 20% Cost Element No. 4 = 10%	Cost Element No. 1 = 30% Cost Element No. 2 = 40% Cost Element No. 3 = 10% Cost Element No. 4 = 20%	Cost Element No. 1 = 30% Cost Element No. 2 = 30% Cost Element No. 3 = 30% Cost Element No. 4 = 10%	Cost Element No. 1 = 25% Cost Element No. 2 = 25% Cost Element No. 3 = 25% Cost Element No. 4 = 25%
HIGHER	3a	3a	3a	3a	3a	3a	3a	3a
	13	13	13	13	13	2	13	13
	12b	2	12b	12b	12b	13	12b	12b
	2	12b	2	2	2	12b	12a	2
	12a	12a	12a	12a	12a	12a	2	12a
	19	19	8b	19	19	19	8b	8b
	8b	8b	19	8b	8b	8b	9	19
	9	20	9	20	11	11	19	9
	11	9	20	9	9	9	11	11
	8a	11	8a	8a	10	20	8a	8a
	20	8a	11	11	20	10	10	10
	10	10	10	10	8a	8a	20	20
	14	18	18	18	14	14	14	14
	15	14	14	14	15	15	15	15
	18	15	6	6	6	18	6	6
	6	6	15	15	18	6	18	18
	16	16	16	16	16	16	16	16
	5	5	5	5	5	5	5	5
	4	4	4	4	4	4	4	4
	17	17	17	17	17	17	17	17
	1b	1b	1b	1b	1b	1b	1b	1b
LOWER	1a	1a	1a	1a	1a	1a	1a	1a

E-800050-6 (2-28-96)

*Note: The combination at far left repeats the ranking from Table III-3 and serves as a baseline for comparison purposes

Table D.6-II. Sensitivity Comparison–Cost Element 1*

Composite Rankings	Alternate Weighting Schemes				
	AHS and Non-AHS Mixing (8) Obstacle Detection (2)	AHS and Non-AHS Mixing (9) Obstacle Detection (1)	AHS and Non-AHS Mixing (7) Obstacle Detection (3)	AHS and Non-AHS Mixing (6) Obstacle Detection (4)	AHS and Non-AHS Mixing (5) Obstacle Detection (5)
HIGHER ↕ LOWER	3a	3a	3a	3a	3a
	13	13	13	13	13
	12b	2	12b	12b	12b
	2	12b	2	2	2
	12a	12a	12a	12a	8b
	19	19	8b	8b	12a
	8b	8b	19	19	20
	9	9	9	20	19
	11	8a	20	11	11
	8a	11	11	9	9
	20	20	8a	10	10
	10	10	10	8a	8a
	14	14	14	15	15
	15	18	15	14	14
	18	6	6	6	6
	6	15	18	16	16
	16	16	16	18	18
	5	5	5	5	5
	4	4	4	4	4
	17	17	17	17	17
	1b	1b	1b	1b	1b
	1a	1a	1a	1a	1a

E-600850-7 (2-28-96)

*Note: The combination at far left repeats the ranking from Table III-3 and serves as a baseline for comparison purposes

Table D.6-III. Sensitivity Comparison–Cost Element 2*

Composite Rankings	Alternate Weighting Schemes Distribution of Intelligence (7) Separation Policy (1) Obstacle Detection (2)	Distribution of Intelligence (6) Separation Policy (2) Obstacle Detection (2)	Distribution of Intelligence (8) Separation Policy (1) Obstacle Detection (1)	Distribution of Intelligence (6) Separation Policy (1) Obstacle Detection (3)	Distribution of Intelligence (7) Separation Policy (2) Obstacle Detection (1)
HIGHER	3a	3a	3a	3a	3a
	13	13	13	13	13
	12b	12b	12b	12b	12b
	2	2	2	2	2
	12a	12a	12a	12a	12a
	19	19	19	8b	19
	8b	8b	8b	19	8b
	9	9	9	9	9
↕	11	11	11	11	11
	8a	8a	8a	8a	8a
	20	20	20	20	20
	10	10	10	10	10
	14	14	14	14	14
	15	18	15	15	18
	18	15	6	18	6
	6	6	18	6	15
	16	16	16	16	16
	5	5	5	5	5
	4	4	4	4	4
	17	17	17	17	17
	1b	1b	1b	1b	1b
LOWER	1a	1a	1a	1a	1a

E-60650-8 (2-28-96)

*Note: The combination at far left repeats the ranking from Table III-3 and serves as a baseline for comparison purposes

Table D.6-IV. Sensitivity Comparison–Cost Element 3*

Composite Rankings	Alternate Weighting Schemes				
	Distribution of Intelligence (3) Obstacle Detection (7)	Distribution of Intelligence (4) Obstacle Detection (6)	Distribution of Intelligence (1) Obstacle Detection (9)	Distribution of Intelligence (2) Obstacle Detection (8)	Distribution of Intelligence (5) Obstacle Detection (5)
	3a	3a	3a	3a	3a
	13	13	13	13	13
H	12b	12b	12b	12b	12b
I	2	2	2	2	2
G	12a	12a	12a	12a	12a
H	19	19	8b	8b	19
E	8b	8b	19	19	8b
R	9	9	9	9	9
▲	11	11	11	11	20
	8a	20	8a	8a	11
	20	8a	20	20	8a
	10	10	10	10	10
	14	14	14	14	18
	15	18	15	15	14
▼	18	15	6	6	15
	6	6	18	18	6
L	16	16	16	16	16
O	5	5	5	5	5
W	4	4	4	4	4
E	17	17	17	17	17
R	1b	1b	1b	1b	1b
	1a	1a	1a	1a	1a

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*Note: The combination at far left repeats the ranking from Table III-3 and serves as a baseline for comparison purposes

Table D.6-V. Sensitivity Comparison–Cost Element 4*

E-600650-10 (2-28-96)

Composite Rankings	Alternate Weighting Schemes				
	Distribution of Intelligence (6) AHS and Non-AHS Mixing (3) Obstacle Detection (1)	Distribution of Intelligence (8) AHS and Non-AHS Mixing (1) Obstacle Detection (1)	Distribution of Intelligence (7) AHS and Non-AHS Mixing (2) Obstacle Detection (1)	Distribution of Intelligence (6) AHS and Non-AHS Mixing (2) Obstacle Detection (2)	Distribution of Intelligence (5) AHS and Non-AHS Mixing (3) Obstacle Detection (2)
HIGHER ↕ LOWER	3a	3a	3a	3a	3a
	13	13	13	13	13
	12b	12b	12b	12b	12b
	2	2	2	2	2
	12a	12a	12a	12a	12a
	19	19	19	8b	8b
	8b	8b	8b	19	19
	9	9	9	9	9
	11	11	11	11	11
	8a	8a	8a	8a	8a
	20	20	20	10	20
	10	10	10	20	10
	14	14	14	14	14
	15	15	15	15	15
	18	18	6	6	18
	6	6	18	18	6
	16	16	16	16	16
	5	5	5	5	5
	4	4	4	4	4
	17	17	17	17	17
	1b	1b	1b	1b	1b
	1a	1a	1a	1a	1a

*Note: The combination at far left repeats the ranking from Table III-3 and serves as a baseline for comparison purposes

APPENDIX E - THE SUPPORTING DATA FOR 4.4 (FLEXIBILITY AND DEPLOYMENT)

E.1. THE EVALUATION CRITERIA DEVELOPED AND APPLIED TO SCORE EACH CONCEPT

This section describes the criteria for evaluating the candidate concepts against each of the system objectives related to flexibility and deployment.

The scoring process was based on the following symbol conversion for the criteria definitions:

& = -9
# = -6
- = -3
0 = 0
+ = +3
x = +6

The page numbers refer to the System Objectives are characteristics document of May 1995.

Inclement Weather (p. 23)

- (-) Performance (safety or throughput) is degraded (as compared to nominal operations) in this concept due to inclement weather.
- (+) Performance (safety or throughput) is unaffected in this concept due to inclement weather.

Infrastructure Compatibility (p. 26)

- (&) This concept requires extensive modifications to the infrastructure, e.g. creation of new travel lanes or entry/exit lanes.
- (#) This concept requires some modifications to the infrastructure, e.g. installation of communication and control equipment.
- (-) This concept requires minimal modifications to the infrastructure, e.g. lane markers, magnetic nails or tape.
- (0) This concept requires no modifications to the infrastructure.

Phased-in Implementation of Technology (p. 27)

- (-) For this concept, technology cannot be phased-in. Requires an "all or nothing" implementation.
- (+) For this concept, technology can be phased-in through discrete, logical steps, optimizing use of technology as it becomes available.

Public Acceptance (p. 27)

- (-) The public may view the AHS, as a whole, negatively because of potential risks and problems associated with deployment of this concept.
- (0) Public perception of AHS technology will not be affected by the deployment of this concept.
- (+) Positive public perception of the AHS expected through deployment of this concept.

High Availability – System Malfunction (p. 28)

- (-) This concept is highly complex, increasing the likelihood of system malfunctions causing performance degradation or AHS shut down.
- (+) This concept is perceived to be simple, such that the design is not prone to performance degradation due to system malfunctions.

Emergency Vehicles (p. 28)

- (-) Response to emergencies (e.g. medical or obstacle removal) will be less effective in this concept, as compared to today's systems.
- (0) Response to emergencies (e.g. medical or obstacle removal) will be as effective in this concept, as compared to today's systems.
- (+) Response to emergencies (e.g. medical or obstacle removal) will be improved by this concept, as compared to today's systems.

Rural Roadways (Mixed Traffic: AHS mixed with Non-AHS Vehicles) (p. 28, 31)

(-) This concept cannot support automated operation of AHS-equipped vehicles on non-AHS dedicated lanes.
(+) This concept may allow some features of AHS to be used on non-AHS dedicated lanes.
(x) This concept allows for automation of AHS vehicles on non-AHS dedicated lanes.

Support a Wide Range of Vehicle Classes (p. 31)

(-) This concept is exclusive to a single class of vehicles (independent of number of lanes).
(+) This concept allows a wide range of vehicle classes to operate on AHS lanes.

Enhance Operations for Freight Carriers (p. 32)

(-) It will not be possible to give priority access to freight carriers in this concept.
(+) Priority to freight carriers, at the discretion of the regional transportation authority, is possible in this concept.

Enhance Operations for Transit Operations (p. 32)

(-) It will not be possible to give priority access to transit vehicles in this concept.
(+) Priority to transit vehicles, at the discretion of the regional transportation authority, is possible in this concept.

Provide System Modularity (p. 33)

(-) This design concept is not a modular architecture.
(+) This concept provides system modularity allowing subsystems and components to be upgraded to accommodate advances in technology.

E.2 THE SPREADSHEET SCORING MATRICES, SUMMARY CHARTS AND GRAPHS DERIVED FROM THE SCORING PROCESS.

Following are the completed evaluation sheets submitted by each of the Flexibility Team members.

Sobetski's Evaluation Sheet

Concept No.	Inclement Weather	Infrastructure Compatibility	Phase-in Technology	Public Acceptance	High Availability—Malfunction	Emergency Vehicles	Mixed Type w/ non-AHS	Vehicle Classes	Freight Carriers	Transit Operations	System Modularity	Score	Rank
01a	-3	0	3	3	3	0	6	3	-3	-3	3	12	2.5
01b	-3	0	3	3	3	0	6	3	-3	-3	3	12	2.5
02	-3	-9	-3	-3	-3	3	-3	3	3	3	3	-9	21
03	-3	-9	-3	-3	-3	-3	-3	3	3	3	3	-15	23
03a	-3	-9	3	0	-3	-3	-3	3	3	3	3	-6	20
04	-3	-9	3	0	3	3	6	3	3	3	3	15	1
05	-3	-3	3	0	-3	0	3	3	3	3	3	9	4
06	-3	-9	3	0	3	0	3	3	-3	-3	3	-3	16
08a	-3	-9	3	0	3	0	3	3	-3	-3	3	-3	16
08b	-3	-9	3	3	3	0	6	3	-3	-3	3	3	6
09	-3	-9	3	0	-3	0	3	3	-3	-3	3	-9	21
10	-3	-6	3	3	-3	0	-3	3	3	3	3	3	6
11	-3	-6	3	0	-3	0	-3	3	3	3	3	0	10
12a	-3	-9	3	0	-3	0	-3	3	3	3	3	-3	16
12b	-3	-9	3	0	-3	0	-3	3	3	3	3	-3	16
13	-3	-9	3	0	-3	0	-3	3	3	3	3	-3	16
14	-3	-6	3	0	-3	0	-3	3	3	3	3	0	10
15	-3	-6	3	0	-3	0	-3	3	3	3	3	0	10
16	-3	-6	3	0	-3	0	-3	3	3	3	3	0	10
17	-3	-6	3	3	3	0	3	3	-3	-3	3	3	6
18	-3	-9	3	3	3	0	3	3	-3	-3	3	0	10
19	-3	-9	3	0	-3	0	-3	3	3	3	3	-3	16
20	-3	-9	3	0	-3	0	-3	3	3	3	3	-3	16
Ave	-3	-7.2	2.48	0.52	-0.9	0	0.13	3	0.91	0.91	3	-0.13	

Bayouth's Evaluation Sheet

Concept No.	Inclement Weather	Infrastructure Compatbility	Phase-in Technology	Public Acceptance	High Availability—Malfunction	Emergency Vehicles	Mixed Type w/ non-AHS	Vehicle Classes	Freight Carriers	Transit Operations	System Modularity	Score	Rank
01a	3	0	3	3		0	3	3	-3	-3		9	10
01b	3	0	3	3		0	3	3	-3	-3		9	10
02	-3	-9	-3	-3		3	-3	3	3	3		-9	21
03	-3	-9	-3	-3		3	-3	3	3	3		-9	21
03a	-3	-9	-3	3		3	3	3	3	3		3	15
04	-3	-9	3	3		3	3	3	3	3		9	10
05	-3	-9	3	3		3	3	3	3	3		9	10
06	-3	-9	-3	-3		3	-3	3	3	3		-9	21
08a	3	-9	-3	-3		3	-3	3	3	3		-3	17
08b	-3	-9	3	3		3	3	3	3	3		9	10
09	-3	-9	3	3		3	3	3	3	3		9	10
10	3	-9	3	3		0	3	3	-3	-3		0	16
11	-3	-9	3	3		3	3	3	3	3		9	10
12a	3	-9	3	3		3	3	3	3	3		15	2
12b	3	-9	3	3		3	3	3	3	3		15	2
13	-3	-9	3	3		3	3	3	3	3		9	10
14	-3	-9	-3	-3		3	-3	3	3	3		-9	21
15	-3	-6	3	3		3	3	3	3	3		12	5
16	-3	-6	3	3		3	3	3	3	3		12	5
17	-3	-6	3	3		3	3	3	3	3		12	5
18	3	-9	3	3		3	3	3	3	3		15	2
19	-3	-9	-3	-3		3	-3	3	3	3		-9	21
20	-3	-9	-3	-3		3	-3	3	3	3		-9	21
Ave	-1.2	-7.8	0.91	1.17	0	2.61	1.17	3	2.22	2.22	0	4.304	

Schuster's Evaluation Sheet

Concept No.	Inclement Weather	Infrastructure Compatbility	Phase-in Technology	Public Acceptance	High Availability—Malfunction	Emergency Vehicles	Mixed Type w/ non-AHS	Vehicle Classes	Freight Carriers	Transit Operations	System Modularity	Score	Rank
01a	-3	-3	3	-3	3	0	3	3	3	3	3	12	16
01b	-3	0	3	3	-3	3	6	3	3	3	3	21	5
02	3	-9	-3	-3	-3	3	-3	3	3	3	-3	-9	22
03	3	-9	-3	-3	-3	3	-3	3	3	3	-3	-9	22
03a	3	-9	-3	3	3	3	-3	3	3	3	3	9	19
04	-3	-9	3	3	3	0	3	3	3	3	3	12	16
05	-3	-9	3	0	3	0	3	3	3	3	3	9	20
06	3	-9	3	3	3	3	3	3	3	3	3	21	5
08a	3	-9	3	3	3	3	3	3	3	3	3	21	5
08b	3	-9	3	3	3	0	3	3	3	3	3	18	10
09	3	-9	3	0	3	3	3	3	3	3	3	18	10
10	3	-9	3	3	3	3	3	3	3	3	3	21	5
11	3	-9	3	0	3	3	3	3	3	3	3	18	10
12a	3	-9	3	3	3	3	3	3	3	3	3	21	5
12b	3	-9	3	3	3	3	3	3	3	3	3	21	5
13	3	-9	3	0	3	3	3	3	3	3	3	18	10
14	-3	-9	3	0	3	3	3	3	3	3	3	12	16
15	-3	-6	3	3	3	0	3	3	3	3	3	15	13
16	3	-6	3	3	3	3	3	3	3	3	3	24	1
17	3	-6	3	0	3	3	3	3	3	3	3	21	5
18	-3	-9	3	3	3	0	3	3	3	3	3	12	16
19	-3	-9	3	0	3	3	3	3	3	3	3	12	16
20	-3	-9	3	3	3	-3	3	3	3	3	3	9	20
Ave	0.65	-8	2.22	1.3	2.22	1.96	2.35	3	3	3	2.48	14.22	

McKendree's Evaluation Sheet

Concept No.	Inclement Weather	Infrastructure Compatbility	Phase-in Technology	Public Acceptance	High Availability—Malfunction	Emergency Vehicles	Mixed Type w/ non-AHS	Vehicle Classes	Freight Carriers	Transit Operations	System Modularity	Score	Rank
01a	-3	0	3	-3	3	0	6	3	3	3	3	18	2
01b	-3	0	3	3	3	0	6	3	3	3	3	24	1
02	-3	-9	-3	-3	-3	0	-3	3	3	3	3	-12	22
03	-3	-9	-3	-3	-3	0	-3	3	3	3	3	-12	22
03a	-3	-9	3	0	-3	0	3	3	3	3	3	3	21
04	-3	-9	3	0	3	0	3	3	3	3	3	9	13
05	-3	-9	3	0	3	0	3	3	3	3	3	9	13
06	-3	-9	3	0	3	0	3	3	3	3	3	9	13
08a	-3	-9	3	0	3	0	3	3	3	3	3	9	13
08b	-3	-9	3	0	-3	0	3	3	3	3	3	3	20
09	-3	-9	3	0	3	0	3	3	3	3	3	9	13
10	-3	-9	3	0	3	0	3	3	3	3	3	9	13
11	-3	-9	3	0	3	0	3	3	3	3	3	9	13
12a	-3	-9	3	0	3	0	3	3	3	3	3	9	13
12b	-3	-9	3	0	3	0	3	3	3	3	3	9	13
13	-3	-9	3	0	3	0	3	3	3	3	3	9	13
14	-3	-9	3	0	3	0	3	3	3	3	3	9	13
15	-3	-6	3	3	-3	3	3	3	3	3	3	12	5
16	-3	-6	3	0	3	3	3	3	3	3	3	15	4
17	-3	-3	3	0	3	3	3	3	3	3	3	18	3
18	-3	-9	3	0	3	0	3	3	3	3	3	9	13
19	-3	-9	3	0	3	0	3	3	3	3	3	9	13
20	-3	-9	3	0	3	3	3	3	3	3	3	12	6
Ave	-3	-7.7	2.48	-0.1	1.7	0.52	2.74	3	3	3	3	8.609	

Chen's Evaluation Sheet

Con-cept No.	Incle-ment Weather	Infra-structure Compat-bility	Phase-in Tech-nology	Public Accept ance	High Availa-bility—Mal-function	Emer-gency Vehicles	Mixed Type w/ non-AHS	Vehicle Classes	Freight Carriers	Transit Operations	System Modu-larity	Score	Rank
01a	3	-3	3	3	3	3	3	3	3	3	3	27	1
01b	-3	-3	3	3	-3	3	6	3	3	3	3	18	2
02												0	
03	3	-9	3	3	-3	3	3	-3	3	3	3	9	17
03a													
04	3	-9	3	3	-3	3	3	3	3	3	3	15	8
05	3	-9	3	3	-3	3	3	-3	3	3	3	9	17
06	3	-9	3	3	-3	3	3	3	3	3	3	15	8
08a	3	-9	3	3	-3	3	3	3	3	3	3	15	8
08b	3	-9	3	3	-3	3	3	-3	3	3	3	9	17
09	3	-9	3	3	-3	3	3	3	3	3	3	15	8
10	3	-9	3	3	-3	3	3	3	3	3	3	15	8
11	3	-9	3	3	-3	3	3	3	3	3	3	15	8
12a	3	-9	3	3	-3	3	3	3	3	3	3	15	8
12b	3	-9	3	3	-3	3	3	-3	3	3	3	9	17
13	3	-9	3	3	-3	3	3	-3	3	3	3	9	17
14	3	-9	3	3	-3	3	3	3	3	3	3	15	8
15												0	
16	3	-9	3	3	-3	3	3	3	3	3	3	15	8
17	3	-9	3	3	-3	3	3	3	3	3	3	15	8
18	-3	-9	3	3	-3	3	3	3	3	3	3	9	17
19	3	-9	3	3	-3	3	3	3	3	3	3	15	8
20	3	-9	3	3	-3	3	3	-3	3	3	3	9	17
Ave	2.09	-7.3	2.61	2.61	-2.3	2.61	2.74	1.04	2.61	2.61	2.61	11.87	

Siddiqui's Evaluation Sheet

Concept No.	Inclement Weather	Infrastructure Compatbility	Phase-in Technology	Public Acceptance	High Availability—Malfunction	Emergency Vehicles	Mixed Type w/ non-AHS	Vehicle Classes	Freight Carriers	Transit Operations	System Modularity	Score	Rank
01a	3	-3	3	3	3	0	3	3	-3	-3	3	12	2
01b	-3	0	3	3	-3	0	6	3	-3	-3	3	6	4
02	-3	-9	-3	-3	-3	3	-3	3	3	3	-3	-15	22
03	-3	-9	-3	-3	-3	-3	-3	3	3	3	-3	-21	23
03a	-3	-9	3	3	-3	-3	-3	3	3	3	3	3	9
04	-3	-6	3	3	-3	0	3	3	-3	-3	3	-3	19
05	-3	-3	3	3	-3	0	3	3	-3	-3	3	0	16
06	-3	-6	3	3	-3	0	3	3	-3	-3	3	-3	19
08a	-3	-9	3	3	-3	-3	3	3	3	3	3	3	9
08b	-3	-9	3	3	-3	-3	3	3	3	3	3	3	9
09	-3	-9	3	3	-3	-3	3	3	3	3	3	3	9
10	-3	-6	3	3	-3	3	3	3	-3	-3	3	0	16
11	-3	-6	3	3	-3	3	3	3	3	3	3	12	2
12a	-3	-9	3	3	-3	-3	3	3	3	3	3	3	9
12b	-3	-9	3	3	-3	-3	3	3	3	3	3	3	9
13	-3	-9	3	3	-3	-3	3	3	3	3	3	3	9
14	-3	-6	3	3	-3	0	3	3	-3	-3	3	-3	19
15	-3	-6	3	3	-3	3	3	3	3	3	3	12	2
16	-3	-3	3	3	-3	0	3	3	-3	-3	3	0	16
17	-3	-6	3	3	-3	0	3	3	-3	-3	3	-3	19
18	-3	-9	3	3	-3	-3	3	3	3	3	3	3	9
19	-3	-9	3	3	-3	-3	3	3	3	3	3	3	9
20	-3	-9	3	3	-3	-3	3	3	3	3	3	3	9
Ave	-2.7	-6.9	2.48	2.48	-2.7	-0.9	2.35	3	0.65	0.65	2.48	1.043	

Overall Combined Evaluation Sheet

Concept No.	In-clement Weather	Infrast-ructure Compatibility	Phase-in Tech-nology	Public Accep-tance	High Avail-ability—Mal-function	Emer-gency Vehicles	Mixed Type w/ non-AHS	Vehicle Classes	Freight Carriers	Transit Opera-tions	System Modular-ity	TOTAL (Average Cumulative Rank)	TOTAL (Sum of Averaged Scores)	Weighted Score	Weighted Score Values
01a	0	-1.5	3	1	3	0.5	4	3	0	0	3	5.6	16	181	181
01b	-2	-0.5	3	3	-0.6	1	5.5	3	0	0	3	4.1	15.4	197	197
02	-1.8	-9	-3	-3	-3	2.4	-3	3	3	3	0	21.6	-11.4	-64	-64
03	-1	-9	-2	-2	-3	0.5	-2	2	3	3	0.6	21.3	-9.9	-46	-46
03a	-1.8	-9	0.6	1.8	-1.5	0	-0.6	3	3	3	3	16.8	1.5	60	60
04	-2	-8.5	3	2	0.6	1.5	3.5	3	2	2	3	11.2	10.1	147	147
05	-2	-7	3	1.5	-0.6	1	3	2	2	2	3	13.3	7.9	121	121
06	-1	-8.5	2	1	0.6	1.5	2	3	1	1	3	13.7	5.6	93	93
08a	0	-9	2	1	0.6	1	2	3	2	2	3	11.3	7.6	115	115
08b	-1	-9	3	2.5	-0.6	0.5	3.5	2	2	2	3	12.0	7.9	127	127
09	-1	-9	3	1.5	-0.6	1	3	3	2	2	3	11.8	7.9	129	129
10	0	-8	3	2.5	-0.6	1.5	2	3	1	1	3	10.7	8.4	112	112
11	-1	-8	3	1.5	-0.6	2	2	3	3	3	3	8.8	10.9	143	143
12a	0	-9	3	2	-0.6	1	2	3	3	3	3	8.8	10.4	143	143
12b	0	-9	3	2	-0.6	1	2	2	3	3	3	10.3	9.4	126	126
13	-1	-9	3	1.5	-0.6	1	2	2	3	3	3	12.5	7.9	116	116
14	-2	-8	2	0.5	-0.6	1.5	1	3	2	2	3	14.5	4.4	83	83
15	-3	-6	3	2.4	-1.5	1.8	1.8	3	3	3	3	7.0	10.5	142	142
16	-1	-6	3	2	-0.6	2	2	3	2	2	3	7.3	11.4	140	140
17	-1	-6	3	2	0.6	2	3	3	1	1	3	7.7	11.6	143	143
18	-2	-9	3	2.5	0.6	0.5	3	3	2	2	3	11.2	8.6	135	135
19	-2	-9	2	0.5	-0.6	1	1	3	3	3	3	13.8	4.9	96	96
20	-2	-9	2	1	-0.6	0.5	1	2	3	3	3	14.8	3.9	81	81

															5.71102
Ave	-1.2	-7.7	2.2	1.33	-0.5	1.16	1.9	2.74	2.13	2.13	2.77				1.12028
Norm	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4	6.4				6.39795
Pair	0.99	1.13	1	1.07	0.9	0.48	2.77	2.65	1.71	1.62	1.31	15.63			
Prod	6.33	7.23	6.4	6.85	5.76	3.07	17.7	17	10.9	10.4	8.38	100			

APPENDIX F - ACCEPTABILITY EVALUATION CRITERIA AND SENSITIVITY STUDIES

F.1 EVALUATION CRITERIA

This section gives the specific criteria used in evaluating the candidate concepts against the objectives discussed in Section 4.5.5 of the main volume.

From 4.5.5.1. Mobility/Access

Trip time predictability

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept supports an *significant* increase in trip time predictability relative to similar driving conditions under manual control
(+)	This concept supports a *moderate* increase in trip time predictability relative to similar driving conditions under manual control
(0)	This concept supports *no* change in trip time predictability relative to similar driving conditions under manual control
(-)	This concept supports a *moderate* decrease in trip time predictability relative to similar driving conditions under manual control
(--)	This concept supports a *significant* decrease in trip time predictability relative to similar driving conditions under manual control
(U)	Unable to determine extent of change in trip time predictability by this concept due to lack of sufficient information.

Trip time

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept supports a *significant* decrease in trip time relative to similar driving conditions under manual control
(+)	This concept supports *a decrease* in trip time compared to similar driving conditions under manual control
(0)	This concept supports *no* decrease in trip time relative to similar driving conditions under manual control
(-)	This concept supports *an increase* in trip time relative to similar driving conditions under manual control
(--)	This concept supports a *significant* increase in trip time relative to similar driving conditions under manual control
(U)	Unable to determine extent of change in trip time by this concept due to lack of sufficient information.

Accessibility

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	*Very* likely to increase accessibility to highway travel for widest range of potential travelers
(+)	*Somewhat* likely to increase accessibility to highway travel for widest range of potential travelers
(0)	Accessible by all who presently use highway system
(-)	Inaccessible to *some* individuals who presently use highway system
(--)	Inaccessible to *many* individuals who presently use highway system
(U)	Unable to determine extent of change in trip time by this concept due to lack of sufficient information.

Intermodal

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept supports intermodal transportation operations to a *tremendous* degree
(+)	This concept supports intermodal transportation operations to a *significant* degree.

(0)	This concept supports intermodal transportation operations to a *moderate* degree.
(-)	This concept supports intermodal transportation operations to a *minimal* degree.
(--)	This concept *does not* support intermodal transportation operations.
(U)	Unable to determine whether or not this concept would support intermodal transportation operations due to lack of sufficient information

From 4.5.5.2. User Issues

Adaptability/training

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept will require *no* prior AHS training or on-road AHS driving time for the driver to adapt (both physically and psychologically) to the AHS driving environment
(+)	This concept will require a *minimal* amount of prior AHS training or on-road AHS driving time for the driver to adapt to AHS driving environment.
(0)	This concept will require a *moderate* amount of prior AHS training or on-road AHS driving time for the driver to adapt to AHS driving environment.
(-)	This concept will require an *significant* amount of prior AHS training or on-road AHS driving time for the driver to adapt to AHS driving environment.
(--)	This concept will require a *tremendous* amount of prior AHS training or on-road AHS driving time for the driver to adapt to AHS driving environment.
(U)	Unable to determine extent of additional AHS driving time required due to lack of sufficient information.

Driver Participation (I)

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept allows drivers to engage in non-driving tasks to a *tremendous* degree
(+)	This concept allows drivers to engage in non-driving tasks to a *significant* degree
(0)	This concept allows drivers to engage in non-driving tasks to a *moderate* degree
(-)	This concept allows drivers to engage in non-driving tasks to a *minimal* degree
(--)	This concept does *not* allow drivers to engage in non-driving tasks
(U)	Unable to determine whether or not this concept would allow drivers to engage in non-driving tasks due to lack of sufficient information

Driver Participation (II)

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept allows drivers to remain actively engaged and to communicate with the system if desired and necessary to a *tremendous* degree
(+)	This concept allows drivers to remain actively engaged and to communicate with the system if desired and necessary to a *significant* degree
(0)	This concept allows drivers to remain actively engaged and to communicate with the system if desired and necessary to a *moderate* degree
(-)	This concept allows drivers to remain actively engaged and to communicate with the system if desired and necessary to a *minimal* degree

(--)	This concept does *not* allow drivers to remain engaged and to communicate with the system if desired and necessary
(U)	Unable to determine whether or not this concept would allow drivers to remain engaged due to lack of sufficient information

From 4.5.5.3. Environment

Vehicle Emissions

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept will support emissions reduction strategies on a per VKT basis to a *significant* degree.
(+)	This concept will support emissions reduction strategies on a per VKT basis to a *moderate* degree.
(0)	This concept will *not* change emissions on a per VKT basis.
(-)	This concept will *increase* emissions on a per VKT basis.
(--)	This concept will *significantly increase* emissions on a per VKT basis
(U)	Unable to determine if this concept will support emissions reduction strategies due to lack of sufficient information.

Fuel Consumption

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept will support fuel consumption reduction strategies on a per VKT basis to a *significant* degree.
(+)	This concept will support fuel consumption reduction strategies on a per VKT basis to a *moderate* degree.
(0)	This concept will *not* change fuel consumption on a per VKT basis.
(-)	This concept will lead to *increases* in fuel consumption on a per VKT basis.
(--)	This concept will lead to significant increases in fuel consumption on a per VKT basis.
(U)	Unable to determine if this concept will support fuel consumption reduction strategies due to lack of sufficient information.

Transportation Demand Management (TDM)/Transportation System Management (TSM)

Policies

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept is compatible with TDM measures and TSM strategies to counter the potential for induced demand effects to a tremendous degree.
(+)	This concept is compatible with TDM measures and TSM strategies to counter the potential for induced demand effects to a significant degree.
(0)	This concept is compatible with TDM measures and TSM strategies to counter the potential for induced demand effects to a moderate degree.
(-)	This concept is compatible with TDM measures and TSM strategies to counter the potential for induced demand effects to a minimal degree.
(--)	This concept is not compatible with TDM measures and TSM strategies to counter the potential for induced demand effects.
(U)	Unable to determine whether this concept is compatible with TDM measures and TSM strategies due to lack of sufficient information.

From 4.5.5.4. Other

Ease of construction & maintenance

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept, when implemented, will be *much easier* to construct and maintain relative to today's highways.

(+)	This concept, when implemented, will be *easier* to construct and maintain relative to today's highways.
(0)	This concept, when implemented, will be *as easy* to construct and maintain relative to today's highways.
(-)	This concept, when implemented, will be *more difficult* to construct and maintain relative to today's highways.
(--)	This concept, when implemented, will be *much more difficult* to construct and maintain relative to today's highways.
(U)	Unable to determine due to lack of sufficient information.

Ease of traffic operations

Attributes	*Evaluation Criteria and Ranking Levels*
(++)	This concept, when implemented, will be *much easier* to operate & manage relative to today's highways.
(+)	This concept, when implemented, will be *easier* to operate & manage relative to today's highways.
(0)	This concept, when implemented, will be *as easy* to operate & manage relative to today's highways.
(-)	This concept, when implemented, will be *more difficult* to operate & manage relative to today's highways.
(--)	This concept, when implemented, will be *much more difficult* to operate & manage relative to today's highways.
(U)	Unable to determine due to lack of sufficient information.

The results of the evaluation are depicted in the Figures 1-12, which depict all the alternative sensitivity analyses, ordered both by concept number as well as by evaluation score. The former method readily shows results corresponding to the original ordering of the concepts which were clustered by certain of the six dimensions. The latter method of illustrating the results clearly indicates where changes in scores occur as well as extent of such changes, i.e. steepness of changes in heights of bars corresponding to each concept score:

F.2 SENSITIVITY ANALYSIS

There were two areas where variability was allowed due to uncertainty. The first area was whether to keep or omit one of the evaluation criteria, namely, Driver participation (II). Four of the seven team members voted "U", and thus any representation of the results including that criteria would necessarily represent only a minority view. Instead of eliminating this criteria from further consideration, it was suggested by the team to include both cases in the sensitivity analyses to investigate the impact of this criteria. The second area was in the set of weights assigned to the twelve (or as just indicated, in some cases eleven) criteria. The default set of weights was equal weight for all criteria. Opinion from team members was solicited on different sets of weights to test out to perform sensitivity analyses to address the uncertainty in knowing which set of weights to use. Different sets of weights were used in conjunction with the original set of evaluation criteria as well as the slightly modified set of criteria (Driver participation (II) omitted).

The following sets of weights were used in the sensitivity analyses run:

1. Default set of weights: equal weights among the criteria
2. Trip time predictability, Accessibility, Vehicle emissions, Ease of construction & maintenance had equal weight and three times the weight of all other criteria, which were weighed equally among themselves.
3. Vehicle emissions, Fuel consumption, Ease of construction & maintenance, and Ease of traffic operations had equal weight and three times the weight of all other criteria, which were weighed equally among themselves.

Each of these sets of weights were used with and without the inclusion of the Driver Participation (II) criteria.

4.5.8 Evaluation Results

The results of the evaluation are depicted in the Figures 4.5.8-1 through 4.5.8-12, which depict all the alternative sensitivity analyses, ordered both by concept number as well as by evaluation score. The former method readily shows results corresponding to the original ordering of the concepts which were clustered by certain of the six dimensions. The latter method of illustrating the results clearly indicates where changes in scores occur as well as extent of such changes, i.e. steepness of changes in heights of bars corresponding to each concept score:

Labels used in the above figures are described as follows:

Driver Participation (II)	DP (II)
Trip time predictability	TTP
Accessibility	A
Vehicle emissions	VE
Ease of construction & maintenance	ECM
Fuel consumption	FC
Ease of traffic operations	ETO

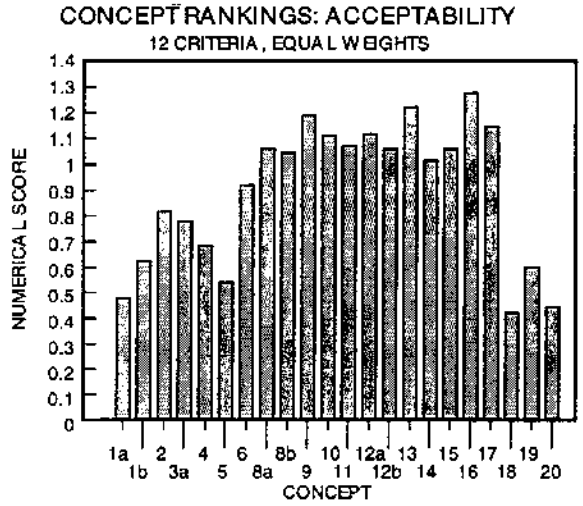

Figure 4.5.8-1. All 12 criteria, with weights as described in 1. above, ordered by concept number

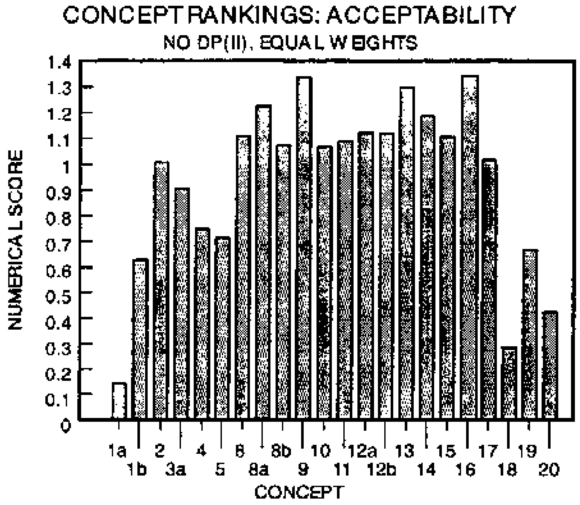

Figure 4.5.8-3. 11 criteria (omit Driver participation (II)), with weights as described in 1. above, ordered by concept number

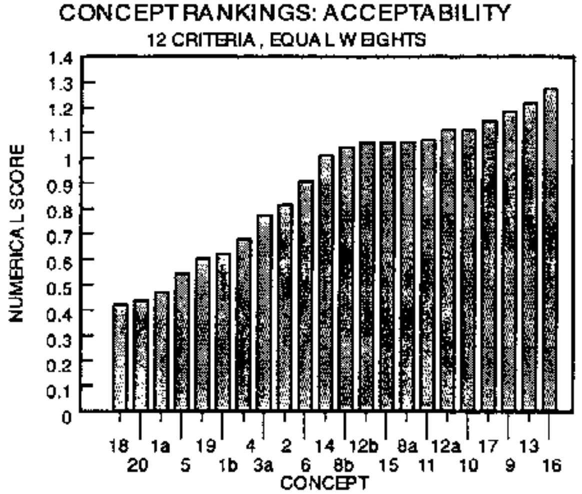

Figure 4.5.8-2. All 12 criteria, with weights as described in 1. above, ordered by evaluation score

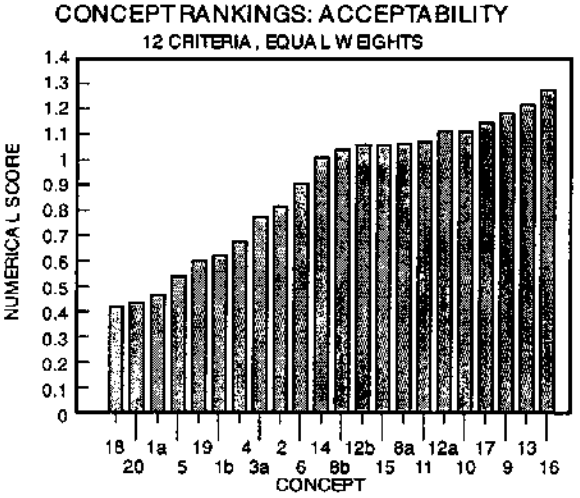

Figure 4.5.8-4. 11 criteria (omit Driver participation (II)), with weights as described in 1. above, ordered by evaluation score

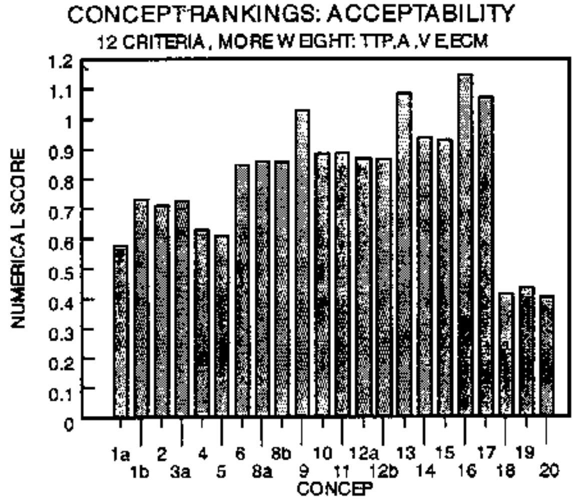

Figure 4.5.8-5. All 12 criteria, with weights as described in 2. above, ordered by concept number

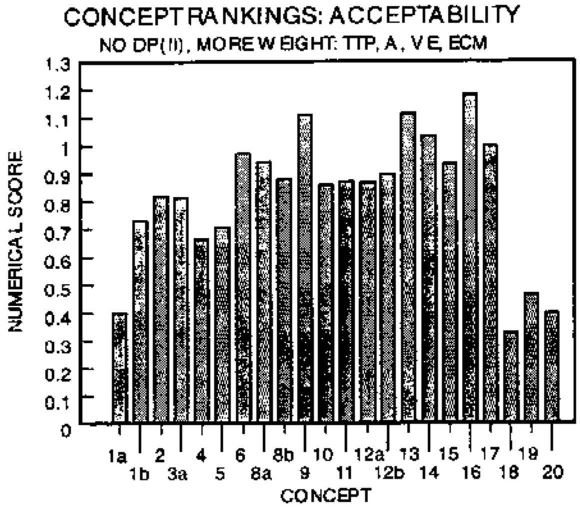

Figure 4.5.8-7. 11 criteria (omit Driver participation (II)), with weights as described in 2. above, ordered by concept number

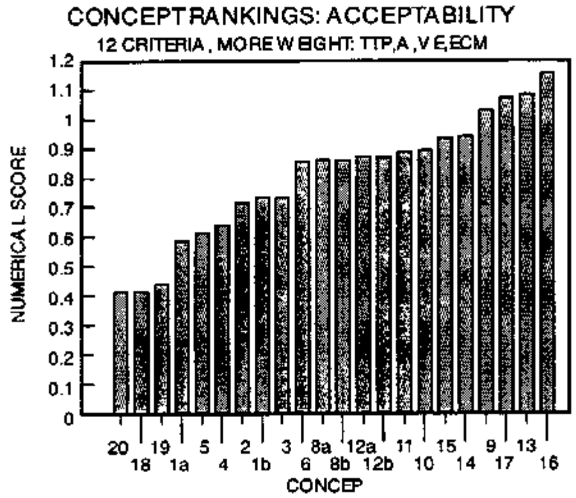

Figure 4.5.8-6. All 12 criteria, with weights as described in 2. above, ordered by evaluation score

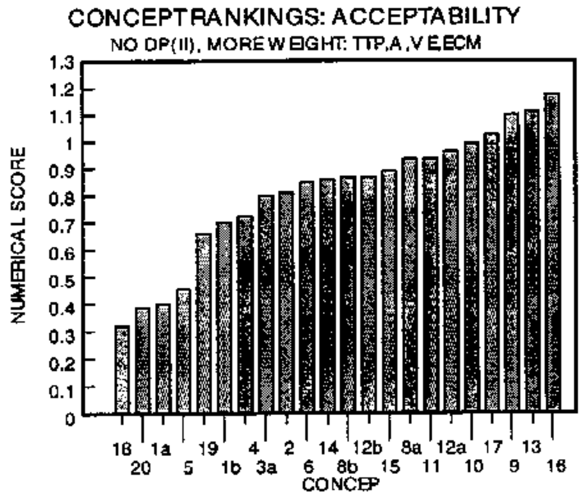

Figure 4.5.8-8. 11 criteria (omit Driver participation (II)), with weights as described in 2. above, ordered by evaluation score

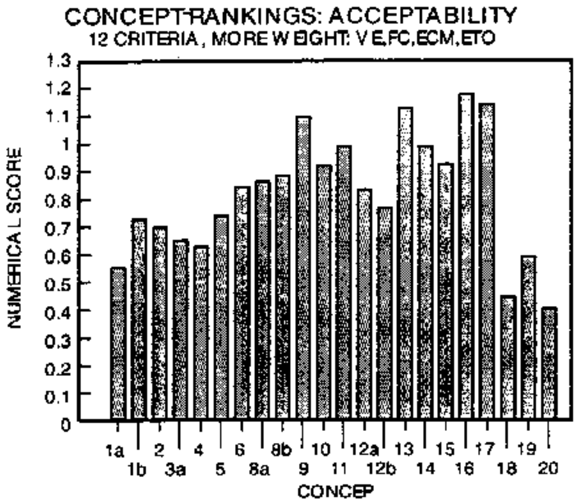

Figure 4.5.8-9. All 12 criteria, with weights as described in 3. above, ordered by concept number

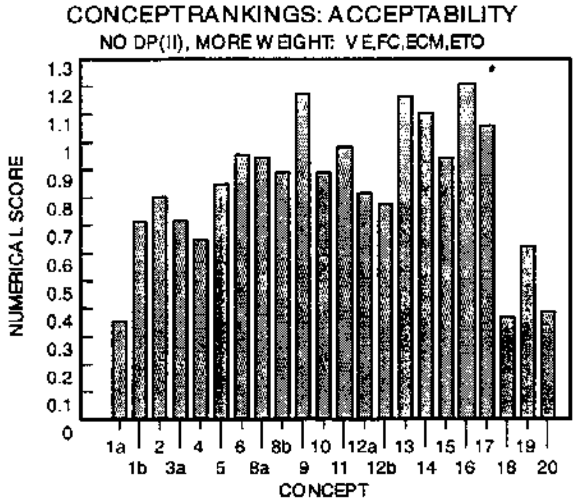

Figure 4.5.8-11. 11 criteria (omit Driver participation (II)), with weights as described in 3. above, ordered by concept number

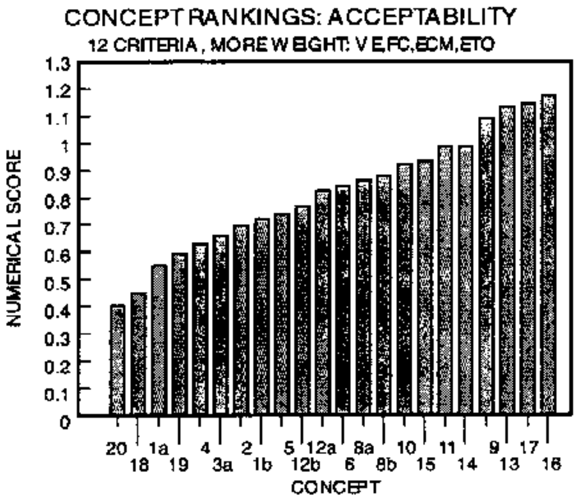

Figure 4.5.8-10. All 12 criteria, with weights as described in 3. above, ordered by evaluation score

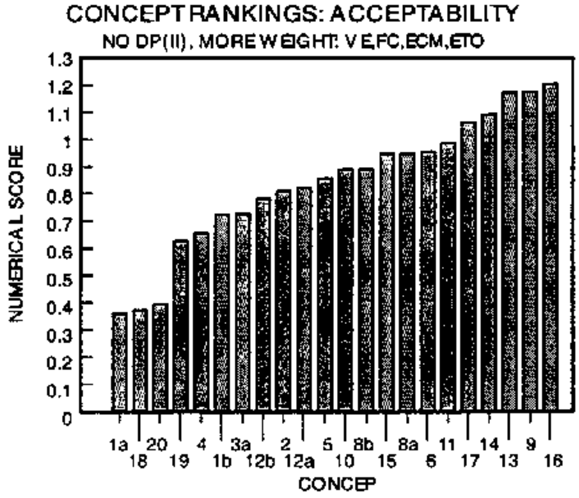

Figure 4.5.8-12. 11 criteria (omit Driver participation (II)), with weights as described in 3. above, ordered by evaluation score

APPENDIX G - OVERALL EVALUATION DATA

Below are the tables from the Excel spreadsheet that combined the various evaluations into the overall evaluation, as discussed in section 4.6 of the main report.

Concept Number	Intel Dist	Sep Pol	AHS/ Non AHS	Veh Cls	Entry/ Exit	Obstacles
1a	Auto	Free Agt	Full Mix	Mixed	Transition	Manual
1b	Auto	Free Agt	Full Mix	Mixed	Transition	Full Auto
2	Infra Cntrl	Free Agt	Phys Bar	Mixed	Dedicated	Full Auto
3a	Infra Spt	Slot	Phys Bar	Not Mixed	Dedicated	Full Auto
4	Coop	Free Agt	Bar w/ Gap	Mixed	Transition	Full Auto
5	Coop	Platoon	Bar w/ Gap	Mixed	Transition	Full Auto
6	Infra Spt	Free Agt	Bar w/ Gap	Mixed	Transition	Full Auto
8a	Infra Spt	Free Agt	Phys Bar	Mixed	Dedicated	Full Auto
8b	Infra Spt	Free Agt	Phys Bar	Not Mixed	Dedicated	Full Auto
9	Infra Spt	Platoon	Phys Bar	Mixed	Dedicated	Full Auto
10	Infra Mng	Free Agt	Bar w/ Gap	Mixed	Transition	Full Auto
11	Infra Mng	Platoon	Bar w/ Gap	Mixed	Transition	Full Auto
12a	Infra Mng	Free Agt	Phys Bar	Mixed	Dedicated	Full Auto
12b	Infra Mng	Free Agt	Phys Bar	Not Mixed	Dedicated	Full Auto
13	Infra Mng	Platoon	Phys Bar	Not Mixed	Dedicated	Full Auto
14	Infra Spt	Platoon	Bar w/ Gap	Mixed	Transition	Full Auto
15	Infra Mng	Free Agt	Full Mix	Mixed	Transition	Full Auto
16	Infra Spt	Free Agt	Virt Bar	Mixed	Transition	Full Auto
17	Coop	Platoon	Virt Bar	Mixed	Transition	Full Auto
18	Coop	Free Agt	Phys Bar	Mixed	Dedicated	Auto/Man
19	Infra Mng	Platoon	Phys Bar	Mixed	Dedicated	Auto/Man
20	Infra Spt	Free Agt	Phys Bar	Not Mixed	Dedicated	Auto/Man

Concept Number	Safety Composite	Safety Score	Cost Composite	Cost Score	Thruput Low	Thruput High	Thruput Score
1a	70	35%	8.10	8%	1	2	13%
1b	70	35%	28.30	28%	1	2	13%
2	85	43%	78.60	79%	1	2	13%
3a	129	65%	85.90	86%	2	3	38%
4	87	44%	37.30	37%	2	3	38%
5	87	44%	40.30	40%	3	3	50%
6	92	46%	45.40	45%	2	3	38%
8a	100	50%	61.00	61%	3	3	50%
8b	121	61%	67.00	67%	3	3	50%
9	100	50%	64.00	64%	4	4	75%
10	127	64%	58.30	58%	3	3	50%
11	127	64%	61.30	61%	3	4	63%
12a	135	68%	73.90	74%	3	3	50%
12b	156	78%	79.90	80%	3	3	50%
13	156	78%	82.90	83%	4	5	88%
14	92	46%	48.40	48%	3	4	63%
15	115	58%	46.90	47%	2	2	25%
16	83	42%	42.40	42%	2	2	25%
17	78	39%	37.30	37%	2	3	38%
18	95	48%	46.90	47%	3	3	50%
19	135	68%	67.90	68%	4	4	75%
20	121	61%	61.00	61%	3	3	50%

Concept Number	Flexibility	Flexibility Score	Acceptability	Acceptability Score	Weighted Score	Normalized Acceptability
1a	16.00	77%	0.44	56%	33%	0.00
1b	15.40	79%	0.70	59%	38%	0.11
2	-11.40	46%	0.79	60%	47%	0.30
3a	1.50	65%	0.75	59%	62%	0.64
4	10.10	76%	0.66	58%	48%	0.32
5	7.90	72%	0.70	59%	51%	0.39
6	5.60	68%	0.93	62%	49%	0.36
8a	7.60	72%	0.96	62%	57%	0.54
8b	7.90	73%	0.92	61%	61%	0.63
9	7.90	74%	1.14	64%	65%	0.70
10	8.40	72%	0.94	62%	60%	0.60
11	10.90	77%	0.96	62%	64%	0.69
12a	10.40	77%	0.90	61%	65%	0.71
12b	9.40	74%	0.89	61%	69%	0.78
13	7.90	73%	1.15	64%	78%	1.00
14	4.40	67%	1.03	63%	56%	0.51
15	10.50	77%	0.97	62%	51%	0.39
16	11.40	76%	1.21	65%	46%	0.29
17	11.60	75%	1.07	63%	47%	0.31
18	8.60	75%	0.39	55%	53%	0.44
19	4.90	70%	0.55	57%	68%	0.77
20	3.90	67%	0.41	55%	58%	0.56

Concept Number	Total Score	Merit Score	Normal Merit Score	Cost Score
1a	51%	40%	5%	8%
1b	48%	41%	8%	28%
2	34%	38%	0%	79%
3a	46%	55%	45%	86%
4	53%	50%	32%	37%
5	55%	54%	40%	40%
6	51%	50%	33%	45%
8a	52%	56%	47%	61%
8b	54%	60%	56%	67%
9	58%	65%	68%	64%
10	56%	61%	58%	58%
11	59%	65%	70%	61%
12a	55%	63%	63%	74%
12b	55%	65%	70%	80%
13	64%	77%	100%	83%
14	57%	58%	52%	48%
15	52%	52%	36%	47%
16	50%	47%	25%	42%
17	53%	50%	31%	37%
18	54%	55%	43%	47%
19	60%	68%	77%	68%
20	53%	57%	50%	61%

APPENDIX H—DESCRIPTIONS OF CANDIDATE CONCEPTS

H.1. INTRODUCTION

As an intermediate step in the C1 effort, leading to the development of six preferred concepts for Automated Highway System to be carried into the C2 effort, 23 system concepts were defined and fleshed out. This appendix is a compilation of the 23 system write-ups.

These 23 concepts were all defined by selecting one option from each of six concept dimensions, as described in 3.1 of the main report. The concept dimensions, and their alternatives, are:

Distribution of intelligence

- Autonomous — The vehicles are driven entirely by on-board automatic control, but vehicles do not coordinate with each other.
- Cooperative — The vehicles are equipped as above, but share data and negotiate decisions. This is a natural allocation for functions involving multiple vehicles in a small area, such as a lane change.
- Infrastructure Supported — Similar to cooperative, but infrastructure provides general or location specific, non-vehicle specific, dynamic information and static information.
- Infrastructure Managed — Like infrastructure supported, but the infrastructure sends specific commands to individual vehicles.
- Infrastructure Controlled — The infrastructure directly commands individual vehicles, controlling their moment by moment trajectories.

Separation Policy

- Free Agent — Vehicles maneuver as individual units.
- Platooning — Coordinated groups of vehicles travel with very tight spacing, but long spacing between groups
- Slotting — Time or space is divided into sections which individual vehicles are assigned to and travel in.

Mixing of AHS and Non-AHS

- Dedicated Lanes with Continuous Physical Barriers — AHS highway is physically isolated along its entire length.
- Dedicated Lanes with Some Gaps — AHS lanes are physically isolated on a highway, with gaps in the barriers allowing traffic to flow between AHS and manual lanes.
- Dedicated Lanes with Virtual Barriers — only AHS vehicles are allowed on the automated lanes, but nothing physically prevents manual vehicles from intruding.
- Full Mixing — AHS vehicles travel fully automated while mixed with manual traffic.

Mixing of Vehicle Classes in a Lane

- Mixed — Multiple AHS vehicles in different classes (e.g., cars, trucks) allowed in the same lane at the same time.
- Unmixed — AHS vehicles in different classes do not travel in the same lane at the same time.

Entry/Exit

- Dedicated — The entry and exit of vehicles to and from AHS lanes is through ramps and other dedicated structures.
- Transition — The entry and exit of vehicles to and from AHS lanes is through transition lanes running parallel and between manual and AHS lanes.

Obstacle

- Automated sensing and automatic avoidance maneuver if possible — AHS, without requiring driver assistance, detects obstacles in the roadway, and attempts to automatically maneuver the vehicles to avoid the obstacles.

- Automatic Sensing, Stop and Manually Avoid — AHS, without requiring driving assistance, detects obstacles in the roadway. When an obstacle is detected, the vehicle is brought to a halt, and the driver takes over temporarily to manually circumvent the obstacle.
- Manual Sensing and Avoidance of Obstacles — The driver is responsible for seeing and avoiding obstacles. Sensors may assist the driver.

The Table below summarizes each of the concepts. After the meeting establishing the initial set of concepts, it was recognized that concept 7 was identical to concept 14, so concept 7 was dropped. Part way through the analysis of these concepts, the consortium decided that infrastructure controlled concepts were unfavorable. Since the only slotted concept in the initial set of 22, was infrastructure controlled, but non-infrastructure controlled slotted concepts are possible, concept 3a was created to give slotting a fair chance to make its case. Both concepts are described in this appendix.

Twenty-Three Candidate Concepts

Candidate Concept Identifiers	1a	1b	2	3	3a	4	5	6	8a	8b	9	10	11	12a	12b	13	14	15	16	17	18	19	20
Distribution of Intelligence																							
Autonomous	X	X																					
Cooperative						X	X													X	X		
Infrastructure Supported								X	X	X	X						X		X				X
Infrastructure Managed					X							X	X	X	X	X		X				X	
Infrastructure Control			X	X																			
Separation Policy																							
Free Agent	X	X	X			X		X	X	X		X		X	X			X	X		X		X
Platooning							X				X		X			X	X			X		X	
Slot				X	X																		
Mixing AHS & Non-AHS Vehicles in Same Lane																							
Dedicated lanes with continuous physical barriers			X	X	X				X	X	X			X	X	X					X	X	X
Dedicated lanes with some gaps in the physical barriers						X	X	X				X	X				X						
Dedicated lanes with virtual barriers																			X	X			
Full Mixing	X	X																X					
Mixing Vehicle Classes in Same Lane																							
Mixed	X	X	X			X	X	X	X		X	X	X	X			X	X	X	X	X	X	
Not Mixed				X	X					X					X	X							X
Entry/Exit																							
Dedicated			X	X	X				X	X	X			X	X	X					X	X	X
Transition	X	X				X	X	X				X	X				X	X	X	X			
Obstacle																							
Manual sensing and avoidance of obstacles	X																						
Automatic sensing, stop or manually avoid																					X	X	X
Automatic sensing and automatic avoidance maneuver if possible		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			

2. CONCEPT 1A: ADAPTIVE CRUISE WITH LANE MONITORING

2.1 OVERVIEW

Adaptive cruise is the simplest of the concepts considered. Its main advantages are that it is a necessary step in the deployment of several of the other concepts, it requires little infrastructure investment, and its early implementation can aid in technical development of a full scale obstacle detection system.

Another way to consider this concept is as the way we would like an AHS vehicle to operate on a non-AHS roadway.

2.2 DIMENSION ALTERNATIVES

- autonomous, free agent vehicles
- mixed vehicle classes and mixing of AHS/non-AHS vehicles
- no special entry/exit for AHS vehicles
- full longitudinal control
- must rely on human for full obstacle detection/avoidance (although limited obstacle detection through longitudinal control sensors)

2.3 OPERATIONAL CONCEPT

Entry/exit is done as a non-AHS vehicle. Once the vehicle is in the lane, driver sets automatic cruise. Forward looking sensors allow vehicle to maintain up to posted speed without colliding with forward vehicles (or most forward obstacles). In addition, road curvature and grade information is coded in the roadway or by a DGPS system in conjunction with a map. This information is used by the longitudinal sensors to avoid false obstacle detection. Lateral position sensors will monitor the vehicle's position in a lane although automatic lane keeping may not be implemented (for reasons below).

The driver can override the system at any time. Most obstacles are detected by the forward-looking sensor but some will be missed (eg. dropped loads, pavement holes, objects moving laterally toward lane). The driver is required to be alert for obstacles not detected by the vehicle sensors.

Driver alertness is a major problem for this concept. One way to handle it would be to utilize a driver alertness sensor. If a sleeping driver is detected, an alarm is sounded and the vehicle slows. An alternative option would be to require the driver to steer the vehicle (i.e. no automated lane keeping). This would help keep the driver awake by giving him a task to do.

2.4 FUNCTIONAL ALLOCATION

- check in/out—none
- transition from manual to auto control-human
- sensing of roadway—human
- sensing of vehicles and obstacles—human and vehicle (mainly by vehicle sensors but backup provided by human)
- sensing of hazards—human
- lane keeping—human (alternatively vehicle)
- headway keeping—vehicle
- maneuver planning and execution—human
- transition from auto to manual control—human (instantaneous)
- flow control—none
- malfunction management—human
- emergency handling—human

2.5 IMPLEMENTATIONS

The following are two of many possible implementations:

2.5.1 Vehicle

Implementation #1:

- forward-looking FMCW radar
- throttle, steering, and brake actuators

- magnetic nail sensors

Implementation #2:

- fused radar/vision forward-looking sensor
- DGPS and accurate map
- throttle, steering, and brake actuators

2.5.2 Infrastructure

Implementation #1:

- magnetic nails

Implementation #2:

- DGPS reference stations (1 per approx. 100 miles)
- radar reflective roadway markings

Note, there is no difference in rural vs. urban operation.

2.5.3 Deployment

A minimal system could be implemented without any infrastructure modifications. This system would have headway sensors but no lane keeping or absolute positioning.

The next step from minimal is the addition of DGPS capabilities. This requires reference stations in the infrastructure. (DGPS will aid the headway control system in recognizing false obstacles at curves and road grades.)

A third step can either be modification of roads (magnetic nails or special pavement markings) to add lateral control, or an improvement in sensing capabilities toward full fledged obstacle detection. (The concept would then evolve to 1b.)

2.6 GENERAL ISSUES

Navigation is not automated although DGPS can provide trip planning and exit notification.

The most critical failure mode is non-detection of a dangerous obstacle by both the vehicle sensors and by a sleeping or distracted driver.

The system relies totally on human backup. The driver can take control of the vehicle on demand.

This concept has no roadway sensing and no special handling (or sensing) of limited visibility conditions (snow, ice, etc. ...)

Speed is not a critical issue—should be no problem handling 65 mph or possibly faster.

This concept (except for lateral control) can work on a conventional roadway.

This concept has no connection with other transportation modes.

Freight carriers may find this concept convenient for long trips (in fact, there exist adaptive cruise control systems for freight use today).

The concept provides no increase in throughput.

Forward-looking sensors increase safety by helping avoid front end collisions.

The concept is cost effective in the sense that it requires minimal investment in infrastructure.

Vehicle maintenance requirements are expected not to be any greater than normal maintenance schedules of today's vehicles.

The main demand for (and the user's view of) this concept will be as a smart cruise control device for long distance travelers (eg. freight carriers).

Another advantage of this concept is in its use as an evolutionary deployment aid for more complex concepts. In fact, any concept requiring full vehicle-based obstacle detection must implement this concept.

Besides helping perfect the obstacle detection capabilities, this concept will get drivers used to the idea of smart vehicle headway control.

A disadvantage of this concept is that it does not represent a "brain-off" driving situation. The driver must always be alert for obstacles. This could project a bad image of AHS if this concept is touted as an early example of AHS.

3. CONCEPT 1B: AUTONOMOUS FREE AGENT VEHICLES MIXING WITH NON-AHS TRAFFIC

3.1 OVERVIEW

This concept, which mixes AHS and non-AHS traffic on the same freeway lanes, requires few or no infrastructure changes to implement. This concept is characterized by autonomous vehicles which have the ability to maneuver appropriately given the following information: number of lanes on the freeway, which lane the vehicle is in, where the vehicle is within that lane, where other vehicles and obstacles are, and lastly, what the relative velocity of these objects are. By eliminating the driver from the loop, a gain in throughput will be realized even without platooning capabilities. Safety gains will also be realized because of the added vigilance of the AHS system. No communications technology is required, although a minimal communications capability would significantly add to this concept.

3.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

Distribution of Intelligence: Autonomous vehicles with no infrastructure intelligence
Separation Policy: Free agent vehicles that do not travel in platoons

Mixing of Vehicles: Full mixing of AHS and non-AHS vehicles in lane

Mixing of Vehicle Classes: Full mixing of all vehicle classes

Entry/Exit: Transition lanes

Obstacle: Automatic sensing and collision avoidance maneuvering

Region Specific Options:

1. Although this option is intended to mix fully automated AHS vehicles with non-AHS vehicles on the same lane, dedicated AHS lanes could be created in order to maximize the benefits of AHS technology.
2. This technology can be used as a requirement for use of HOV lanes in order to encourage car-pooling.

3.3 OPERATIONAL CONCEPT

3.3.1 Check In

Once a vehicle has entered a freeway and the driver wishes to utilize the AHS features, a brief systems check is performed by the vehicle. If all required systems are operational, the on-board AHS system will gracefully assume control of the vehicle. At the point where the vehicle is successfully integrated into the traffic flow, the computer will prompt the driver for destination information. The driver will specify one of three options: that he will manually assume control a later point in time, that the vehicle will transition control to the driver after a certain number of miles, or that the vehicle will transition control to the driver in time for the driver to leave the freeway at a particular exit.

3.3.2 Normal Operations, Including Obstacle Detection

The vehicle will determine its location on the highway either through vision data or GPS used in conjunction with an on-board database. The vehicle will be able to determine the number of lanes on the freeway and which lane the vehicle is in. The vehicle has 360 degree obstacle detection sensors that detect other vehicles and obstacles. The vehicle will also be capable of detecting the relative velocity of these objects. The on-board logic uses the above information to maneuver the vehicle so that it travels with the flow of the traffic and maintains a safe distance from other vehicles. A gain in throughput is achieved because intelligent vehicles can use smaller headways due to faster reaction times to received information. Even given mixed traffic flow, increases in flow rates are predicted to improve. In the event that the AHS vehicle is closing on another object, be it a stationary obstacle or a slower moving vehicle, the AHS system will determine if it is safe to maneuver around the object by passing in another lane. The vehicle will automatically signal its intentions by using the turn signal. If a space is available for safe passing, the vehicle will do so. If a safe opportunity does not present itself, the vehicle will decelerate and potentially stop in order to avoid a collision. In severe emergencies, it will be possible for the vehicle to gracefully maneuver onto the shoulder.

A potential technology used to detect the relative motion of surrounding objects could be a non-vision based technology such as Doppler radar. A secondary, vision-based system may have sensors to detect the brake lights of vehicles around them. If a brake light is detected, the AHS vehicle will brake in a timely and appropriate manner or maneuver out of the way. The integration of cyberlight technology (whereby the brake light flash frequency can be detected by the vision system) may be required so as to determine the degree of braking required.

Additional vision system benefits include the ability of AHS vehicles to detect turn signals on other vehicles. They will have the logic to automatically create a space for a vehicle in another lane that has signaled its intention to merge into its own lane. This kinder, gentler vehicle will either accelerate past that vehicle or slightly decelerate in order to create a space.

AHS vehicles will also have sensors capable of detecting hazard signals for stalled or very slow vehicles. This information will also feed into the maneuvering and braking algorithms on-board, and will supplement the vehicle/obstacle and relative velocity information obtained.

Integration of a very simple, locally directed communications system would greatly simplify this concept. The vision system concept has significant technical concerns due to latency issues and non-functioning brake lights on non-AHS vehicles. By integrating a basic communications "beacon" that signals AHS capability and motion intentions, this system would be greatly simplified. It is also possible that all non-AHS vehicles be required to install a communications system that signals motion intention (lane changes and braking) so as to further enhance safety.

The backwards looking sensors will be continually scanning for vehicles which are approaching with a problematic delta v. The vehicle can signal the approaching vehicle by "flashing" its brake lights to gain the attention of the on-coming vehicle. If this is unsuccessful and a collision is imminent, the AHS vehicle will maneuver out of the lane to avoid a collision.

3.3.3 System Tailoring and Aggressive Driver Avoidance

Algorithms will be developed so that highly aggressive, manually driven vehicles do not "work the system" so as to run AHS vehicles out of the lane or off the road.

There will be a limited number of options to tailor the vehicle to the driver's preferences. For example, if an elderly driver prefers to stay in the right hand land regardless of the speed of travel, he will be able to do so. The driver can also insist that the vehicle never exceed a certain speed for personal comfort considerations or in order to torment his teenage children. Other items of user comfort, such as headway tolerance, could be specified within a range determined by the AHS. Lastly, the "kinder, gentler" feature that allows other vehicles to merge into your lane could be turned off at the option of the driver.

3.3.4 Use of AHS Technology for Rural and Inner-City Driving

Certain features of the AHS system, such as lane-keeping and headway maintenance, can be used independent of other features. This will provide additional safety benefits during inner-city driving as well as rural roadway driving. Partial-use of AHS features will be terminated manually.

3.3.5 System Transition from Automated to Manual Control

Terminating the full use of the AHS features will be done in one of two ways. In the first method, the vehicle will signal the driver via visual and audio cues that the desired exit is approaching or that the specified number of miles have been traveled. Transition from AHS to manual use will be done in steps, ensuring that the driver is physically responding to necessary cues. First, the AHS system will ensure there is sufficient headway distance between itself and the lead vehicle for the transfer to manual control. It will then return control of the accelerator to the driver. When the system determines that the driver has adequate control of the velocity and acceleration of the vehicle, it will return control of the braking and maneuvering functions as well. In the rare instance that the vehicle is slowing to a stop because the driver has not assumed control of the accelerator, the AHS system will regain all automated functions and safely pull to the side of the freeway.

3.3.6 Manual Termination of AHS Capabilities

The second method of transitioning an AHS vehicle from automated to manual control is through driver-initiation. This method also requires a graceful transition, however this transition period could be shorter and may even be immediate for emergency situations.

3.4 FUNCTIONAL ALLOCATION

In this concept, all intelligence is assigned to the vehicle. No infrastructure changes have been implemented to support AHS. Additional functional allocation information is summarized under "3.3. Operational Concept."

3.5 IMPLEMENTATION

Implementation of intelligence is strictly placed in the vehicle. No infrastructure support will be required.

3.5.1 Vehicle

The following technologies will be examined in order to achieve this concept:

- Forward and backward looking Doppler Radar
- GPS
- Side looking proximity sensors
- Infrared technology
- Vision system technology

3.5.2 Infrastructure

There will be no infrastructure support in this concept other than already existing GPS infrastructure. No TOC will be necessary or available. If communications are added to this concept, this statement is subject to review.

3.5.3 Deployment

This system will have tremendous appeal because of the safety advantages, early implementation of technology, and wide applicability of technology. Vehicles can be equipped with AHS technology as soon as it is proven and requires no timely and costly infrastructure changes. AHS capability can not only be utilized on freeways but can also be used, at least partially, in the city and on rural roadways. This provides significant and immediate benefit to the consumer.

3.6 GENERAL ISSUES AND CONSIDERATIONS

Were basic communications capability integrated into this concept, significant benefits would be realized. By allowing vehicles to electronically signal their intentions and/or braking data, the system architecture could be greatly simplified. Visual detection, with the associated latency problems and the complicated algorithms that are required to support a variety of detection features, would not be necessary.

4. CONCEPT 3: SPACE/TIME SLOT SEPARATION [INFRASTRUCTURE CONTROLLED]

4.1 OVERVIEW

Space/Time Slot Control is a configuration which allows synchronous control of all vehicles within a specific moving space on the AHS roadway. The coordination unit is the level at which traffic management functions such as merging are coordinated on the AHS. The coordination unit for the slot control concept is the slot, which corresponds to a single vehicle. Synchronous control refers to the system wide coordination of the motion of vehicle slots. This form of control can be referred to as point following.

The desired local vehicle speed or timing is controlled by the infrastructure, as is the spacing. Slot dynamics can be modified based on vehicle performance capabilities or current traffic densities. The vehicle adjusts its speed to track the slot dynamics commanded by the infrastructure. The merge decisions for each vehicle are determined by the infrastructure at the time the vehicle is assigned to a slot; the vehicle follows infrastructure commands to reach merge speed and adjust its position to merge into its assigned slot.

This concept has been selected for discussion due to its unique approach to the traffic flow problem. Other concepts featuring free agents and platoon architectures are asynchronous, in that the dynamically changing distribution of vehicles within the system is not coordinated in a global manner, but is managed within the coordination unit at the vehicle or platoon level. The slot or point-following architecture provides a concept in which the distribution and flow of all the vehicles within a region are managed in time synchronization. This approach requires processing (intelligence) at the regional and zone level. The slot architecture can be implemented in a manner which places the majority of processing and sensing in the infrastructure, theoretically minimizing the extent of vehicle instrumentation. The advantage of this approach is that a larger percentage of vehicles may be compatible with AHS retrofit in the early stages of deployment and the cost of AHS specific instrumentation will not be prohibitive in new car models which feature AHS equipment.

4.2 DIMENSION ATTRIBUTES

4.2.1 Distribution of Intelligence: Infrastructure Control

Vehicle control loop commands are generated by the infrastructure. Slot positions are scheduled at the regional level and monitored at the zone level. Vehicle directives may be in the form of acceleration, deceleration and maneuver instructions, in which case the vehicle calculates the appropriate throttle, brake, and steering commands to vehicle actuators. Alternately, the infrastructure may perform the throttle, brake, and steering calculations and transmit these commands to the vehicle. The vehicle instrumentation provides the ability to translate commands into corresponding input to actuators. The vehicle also is capable of monitoring on-board measurement systems and adjusting vehicle performance to meet command requirements.

4.2.2 Separation Policy: Slot

The slot attribute provides unique slots in space and time for individual vehicles. The separation between vehicles is determined by the size of the slot. Smaller slots correspond to higher lane density. The ability to maximize density will depend on the ability to safely monitor and maintain vehicle headway in closely spaced slots. This will depend on the ability of infrastructure instrumentation to accurately determine on a continuous basis the position of all slots in its vicinity. A single vehicle is the coordination unit, the goal of the infrastructure control is to maintain individual vehicles in their assigned slot, and no interaction between vehicles occurs.

4.2.3 Mixing of AHS and Non-AHS Vehicles: Dedicated Lanes With Continuous Physical Barriers

Continuous physical barriers will prevent access of unauthorized vehicles into spaces between slots. Unqualified vehicles which breach the entry facility can be detected by the infrastructure instrumentation at the zone level as slot spacing is monitored. This information can be relayed to the regional slot allocation function and slot spacing around intruders or travel speed can be adjusted to allow operation to continue until the non-AHS vehicle can be removed.

4.2.4 Mixing of Vehicle Classes: Not Mixed

The preliminary attribute assignment specified no mixing of vehicle classes. This will permit maximum passenger vehicle density and travel speed within a single lane. Slot allocation will be determined based on the lowest common denominator of vehicle performance of the set of vehicles allowed on a certain lane. Slots will be allocated at a certain spacing for passenger cars based on the slowest accelerating and longest braking distance of allowed cars. Slots in a commercial vehicle lane will be spaced at greater intervals, corresponding to the performance of vehicles authorized for that lane.

An option for rural or less congested areas might allow mixing of vehicle classes. The regional allocation of slots could take into account vehicle performance factors when assigning slots to vehicles requesting entry to the automated lanes. Slot spacing could be adjusted to accommodate lower performing trucks or buses, or several slots could be assigned to a single vehicle as another approach.

4.2.5 Entry/Exit: Dedicated

Vehicles will access the automated lanes via entry facilities. The infrastructure will regulate access to the AHS as slots are available. A vehicle may need to wait in the entry facility for an empty slot to arrive in a highly congested lane. Alternately, the regional controller may reassign slots within a zone to accommodate entering vehicles more quickly.

Vehicles will exit the automated lanes through a dedicated exit facility. The infrastructure will generate maneuver commands which allow the vehicle to separate from the assigned slot and demerge from the automated lane at a point which corresponds with the requested exit location.

4.2.6 Obstacle: Automated Sensing and Avoidance Maneuver

The vehicle control loop for this concept is closed in the infrastructure. Acceleration, deceleration, and maneuvers are coordinated by the infrastructure at the zone level. Obstacle detection can be performed by the vehicle or by the infrastructure. Resolution and accuracy are key performance factors in determining the ability to deploy infrastructure detection of obstacles. Vehicle detection of obstacles must be coordinated with the infrastructure generation of vehicle control loop commands. The vehicle must be able to communicate the obstacle information to the infrastructure, increasing the response delay time before an avoidance maneuver can be commanded and performed.

4.3 OPERATIONAL CONCEPT

Slot separation is based on the concept of a virtual string of continuously moving points in an unbroken chain. The distance between points in the chain is referred to as the slot. The slot between points in the chain can be measured in time or space, generating the title space/time slot. Figure H.4.3-1 illustrates the relationship of the TOC, the zone controller, and the chain of points moving through space and time. The vehicle must maintain its position relative to its assigned point in space within the required tolerance in close following modes. The rationale for maintaining the position in the slot relative to a specific point can be shown by imagining a leading vehicle positioned at the back edge of its slot, and the following vehicle at the front edge of its slot. A vehicle will encroach on the assigned slot of another if the longitudinal position error exceeds the slot length minus the length of the vehicle.

The regional TOC is responsible for slot assignments. Zone controllers monitor vehicle position relative to its assigned slot position. The infrastructure must sense vehicle position at intervals equivalent to the slot length within the local zone. The sensor spacing will depend on the capability to pinpoint location of multiple targets at the required resolution over a given range. There is also the requirement to update the vehicle position information at up to 50 msec rate.

Vehicles will request entry to the automated lanes from a dedicated entry facility. The regional traffic operations center (TOC) hasa dynamic map of available slots and assigns a slot to the entering vehicle which corresponds to his entry point. A region is envisioned to encompass a metropolitan area in urban environments. Rural regions may encompass a single county or several counties, depending on the traffic density, geographic separation of population centers, and level of infrastructure instrumentation. The relative positions of slots is constant in steady state operations. The zone controller gives the entering vehicle maneuver commands and monitors the vehicle's position relative to the assigned slot location and updates the acceleration/deceleration and turning commands as necessary to allow the

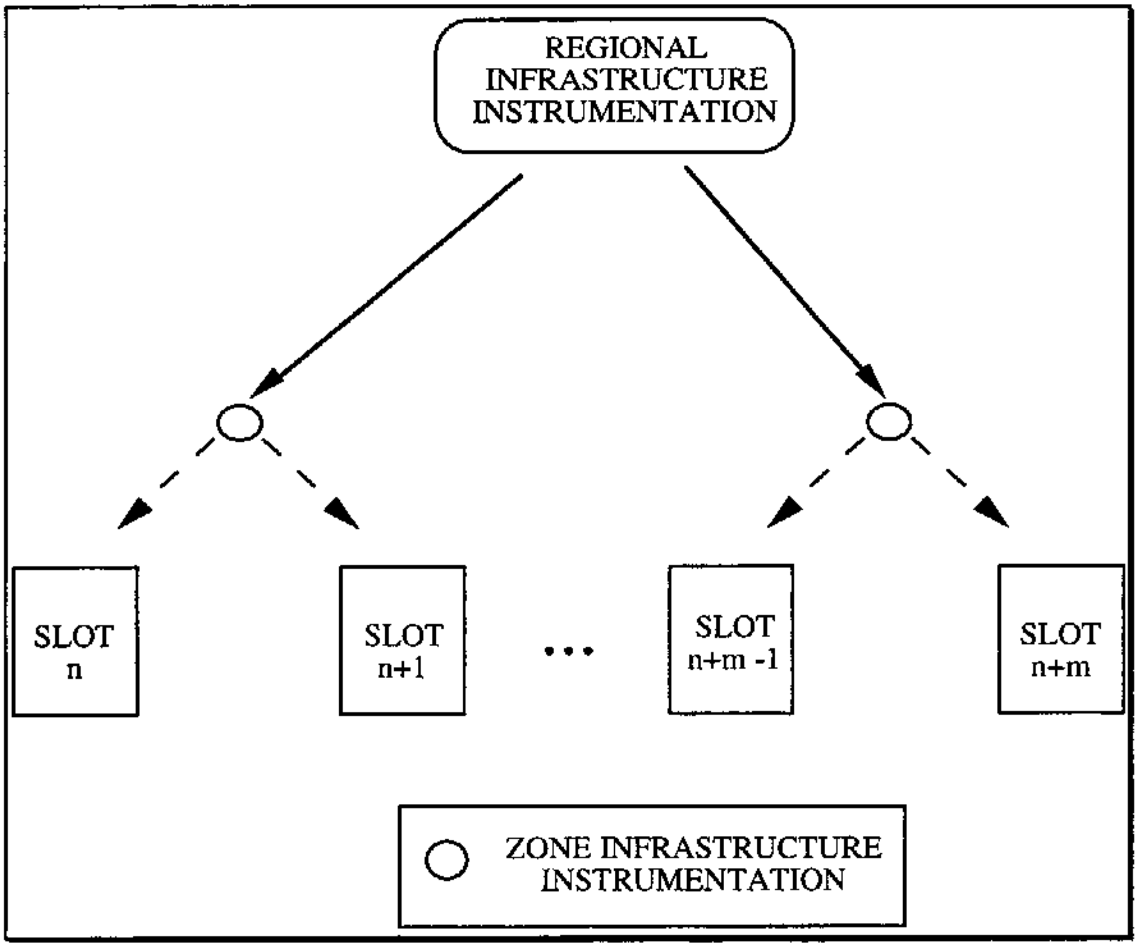

Figure H.4.3-1. Slots are the distance in space or time between points in a continuous chain

vehicle to merge into the moving slot. Zone controllers may encompass the local area surrounding an entry/exit facility. The field of responsibility of zone controllers must overlap to some extent to allow transfer of control as slots move through local zones.

Infrastructure instrumentation is required to monitor the location of vehicles within the assigned slots. Vehicle position will be detected using infrastructure based instrumentation, such as loop detectors or infrared sensors. The infrastructure will monitor the position of passing vehicles relative to their assigned slot position, and compare with expected time synchronization. The infrastructure will generate maneuver commands and transmit information addressed to the vehicle traveling in slot n. Commands will include data necessary for the vehicle to maintain its position within its assigned slot. Vehicles will monitor infrastructure commands and respond to data that is addressed to their assigned slot.

A vehicle is assigned a slot at the entry point that is associated with an absolute position in space or time. The motion of the slot is defined by the infrastructure, so the expected position of the vehicle is known by the infrastructure. The infrastructure knows where each slot should be at any point in time and periodically senses the position of the vehicles and maps this against the expected position of vehicles based on slot assignments. Vehicles detected out of tolerance in the assigned position are commanded to adjust speed until the correct position is attained.

Longitudinal position is adjusted by the vehicle responding to infrastructure speed commands until the infrastructure senses that the vehicle within slot n is positioned correctly. Lateral position is adjusted relative to a lateral control reference, such as magnetic markers. The vehicle lateral control system maintains the vehicle in the center of its assigned lane unless a maneuver command over rides the lateral control algorithm. The vehicle uses its lateral position relative to the lateral control reference and responds to infrastructure lateral commands which define a lateral rate of change in terms of a delta from the lane reference to accomplish lane changes and merges.

The spacing of infrastructure instrumentation within each zone must be sufficient to update vehicle commands to slots in its domain at an adequate rate to support safe and comfortable headway maintenance. Regional traffic operations centers will map and assign slots at the regional level and subdivide slot assignments to the local zone level. Zone based traffic controllers will transfer slot assignments to the vehicles and provide updates of slot control commands. Monitoring of vehicle position relative to its assigned time synchronization must be coordinated between zone controllers. Slots move continuously through time and space, passing from one local zone control range to the next.

The chain of points which define the slot spacing must also be coordinated at the global level. Chains associated with intersecting highways must merge at the intersection of the highways. The intersection of chains at highway interchanges can be thought of as teeth in a zipper which mesh when the paths intersect and separate when the paths diverge. The chain of points must continue into infinity, and a vehicle is associated with a single point throughout its journey within a region. Vehicles are transferred to slots in a separate chain when vehicles merge to another highway. As slots move out of the control of a specific TOC, the vehicle within the slot is assigned a slot in the next TOC. The virtual slot then joins the chain of moving slots at the starting point of the control area of the TOC. The coordination of slots at the TOC level is shown in Figure H.4.3-2.

The regional TOC is responsible for coordinating the merge of slots at highway interchanges. Slots n through n+m are assigned to Route A. Slots j through j+k are assigned to Route B. The TOC must ensure that if Route A and Route B merge to one lane, slots assigned to vehicles on Route A interleave with slots assigned to vehicles on Route B. Vehicles in Route A remain associated with their slot n+m assignment unless the vehicle is transferring to route B. When a vehicle on Route A is transferred to Route

B, the slot n+m assignment is transferred to a slot j+k assignment. The TOC must ensure that the chain of slots is timed correctly to allow a smooth transition from one chain to another. The processing required to maintain this type of coordination is significant. The TOC must plan slot assignments and synchronization on a network wide basis, coordinating slot availability with route plans for all vehicles on all routes under regional control. Failure to coordinate the slot assignments could result in adjusting slot assignments on the routes or modifying the slot motion on route A, delaying traffic flow to allow a vehicle to transfer to the next available slot on Route B.

4.4 SYSTEM DIAGRAM

4.4.1 TOC to Zone Controller Interface

The TOC passes slot assignments to the zone level. The TOC provides flow control information to the zone level regarding slot spacing, lane closures, entry and exit availability. The zone controller passes environment and incident reports to the TOC.

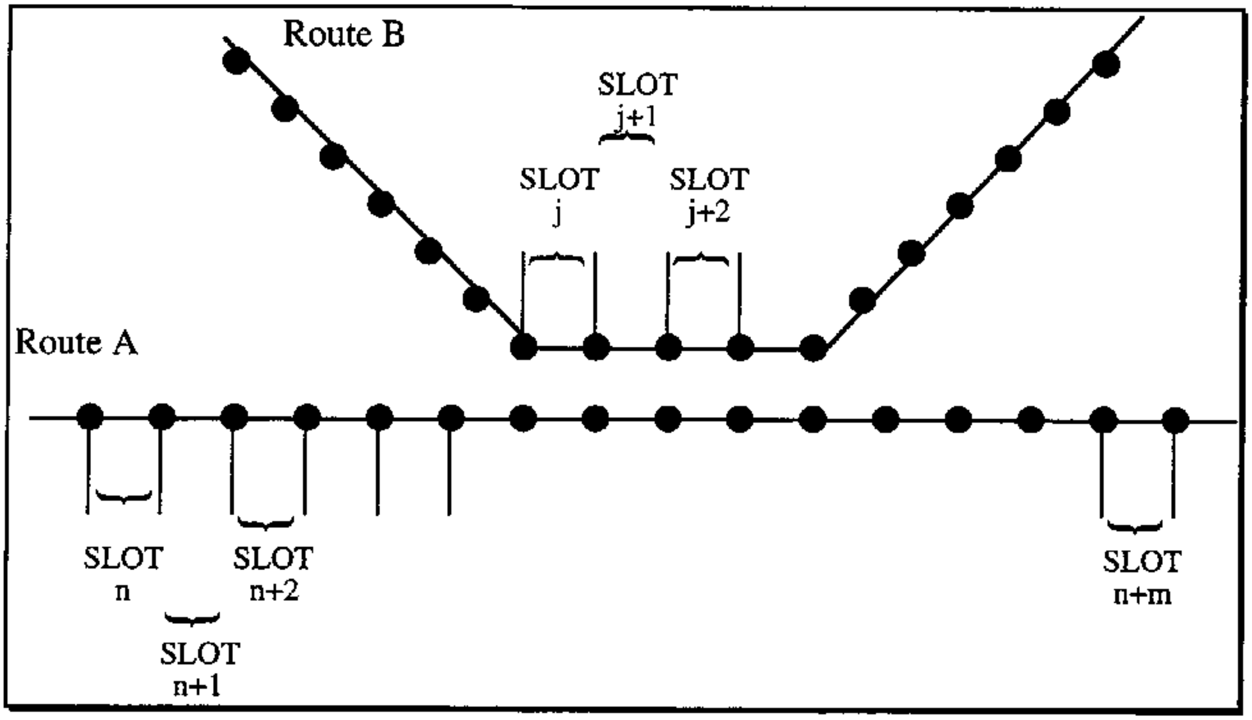

Figure H.4.3-2. Coordinating Chains of Slots at Interchanges

4.4.3 Roadway Condition Sensors to Roadway

The roadway condition sensors detect congestion levels, surface parameters, and weather conditions.

4.4.4 Zone Controller to Range Detection Sensors

The range condition sensors pass information to the zone controllers concerning the position of vehicles relative to their assigned slot.

4.4.5 Range Detection Sensors to Vehicle

The range sensors detect the distance between vehicles and speed of vehicles. Range detection may include comparison to known slot assignments to identify all moving objects not in an assigned slot as an obstacle.

4.4.6 Zone Controller to Vehicles

The zone controllers transmit slot addresses to vehicles requesting entry to the automated lanes based on slot assignments made by the TOC. The zone controllers transmit speed and lateral adjustment commands based on range calculations and maneuver requirements.

4.4.7 Vehicle Sensors to Lateral Reference

Vehicles will sense lateral control reference.

4.5 FUNCTIONAL ALLOCATION

Figure H.4.5-2 provides a graphical representation of a preliminary functional block diagram of the slot concept. The following text describes where each functional block is located and the tasks the functions are responsible for.

4.5.1 Position Control

Infrastructure control of the slot spacing is based on maintaining the relationship of vehicles within its assigned moving slot. Measurement of the longitudinal position is made by infrastructure sensors. The sensor information is processed by zone controllers which generate position control commands for each slot in its authority. Lane assignments are incorporated into the slot assignments. The vehicle senses its lateral position with respect to its assigned lane position. Lane changes and other lateral position adjustments are made when the infrastructure provides lateral control instructions containing lateral position increments relative to the assigned lane position.

The position control function is performed in the vehicle based on longitudinal control instructions obtained from the infrastructure, and vehicle-generated lateral reference information combined with incremental lateral movements commanded by the infrastructure. The longitudinal control subsystem receives acceleration/deceleration commands from the maneuver coordination function and generates throttle and brake signals to adjust the longitudinal position. The lateral control subsystem receives turning commands from the maneuver coordination function and generates steering signals to implement lateral changes commanded by the infrastructure.

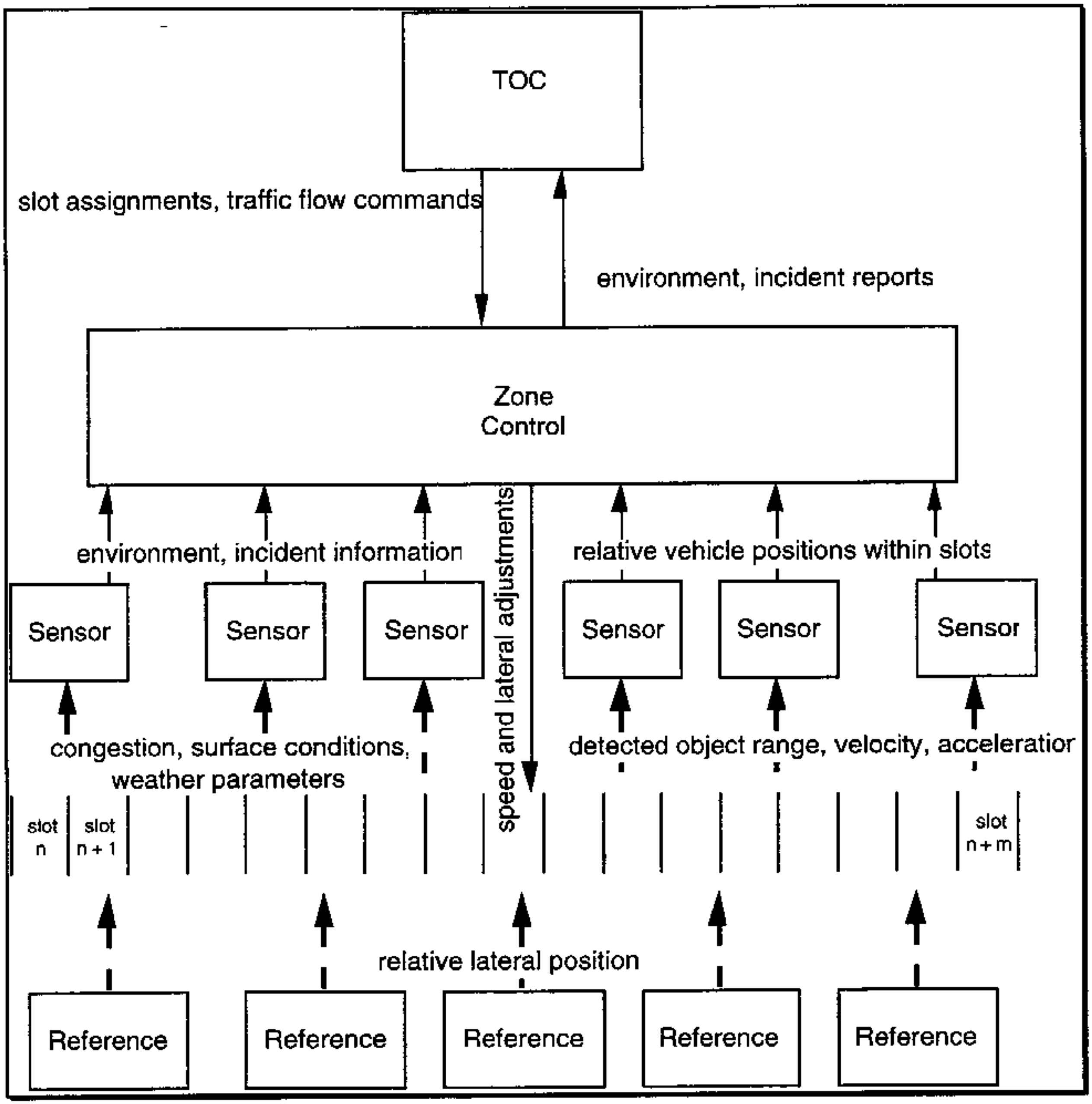

Figure H.4.4-1. Slot Control Interface Diagram

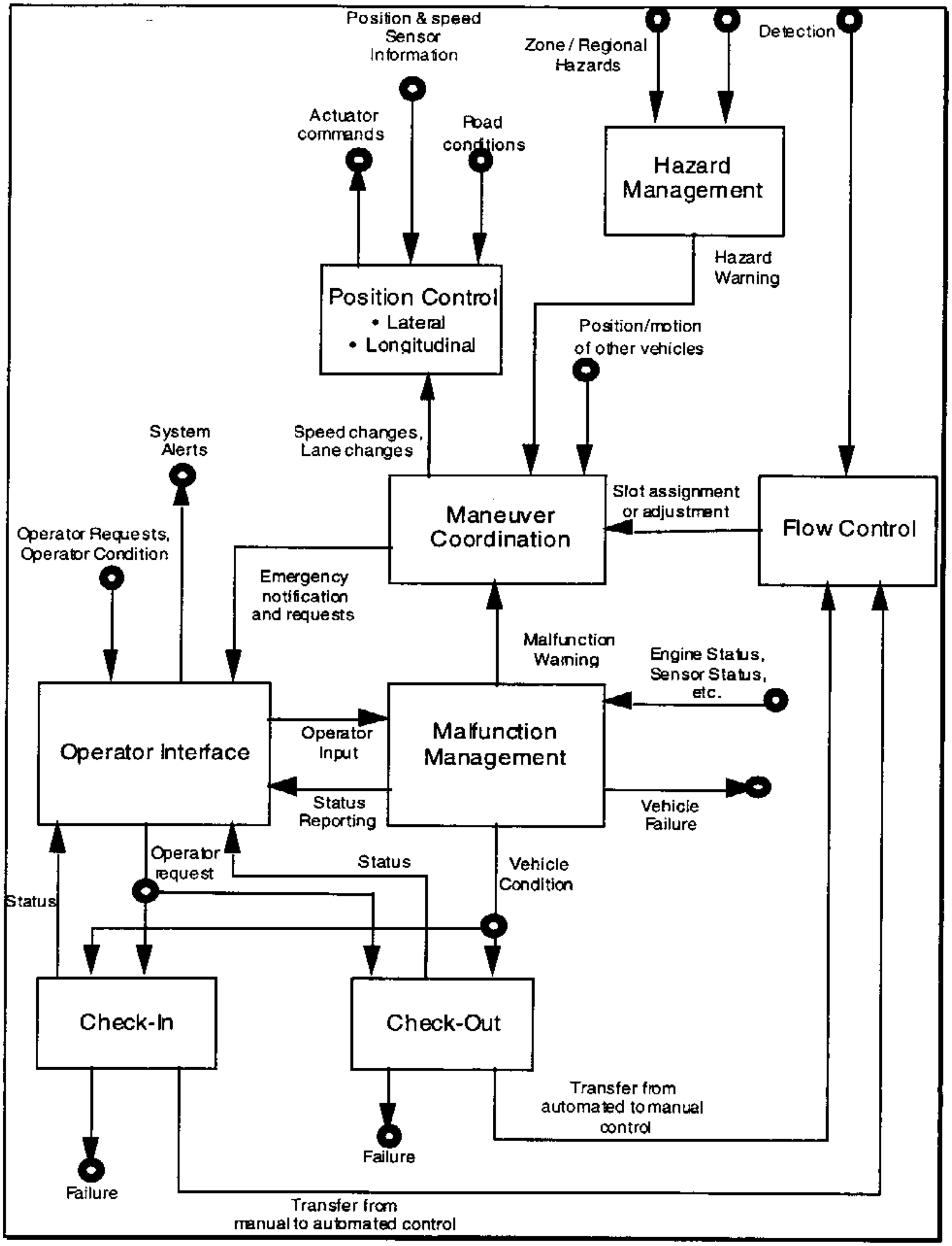

Figure H.4.5-2. Functional Block Diagram

position and speed. The vehicle performs The position control function processes sensor input regarding steady state vehicle steady state adjustments to longitudinal and lateral position using sensor inputs to generate actuator signals.

4.5.2 Maneuver Coordination

The maneuver coordination function is performed in the infrastructure. The maneuver coordination function receives maneuver requests from the flow control function, hazard warnings concerning obstacles or other traffic incidents from the hazard management function, and malfunction warnings concerning vehicle or operator detected failures from the malfunction management function. This function receives information concerning the position and motion of vehicles at the zone level.

The maneuver coordination function responds to maneuver commands received from the flow control function by generating acceleration, deceleration, and turning commands which allow vehicles to enter or exit the automated lane in the slot assigned by the flow control function. The maneuver coordination function responds to hazard and malfunction warnings by generating acceleration, deceleration, and turning commands which allow vehicles to mitigate malfunctions or avoid hazards in a safe manner. This function transmits the control signals addressed to the vehicle in the affected slot.

The maneuver coordination function provides notification to the operator interface of merge, demerge, or emergency maneuvers. Notification to the operator interface will be coordinated with the maneuver to prepare the driver for unexpected changes in vehicle speed or position.

4.5.3 Hazard Management

The hazard management function is performed in the infrastructure. The hazard management function receives incident information and detects obstacle using sensors deployed in the infrastructure. The hazard management function generates a hazard warning message which is passed to the maneuver coordination function for appropriate action.

4.5.4 Malfunction Management

The malfunction management function is performed in the vehicle. This function receives vehicle system status information from onboard vehicle diagnostics, and operator input regarding system conditions or hazards. The malfunction management function generates a malfunction warning message which is passed to the maneuver coordination function for appropriate action based on processing of vehicle and operator data. This function provides vehicle failure information to the traffic operations center and provides status messages to the operator.

The vehicle does not have a direct communications link with the infrastructure to advise the zone controller of vehicle malfunctions. The infrastructure will be capable of sensing irregularities in the position of vehicles relative to their assigned slot and may adjust slot velocity or size when it is determined that a vehicle is not maintaining the correct position relative to the slot. The vehicle must also be capable of detecting when an infrastructure failure prevents slot adjustment commands from occurring at the expected rate. A default operating mode must be available to allow vehicles to maintain safe control when infrastructure management fails.

4.5.5 Flow Control

The flow control function is performed in the infrastructure. The flow control function receives requests to enter the automated lane from the check-in function, and requests to exit the automated lanes from the check-out function. The flow control function generates maneuver commands at the regional level. This function assigns slots to entering vehicles based on slot availability and entry location. The flow control function keeps track of unused slots following exit of a vehicle and reassigns slots or adjusts slot spacing based on current traffic flow.

4.5.6 Operator Interface

The operator interface function is performed in the vehicle. The operator interface receives inputs from the operator concerning entry and exit requests and generates requests to enter and exit the automated lanes for the check-in and check-out functions. This function processes inputs from the operator concerning system operating conditions, including hazards or malfunctions and generates messages to the malfunction management function indicating a detected hazard or malfunction.

The operator interface provides sensory notification to the driver to indicate impending maneuvers based on messages received from the maneuver coordination function. This function also provides status to the operator concerning ongoing vehicle and system operating conditions. The operator interface will generate messages which provide status and instructions regarding entry or exit procedures.

4.5.7 Check-In

The check-in function is performed in the vehicle. This function receives operator requests to enter the automated system and initiates the check-in process. The check-in function processes vehicle condition information received from the malfunction management function concerning the integrity of the automated control subsystems. This function verifies the ability to perform the transition from manual to automated control safely and generates a message to the flow control function to request a slot and initiate entry to the automated lane. The transfer from manual to automated control is performed on the entry ramp. Once the transfer of control is completed, the vehicle begins to adjust speed in response to infrastructure commands and merges to the automated lane under automated control.

Vehicles which fail the check-in process will not be assigned a slot and will be denied access to the automated lane. A message will be generated to the operator interface function which indicates the status of the check-in results and initiates the process for returning to the conventional lanes.

4.5.8 Check-Out

The check-out function is performed in the vehicle. This function receives operator requests to exit the automated system and initiates the check-out process. This function verifies the ability to perform the transition from automated to manual control safely and generates a message to the flow control function to initiate exit from the automated lane. The transfer from automated to manual control is performed on the exit ramp. The vehicle demerges from the automated lane under automated control and adjusts speed to allow the transfer of control to occur at a safe speed.

The check-out function will generate a message to the operator interface function which will allow the transition of control to occur. The operator interface will pass a message back to the check-out function when the operator has performed the required tasks successfully.

Vehicles which fail the check-out process will remain in automated control and moved to a safe position as close as possible to the requested exit. A message will be generated to the operator interface function which indicates the status of the check-out results and initiates the process for exiting under automated control. Slot assignments are released as vehicles exit the facility, and the TOC updates the database of available slot assignments. The released address can then be assigned to the next vehicle which enters the continuous chain of virtual slots.

4.6 IMPLEMENTATION OPTION(S)

4.6.1 Vehicle Electronics

Obstacle detection (option): the vehicle may be responsible for obstacle detection. Implementation of this option would require an interface between the vehicle obstacle detection subsystem and the position control subsystem to allow avoidance maneuvers if necessary. A communications link with the zone processor is an option to provide obstacle information to the local flow controller. This option would require a two way vehicle-infrastructure channel.

Maintain position: update actuator control signals as necessary

Sense lateral position: the vehicle is assigned its longitudinal position in space/time so there is no need for determination of absolute position. This concept could use a vision based or passive marker type lateral control approach.

Receive slot information messages: The communications device could be receive only, with the ability to screen messages to determine commands addressed to the assigned slot.

Process slot control commands: based on current speed, calculate acceleration/ deceleration parameters required to adjust slot position in response to infrastructure commands.

Operator interface: generate entry and exit request messages, support maneuver notification and obstacle avoidance alerts.

4.6.2 Infrastructure Instrumentation

TOC: manage global traffic flow. Generate slot assignments and update slot directory as vehicles enter and exit the system. Collect incident information from zone controllers and modify slot spacing as necessary.

Zone controller: collect incident information, transfer to TOC as necessary.

Slot sensors: monitor slot spacing. Generate slot control messages as necessary to regulate vehicle spacing within slots.

Broadcast slot information: transmit addressed slot messages. Unique addresses permit broadcast RF to be used. Only vehicles assigned with unique slot address respond to flow control commands.

Incident detection: sense local traffic congestion.

Obstacle detection (option): The infrastructure can be assigned the responsibility for obstacle detection. Radar ranging may be used to determine the relative spacing, velocity, and acceleration of vehicles traveling in slots. A roadside radar can determine the position of numerous targets by converting the time delay of the echo signal received from each target into a distance measurement and pinpointing the location relative to the radar. Resolution to a fraction of a meter may be necessary. The locations of expected targets known from system slot assignments may be mapped against the radar picture. Obstacles can be identified as targets which do not correlate with the known occupied slots. The ability of the radar ranging technique to discriminate legitimate obstacles from echoes such as background clutter and volume clutter caused by rain is an issue.

Lateral markers (option): passive markers in the roadway can be used as the lateral control reference.

4.6.3 Roadway Infrastructure

This concept requires conversion of a conventional lane to a dedicated AHS lane with a barrier separating the conventional and AHS lanes. An alternate approach

4.6.3.1. Rural Highway

Areas in which right-of-way is available may be compatible with construction of additional facilities. A dedicated automated lane might be built parallel to existing highways. Adding a transition lane may also be necessary, depending on the number of conventional lanes available for AHS use. Construction of both lanes may be required in areas where only two lanes are available on the conventional highway.

Rural areas with traffic flow which does not justify two AHS lanes in addition to two conventional highway lanes in each direction of travel may not be compatible with this approach. The transition lane may consist of no more than a ramp merging from the conventional lane to the automated lane. This implementation would appear similar to divided roadways with occasional strips of pavement connecting them to form the transition lane at access and egress points. Using unpaved physical space between the automated lane and the conventional lanes can be considered a barrier, and construction of a vertical barrier may be avoided.

4.6.3.2. Urban Region

Modify gap spacing to optimize capacity

Restrict heavy vehicles to off-peak hours

Limit frequency of access points for heavy vehicles to encourage longer trips

4.6.4 Deployment

This concept contains a high degree of infrastructure electronics. The efficacy of instrumenting long stretches of rural highway is a concern. The ability to serve larger numbers of vehicles per lane mile of instrumentation will improve the cost benefit ratio.

4.7 ISSUES

A very high level of real-time processing of sensor data and generation of vehicle commands will be required. The update rate of commands from the infrastructure to the vehicles is expected to be very high. Update rates on the order of 50 msec may be necessary to support close-vehicle following. Limitations in position sensing accuracy from the roadside of vehicles within expected time/space synchronization slots will determine maximum lane densities. The spacing of infrastructure instrumentation to support tracking of vehicle slots in a zone will depend on roadside sensor capabilities. The roadside sensors must accurately detect the position of vehicles at a rate sufficient to maintain the slot spacing. Tight slot spacing will require greater accuracy in position determination and higher update rates. Less capable sensors may be required to be spaced at very close intervals.

5. CONCEPT 3A: SPACE/TIME SLOT SEPARATION [INFRASTRUCTURE MANAGED]

In the preliminary assessment of the 22 concepts, it appeared that infrastructure control was a more expensive, less safe, less flexible alternative than any other. There was considerable sentiment to discard infrastructure control as an option.

Slot's, however, still seemed like a somewhat viable concept. In order to fairly assess slots, without biasing the results with the weaknesses of infrastructure control, concept 3a was created, which is concept 3 modified to be infrastructure managed, rather than infrastructure controlled. Thus, much of chapter 5 is repeated from chapter 4.

5.1 OVERVIEW

Space/Time Slot Control is a configuration which allows synchronous control of all vehicles within a specific moving space on the AHS roadway. The coordination unit is the level at which traffic management functions such as merging are coordinated on the AHS. The coordination unit for the slot control concept is the slot, which corresponds to a single vehicle. Synchronous control refers to the system wide coordination of the motion of vehicle slots. This form of control can be referred to as point following.

The desired local vehicle spacing is determined by the infrastructure. Different vehicle classes can be accommodated by increasing the separation distance between the point assigned to a truck and a passenger vehicle, for example. Slot synchronization may be modified in preparation for merges. The vehicle adjusts its speed to track the slot dynamics coordinated by the infrastructure. The merge decisions for each vehicle are determined by the infrastructure at the time the vehicle is assigned to a slot; the vehicle adjusts control loop parameters to reach merge speed and maintain its position to merge into its assigned slot.

This concept has been selected for discussion due to its unique approach to the traffic flow problem. Other concepts featuring free agents and platoon architectures are asynchronous, in that the dynamically changing distribution of vehicles within the system is not coordinated in a global manner, but is managed within the coordination unit at the vehicle or platoon level. The slot or point-following architecture provides a concept in which the distribution and flow of all the vehicles within a region are managed in time synchronization. This approach requires processing (intelligence) at the regional and zone level. The primary advantage of the synchronous system is in facilitating merging and coordination of highway network interchanges.

There has been some debate concerning the potential capacity of a synchronous system. A single corridor may not benefit from synchronized coordination of traffic flow. A complex highway system with interchanges can be more efficient if the flow of vehicles is coordinated at the regional level. The more congested a channel is in steady (non-bursty) loads, the more benefit to be gained from synchronized management to regulate flow system wide. The spacing of vehicles is expected to be on the same order as free agents, providing comparable potential capacity with free-agent, infrastructure managed concepts.

5.2 DIMENSION ATTRIBUTES

5.2.1 Distribution of Intelligence: Infrastructure Managed

The infrastructure assigns vehicles entering the system to a moving point in space or time which the vehicle must track. The relative position of points or spacing is scheduled at the regional level and monitored at the zone level. The vehicle monitors its speed and position relative to its assigned slot and adjusts control loop parameters to maintain headway and lateral position.

5.2.2 Separation Policy: Slot

The slot attribute provides unique slots in space and time for individual vehicles. The separation between vehicles is determined by the size of the slot. Smaller slots correspond to higher lane density. The ability to maximize density will depend on the ability to safely monitor and maintain vehicle headway in closely spaced slots, similar to the constraints of free agent spacing. The coordination of traffic flow will depend on the ability of infrastructure instrumentation to track the status of all slots in its vicinity on a continuous basis, and to hand-off control of slots as they pass from zone to zone. Vehicles do not communicate directly, the infrastructure provides slot assignment updates as necessary to allow merging.

5.2.3 Mixing of AHS and Non-AHS Vehicles: Dedicated Lanes With Continuous Physical Barriers

Continuous physical barriers will prevent access of unauthorized vehicles into spaces between slots. Unqualified vehicles which breach the entry facility can be detected by the infrastructure instrumentation at the check-in facility as slots are assigned. This information can be used to by the zone controller to provide a buffer between the rogue vehicle and the next vehicle permitted to enter. Vehicles following a rogue vehicle may be assigned to another slot or travel speed can be adjusted to allow operation to continue until the non-AHS vehicle can be removed.

5.2.4 Mixing of Vehicle Classes: Not Mixed

The preliminary attribute assignment specified no mixing of vehicle classes. This will permit maximum passenger vehicle density and travel speed within a single lane. Slot allocation will be determined based on the lowest common denominator of vehicle performance of the set of vehicles allowed on a certain lane. Slots will be allocated at a certain spacing for passenger cars based on the slowest accelerating and longest braking distance of allowed cars. Slots in a commercial vehicle lane will be spaced at greater intervals, corresponding to the performance of vehicles authorized for that lane.

An option for rural or less congested areas might allow mixing of vehicle classes. The regional allocation of slots could take into account vehicle performance factors when assigning slots to vehicles requesting entry to the automated lanes. Slot spacing could be adjusted to accommodate lower performing trucks or buses, or several slots could be assigned to a single vehicle as another approach.

5.2.5 Entry/Exit: Dedicated

Vehicles will access the automated lanes via entry facilities. The infrastructure will regulate access to the AHS as slots are available. A vehicle may need to wait in the entry facility for an empty slot to arrive in a highly congested lane. Alternately, the regional controller may reassign slots within a zone to accommodate entering vehicles more quickly.

Vehicles will exit the automated lanes through a dedicated exit facility. The infrastructure will notify the vehicle to separate from the assigned slot and demerge from the automated lane at a point which corresponds with the requested exit location.

5.2.6 Obstacle: Automated Sensing and Avoidance Maneuver

Obstacle detection can be performed by the vehicle or by the infrastructure. Resolution and accuracy are key performance factors in determining the ability to deploy infrastructure detection of obstacles. Obstacle detection by the infrastructure may increase the response delay time before an avoidance maneuver can be performed by the vehicle. Vehicle detection of obstacles must be coordinated with the infrastructure processor monitoring slot positions. The vehicle must be able to communicate obstacle avoidance information to the infrastructure to allow the infrastructure to adjust slot position or timing to accommodate emergency vehicle maneuvers.

5.3 OPERATIONAL CONCEPT

Slot separation is based on the concept of a virtual string of continuously moving points in an unbroken chain. The distance between points in the chain is referred to as the slot. The slot between points in the chain can be measured in time or space, generating the title space/time slot. Figure H.5.3-1 illustrates the relationship of the TOC, the zone controller, and the chain of points moving through space and time. The vehicle must maintain its position relative to its assigned point in space within the required tolerance in close following modes. The rationale for maintaining the position in the slot relative to a specific point can be shown by imagining a leading vehicle positioned at the back edge of its slot, and the following vehicle at the front edge of its slot. A vehicle will encroach on the assigned slot of another if the longitudinal position error exceeds the slot length minus the length of the vehicle.

Vehicles will request entry to the automated lanes from a dedicated entry facility. The regional traffic operations center (TOC) has a dynamic map of available slots and assigns a slot to the entering vehicle which corresponds to his entry point. A region is envisioned to encompass a metropolitan area in urban environments. Rural regions may encompass a single county or several counties, depending on the traffic density, geographic separation of population centers, and level of infrastructure instrumentation. The relative positions of slots is constant in steady state operations. The zone controller monitors information transmitted by the entering vehicle concerning the vehicle's position relative to the assigned slot location as the vehicle merges into the moving slot. Zone controllers may encompass the local area surrounding an entry/exit facility. The field of responsibility of zone controllers must overlap to some extent to allow transfer of control as slots move through local zones.

Infrastructure instrumentation is required to track the location of vehicles within the assigned slots. Vehicles will transmit position information, and the infrastructure will compare the position of passing vehicles relative to their assigned slot position. The infrastructure will generate updates containing relative slot position information addressed to the vehicle traveling in slot n as necessary to manage the slot spacing. Vehicles will monitor infrastructure commands and respond to data that is addressed to their assigned slot.

A vehicle is assigned a slot at the entry point that is associated with a moving position in space or time. The motion of the slot is defined by the infrastructure, so the expected position of the vehicle is known by the infrastructure. The infrastructure knows where each slot should be at any point in time and periodically compares the transmitted position of the vehicles and maps this against the expected position of vehicles based on slot assignments. Vehicles which are out of tolerance in the assigned position are directed to adjust speed and are given a targeted longitudinal delta. This is necessary to maintain precise slot position in the absence of a vehicle to follow in the adjacent slot.

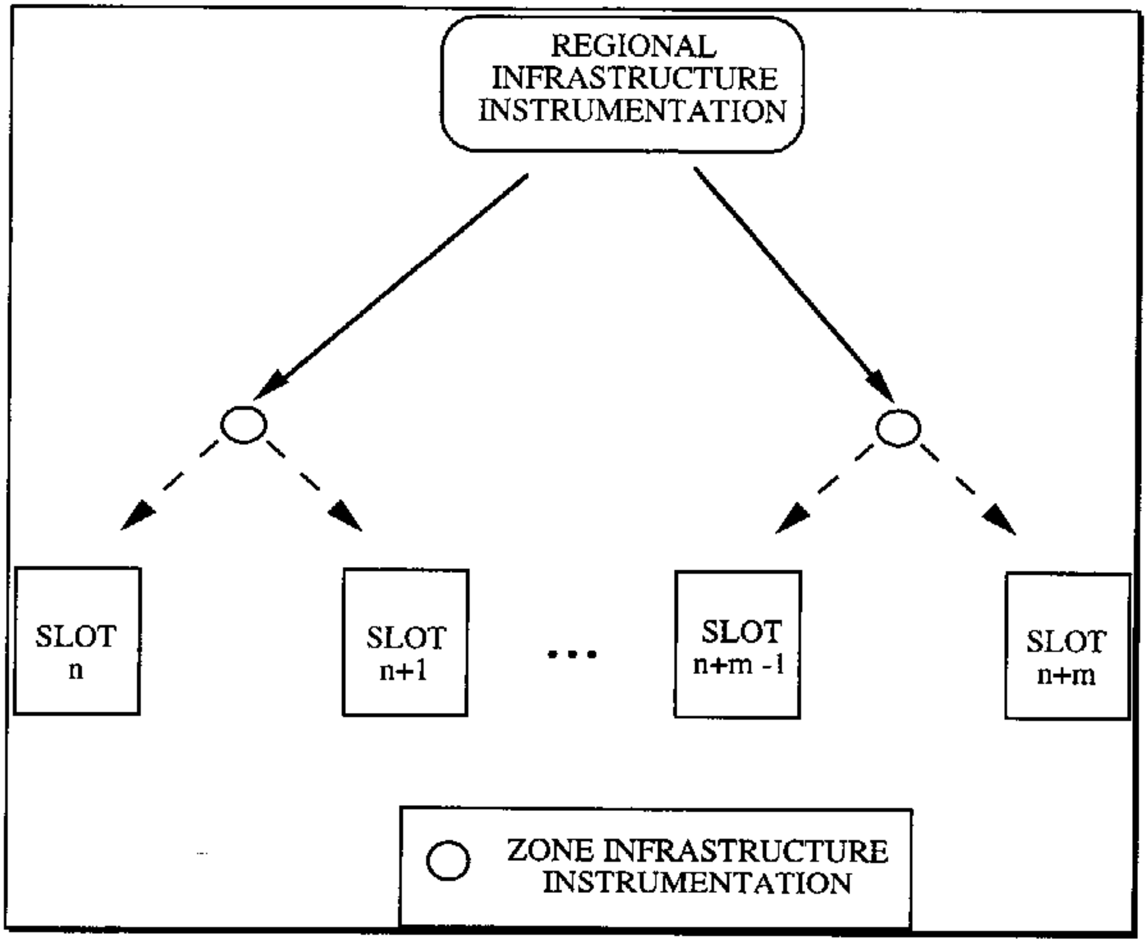

Figure H.5.3-1. Slots are the distance in space or time between points in a continuous chain.

Lateral position is adjusted relative to a lateral control reference, such as magnetic markers. The vehicle lateral control system maintains the vehicle in the center of its assigned lane unless a maneuver command over rides the lateral control algorithm. The vehicle uses its lateral position relative to the lateral control reference and responds to infrastructure lateral commands which define a lateral rate of change in terms of a delta from the lane reference to accomplish lane changes and merges.

The spacing of infrastructure instrumentation within each zone must be sufficient to update vehicle commands to slots in its domain at an adequate rate to support safe and comfortable slot position maintenance. Regional traffic operations centers will map and assign slots at the regional level and subdivide slot assignments to the local zone level. Zone based traffic controllers will transfer slot assignments to the vehicles and provide updates of slot position commands. Monitoring of vehicle position relative to its assigned time synchronization must be coordinated between zone controllers. Slots move continuously through time and space, passing from one local zone control range to the next.

The chain of points which define the slot spacing must also be coordinated at the global level. Chains associated with intersecting highways must merge at the intersection of the highways. The intersection of chains at highway interchanges can be thought of as teeth in a zipper which mesh when the paths intersect and separate when the paths diverge. The chain of points must continue into infinity, and a vehicle is associated with a single point throughout its journey within a region. Vehicles are transferred to slots in a separate chain when vehicles merge to another highway. As slots move out of the control of a specific TOC, the vehicle within the slot is assigned a slot in the next TOC. The virtual slot then joins the chain of moving slots at the starting point of the control area of the TOC. The coordination of slots at the TOC level is shown in Figure H.5.3-2.

The regional TOC is responsible for coordinating the merge of slots at highway interchanges. Slots n through n+m are assigned to Route A. Slots j through j+k are assigned to Route B. The TOC must ensure that if Route A and Route B merge to one lane, slots assigned to vehicles on Route A interleave with slots assigned to vehicles on Route B. Vehicles in Route A remain associated with their slot n+m assignment unless the vehicle is transferring to route B. When a vehicle on Route A is transferred to Route B, the slot n+m assignment is transferred to a slot j+k assignment. The TOC must ensure that the chain of slots is timed correctly to allow a smooth transition from one chain to another. The processing required to maintain this type of coordination is significant. The TOC must plan slot assignments and synchronization on a network wide basis, coordinating slot availability with route plans for all vehicles on all routes under regional control. Failure to coordinate the slot assignments could result in adjusting slot assignments on the routes or modifying the slot motion on route A, delaying traffic flow to allow a vehicle to transfer to the next available slot on Route B.

5.4 SYSTEM DIAGRAM

5.4.1 TOC to Zone Controller Interface

The TOC passes slot assignments to the zone level. The TOC provides flow control information to the zone level regarding slot spacing, lane closures, entry and exit availability. The zone controller passes environment and incident reports to the TOC.

5.4.2 Zone Controller to Roadway Condition Sensors

The roadway condition sensors pass congestion and environment information to

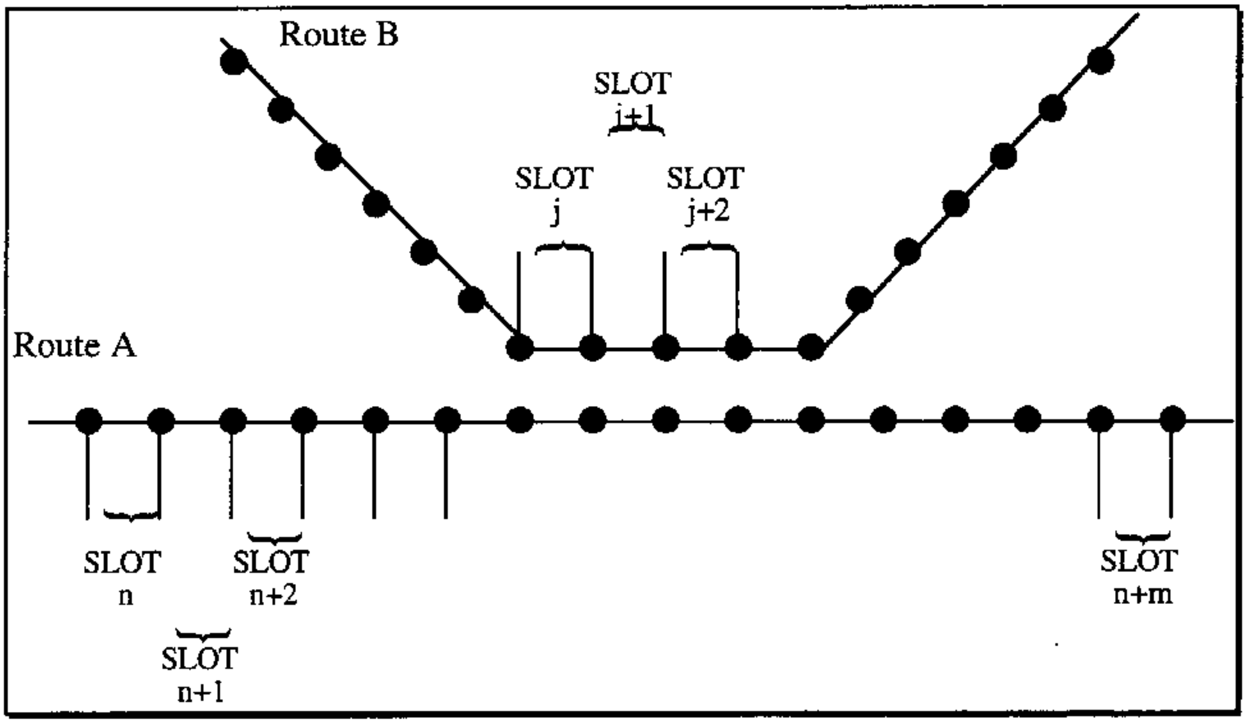

Figure H.5.3-2. Coordinating Chains of Slots at Interchanges the zone controllers.

5.4.3 Roadway Condition Sensors to Roadway

The roadway condition sensors detect congestion levels, surface parameters, and weather conditions.

5.4.4 Zone Controller to Range Detection Sensors

The vehicles transmit absolute position and detected obstacle information to the zone controllers.

5.4.5 Range Detection Sensors to Vehicle

Range sensors detect the distance between vehicles and relative speed of adjacent vehicles. Range detection can be supplemented with known slot assignments to identify objects not in an assigned slot as an obstacle.

5.4.6 Zone Controller to Vehicles

The zone controllers transmit slot addresses to vehicles requesting entry to the automated lanes based on slot assignments made by the TOC. The zone controllers transmit relative position corrections based on known assigned slot position and actual vehicle position transmitted from the vehicle.

5.4.7 Vehicle Sensors to Lateral Reference

Vehicles will sense lateral control reference.

5.5 FUNCTIONAL ALLOCATION

Figure H.5.5.4 provides a graphical representation of a preliminary functional block diagram of the slot concept. The following text describes where each functional block is located and the tasks the functions are responsible for.

5.5.1 Position Control

The position control loop is closed within the vehicle. Absolute position is determined by the vehicle. The vehicle transmits position data to the zone controller which compares actual vehicle position with expected position for each slot in its authority. Longitudinal position adjustments are made when the infrastructure provides position increment data relative to the assigned slot position. Lane assignments are incorporated into the slot assignments. The vehicle senses its lateral position with respect to its assigned lane position. Lane changes and other lateral position adjustments are made when the infrastructure provides lateral position increments relative to the assigned lane position.

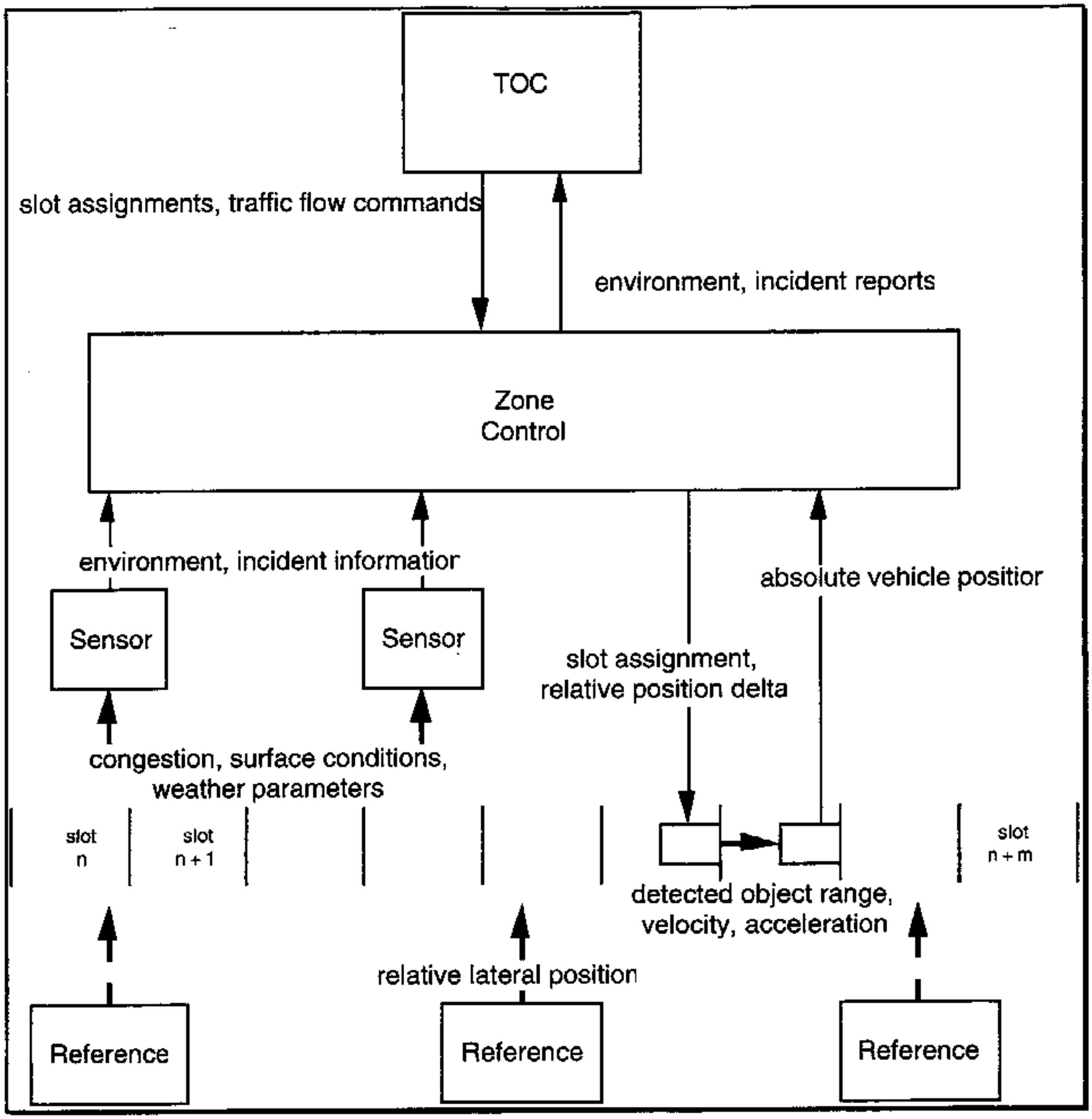

Figure H.5.4-3. Slot Control Interface Diagram

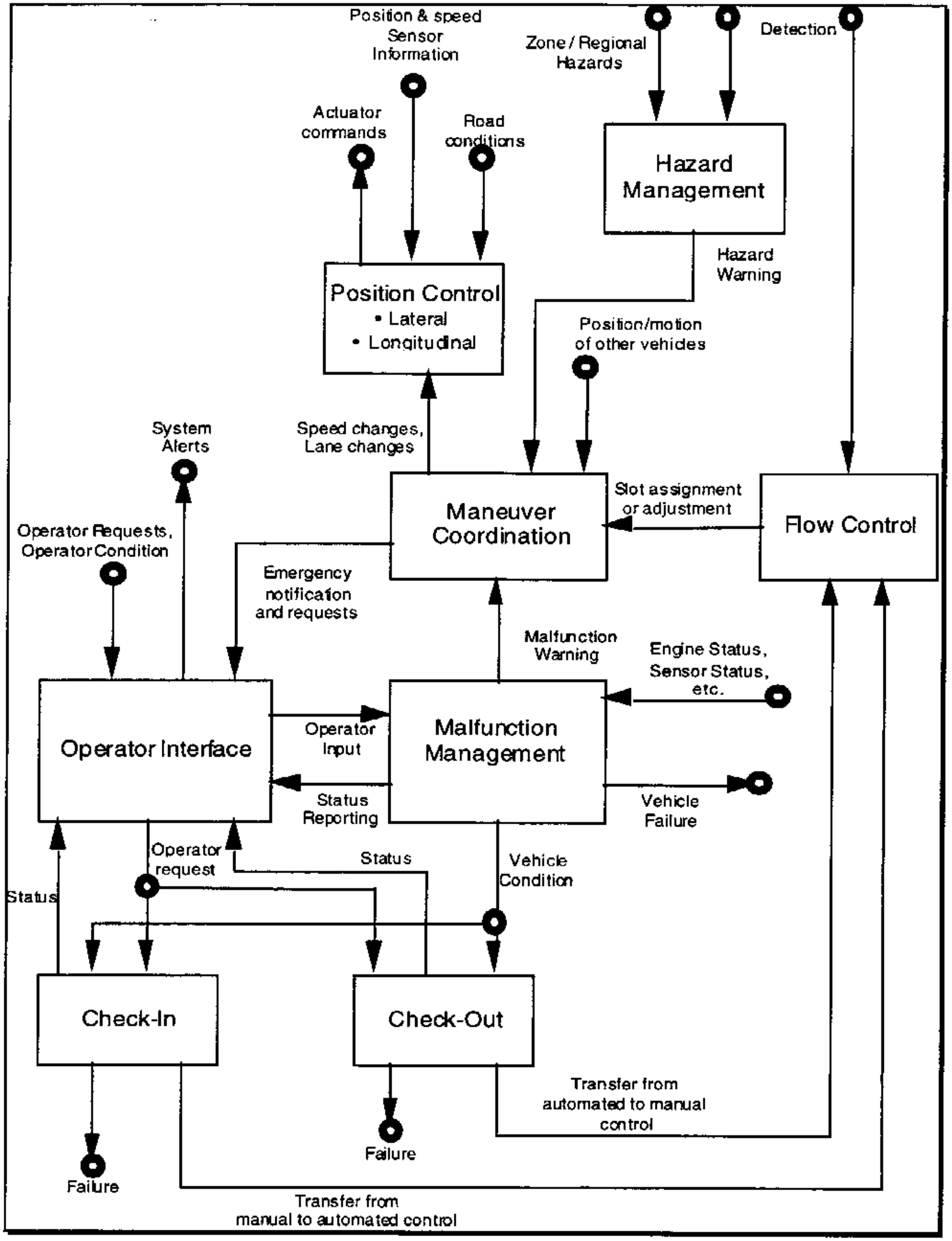

Figure H.5.5-4. Functional Block Diagram

5.5.2 Maneuver Coordination

The maneuver coordination function is performed in the infrastructure. The maneuver coordination function receives maneuver requests from the flow control function, hazard warnings concerning obstacles or other traffic incidents from the hazard management function, and malfunction warnings concerning vehicle or operator detected failures from the malfunction management function. This function receives information concerning the position and motion of vehicles at the zone level.

The maneuver coordination function responds to maneuver commands received from the flow control function by generating position offset commands which allow vehicles to enter or exit the automated lane in the slot assigned by the flow control function. The maneuver coordination function responds to hazard and malfunction warnings by generating changes to slot assignments or spacing which allow vehicles to mitigate malfunctions or avoid hazards in a safe manner. This function transmits maneuver information signals addressed to the vehicle in the affected slot.

The maneuver coordination function provides notification to the operator interface of merge, demerge, or emergency maneuvers. Notification to the operator interface will be coordinated with the maneuver to prepare the driver for unexpected changes in vehicle speed or position.

5.5.3 Hazard Management

The hazard management function is performed in the infrastructure. The hazard management function receives incident information from roadside sensors and obstacle data from individual vehicles. The hazard management function generates a hazard warning message which is passed to the maneuver coordination function for appropriate action.

5.5.4 Malfunction Management

The malfunction management function is performed in the vehicle. This function receives vehicle system status information from onboard vehicle diagnostics, and operator input regarding system conditions or hazards. The malfunction management function generates a malfunction warning message which is passed to the maneuver coordination function for appropriate action based on processing of vehicle and operator data. This function provides vehicle failure information to the traffic operations center and provides status messages to the operator.

A default operating mode must be available to allow vehicles to maintain safe control when infrastructure management fails. Vehicles can degrade to a free agent operating mode when the roadside-vehicle communications link is lost, for example. The vehicle may default to independent obstacle avoidance and headway maintenance based on safe stopping distances to adjacent vehicles.

5.5.5 Flow Control

The flow control function is performed in the infrastructure. The flow control function receives requests to enter the automated lane from the check-in function, and requests to exit the automated lanes from the check-out function. The flow control function generates maneuver commands at the regional level. This function assigns slots to entering vehicles based on slot availability and entry location. The flow control function keeps track of unused slots following exit of a vehicle and reassigns slots or adjusts slot spacing based on current traffic flow.

5.5.6 Operator Interface

The operator interface function is performed in the vehicle. The operator interface receives inputs from the operator concerning entry and exit requests and generates requests to enter and exit the automated lanes for the check-in and check-out functions. This function processes inputs from the operator concerning system operating conditions, including hazards or malfunctions and generates messages to the malfunction management function indicating a detected hazard or malfunction.

The operator interface provides sensory notification to the driver to indicate impending maneuvers based on messages received from the maneuver coordination function. This function also provides status to the operator concerning ongoing vehicle and system operating conditions. The operator interface will generate messages which provide status and instructions regarding entry or exit procedures.

5.5.7 Check-In

The check-in function is performed in the vehicle. This function receives operator requests to enter the automated system and initiates the check-in process. The check-in function processes vehicle condition information received from the malfunction management function concerning the integrity of the automated control subsystems. This function verifies the ability to perform the transition from manual to automated control safely and generates a message to the flow control function to request a slot and initiate entry to the automated lane. The transfer from manual to automated control is performed on the entry ramp. Once the transfer of control is completed, the vehicle begins to adjust speed in response to infrastructure commands and merges to the automated lane under automated control.

Vehicles which fail the check-in process will not be assigned a slot and will be denied access to the automated lane. A message will be generated to the operator interface function which indicates the status of the check-in results and initiates the process for returning to the conventional lanes.

5.5.8 Check-Out

The check-out function is performed in the vehicle. This function receives operator requests to exit the automated system and initiates the check-out process. This function verifies the ability to perform the transition from automated to manual control safely and generates a message to the flow control function to initiate exit from the automated lane. The transfer from automated to manual control is performed on the exit ramp. The vehicle demerges from the automated lane under automated control and adjusts speed to allow the transfer of control to occur at a safe speed.

The check-out function will generate a message to the operator interface function which will allow the transition of control to occur. The operator interface will pass a message back to the check-out function when the operator has performed the required tasks successfully.

Vehicles which fail the check-out process will remain in automated control and will move to a safe position as close as possible to the requested exit. A message will be generated to the operator interface function which indicates the status of the check-out results and initiates the process for exiting under automated control. Slot assignments are released as vehicles exit the facility, and the TOC updates the database of available slot assignments. The released address can then be assigned to the next vehicle which enters the continuous chain of virtual slots.

5.6 IMPLEMENTATION OPTION(S)

5.6.1 Vehicle Electronics

Obstacle detection: vehicle based sensors are required to detect obstacles.

Sense lateral position: vision based or magnetic sensors are required to determine lateral position.

Determine absolute position: the vehicle must know its position relative to the assigned slot in space/time. Absolute position may be determined using GPS.

Transfer position data messages: Two-way vehicle-roadside communications is required to support transmission of vehicle position information to the roadside processor, and transmission of slot offset messages to the vehicle from the processor. The communication system must provide address capability to direct unique offsets to vehicles in assigned slots.

Process slot control commands: based on current speed, calculate acceleration/ deceleration parameters required to adjust slot position in response to infrastructure commands.

Operator interface: generate entry and exit request messages, support maneuver notification and obstacle avoidance alerts.

5.6.2 Infrastructure Instrumentation

TOC: manage global traffic flow. Generate slot assignments and update slot directory as vehicles enter and exit the system. Collect incident information from zone controllers and modify slot spacing as necessary.

Zone controller: collect incident information, transfer to TOC as necessary.

Slot sensors: monitor slot spacing. Generate slot control messages as necessary to regulate vehicle spacing within slots.

Broadcast slot information: transmit addressed slot messages. Unique addresses permit broadcast RF to be used. Only vehicles assigned with unique slot address respond to flow control commands.

Incident detection: sense local traffic congestion.

Obstacle detection (option): The infrastructure can be assigned the responsibility for obstacle detection. Radar ranging may be used to determine the relative spacing, velocity, and acceleration of vehicles traveling in slots. A roadside radar can determine the position of numerous targets by converting the time delay of the echo signal received from each target into a distance measurement and pinpointing the location relative to the radar. Resolution to a fraction of a meter may be necessary. The locations of expected targets known from system slot assignments may be mapped against the radar picture. Obstacles can be identified as targets which do not correlate with the known occupied slots. The ability of the radar ranging technique to discriminate legitimate obstacles from echoes such as background clutter and volume clutter caused by rain is an issue.

Lateral markers (option): passive markers in the roadway can be used as the lateral control reference.

5.6.3 Roadway Infrastructure

This concept requires conversion of a conventional lane to a dedicated AHS lane with a barrier separating the conventional and AHS lanes. An alternate approach

5.6.3.1. <u>Rural Highway</u>

Areas in which right-of-way is available may be compatible with construction of additional facilities. A dedicated automated lane might be built parallel to existing highways. Adding a transition lane may also be necessary, depending on the number of conventional lanes available for AHS use. Construction of both lanes may be required in areas where only two lanes are available on the conventional highway.

Rural areas with traffic flow which does not justify two AHS lanes in addition to two conventional highway lanes in each direction of travel may not be compatible with this approach. The transition lane may consist of no more than a ramp merging from the conventional lane to the automated lane. This implementation would appear similar to divided roadways with occasional strips of pavement connecting them to form the transition lane at access and egress points.

Using unpaved physical space between the automated lane and the conventional lanes can be considered a barrier, and construction of a vertical barrier may be avoided.

5.6.3.2. <u>Urban Region</u>

Modify gap spacing to optimize capacity

Restrict heavy vehicles to off-peak hours

Limit frequency of access points for heavy vehicles to encourage longer trips

5.6.4 Deployment

This concept contains a high degree of infrastructure electronics. The efficacy of instrumenting long stretches of rural highway is a concern. The ability to serve larger numbers of vehicles per lane mile of instrumentation will improve the cost benefit ratio.

5.7 ISSUES

A high level of real-time processing of vehicle position updates and calculation of offsets from assigned slot positions will be required. The update rate of slot offsets from the infrastructure to individual vehicles will be determined by the ability of the vehicles position control and navigation functions to maintain the vehicle's relative position within its assigned slot. Maximum lane densities will also be determined by the ability to maintain expected time/space synchronization. Tight slot spacing will require greater accuracy in position maintenance and possibly higher update rates. Infrastructure processors and beacons will be required at certain intervals to support tracking of vehicle slots and transfer of vehicle position data and slot offset updates.

6. CONCEPT 4: COOPERATIVE, FREE AGENT ON DEDICATED LANES WITH GAPS IN BARRIERS

6.1 OVERVIEW

Concept #4 takes all the best attributes from the trade space and is a unique example of a very flexible system: cooperative intelligence of free agents that can achieve platoon efficiency without enforcing platoons for mixed vehicles, dedicated lanes with numerous gaps to enter/exit through the transition lane on the fly, and autonomous obstacle avoidance that benefits from inter-vehicle communications. The final AHS system should have all of these characteristics. In this concept, the features tend to be balanced evenly. Mixed vehicle classes do not place unnecessary restrictions and limitations on the system. By being a free agent in the system, each vehicle (automobiles, buses, trucks) will establish and control its own separation distance. By doing so, the system could still behave like a platoon with all of its benefits. This pseudo platoon will have both close and far spacings based on individual vehicle's stopping distance, turning radius, acceleration capability, etc. that is communicated to adjacent vehicles (closest neighbors philosophy).

There is a feeling of safety based on having a dedicated lane with physical barriers. This is a leap over continuous barriers in the amount of flexibility the system can afford by having periodic gaps where one could enter and exit freely. This works well with the transition lane to enter and exit seamlessly on the fly. There is also a cost saving by not having a dedicated entry and exit facility/infrastructure. Concept #4 will provide the optimum throughput for the final AHS system. It is very important to the passengers to have automatic obstacle detection and avoidance. It is just another safety feature that is expected and provides a peace-of-mind feeling. Moreover by having inter-vehicle communications, some of the detection systems can be turned off to save power, add redundancy, or increase coverage.

6.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

Concept #4 has the following alternatives from the concept space:

1) Cooperative Distribution of Intelligence—There is minimal infrastructure intelligence, but there is vehicle-to-vehicle communications. The infrastructure provides the basic ITS services, i.e. in-vehicle information and routing. The vehicle senses the lane and controls the vehicle.
2) Free Agent Separation Policy—The separation policy is free agent. Each vehicle (automobile or truck or bus) operates independently and freely. However, by acting freely and communicating with its nearest neighbor, the series of vehicles may act as a pseudo platoon in terms of throughput. The spacing between vehicles will vary depending on the type and performance of each individual vehicle.
3) Dedicated Lanes with some Gaps in the Physical Barriers—Dedicated lanes are desirable for safety concerns and to achieve maximum throughput. To gain maximum flexibility, there will be periodic gaps in the barriers from which to enter and exit via the transition lane. The gaps in the barriers complement the transition lane concept perfectly. Gaps will occur only on straight-aways. Length of gap will be such that the driver continuously sees both ends to know that this is a dedicated AHS lane and will be sufficient for merging and de-merging.
4) Mixed Vehicle Classes in a Lane—There will be a mix of light vehicles such as automobiles and small trucks and larger

vehicles such as buses and semi-trucks. Mix vehicles will be the most robust option analogous to current everyday traffic patterns. In some areas of the country, there will be more trucks than automobiles and vice versa. To platoon only "like" vehicles could cause long delays and ineffectiveness of the system.

5) Transition Lane for Entry/Exit—Transition lanes are desirable for transparency of using the system. Vehicles in the transition lane have a greater opportunity to merge and de-merge while communicating to oncoming vehicles on the AHS lane, timing the openings in the stream of vehicles, and accelerating to the appropriate speed to accomplish lane change. Dedicated lanes are usually associated with higher infrastructure cost and possible delays. With transition lanes, exit and entry would have to be done on the fly, a very desirable feature.

6) Automatic Obstacle Sensing with Automatic Avoidance Maneuver—Automatic sensing and avoidance is a necessity for a fully operational system. Manual sensing nor avoidance are not characteristics of an automated highway. Any manual functions are only steps towards an automatic system. Automatic sensing will be easier in this concept due to the dedicated lanes and augmented by the inter-vehicle communications.

6.3 OPERATIONAL CONCEPT

Mixed vehicles are traveling along the dedicated lane, each vehicle insuring its own safe spacing (longer space for buses and closer space for automobiles). Some vehicles are at its optimal spacing with respect to their neighbors while others are by themselves (singular free agents). There will be larger spaces between the pseudo platoons. A car turns onto the freeway and drives for a while on the manual lane. It wishes to enter the dedicated, automated lane. The car is manually driven into the transition lane, which is a buffer between the manual lane and the dedicated lane. The AHS lane is further protected by a physical barrier with periodic gaps. The gaps are only on straight-aways and designed to accommodate the large vehicles (buses, semi- tractor trailers, etc.).

While on the transition lane, it does a self check and communicates with the infrastructure for system compliance and permission to enter the AHS (only time the vehicles communicate with the infrastructure in addition to standard ITS features). At this point the vehicle is controlled in a shared mode, the car is driving itself , but the driver can still regain control and override its automated functions. It communicates with any "close" vehicles. If there is none, it enters through a gap in the barrier and accelerates to the proper operational speed that is set by the infrastructure. If there is a pseudo platoon (no more than 10-20 vehicles, size dependent on the mix) of vehicles at their optimum spacing (a function of individual turning, braking, acceleration, top speed, weather factor, etc.) on the AHS, the joining vehicle must cruise at a slower speed, waiting for the appropriate gap/time to enter. The vehicle enters through the gap and into the open space in the stream of automated vehicles. The head of a pseudo platoon or a single, free agent vehicle will have automated sensing and will be aware of entering vehicles and other potential obstacles. To regulate the throughput, the infrastructure may choose to raise or lower the operating speed of the dedicated lane.

When a vehicle needs to exit, it signals its neighbors of its intentions. The separation distances and speeds of the departing vehicle as well as its closest neighbors adjust for this upcoming maneuver. All the effected vehicles also sense the adjacent transition lane, looking for entering vehicles or manual vehicle and the like. Having a clear transition lane, the exiting vehicle makes its maneuver off of the automated lane. The remaining vehicles in the AHS stream return to their optimum mode, prior to the exiting vehicle. Checkout is done on the fly as it passes through the transition lane. If an obstacle is detected on the dedicated AHS lane, the stream must first slow down and take a cautious position. The vehicles could either come to a complete stop in the AHS lane or maneuver through a gap on to the transition lane and back on again for a swerve maneuver, avoiding that area of the road until the obstacle can be removed.

6.4 SYSTEM DIAGRAM

Since each vehicle is a free agent, each agent will have a low-level control layer, a mid-level local action layer, and a high-level global action layer. The servo loops in the control layer will have milliseconds update rate, the local action layer will also be real-time but slower, and the global action layer will have update rates in the seconds.

There is in-vehicle communications through the different layers of architecture. To accomplish this, there must be a standard message protocol and server resident in each vehicle. There is also vehicle-to-vehicle communications that is a function of the co-operative distribution of intelligence and is real-time. Vehicle-to-vehicle information includes speed, steering direction, any emergencies, possible obstacles and verifications, any coordinated maneuvers, and any relevant health & status/system condition data. At the highest level, there is no continuous vehicle-to-infrastructure communications, however, there is some sparing communications at this level for standard ITS features, i.e. routing requests or Mayday.

6.5 FUNCTIONAL ALLOCATION

Baseline Functions:

- Check-In—Check-In is allocated to the vehicle with a final output stating if it is acceptable or not for entry into the AHS lane. This simple "accept" or "reject" is communicated to the infrastructure as a standard ITS feature. The routing of the vehicle is also queried and tracked by the infrastructure.
- Transition from manual to automatic control—Transition is also in-vehicle. It is accomplished in the transition lane and merge into the dedicated lane is automatic. The transition is verified by some positive indication between the driver and the vehicle.
- Automated Driving—All driving functions are in-vehicle. Sensing of roadway, other vehicles, lane keeping, and headway keeping are all in-vehicle functions. There is also communications between the pseudo platoons where it is important for the lead and end vehicles to keep constant coordination for the safety of their special group. The intermediate vehicles could function as repeaters or relays to understand the actions of the group. Vehicle-to-vehicle communications in a pseudo platoon is

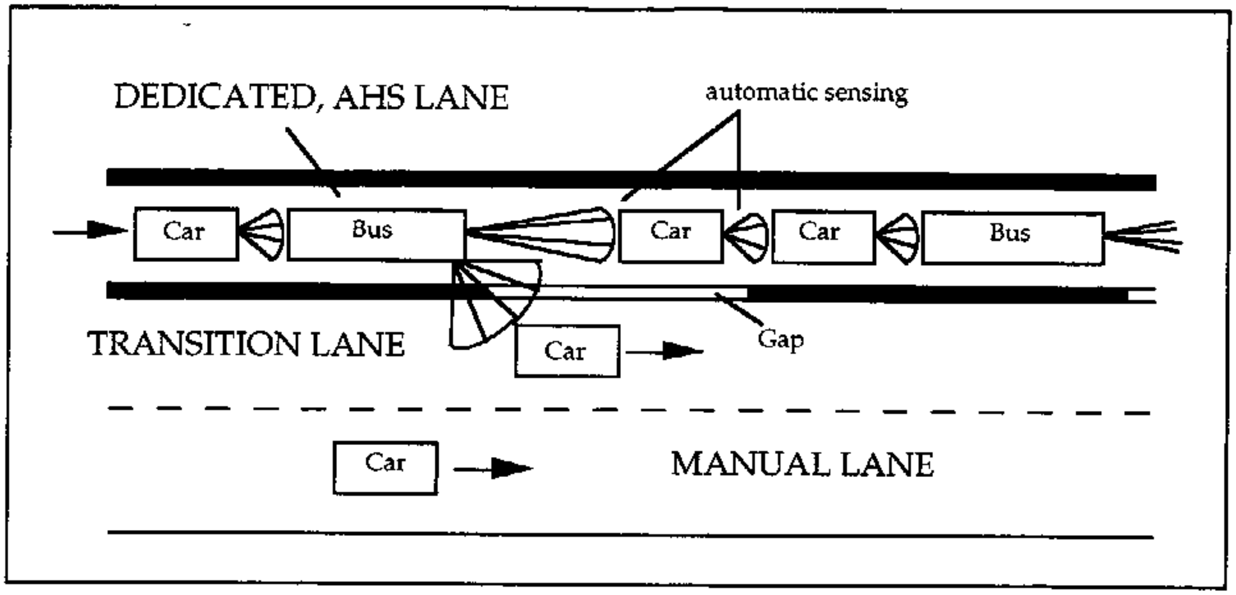

Figure H.6.4-1.

necessary for maneuver planning (normal and emergency), as well as maneuver execution. There is some communications between pseudo platoons for coordination issues on the system level. When it comes to the detection of hazards, everyone does obstacle detection (some for redundancy) and it is especially important for the lead vehicles.

- Transition from automatic to manual control—Transition is in-vehicle and accomplished again in the transition lane. Automatic control takes the vehicle from the dedicated lane into the transition lane. At this time, the automated vehicle insures that the driver is ready to accept control of the vehicle and the vehicle transitions control to the driver, insuring a positive hand-off.
- Check-out—check-out is allocated to the vehicle with just a ending message to the infrastructure to control accountability in the system. The details for check-out are done at the various levels of the architecture in the vehicle, i.e. statusing.
- Flow Control—At the macro level for routing purposes, flow is managed in the infrastructure. The infrastructure may chose to limit entrance into the dedicated lane to preserve flow or for some other logistical reason. There is also micro flow control when a vehicle is let onto the dedicated lanes and the size/average speed of the pseudo platoons. There may be no pseudo platoons, but all separate and independent agents, which is also an indicator of flow.
- Malfunction Management—Malfunction management is primarily in the vehicle. There is other options such as an obstacle in the dedicated lane, which becomes a joint vehicle, pseudo platoon, and infrastructure problem.
- Handling of Emergencies—Handling of emergencies is another joint problem between the individual vehicles, any impacted pseudo platoons, and the infrastructure.

6.6 IMPLEMENTATION

6.6.1 Vehicle

- Vehicle-to vehicle communications
- Adaptive cruise control or some type of headway control system
- Positive lateral control such as magnetic strip sensor with redundant vision system
- Forward looking radar and camera for obstacle detection

- Side looking radar for obstacle detection, especially during merging and splitting

6.6.2 Infrastructure

- Vehicle-to-infrastructure (and vice versa) communications for standard ITS features
- Magnetic strip for lateral control
- Infrastructure obstacle detection camera or radar
- Traffic Management Operations Center

6.6.2.1. Rural Highway:

There would not be a dedicated lane with gapped barriers. Rural lanes will be either one or two lanes in each direction with a high flow rate. The left most lane (if their is more than a single lane) will be a transition lane that can accommodate both automated and manual driving to some degree. Obstacle detection and adaptive cruise control will enhance any vehicle.

6.6.2.2. Urban Region:

The concept described with the dedicated lane, transition lane, and manual lane will be optimized in a urban and extended urban region where the flow is stagnated.

6.6.3 Deployment

- Dedicated lane with gaps in the barriers
- Transition lane

6.7 GENERAL ISSUES AND CONSIDERATIONS

- Navigation is independent, in-vehicle and autonomous with opportunities to do cooperative operations/maneuvers, i.e. pseudo platoons
- Failure modes are in matched performances, degradation of performances due to usage (function of all the concepts), etc.
- We can utilize redundant in-vehicle sensors for lateral control, longitudinal control, and obstacle detection. These sensors might also be able to do overlapping functions, e.g. forward obstacle detection and longitudinal control, side obstacle detection and lateral control, inter vehicle communications for headway sensing.
- Under no circumstances is control passed to the driver, only on the transition lane to change modes: automatic to manual control and from manual to automatic control
- Reduced visibility, ice, snow, rain impacts the overall effectiveness of the entire system. There is an impact to the infrastructure and traffic management operation center to reduce flow by decreasing the AHS set speed and increasing the spacing between vehicles.
- Typical users would travel at 120 km/hr or higher (~180 km/hr). It should be a significant increase over manual driving.
- It would have limited autonomy, a minimum of adaptive cruise control. The average free agent would be autonomous for limited and special situations where the driver would be supervisory. All safety systems will be in place and functional. On long, lonely stretches of highway, the vehicle will be virtually autonomous with a mode transfer capability for special situations, i.e. lack of definition in its assigned path, etc.
- This system is adaptable to forms of mass transit like buses and will also be connected in the information/scheduling sense to other ITS functions like trip planning, scheduling or tracking.
- This system has freight carriers designed into the system. It will further assist in on-time delivery and efficiency in transporting goods from start to destination.
- High speed, system flexibility, and insured safety will all contribute to increased throughput for the present system.
- Automatic obstacle detection and avoidance, together with vehicle-to-vehicle communications, will show conformity

to standards of travel that will increase safety.

- A robust vehicle that has been standardized (in terms of component interfaces) will make for a cost-effective vehicle. The infrastructure will also benefit from being mainly passive except for the gapped barriers and the standard ITS functions allowable for cooperative distribution.
- Vehicle maintenance will be similar to existing vehicles (safety through periodic maintenance).
- Infrastructure maintenance will be similar to existing infrastructure with added tasks like checking connectivity of metal strips for lateral control.
- Support from the external world include safety inspection and automated vehicle compliance during registration and enforcement in dedicated lanes through periodic law enforcement and video entrapment with strict penalty.
- Since the concept is flexible to support all users, demand should be the same as current traffic patterns.
- The system will be intuitive, easy, foolproof, and at the least, the safest mode of transportation available on the ground. The driver should be at ease when he/she relinquishes control. He should have automatic, normal updates and exception handling updates to make him/her and their passengers feel at ease and confident the system is safe.

7. CONCEPT 5: COOPERATIVE PLATOONING IN DEDICATED LANES WITH GAPS IN PHYSICAL BARRIERS

7.1 OVERVIEW

This concept considers a cooperative platooning configuration of vehicles for an automated highway system (AHS) together with the allowance of mixed vehicle classes in the same automated lane. The six fundamental components to each AHS concept, namely (1) distribution of intelligence, (2) separation policy, (3) mixing of AHS and non-AHS vehicles in same lane, (4) mixing of vehicle classes in same lane, (5) entry/exit configuration, and (6) obstacle detection handling, offer numerous combinations for feasible AHS concepts. This concept is being considered since it is a viable alternative that places the distribution of intelligence more heavily weighted on the vehicle and not the infrastructure. While it has the potential for achieving increases in capacity and safety to the automated facility by adding intelligence and obstacle detection and avoidance capability to the vehicle, upon more thorough examination, it will be revealed that relying too heavily on the vehicle without some minimum of infrastructure support for the communication of dynamic information, too many disadvantages result for this concept.

7.1.1. Distinguishing Features

- *Platooning* which will help to increase throughput, however, as will be discussed later, without the infrastructure support available to provide dynamic information, will not provide a system optimum relative to traffic flow control.
- *Minimal infrastructure involvement* resulting from the vehicle carrying most of the weight of the distribution of intelligence.
- *Very local level of authorized communication among platoons* which will lead to problems in trying to optimize traffic flow, coordinating the merging of vehicles into the automated lanes, and handling emergency situations.

7.2 SELECTED ALTERNATIVES FROM EACH DIMENSION

7.2.1 Cooperative Intelligence Among Vehicles

In this concept, communication among adjacent platoons is utilized to provide dynamic information, to the extent that is possible, given the local nature of this communication protocol. Only static information will be communicated from the roadside to the vehicle, such as upcoming exit locations, posted speed limits, etc.

7.2.1.1. <u>Local Tailorability</u>

Because the vehicle coordination is local, possibly resulting in difficulties in achieving an optimal flow control for numerous functions, such as entry and exit, merging, and emergency maneuvers, variances to this local communication and coordination protocol may be allowed.

7.2.2 Platooning

Where traffic levels are high enough, vehicles will travel in platoons to increase throughput.

7.2.3 Dedicated Lanes With Gaps in Physical Barriers

Dedicated lanes will be for the use of automated vehicles only, that is, there is no permitted mixing of AHS-equipped vehicles driving in automated mode with non-AHS equipped manually driven vehicles or with AHS-equipped vehicles who fail check-in but want to enter the AHS lane nevertheless. There is a transition lane for entry and exit activities in which there will be permitted mixing of AHS-equipped vehicles in automated mode in the process of merging into the automated lane with AHS-equipped vehicles who have failed the check-in process and need to exit the transition lane to return to the manual lane. Thus, the mixing of automated and manual traffic is of a transitory and temporary nature. The three lane types, automated lane, transition lane, and manual lanes are separated by an intermittent physical barrier with openings to allow vehicles to enter from the manual or conventional non-automated lanes to the automated lanes via the transition lane.

7.2.4 Mixed Classes of Vehicles in a Lane

This concept allows for the mixing of vehicle classes in the same automated lane.

7.2.4.1. <u>Local Tailorability</u>

Local officials may choose, if there is available additional roadway space, to have separate automated lanes for the two major vehicle classes, namely, light-duty and heavy-duty vehicles (trucks and buses). In addition, the lane for light-duty vehicles may have a faster operating speed and narrower lane width than the other automated lane. Under such circumstances, such a lane for light-duty vehicles would be placed in the inner-most position, in which case light-duty vehicles would weave through the heavy-duty vehicle lane to access their lane.

7.2.5 Transition Lane Entry/Exit

The transition lane will be used by AHS-equipped vehicles to maneuver from the manual lane to the automated lane, possibly going through a check-in procedure in-motion after the vehicle enters the transition lane. Thus, all vehicular traffic will use conventional freeway on- and off-ramps to first access the freeway, then those AHS-equipped vehicles who want to use the automated lane(s) need to weave through all manual lanes to first enter the transition lane, then move over to the automated lane(s).

7.2.5.1. <u>Local Tailorability</u>

It may be the case that for implementation locations, at particularly heavily used entry/exit points that a variation of the transition lane entry/exit be allowed, that is, that a dedicated entry/exit area be added if feasible (sufficient right-of-way) and needed.

7.2.6 Automated Obstacle Avoidance

Obstacles will be detected automatically by the vehicles, which will automatically avoid them, if possible.

7.2.7 Options

The following options will be discussed in more detail in the remainder of the document, however, they are highlighted here:

- Transition lanes can be continuos or intermittent
- There may be a breakdown lane or area for use by automated vehicles
- If there are multiple AHS lanes, light-duty vehicles may have the option of traveling on a separate lane that is narrower and has a higher speed limit than for heavy-duty vehicles

7.2.8 Assumptions

The following assumptions were made during the course of this investigation of the cooperative platooning concept:

- *There is no mixing of vehicle classes in a platoon*-This assumption is made for safety reasons since not only do the (1) differences in speed among intra-platoon vehicles and (2) intra-platoon spacing have to be taken into account, but the differences in the masses that would exist if, for example, a truck or bus were leading or following a small light-duty vehicle.
- *If multiple AHS lanes exist and mixing of vehicle classes is transitory, then light-duty vehicles would travel on the innermost lane*

7.3 OPERATIONAL CONCEPT

The AHS system relies on the intelligence of vehicles without support or management from infrastructure. The vehicles are equipped with sensing and communication systems to exchange information and data among themselves. The sensing system on the vehicles allows the vehicles to detect and identify the existence of other vehicles and roadways. The on-board sensing system may also obtain information from components on the roadway or infrastructure but such components do not provide controlling signals. Communication among vehicles facilitates the exchange of information such as spacing, location, and vehicle dynamics. Such communication systems exist among vehicles of which the motions must be coordinated.

The AHS system adapts the concept of vehicle platooning. Vehicle platoons are formed with small spacing, in a range of 1 to 10 meters, among a group of vehicles, with a number from 2 to 20 for instance, in a lane. The small spacing between vehicles allows a higher highway throughput and reduces the speed difference in impacts if sudden deceleration or acceleration occur. Communication is required within a platoon to maintain the string stability and integrity of spacing control. Vehicles become free agents when they are not operating in platoons.

The AHS system does not allow mixing of non-AHS vehicles in automated lanes. The AHS lanes are separated from the manual traffic by physical barriers. Gaps exist in these barriers. Vehicles enter and exit AHS lanes through gaps in barriers. Barriers may or may not exist between multiple AHS lanes.

The entry and exit to the AHS lanes are accomplished through transition lanes. Manual traffic enters the transition lanes manually. In transition lanes, vehicles switch from manual to automatic modes. The automated vehicles then enter AHS lanes through gaps in barriers. Automated vehicles exit by moving into transition lanes through gaps in barriers. The vehicles switch from automatic to manual modes in transition lanes and drivers resume control.

Mixing of vehicle classes is allowed in a lane. Trucks, buses, and passenger cars may travel simultaneously on a lane in a transitional stage or in a regular operation. If there are multiple automated lanes, one class of vehicles may be advised to travel in the inside lanes while other classes are advised to travel in the outside lanes. The distribution of traffic classes will be accomplished through lane changes maneuvers in AHS lanes.

The vehicles in the AHS systems will sense and avoid obstacles automatically. The vehicles will detect the existence and determine the type of obstacles. The control systems on vehicles will then take appropriate actions to avoid obstacles to mitigate the consequences. Such actions may include the control of throttle, braking, and steering.

7.4 SYSTEM STRUCTURE

All vehicles sense the surrounding vehicles and roadways. Communication among vehicles is required if coordination is needed. Two-way communication is necessary in general but one-way transmission may be applicable in a broadcast mode.

In normal operations, vehicles within a platoon communicate by sending vehicle position number, speed, acceleration, and the speed and acceleration of the leading vehicles. The message transmission rate is in the order of 100kb/sec. A communication loop time below 20 msec is desired. In a join or split maneuver, a request is made and a consensus among affected vehicles is reached through communication prior to the activation of such maneuvers. Lane change maneuvers of single vehicles are typically preceded by a platoon split maneuver.

If a vehicle is separated from a platoon, it becomes a free agent. A free agent may or may not maintain communication with other vehicles. Without communication, the free agent will rely on the sensing system to perform functions of speed tracking, vehicle following, lane keeping, and lane changing. In lane changing maneuvers, vehicles must detect and identify the existence, position, and speed of vehicles in the adjacent lane.

7.5 FUNCTIONAL ALLOCATION

7.5.1 Check-In and Entry

Vehicles move from manual lanes into transition lanes manually. Drivers instructed vehicles to prepare entering AHS. Vehicles enter check-in stations or points. If vehicles successfully check in, vehicles switch from manual to automatic modes. Lane keeping and speed tracking are now automatically controlled. Vehicles communicate with the upcoming free agent or platoon in the adjacent lane to coordinate entry speed and timing. If a consensus is not reached, the entering vehicle waits for the next free agent or platoon. If the request to enter is permitted, the entering vehicle moves into the adjacent AHS lane in front of the communicated free agent or platoon.

7.5.2 Automatic Driving

A driver may indicate or change the destination before, during, or after the entry process. Vehicles automatically sense the roadway marker or sections and decide the proper merging, diverging, or exit points along the AHS infrastructure.

7.5.2.1. Platoon Join and Split

Once in the AHS, a free agent will communicate with the preceding free agent or platoon and request to join. If the request is granted, a join maneuver is made and the free agent becomes a following vehicle in a platoon. If the request is rejected, the free agent will wait to become a leader for the trailing vehicle or try to join a platoon later.

A vehicle in a platoon may need to change its path and depart from the platoon. Before the vehicle changes its speed or path, it needs to request a split maneuver within the platoon. If a consensus is reached, the platoon is split to make room for this vehicle to make its move. If the departing vehicle is the leader of a platoon, the 2nd vehicle in the platoon assumes the leader functions and the leading vehicle becomes a free agent. If the departing vehicle is a follower, the platoon is split before and after this vehicle to make room for this vehicle to make its move. The vehicle behind it will become the leader of a new platoon.

7.5.2.2. Lane Keeping, Speed and Vehicle Following

The vehicles perform its lane keeping function by an on-board sensing system. The sensing system provides information regarding the lane boundary, preview of roadway curvature, junctions, entry and exit locations, and absolute positions on a highway section. The vehicles are also equipped sensing system to measure the relative speed and distance between vehicles to provide inputs to its control systems to track speed or maintain spacing between vehicles.

If a vehicle becomes a free agent, the control system will regulate the vehicles to maintain its speed at the speed limit or a safe distance from the preceding vehicle. If a vehicle joins a platoon, it will maintain a proper spacing at the speed of the platoon leader through communication. The leading vehicle of a platoon will travel at the speed limit if the traffic, weather and roadway conditions allow it.

7.5.2.3. Lane Change

A free agent or the leader of a platoon may decide to make a lane change. Such decisions may result from the detection of an obstacle or slowing traffic, or the need to change its path. To make a lane change maneuver, the free agent or platoon must communicate with the upcoming free agent or platoon to coordinate such moves. Vehicles will use its sensing system to detect any potential hazards on the adjacent lanes even after the consensus with the upcoming vehicle is reached.

7.5.2.4. Obstacle Avoidance

If an obstacle is detected on the roadway ahead, a free agent or a platoon leader may decide to come to a stop or to change lanes.

The decision is made by the vehicle through an assessment of the surrounding traffic. A free agent will use a deceleration to come to stop in time or to minimize the impact speed with the obstacle. The leader of a platoon will coordinate with its followers to use an appropriate braking strategy to mitigate the consequences for the whole platoon.

7.5.3 Exit and Check-Out

A vehicle exits the AHS lane by moving into the transition lane first. If the vehicle is in a platoon, it needs to request a split maneuver so that it can depart from the platoon. Once in the transition lane, the vehicle will pass through check-out stations. Once the check-out process is completed, the vehicle switches from automated to manual modes and the driver resumes control. The driver will move the vehicle manually from the transition lane into the manual traffic lane.

7.5.4 Flow Control

There is no system or infrastructure control of traffic flow. The traffic flow is determined by the local coordination of vehicles. Each free agent or platoon decides its speed by observing the speed limit or maintaining a proper distance from the preceding vehicle. The decision of a vehicle to make a lane change maneuver in a multiple-lane AHS is either prompted by the need to reach destination or by detecting an empty space in the adjacent lane.

7.5.5 Malfunction and Emergency Handling

Drivers are not involved in the obstacle avoidance process described in the preceding section. In malfunction or emergency situations, the automated modes of vehicles may be deactivated and the vehicles are brought to a stop. The drivers may be alerted and requested to resume control and to bring these vehicles to a safe location. The vehicles may also remain disabled until they are removed by highway maintenance crews. The occurrence of malfunction or emergency may be communicated to notify the highway management center.

7.6 IMPLEMENTATIONS

7.6.1 Vehicle

There are multiple specific vehicular technologies for sensing and communication.

7.6.2 Infrastructure

The implementation-related dimensions to consider include barrier configurations, entry/exit placement, lateral expansion of the roadway, vehicle classes allowed on the automated roadway, number of manual lanes, number of automated lanes, lane widths, extent of transition lane, and existence of an emergency/breakdown lane for automated vehicle usage.

In the cooperative concept, there is minimal infrastructure-vehicle communication through basic ITS services, such as traffic advisories that are transmitted globally, if not regionally. The vehicles sense the roadway through the use of magnetic markers/nails through which the automated steering system would be implemented. There would be physical barriers with openings to separate the automated lane(s) and the transition lane, and the transition lane and the manual lane(s).

7.6.2.1. Barrier Configurations & Entry/Exit Placement

Alternative configurations exist to implement this concept. These configurations may be classified by two parameters: (I) design, extent, and placement of barriers separating automated, transition, and manual traffic and (II) proximity of entry and exit activities. For the first parameter, the following three alternatives were considered:

1. Physical barrier between automated lane(s) and transition lane with openings and only a virtual barrier (lane stripings) between the transition lane and the manual lane(s). Only standard lane boundary markings would exist separating multiple automated lanes.

2. Physical barrier between both automated lane(s) and transition lane and between transition lane and manual lane(s). Both barriers would have openings for access to and egress from the automated lane(s). Openings in the barriers between the transition and manual lane(s) would be slightly upstream, i.e. offset, from their respective counterparts in the barrier between the automated and transition lane, though there is still substantial overlap in the two barrier opening areas.
3. Same as (2) except that the offset in the barrier openings would be substantially more pronounced. That is, the area for barrier openings between the manual lane(s) and the transition lane has NO overlap with the area for barrier openings between the transition lane and automated lane(s). In fact, corresponding to the barrier opening area between the transition and automated lane(s) is a continuous barrier between the transition and manual lane(s).

For proximity of entry and exit areas, the following two alternatives were considered:

1. A single area allowing for all entry and exit maneuvers or movements to occur
2. Two areas that are sequentially placed, first entry and then exit completely segregated from each other.

Alternative (1) would require substantially more complex communication and sensing coordination among the vehicles to insure the same level of safety than for alternative (2) since vehicles would be entering and exiting within the same general physical area.

It is suggested that entry points, i.e. automated facility check-in points, be located approximately 3.5 km apart. Exit points (check-out) would need to be located approximately 2 km following each entry point in order to allow for adequate space in which to perform entry and exit maneuvers to and from the automated lane. Vehicles wishing to exit the freeway must use an exit point far enough upstream of the desired off-ramp to allow sufficient distance in which to weave through traffic to the right lane prior to reaching the off-ramp, which will vary with traffic conditions. Entry/exit zones (check-in to check-out), areas of approximately 2 km in length in which automated lane entry and exit maneuvers take place between the automated and transition lanes, would be spaced approximately 1.5 km apart to allow for the movement of vehicles between manual and transition lanes. Within these 1.5 km weaving zones, there would be no barrier between the transition lane and the adjacent manual lane and no openings in the barrier between the transition lane and the automated lane.

Barrier openings should be offset so that at all points along the automated facility at least one barrier separates the automated and non-automated lanes. Under this option, vehicles utilizing the automated facility enter and exit the highway through existing on- and off-ramps, thereby minimizing construction costs and environmental impacts.

7.6.2.2. <u>Lateral expansion of the roadway</u>

Due to the spatial requirements of lane barriers, on many urban freeways lateral expansion of roadways would be necessary. In each direction of travel, lane barriers and barrier shoulders would require the traveled way to be widened. The need for lateral expansion of the roadway beyond the outside shoulder is dependent upon the availability of median space and lane widths. The standard minimum median width for freeways is typically considered to be 1.2 meters, comprised of a concrete median barrier (0.6 meters wide at the base) and 0.3 meters inside shoulders on each side of the barrier. It is proposed that inside shoulders would not be necessary along median barriers in an automated system since vehicles in the median lanes would be under automated control at all times. Many freeway medians are wider than 1.2 meters and in many cases are significantly wider. Upon conversion of a freeway to this configuration, it is recommended that, to the extent possible after allowing for needed center supports for overpasses, available median space be converted to roadway in order to minimize the extent of lateral expansion beyond the outside shoulder.

7.6.2.3. Vehicle classes allowed on the automated roadway

The classes of vehicles allowed on the automated facility is another implementation-based feature, which has consequences for lane width and need for multiple automated lane usage. The mixing-of-vehicle-classes-in-a-lane feature may also be implemented in more than one way. The mixing may be allowed on all lanes carrying automated vehicles, i.e. the mainline automated lane and the transition lane, or the transition lane only. If mixing is permitted on the automated mainline, then we only need a single automated lane, though more than one lane may be desired. If mixing of vehicle classes is allowed only on the transition lane, and we assume that all vehicle classes are allowed on the automated facility, multiple automated mainline lanes would be required to carry the different vehicle class traffic.

7.6.2.4. Number of manual lanes

A minimum of four lanes in each direction of travel would likely be required, assuming one automated lane, one transition lane, and two manual lanes. It is implicitly assumed that the market penetration of automated vehicles is consistent with having taken away two lanes from manual use. A minimum of two manual lanes is necessary, to adequately accommodate AHS entry/exit maneuvers, weaving movements between the manual lanes and transition lane, on- and off-ramp movements, and to allow for passing in the manual lanes to accommodate slower moving manual traffic. For highway segments with less than four lanes in each direction, the implementation would require the lateral expansion of the roadway. Depending upon the availability of usable space within the existing ROW and the severity of restrictions to lateral expansion beyond the ROW, implementation may be costly and may displace existing land uses and other physical obstacles.

7.6.2.5. Number of automated lanes

The number of automated lanes is an additional implementation-based characteristics. Again, if the implementation includes multiple vehicle classes and mixing of these classes is transitory, i.e. only allowed on the transition lane, then multiple automated lanes are necessary. With multiple automated lanes, barriers may or may not be used. Since traffic is automated in both lanes, barriers between automated lanes would not be necessary. In the case of two automated lanes, one for light-duty vehicles and the other for heavy-duty vehicles, another implementation issue to address would be the placement of these automated lanes, i.e. should the light-duty vehicle automated lane be the inner-most lane or not? If the light-duty vehicle automated lane were to be traveling at faster speeds than the other automated lane and of narrower width, than it is recommended that the light-duty vehicle automated lane be the inner-most lane, i.e. closest to the median barrier.

7.6.2.6. Lane widths

The lane widths for both the automated mainline lane and the transition lane is another implementation-related characteristic. If heavy-duty vehicles such as buses and trucks are allowed on the automated facility, then lane widths would probably have to remain the standard width they currently are. If there were two automated lanes, one for light-duty vehicles and one for heavy-duty vehicles, then an implementation option would be to have the light-duty vehicle lane be of shorter lane width than the other automated lane and possibly having these vehicles traveling at faster speeds.

7.6.2.7. Extent of transition lane

The transition lane may be a continuous lane or an intermittent lane. To save on the use of real estate, it would be prudent to begin and end the transition lane to accommodate the entry and exit functions. The transition lane may, however, be a de facto continuous lane if adjacent entry/exit zones are very closely spaced together.

7.6.2.8. Existence of breakdown/emergency lane for automated usage

If the need for a breakdown lane to the left of the automated lane for emergency purposes to help avoid blocking the automated lane under such circumstances, then additional right-of-way would be needed. This lane would not necessarily have to be a continuous lane for the entire length of the automated lane. A combination of both an intermittent transition and breakdown lane could be configured so as to require only an additional single lane-width of space.

7.6.2.9. Additional right-of-way needed

As mentioned above, additional right-of-way may be needed to accommodate lateral roadway expansion for a breakdown lane, physical barriers, any needed additional buffer space to help alleviate any feeling of confinement while driving through areas where there are barriers, possibly short roadway sections with barriers on both sides of the roadway, and shoulder space.

7.6.3 Differences Between Urban and Rural Implementation

There are numerous differences in the physical aspects between urban and rural/suburban environments. Such aspects including roadway characteristics and surrounding land use are listed as follows:

- availability of median and median widths
- availability of right-of-way for lateral expansion
- terrain: mountainous with possible steep cuts and slopes in rural areas
- extent of separation of roadbeds in opposite directions
- possibility of lots of congestion at entry/exit points in urban areas
- possible overpass bridge reconstruction necessary to accommodate lateral expansion of roadway

7.6.4 Deployment

- Minimal deployable system
- Incentive to buy an AHS vehicle
- Incentive to extend AHS facility

7.7 GENERAL ISSUES AND CONSIDERATIONS

7.7.1 Local Coordination

Coordination is local. Difficulties may arise in achieving an optimal flow control for numerous functions, such as entry and exit, merging, and emergency maneuvers.

7.7.2 Heavy Reliance on Individual Vehicle Intelligence

Since no support is received from the infrastructure other than static information such as posted speed limits, or location and distance to an off-ramp, vehicles must carry out all sensing and communication functions. The requirements on these components, therefore, must be made more stringent than if there were more substantive infrastructure support.

7.7.3 Cooperative or Selfish?

Protocols for cooperative maneuvers must be developed to avoid selfishness. A communication of priority or urgency may be necessary. For example, upon entry to the automated lane(s) from the transition lane, an entering vehicle must first determine whether there is sufficient lane space with which to merge into the automated lane and get permission to enter from the closest approaching platoon to execute this merge maneuver. What happens if permission is repeatedly not granted causing backups on the transition lane? This potential problem needs to be avoided.

7.7.4 Communication Range and Channels

To effectively coordinate maneuvers, the means for vehicles to "tune in" to appropriate communication channels must be established. Difficulties in assigning proper channels or frequencies may arise when no infrastructure support is provided.

7.7.5 Transition Lane

- The transition lane at entry and exit points should be designed to minimize the mixing of manual and automated traffic.
- Accessibility of automated lanes may be hindered due to the difficulty in weaving through manual lanes to access the automated lanes.
- Capacity of manual lanes may be reduced due to the increased weaving activity to access the automated lanes.

7.7.6 Platooning and Mixed Classes of Vehicles

Prohibition of mixed classes in the same platoon will increase numbers of free agents while mixing classes of vehicles in the same platoon could substantially complicate user comfort and safety of automated facility users. If upon entry to the automated facility a heavy duty vehicle, such as a truck or a bus, either enters the automated lane as a free agent or waits until a platoon of the same vehicle class approaches. Waiting for such a platoon could lead to backups on the transition lane for vehicles waiting to enter the automated lane. Safety issues need to be addressed in the event of a multi-vehicle class platoon during an incident, due to the potentially large differences in size and mass of the vehicles within the same platoon.

7.7.7 Potential for Additional Right-of-Way Required

Implementation of this concept in a dense urban environment may not always be feasible if there is insufficient right-of-way that could be needed to accommodate roadway lateral expansion for barriers or shoulder space.

8. CONCEPT 6: FREE AGENT WITH MODERATE NON-AHS EXPOSURE

8.1 OVERVIEW

This configuration features free agent separation using infrastructure supported intelligence. The coordination unit is the level at which traffic management functions such as merging are coordinated on the AHS. The coordination unit for this configuration is a single vehicle. This concept is very similar to #8a, with the exception of the attribute defining the mixing of AHS and non-AHS vehicles. Concept #6 operates the automated lanes in dedicated facilities with gaps in the physical barrier, introducing the possibility for intrusion by unauthorized vehicles. A transition lane is defined as the entry/exit facility for this concept, introducing another level of interface with non-AHS vehicles. Other attributes concept #6 has in common with #8a are integration of vehicle classes within a single lane and automated sensing and avoidance of obstacles.

Concept #6 features the ability to accommodate entry/exit in a dedicated facility with physical barriers through transition lanes rather than a dedicated ramp. Gaps in the barriers will be evaluated as an access and egress method. Another influence on the definition of this concept will be effect of non-AHS vehicles on infrastructure supported free-agent operation in mixed-vehicle class lanes.

8.2 DIMENSION ATTRIBUTES

8.2.1 Distribution of Intelligence: Infrastructure Supported

This dimension assumes that acceleration, deceleration and possibly maneuver data concerning adjacent vehicles in a local area is available to the single vehicle coordination unit. The infrastructure supported dimension provides infrastructure monitoring of global events such as traffic flow and incidents. The infrastructure communicates pertinent information to vehicles within its local zone. Data is expected to include general parameters such as assigned travel speed, headway, or roadway geometry.

Vehicle control loop commands are generated by the vehicle. The vehicle control loop can use local zone information generated by the infrastructure to improve maneuver planning. Individual vehicles are not responsible for roadway condition or environment sensing, allowing vehicle sensors to focus on obstacle detection and headway measurement. The reduced responsibility in terms of vehicle sensors is balanced by an increase in infrastructure instrumentation to support sensing and communications between the vehicle and the infrastructure.

8.2.2 Separation Policy: Free Agent

The separation policy specifies that individual vehicles operate as the coordination unit for AHS maneuvers such as merge and separation to and from the automated lane. The vehicle separation is determined by an infrastructure controller at the zone or regional level and communicated to the vehicles at check-in or enroute. The vehicles maintain their own headway through sensing of adjacent vehicles and internal generation of acceleration, deceleration, and turning control loop commands. Vehicles may cooperate by sharing speed and acceleration/deceleration data with adjacent vehicles, allowing coordination of maneuvers within a local zone.

8.2.3 Mixing of AHS and Non-AHS Vehicles: Dedicated Lanes With Some Gaps in the Physical Barriers

The geometry of the barrier gaps will be dictated by the vehicle classes which must access the automated lane. Longer gaps will be required to support commercial and transit vehicles. The roadway design can be tailored to accommodate local needs. Areas with a high percentage of truck and bus traffic might allow access at all barrier gaps. Areas with greater passenger vehicle congestion might shift the balance and allow passenger cars only at certain barriers to minimize the impact to traffic flow as slower and less maneuverable vehicles enter the automated lane.

The impact to roadway infrastructure of transition lanes to access the dedicated facility will be evaluated with respect to dedicated entry and exit ramps. The impact to facility size and geometry are considerations. The spacing of gaps will impact system efficiency and the physical design of the barrier opening will have safety implications.

Continuous physical barriers are expected to prevent intrusion of unauthorized vehicles into the automated lane. Gaps in the physical barrier provide the opportunity for AHS vehicles to merge into and out of the AHS lanes, but allows the possibility for unqualified vehicles to access the automated lane. Unauthorized vehicles which breach the barrier gap must be detected by AHS vehicles and speed and spacing will be adjusted independently by the free agent since the coordination unit is a single vehicle. Information concerning emergency maneuvers will be shared with adjacent vehicles, and each free agent will plan and execute related emergency maneuvers as necessary in response to obstacles or rogue vehicles.

8.2.4 Mixing of Vehicle Classes: Mixed

This attribute assignment specifies allowing integration of vehicle classes within a lane. Mixing of commercial, transit, and passenger vehicles will impact the maximum lane density and operating capacity. This feature is best suited for areas with little congestion problem and a need to improve the safety and reliability of long trips. A minimum trip length may be necessary to optimize the frequency and location of barrier gaps.

An option for highly congested areas might require separate lanes for commercial or transit vehicles. This will allow tailoring of speed and headway to optimize passenger vehicle capacity in areas where trucks and buses provide a large enough population to support a commercial/transit vehicle lane.

8.2.5 Entry/Exit: Transition

Vehicles will access the automated lanes via a transition lane. The vehicle will transfer to automated control while in the transition lane. The vehicle will be informed of the location of gaps in the barrier by the infrastructure. The vehicle must move into the automated lane while sensing for potential obstacles in the transition lane and the automated lane. The ability to cooperate among vehicles will enhance the ability to enter the automated lane safely. An entering vehicle can monitor adjacent vehicle position and speed information prior to initiating a lane change maneuver through the gap.

Vehicles will exit the automated lanes via a transition lane. The vehicle will transfer to manual control while in the transition lane. The vehicle will be informed of the location of gaps in the barrier by the infrastructure. The vehicle must move into the transition lane while sensing for potential obstacles in the transition lane and the automated lane. The ability to cooperate among vehicles will enhance the ability to exit the automated lane safely. The exiting vehicle can communicate position and speed information to adjacent vehicles prior to initiating a lane change maneuver through the gap. Following vehicles may adjust their spacing in a cooperative manner if necessary.

8.2.6 Obstacle: Automated Sensing and Avoidance Maneuver

Obstacle detection is performed by the vehicle. Vehicle detection of obstacles can be shared cooperatively with adjacent vehicles. Acceleration, deceleration, and maneuver commands are generated by single vehicle units based on internal information and data obtained cooperatively.

8.3 OPERATIONAL CONCEPT

Vehicles will initiate entry to the automated lanes from a transition lane. Preliminary speed and headway parameters are provided by the infrastructure. The vehicle plans its maneuver into the automated lane based on lane availability gathered cooperatively from adjacent vehicles and the vehicle obstacle detection sensors.

Vehicles monitor infrastructure instrumentation to gather roadway operational data such as surface conditions, environmental factors, speed advisories, and route information. Vehicles monitor adjacent vehicles to gather position and speed data and obstacle information to enhance maneuver planning.

The vehicle exits the automated lane under automated control into a transition lane. Barrier gap information is gathered from the infrastructure and exit maneuver data is shared cooperatively with adjacent vehicles. Control is transferred from automated to manual in the transition lane. The vehicle may continue traveling in the transition lane or may be maneuvered under manual control to other non-AHS lanes.

8.4 SYSTEM DIAGRAM

8.4.1 TOC to Zone Controller Interface

The TOC provides flow control information to the zone level regarding lane closures, entry and exit availability. The zone controller passes environment and incident reports to the TOC.

8.4.2 Zone Controller to Roadway Condition Sensors

The roadway condition sensors pass congestion and environment information to the zone controllers.

8.4.3 Roadway Condition Sensors to Roadway

The roadway condition sensors detect congestion levels, surface parameters, and weather conditions.

8.4.4 Range Detection Sensors to Vehicle

The range sensors detect the distance between vehicles and speed of vehicles. Range detection may include comparison to known slot assignments to identify all moving objects not in an assigned slot as an obstacle.

8.4.5 Vehicle to Vehicle Communications Interface

Vehicles transmit position and maneuver planning data. Vehicles within receive range respond with position and maneuver plan information.

8.4.6 Zone Controller to Vehicles

The zone controllers transmit traffic flow parameters to vehicles within receive range.

8.4.7 Vehicle Sensors to Lateral Reference

Vehicles will sense lateral control reference.

8.5 FUNCTIONAL ALLOCATION

8.5.1 Position Control:

The position control function is performed in the vehicle. Free agent spacing can be maintained by vehicle-based sensing of adjacent vehicles to maintain headway and lane parameters to maintain lateral position. Vehicle position can also be determined using absolute position location and map matching, with position location data gathered cooperatively used to maintain relative spacing between adjacent vehicles. The individual vehicle is also responsible for obstacle detection and avoidance. The position control function receives absolute position and speed data from onboard vehicle sensors. This function receives commands to change position and speed from the maneuver coordination function. The position control function generates throttle, brake, and steering signals and implements longitudinal and lateral changes to maintain headway and lane keeping, and in response to maneuver commands as required.

8.5.2 Maneuver Coordination

The maneuver coordination function is performed in the vehicle. The maneuver coordination function receives zone and regional roadway information from the flow control function, hazard warnings concerning local obstacles from the hazard management function, and malfunction warnings concerning vehicle or operator detected failures from the malfunction management function.

The maneuver coordination function receives acceleration, deceleration, and turning information from adjacent vehicles allowing maneuvers to be planned in terms of local vehicle motion. This function generates commands to change speed or lane position based on information received from the infrastructure regarding current travel conditions and from adjacent vehicles regarding their position and speed.

The maneuver coordination function receives a message from the check-in function when a vehicle is prepared to access the automated lane and control has been transferred from manual to automated. The maneuver coordination function responds by generating speed and lane change commands which allow the vehicle to move into the automated lane.

The maneuver coordination function receives a message from the check-out function when a vehicle is prepared to exit the automated lane. In the case of exit, control is transferred from automated to manual after the vehicle has moved into the transition lane. The maneuver coordination function generates speed and lane change commands which allow the vehicle to move out of the automated lane. Control is transferred to the operator while the vehicle is traveling in the transition lane.

The maneuver coordination function responds to hazard and malfunction warnings by generating commands to change speed or lane position which allow vehicles to mitigate malfunctions or avoid hazards in a safe manner. This function transmits the control signals addressed to the vehicle in the affected slot. The maneuver coordination function provides notification to the operator interface of merge, demerge, or emergency maneuvers. Notification to the operator interface will be coordinated with the maneuver to prepare the driver for unexpected changes in vehicle speed or position.

8.5.3 Hazard Management

The hazard management function is performed in the vehicle. The hazard management function detects obstacles and adjacent vehicles using onboard vehicle sensors. The hazard management function generates a hazard warning message when an obstacle or vehicle enters a specified control zone, and it is passed to the maneuver coordination function for appropriate action.

This concept does not include a vehicle-infrastructure communications link. The infrastructure cannot be informed of hazards by the vehicle directly. Hazards which affect traffic flow significantly will be detected by the incident detection sensors, and the zone processor will be able to generate traffic flow commands to adjust traffic flow downstream as necessary.

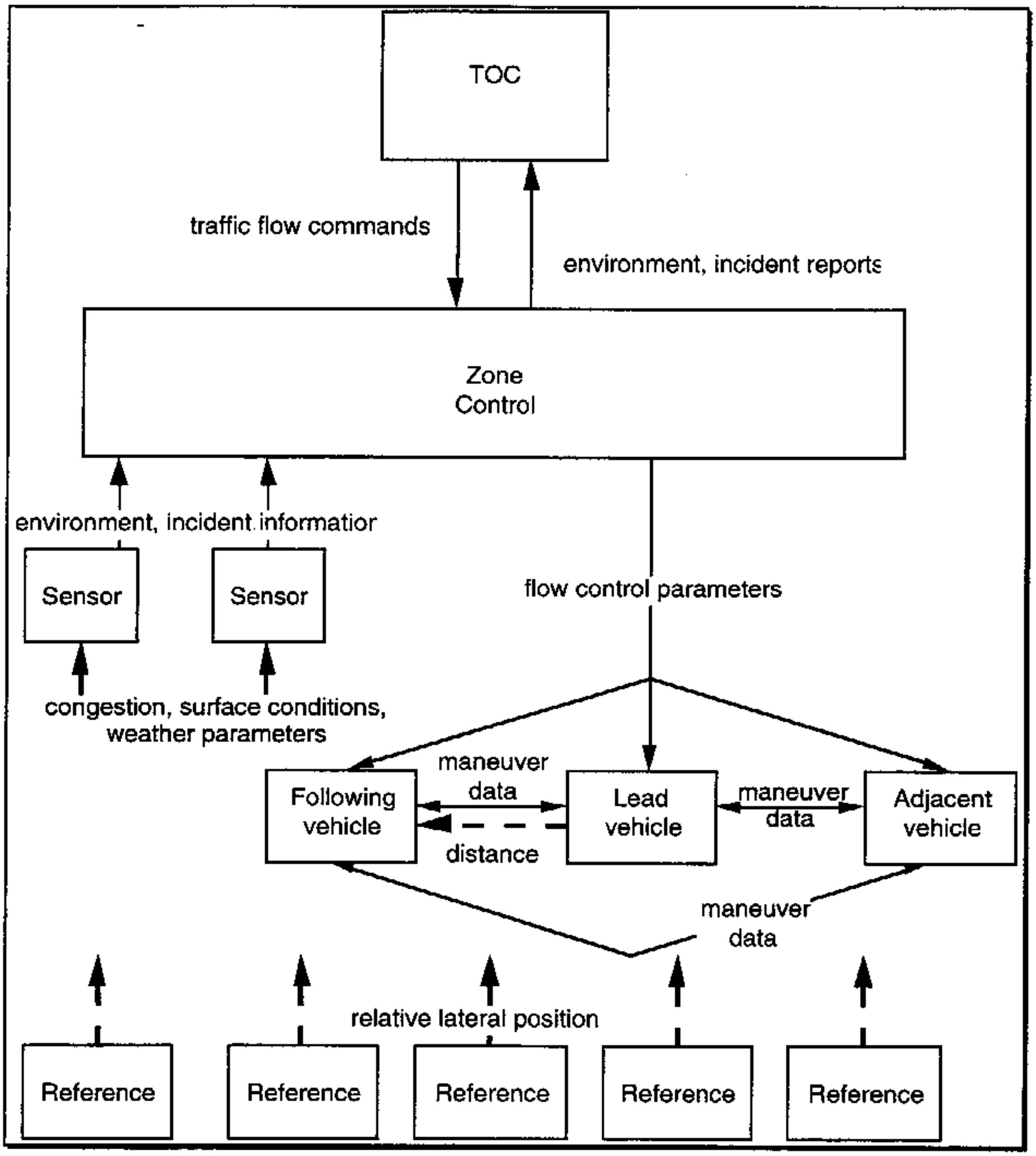

Figure H.8.5-1. System Interface Diagram

8.5.4 Malfunction Management

The malfunction management function is performed in the vehicle. This function receives vehicle system status information from onboard vehicle diagnostics, and operator input regarding system conditions or hazards. The malfunction management function generates a malfunction warning message which is passed to the maneuver coordination function for appropriate action based on processing of vehicle and operator data. This function provides vehicle or system failure information to the traffic operations center and provides status messages to the operator.

8.5.5 Flow Control

The flow control function is performed in the infrastructure. The flow control function monitors infrastructure sensors at the zone level and provides information regarding roadway conditions and local incidents to the maneuver coordination function. This function monitors traffic flow at the regional level and provides operating information to the maneuver coordination function such as congestion at entry/exit points, travel speed, and lane or route closures.

8.5.6 Operator Interface

The operator interface function is performed in the vehicle. The operator interface receives inputs from the operator concerning entry and exit requests and generates requests to enter and exit the automated lanes for the check-in and check-out functions. This function processes inputs from the operator concerning system operating conditions, including hazards or malfunctions and generates messages to the malfunction management function indicating a detected hazard or malfunction.

The operator interface provides sensory notification to the driver to indicate impending maneuvers based on messages received from the maneuver coordination function. This function also provides status to the operator concerning ongoing vehicle and system operating conditions. The operator interface will generate messages which provide status and instructions regarding entry or exit procedures.

8.5.7 Check-In

The check-in function is performed in the vehicle. This function receives operator requests to enter the automated system and initiates the check-in process. The check-in function processes vehicle condition information received from the malfunction management function concerning the integrity of the automated control subsystems. This function verifies the ability to perform the transition from manual to automated control safely and generates a message to the maneuver coordination function to initiate entry to the automated lane. The transfer of control from manual to automated takes place in the transition lane prior to entry to the automated lane.

Vehicles which fail the check-in process will be denied access to the automated lane. A message will be generated to the operator interface function which indicates the status of the check-in results and notifies the driver that the vehicle will remain in manual control and will not maneuver to the automated lane.

8.5.8 Check-Out

The check-out function is performed in the vehicle. This function receives operator requests to exit the automated system and initiates the check-out process. This function verifies the ability to perform the transition from automated to manual control safely and generates a message to the maneuver coordination function to initiate exit from the automated lane.

The check-out function will generate a message to the operator interface function which will allow the transition of control to occur. The operator interface will pass a message back to the check-out function when the operator has performed the required tasks successfully. The vehicle will be maneuvered through the barrier gap and the operator will be prompted to resume manual control prior to transfer from automated to manual control.

Vehicles which fail the check-out process will remain in automated control and will be moved to a safe location. A message will be generated to the operator interface function which indicates the status of the check-out results and initiates the process for exiting under automated control.

8.6 IMPLEMENTATION OPTION(S)

The separation policy specifies that individual vehicles operate as the coordination unit for AHS maneuvers such as merge and separation to and from the automated lane. The vehicle separation is determined by an infrastructure controller at the zone or regional level and communicated to the vehicles at check-in or enroute. The vehicles maintain their own headway through sensing of adjacent vehicles and internal generation of acceleration, deceleration, and turning control loop commands. Vehicles may cooperate by sharing speed and acceleration/deceleration data with adjacent vehicles, allowing coordination of non-emergency maneuvers within a local zone.

8.6.1 Vehicle Electronics

Headway maintenance: Longitudinal position relative to leading vehicle is measured using vehicle-based radar ranging. Speed adjustments are calculated based on range and closing rate to the vehicle immediately in front, and control signals are generated within the vehicle to maintain headway. Obstacle detection will be integrated with the headway maintenance function. A ranging radar similar to adaptive cruise control (ACC) technology may be implemented. Range and resolution are key considerations in evaluating the effectiveness of radar technology in performing the obstacle detection function. A system which provides adequate performance for obstacle detection may increase the cost of the radar subsystem dramatically. Processing required to support target discrimination is also an issue.

Lane keeping: Cooperative sharing of lane position data between free agents will allow coordination of lane changes between adjacent vehicles.

(option A): A vision based lateral control approach to determining lateral position relative to lane markings can be implemented.

(option B): A lateral control approach using passive lane markers can be used to determine lateral position relative to the lane boundaries.

(option C): Absolute position can be determined using geographic positioning techniques, combined with map matching to maintain lateral position.

Transfer maneuver coordination messages: Two-way vehicle-vehicle communications will provide transfer of relative longitudinal and lateral position data between adjacent vehicles. Vehicles planning to make maneuvers will broadcast their position data and intended maneuver. Vehicles in communication range respond with appropriate position information. Access to the receive bandwidth of the vehicle requesting adjacent position data is an issue. The vehicles may require addressing to avoid collisions of return messages. The vehicle must have roadway knowledge to map the positions of cooperating vehicles in the general vicinity to assist in maneuver coordination. The vehicle operates as a free agent, generating maneuvers independently of other vehicle's travel plans using knowledge shared with other vehicles to facilitate lane change, merge and demerge maneuvers.

Receive and process traffic flow commands: Vehicle receiver monitors infrastructure transmissions of flow control information. Vehicle operating speed and minimum headway are adjusted according to environmental and incident advisories. Lane closure and congestion information are incorporated into route planning.

Operator interface: generate entry and exit request messages, support maneuver notification and obstacle avoidance alerts.

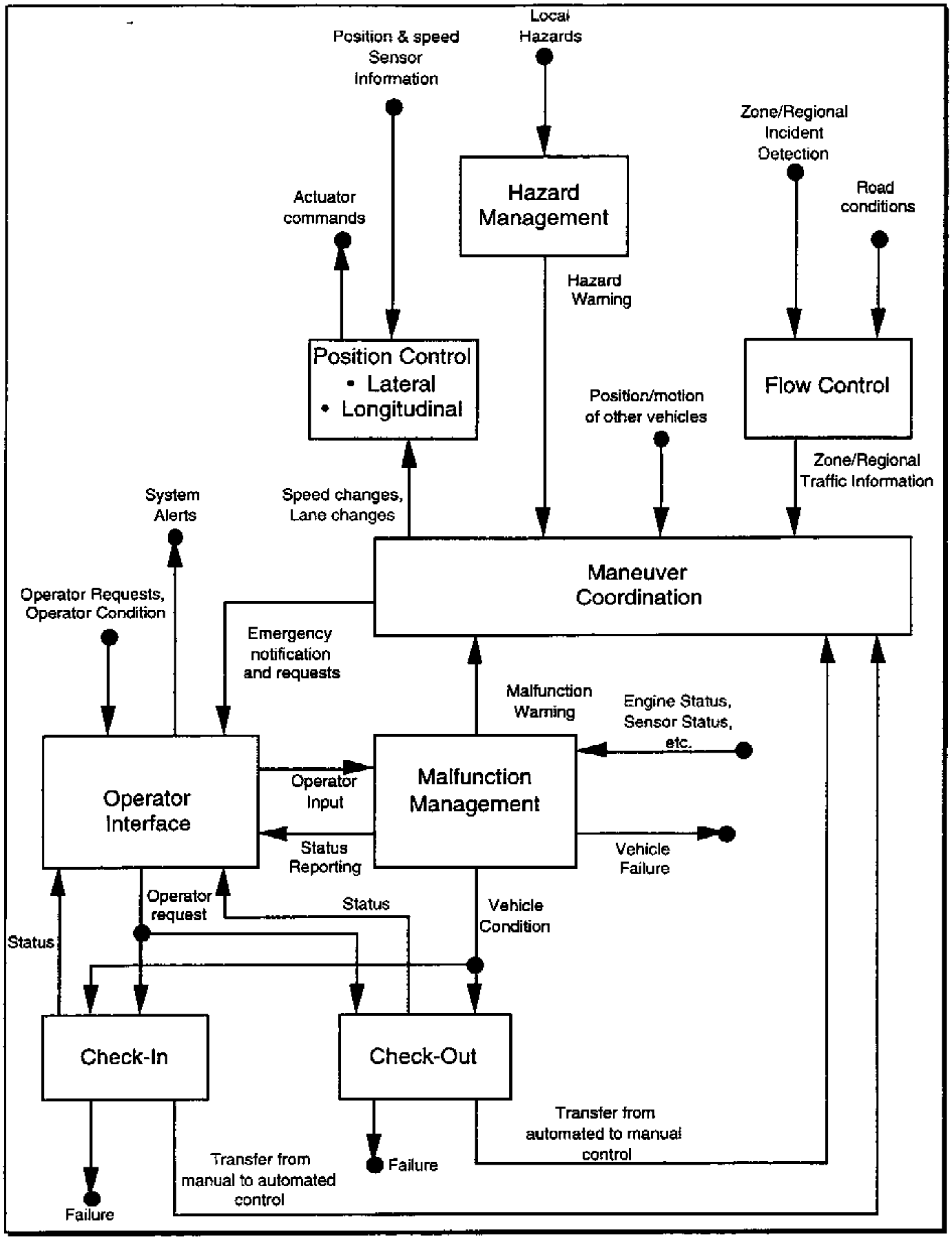

Figure H.8.6-1. Functional Block Diagram

8.6.2 Infrastructure Instrumentation

TOC: monitor global traffic flow. Collect incident information from zone controllers and modify travel advisories as necessary.

Zone controller: collect incident information, transfer to TOC as necessary. Transmit local travel advisories on one-way channel to vehicles. Broadcast RF can be used since headway and speed commands will be set at the local zone level and is not addressed to individual vehicles. Expected range of transmission is on the order of 100 ft. Spacing of local transmitters linked to the zone controller necessary to provide effective zone control is an issue. One transmitter for every entry/exit location may be sufficient.

There may be long sections of roadway between entry/exit points not within the range of zone transmissions in rural areas. This may be acceptable since traffic flow dynamics are not expected to affect lane throughput significantly in the time elapsed until the next transmission in less congested areas. Urban areas typically have frequently spaced entry/exit points. Vehicles can be expected to pass an entry/exit point on the order of once per minute in urban areas.

Incident detection: sense local traffic congestion.

Monitor environment: sense roadway conditions such as surface wetness or visibility.

Lateral reference:

(option A): existing lane striping may be used.

(option B): passive markers in the roadway must be installed.

(option C): assumes existing geographic positioning infrastructure, local beacons possibly required in urban canyons.

8.6.3 Roadway Infrastructure

This concept requires a dedicated lane with a barrier separating the conventional and AHS lanes. A physical barrier provides separation between the AHS lane and the conventional lanes, with a transition lane used to access the automated lane through gap in the barrier. It is assumed that the transition lane is used only by vehicles entering or exiting the automated lane(s).

8.6.3.1. <u>Rural Highway</u>

Areas in which right-of-way is available may be compatible with construction of additional facilities. A dedicated automated lane might be built parallel to existing highways. Adding a transition lane may also be necessary, depending on the number of conventional lanes available for AHS use. Construction of both lanes may be required in areas where only two lanes are available on the conventional highway.

Rural areas with traffic flow which does not justify two AHS lanes in addition to two conventional highway lanes in each direction of travel may not be compatible with an approach which requires two full length AHS lanes to support AHS travel and the transition lane. The transition lane may be little more than an entry/exit ramp connecting the conventional lanes with the gap in the barrier in areas with low congestion. This implementation would appear similar to divided roadways with occasional strips of pavement connecting them to form the transition lane at access and egress points. Using unpaved physical space between the automated lane and the conventional lanes can be considered a barrier, and construction of a vertical barrier may be avoided. This approach is illustrated in Figure H.8.6-3, which illustrates two lanes of a four-lane divided highway where the AHS lane is placed in the median and transition lanes are built at periodic intervals to accommodate entry and exit.

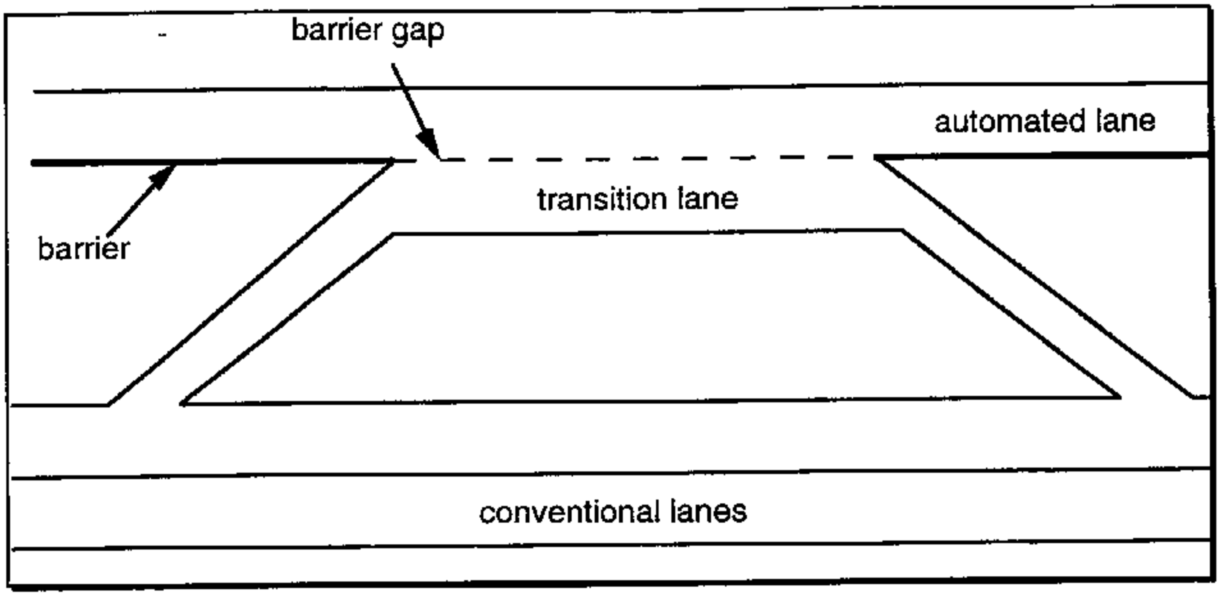

Figure H.8.6-2. Possible Rural Transition from Conventional Lanes to Automated Lane

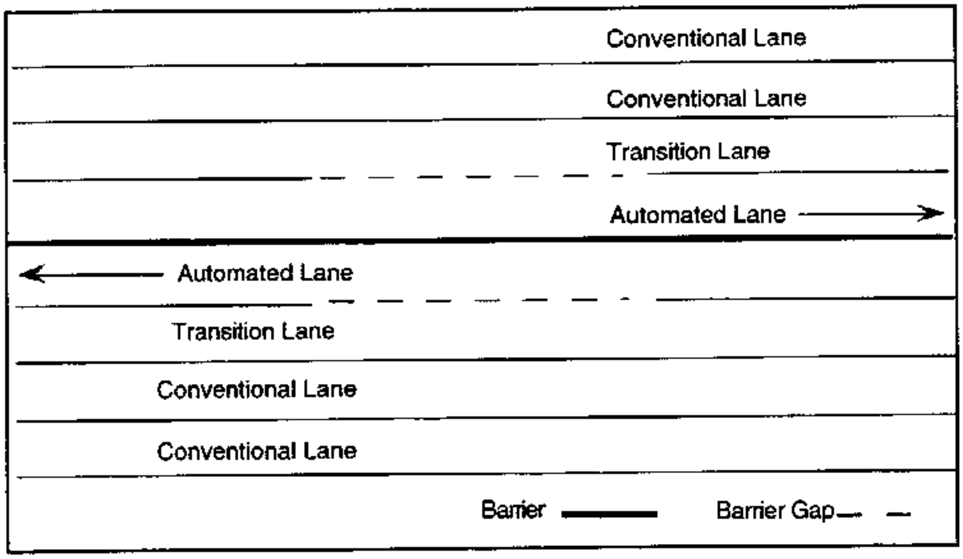

Figure H.8.6-3. Possible Urban Transition from Conventional Lanes to Automated Lane

8.6.3.2. Urban Region

It is expected that the transition lane would extend parallel to the entire length of the automated lane in urban areas. The transition lane is expected to be continuous in urban regions due to higher volumes of traffic entering and exiting the AHS facility at more closely spaced intervals. Spacing and usage of access and egress points will determine the configuration of the transition lane. The barrier gap spacing should be designed to optimize capacity in congested areas. The number and frequency of entry and exit points may be limited to encourage longer trips and improve efficiency. Another urban alternative is to restrict heavy vehicles to off-peak hours due to the longer transition time required to reach AHS speeds and perform merge and lane change maneuvers.

8.6.4 Deployment

This concept contains a moderate degree of infrastructure instrumentation. A large percentage of the infrastructure electronics may be expected to be associated with related ITS services such as automated vehicle location (AVL) and automated vehicle control systems (AVCS). Current trends in incident detection and highway advisory systems also support some of the features included in this concept, providing a smooth evolutionary transition to full automation through instrumentation of the vehicle to allow cooperative maneuver planning through vehicle-vehicle communications.

This concept can be deployed effectively in rural areas with low traffic density using a single lane. Commercial vehicles and passenger vehicles can be permitted to use the lane concurrently, since longer vehicle headways can be specified by the infrastructure supported intelligence as necessary to maintain safety while supporting mixed vehicle class usage. A single lane AHS in rural areas may require supplementation with passing lanes on grades to maintain travel speed for passenger vehicles.

Two full lanes are the minimum required to support efficient deployment in congested urban areas. One lane is dedicated to mainline AHS travel. A second lane is used to provide a transition area for entering and exiting the AHS, and may also be used to divert AHS traffic in emergency situations.

9. CONCEPT 8A: INFRASTRUCTURE SUPPORTED FREE AGENT ON DEDICATED LANES, WITH MIXED CLASSES

9.1 OVERVIEW

We are considering this concept because Infrastructure Supported was widely seen as probably the best answer for distribution of intelligence, and there was a desire to have many concepts exploring this part of the design space. What distinguishes this concept from the other Infrastructure Supported Free Agent on Dedicated Lanes concepts is that this is the only one which supports mixed classes.

It is accomplished in this version using differential GPS between vehicles, along with passive markings on the roadway, and using a significant bandwidth vehicle to vehicle communications wireless LAN. This version puts significant intelligence in the vehicles.

9.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

Prior to the generation of this concept, the AHS team developed a set of six dimensions, and selected points within the resulting space of options to be fleshed out as concepts. Where this concept falls on these dimensions is mentioned below.

9.2.1 Infrastructure Supported

Infrastructure support primarily consists of the GPS signal and passive markings on the roadway. Other infrastructure support could include roadside beacons (using the vehicle-to-vehicle communications protocol) and special GPS support such as Pseudolites, or local (regional) GPS Beacons, as local options.

All the infrastructure support is not directed to specific vehicles, except during check in.

This particular concept has been designed with very substantial vehicle-to-vehicle communications bandwidth. The inter-operations of these vehicles will somewhat resemble a Cooperative concept.

9.2.2 Free Agent

Vehicles travel independently as individual units, coordinating with other vehicles through their shared information.

It is plausible that this concept might offer an upgrade path to a more advanced system that would support platooning.

9.2.3 Dedicated Lanes With Continuous Physical Barrier

This concept presumes a continuous physical barrier, such as a Jersey barrier, between the AHS lanes and the non-AHS lanes. This minimizes the need for AHS vehicles to interact with non-AHS vehicles.

The specific concept description in this document might be easily modified to accommodate a less strongly segregated AHS.

9.2.4 Mixed Vehicle Classes in Lanes

This concept can accommodate multiple vehicle classes (e.g., cars and trucks) in the same lane. Non-Mixed class lanes may be specified as a local option.

9.2.5 Dedicated Entry and Exit

Entry and exit to AHS is controlled through physically isolated, dedicated lanes, with physical control of individual entering vehicles. This supports “Dedicated Lanes With Continuous Physical Barriers” in minimizing the need for AHS vehicles to interact with non-AHS vehicles. The entry facilities will function properly to politely prohibit non-AHS vehicles from entering the AHS roadway.

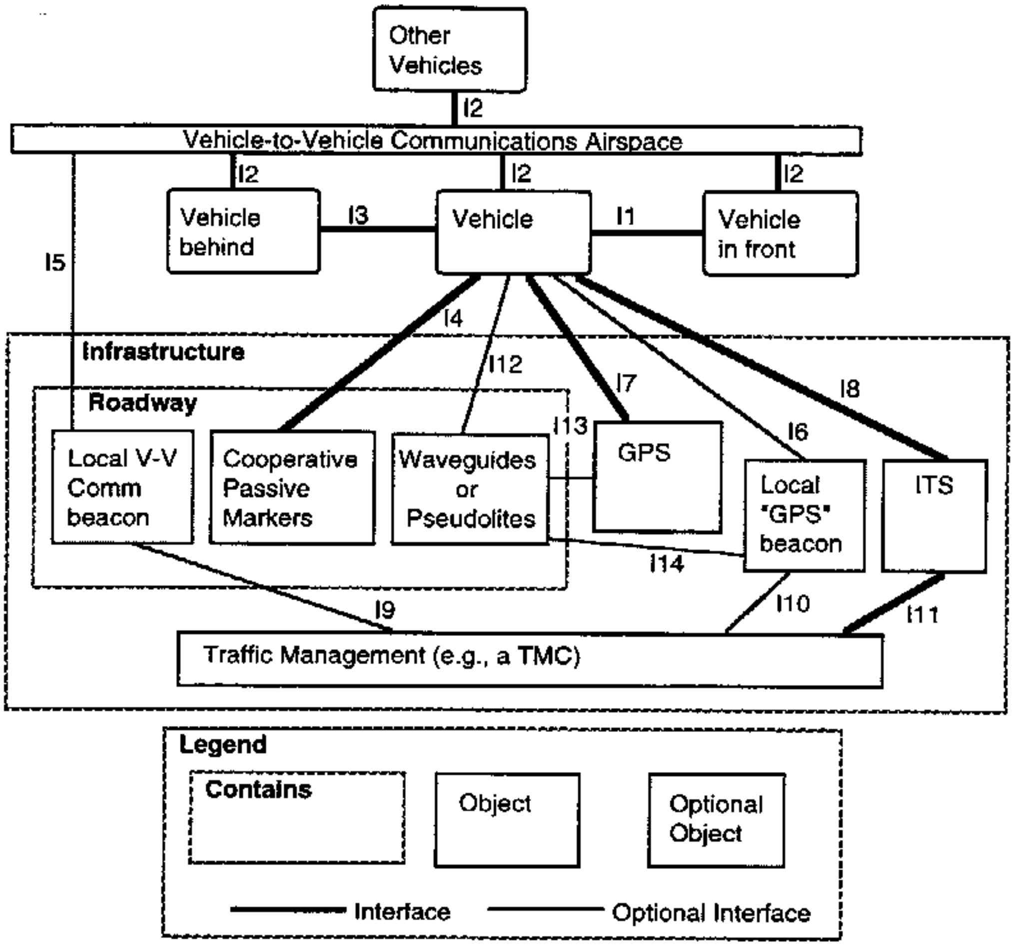

Figure H.9.2-1.

As a local option, there may be AHS entries and exits into specific areas other than into local roadways (e.g., intermodal parking, regional attraction parking, AHS-customer "truck stops," etc.).

The specific concept description in this document might be feasibly modified to accommodate a less strongly segregated AHS.

9.2.6 Automatic Sensing and Avoidance

Vehicles, both individually using on-board sensors, and cooperatively, passing information, are responsible to sensing obstacles and hazards. The vehicles then maneuver (where possible) under automated self control to avoid these obstacles and hazards. As a local option, a section of road could have a sensor suite deployed to monitor for obstacles and hazards, and were detected, inform vehicles using the vehicle-to-vehicle communications protocol.

9.3 OPERATIONAL CONCEPT

AHS vehicles enter and exit the system on dedicated transition lanes, going through check-in via communications with a local beacon, the local traffic, or on its own if entering at an isolated entry with no traffic nearby.

The vehicle receives GPS data, and communicates with vehicles around it. This communication includes passing GPS data for differential GPS between vehicles, allowing the estimation of inter-vehicle distances. The vehicle also senses the distance to the next vehicle. This all allows the maintenance of a comprehensive map of the relative positions and velocities of vehicles around each vehicle. Direct sensing of the passive beacons also allows very accurate absolute positioning.

The vehicle then drives under fully automated control until it approaches the driver's desired exit. At that point, it tests the driver, and if the driver passes, enters the dedicated exit transition lane, where control is handed off to the driver.

9.4 SYSTEM DIAGRAM

Figure H.9.2-1 shows the vehicles and infrastructure and data flows among them, including sensing.

9.4.1 Interface 1 (I1)—Vehicle to Vehicle in Front

Vehicle directly senses the cooperative passive markers on the vehicle in front to measure relative positions. The range should be brick-wall stopping distance (if possible), the update rate should be on the order of at least 10/sec, the information should include very accurate distance measurements, and the ability to infer or measure relative speeds and relative accelerations.

9.4.2 Interface 2 (I2)—Vehicle to Other Vehicle

Pure communications interface. Protocol needs definition, but is should be a very short-range RF system like a wireless LAN. Primary communications load is communication of differential GPS data with other vehicles. Other vehicle-to-vehicle comm includes situational information, and maneuver requests such as slowing to create a gap for merging.

I do not have the actually GPS message description, but ~50 bits is a good guess. Cars need to transmit GPS data from 4 satellites, and will have other data (e.g., speed, direction, obstacles seen), for say

In the worst update rate case, a large number of vehicles would be maneuvering at high speeds at short ranges, with frequent turns and speed changes. (This worst case might be the response of a huge high-speed traffic flow following the catastrophic failure of a vehicle in its midst.) In this case

Broadcast range should be variable. The protocol must support ranges slightly greater than the longest brick-wall-stopping distance of any vehicle that will travel on the AHS. Call that 100 m. It also must support communication with several vehicles to allow triangulation of lengths. A minimum broadcast range of 15 m should keep the worst case communications traffic load below 50 vehicles.

The required bandwidth estimate is then:

> { (4 satellites x 50 bits/satellite + 50 "other" bits)/ transmission x 10 transmissions/ (second • vehicle) x 50 vehicles } x (100% + 100 % margin) = 250, 000 bits/second

In ordinary situations, this bandwidth could be used for other messages.

Other requirements or features. The communications protocol must support multiple overlapping groups (e.g., A & B are in range of each other and talk, B & C are in range of each other and talk, but A & C are not in range of each other and cannot talk. A & C cannot have their signals step on each other, since B won't be able to hear them both. Also, A & C cannot coordinate directly).

The default approach is to have every vehicle transmit its most recent GPS, at the point when it must broadcast. An alternate approach is for the local vehicles to set up a "clock", and send out their GPS information at that last clock time. The first approach is simpler, but the second approach allows the vehicles to directly calculate intervehicle distances between pairs of vehicles other than themselves (which then will support triangulation, and better traffic picture coherence).

9.4.3 Interface 3 (I3)—Vehicle to Vehicle Behind

The exact mirror image of interface I1. The vehicle is responsible for having the appropriate cooperative passive markers for easy sensing by the vehicle behind it.

9.4.4 Interface 4 (I4)—Vehicle to Roadway Markers

Vehicle sensors directly observe passive roadway markers, determining their positions, and thus, roadway boundaries and lanes. These markers would be read at a very high rate (10+/sec) to high positional accuracy (~99%). The range would be on the order of meters, although the lane markings could be center-line, read as they are driven over.

9.4.5 Interface 5 (I5)—Local Vehicle-to-Vehicle Communications Beacon

As a local option, roadside beacons may be deployed to communicate with vehicles. This interface is identical interface protocol to I2; the beacons are perceived by the vehicles as stationary "vehicles" that also can pass information about the immediate surroundings, including messages from the TMC, hazards observed by infrastructure sensors, and local roadway geometry, as well as differential GPS data. The total data rate supported ~5000 bps (broadcast).

9.4.6 Interface 6 (I6)—Local "GPS" Beacon to Vehicle

It is an option for local region to deploy a local "GPS" beacon. This is a transmitter at a fixed point, sending out a signal as if it were a GPS satellite. The likely range would be 10-50 miles. This should allow higher precision in denser traffic areas, and could also be positioned to avoid some GPS signal blockage issues. It might be more accurate than GPS, which is forced to transmit a degraded mode for military reasons.

Also, such Local "GPS" Beacons could be considered in those cases where local geography (e.g., urban "canyons" between skyscrapers) does not permit adequate receipt of GPS satellite signals from GPS satellites, and the use of pseudolites (see 4.12) is more difficult.

9.4.7 Interface 7 (I7)—ITS to Vehicle

The Intelligent Transportation System services, provided as transparently as ITS would serve non-automated vehicles. The content, general message size, update rate, range, bandwidth, and other requirements or features would be as appropriate to match the National ITS Architecture program.

9.4.8 Interface 8 (I8)—GPS to Vehicle

The standard interface between GPS and a GPS receiver. The vehicle receives the GPS signal, with no return signal. That signal primarily consists of a very accurate clock time. I don't know the message size, but I'm guessing ~50 bits/ message, at a high update rate. The range is from the GPS satellites, in high Earth orbit.

9.4.9 Interface 9 (I9)—Traffic Management to Local Vehicle-to-Vehicle Communications Beacon

This link passes information to beacons for their control, and to pass on to vehicles. The beacon can also send information to traffic management on the ongoing status of traffic in it's region, along with special messages provided by vehicles which pass (e.g. "there is a lane-closing obstacle 1/2 mile back in lane #2").

This is a long-range link (1-100 miles), possibly carries by land-lines.

9.4.10 Interface 10 (I10)—Traffic Management to Local "GPS" Beacon

A very low bandwidth connection. May include emergency shutdown of the local "GPS" beacon for emergency reasons. May not exist even when Local "GPS" Beacon is deployed.

9.4.11 Interface 11 (I11)—Traffic Management to ITS

The standard interface between traffic management and the rest of ITS, supplemented with information required to support AHS.

9.4.12 Interface 12 (I12)—Pseudolites to Vehicle

In some locations, line-of-sight to GPS may be blocked. To compensate, the roadway could have devices to carry GPS signals from GPS satellites around the obstruction. These are sometimes called Pseudolites. The interface is identical to I8 (GPS to vehicle). The expected range, however, is very short, as the Pseuduolite is functioning in small areas (e.g., within a tunnel, between a few buildings).

9.4.13 Interface 13 (I13)—GPS to Pseudolites

This is merely the Pseudolite receiving the GPS signal, so that it can carry that signal, or to support the Pseudolite in generating its own signal. Note, the pseudolites may need extended antennas in some locations to reach Line of site to the GPS satellites.

9.4.14 Interface 14 (I14)—Local "GPS" Beacon to Pseudolites

Similar to I13, this interface is merely the receipt by a Pseudolite of the GPS signal sent out by any Local "GPS" Beacon in the region.

9.5 FUNCTIONAL ALLOCATION

9.5.1 Check-In

AHS vehicles enter and exit the system on dedicated transition lanes, going through check-in via communications with a local beacon, the local traffic, or on its own if entering at an isolated entry with no traffic nearby.

Check-in would ordinarily performed jointly by the infrastructure and the vehicle. A Local Vehicle-to-Vehicle Communications Beacon will control a particular entrance. While driving in the transition lane, the vehicle will establish communications with the beacon, and the beacon will check the vehicle's signal, including its ability to receive and properly process GPS. As a local option the beacon might also pose one or more tests to the vehicle's processor. The vehicle will also go thought a built-in test of its systems, to assure that they are functioning properly. If all of this is successful, the beacon will approve the vehicle for entry. If not, then the beacon will direct the vehicle to an "entry denied" lane, which will bring the vehicle back into manual traffic.

As a local option the Beacon might control a physical barrier to help make sure that unapproved vehicles do not enter the system.

As a local option, there might be an uncontrolled transition lane. In this implementation, the vehicle would establish communications with other vehicles already in the AHS. These vehicles would conduct a simple check-in procedure with the entering vehicle, to assure that it is acting compatibly. In this local option, if there is no nearby traffic, there is no formal check-in, and the vehicle simply enters and drives on the AHS.

9.5.2 Transition from manual to automatic control

This function is performed by the vehicle and the driver, while the vehicle is going through check in. The driver must command the vehicle go to automatic driving, before the vehicle will initiate check-in. If approved, the vehicle will announce that success, and that it is taking over driving control. It will then do so, and drive the vehicle into traffic.

During check-in, and as desired thereafter, the driver must inform the vehicle of the desired exit.

If check-in is refused, the vehicle will inform the driver, and remind the driver do maintain manual control, and exit the AHS roadway.

9.5.3 Automated driving

Automated driving is controlled by individual vehicles, using information provided by other vehicles, and a supporting infrastructure.

9.5.3.1. Sensing of roadway, vehicles, and obstructions

The vehicles carry inexpensive sensors which observe coded, cooperative passive markings on the other vehicles and the roadway. Deliberate obstructions (e.g., traffic cones) have their own machine readable passive markings.

The physically isolated roadway is meant in part to minimize unauthorized obstructions. In general, obstructions are sensed when the sensors sense something that is not coded with a proper passive marking, or which is not behaving as something with that passive marking should. Any such item is taken as an obstruction to avoid. Vehicles alert each other of obstructions they see. Vehicles use the ITS Mayday function to call in any particularly large on long-standing obstruction to local authorities. In an immediate area with some particular issue of sudden obstructions, an infrastructure sensor can be deployed, and broadcast the location of any obstructions sensed, using the vehicle-to-vehicle communications protocol.

Vehicles also sense each other indirectly through mutual communication. All the vehicles broadcast their GPS data, and differential GPS between vehicles allows them to develop dynamic maps of the dynamic traffic structure in their immediate vicinity. As part of this indirect sensing of other vehicles, messages would include (at a very low rate) information on the characteristics of the vehicles (dimensions, brick-wall stopping distance, preferred braking rate, preferred acceleration, etc.).

As a local option, localities may establish a stationary, GPS-like broadcast. This would be a fixed beacon sending out signals must like a GPS satellite. The signals would be used by vehicles to support more precise relative positioning and traffic navigation. It is anticipated that this could be an attractive option to support denser traffic flow in urban areas.

As a local option, localities may establish roadways with regular beacons. These beacons would act like stationary vehicles, transmitting their local GPS information, along with the geometry of the local roadway. This would allow the vehicles, which already calculate there relative positions to also determine their position relative to the roadway, and thus, keep within their lanes. Roadways certified to this higher level could be authorized to carry less expensive vehicles which rely solely on communications and forego sensors.

To the extent any vehicles have other sensors (e.g., for adaptive cruise control on non-automated highways), information from those sensors are also broadcast to the local community of vehicles.

One concept would be to provide some continuous, machine-readable pattern, the interruption of which would be taken as an obstacle.

9.5.3.2. Lane and headway keeping

Vehicles use sensors and vehicle-to-vehicle communication to determine their position within lanes and their headway. They maneuver under automated self-control to stay in lanes and maintain headway.

Each vehicle communicates back its brick-wall stopping distance. Vehicles maintain headway so that within their own brick-wall stopping distance they will not hit a vehicle which suddenly stops within its brick-wall stopping distance, plus a margin. If a vehicle gets closer than brick-wall stopping distance to where another vehicle could stop (which is not supposed to happen), then it's "brick-wall stopping distance" is calculated to be the distance until it would hit the next vehicle because of that vehicle's brick wall stopping distance.

As a local option, the infrastructure may broadcast driving parameters for vehicles to follow in order to smooth out roadway conditions, or otherwise optimize traffic flow. Example parameters include preferred speed, allowed spacing margin, preferred acceleration rate, preferred deceleration rate, nominal headway correction factor, and restricted class lanes.

9.5.3.3. Detection of hazards

When hazards exist they should ordinarily be detected by the vehicle's on-board sensors, or communicated to the vehicle by other vehicles.

In an immediate area with some particular issue of sudden hazards, an infrastructure sensor can be deployed, and broadcast the location of any hazards sensed, using the vehicle-to-vehicle communications protocol. Less elaborately, local officials could deploy a "virtual traffic barrier" that used the vehicle-to-vehicle communications protocol to inform other vehicles of an area of roadway to avoid, that was programmed into the device.

The ultimate detection of hazards occurs when a vehicle strikes a hazard. As part of the vehicle's panic response, it immediately broadcasts its position and any understanding of the hazard it struck.

9.5.3.4. Maneuver planning (normal or emergency)

Normal maneuver planning is distributed between vehicles. If a vehicle wishes to merge right, and there is adequate room, then it announces the maneuver, and merges. If there is not room, then it requests a space. Adjacent vehicles open up a gap when safe, and the vehicle merges into that gap.

Stereotyped emergency responses are pre-programmed into the vehicle, and defined in the communications specification. This allows a vehicle responding to an emergency to announce their responses using very little bandwidth, and rapidly coordinate during the emergency maneuvers.

The system might be designed so that vehicles negotiate various contingency plans as part of their communications overhead, and thus, are in a position to execute such plans if suddenly needed. The set of basic contingency plans might be incorporated into the AHS standard, making this negotiation overhead very small.

9.5.3.5. Maneuver execution

Maneuvers are executed by the vehicle, which uses its on-board processor and actuators to control the throttle, steering position, etc.

9.5.4 Transition From Automatic to Manual Control

As the driver's requested exit approaches, the vehicle alerts the driver, and asks for an acknowledgment.

9.5.5 Check-Out

The check-out function is performed in the vehicle, in cooperating with the human. This function occurs once on-board navigation decides that the desired exit is approaching. It could also start if the vehicle receives operator requests to exit the automated system. The vehicle then initiates the check-out process. This function verifies the ability to perform the transition from automated to manual control safely (including the driver's ability and readiness to retake control) and maneuvers to the exit transition lane. The vehicle will maneuver through the transition lane and the operator will be resume manual control.

Vehicles which fail the check-out process will remain in automated control and will be moved to a safe location. The driver will be informed of the failure of the check-out.

9.5.6 Flow Control

To the extent there is flow control, it is managed by the infrastructure.

On long travel distances where there is only one lane, perhaps on interstates for example, the automated roadway would periodically expand to two lanes to allow passing.

9.5.7 Malfunction Management

Vehicles have built in test, and continually assess the abilities of vehicle systems. The on-board process takes this further by using trend analysis to predict when a failure might occur. When a malfunction is expected, the driver is warned, and the vehicle is ordinarily directed out of the AHS system. When an on-board failure is detected, the vehicle goes through a pre-programmed failure response, which depends upon the nature of the failure detected.

9.5.8 Handling of Emergencies

Vehicles respond to emergencies, generally using pre-programmed emergency responses (including "Brake hard to a stop"). When a vehicle senses an emergency, it broadcasts that fact. Note: the Communications protocol may have to change modes during an emergency.

Vehicles might continually negotiate contingency plans for various emergencies using the slack communications bandwidth during ordinary operations

9.6 IMPLEMENTATIONS

Following is a potential implementation of the concept, specifically what will be in the vehicle, the roadside and the AHS TOC, above and beyond the standard and ITS.

9.6.1 Vehicle

- Forward looking sensor
- Passive marker sensor (May be the forward looking sensor)
- Differential GPS (receiver and communications)
- Transmitter/Receiver integrated with processor (Short range RF vehicle-to-vehicle communications)
- [Other sensors, optionally]

It might be argued that a no-sensor version of this concept would be feasible, using roadside beacons to convey road geometry information. In this implementation, vehicles would not require forward looking sensors, nor passive marker sensors.

9.6.2 Infrastructure

Passive markers marking the edges of the roadway, possibly the lanes, and maybe other vehicles. If the edges of the roadway are marked, they must be coded to indicate the distance to the nearest lane, the default lane width, and the default number of lanes.

The roadway must also have continuous physical separation. This can be a specially-built road, or by modifying existing roadway, for example using Jersey barriers.

9.6.2.1. <u>Rural Highway</u>

Long section of highway, a single lane wide, separated from main road by Jersey Barriers, or poured permanent barriers. Entry/Exit lanes would be many miles apart, and the Rural AHS would be intended for long travels, both rural to distant rural locations, and inter-urban trips.

9.6.2.2. <u>Urban Region</u>

Dedicated lanes on existing urban highways, with roadside markers, and dedicated entry/exit locations, spaced more widely than regular highway entrances and exits.

9.6.3 Deployment

Since the roadway has the large per mile expense of total physical isolation (even if just achieved by deploying continuous Jersey barriers), the minimal deployable roadway is probably in an urban area.

It is taken to be a dedicated lane on a commute corridor, isolated by Jersey barriers, with city transit along that corridor fitted for AHS use, and AHS capability available as a factory option and/or as an aftermarket option for private vehicles. Equipped private vehicles are allowed on the AHS lane.

Given this minimal deployment, incentives are as follows. Those who commute along the modified corridor have an incentive to buy or retrofit a vehicle to operate in the AHS system. This will earn the driver a "brain-off" commute, and a probably a much faster commute. The local transit authority has some incentive to extend the AHS lanes to more of the local transit lines, and to concurrently transition its fleet to AHS capable vehicles. This earns the greater use and more flexibility with its AHS-capable vehicles, faster transit runs (hopefullydrawing more customers), and reduced accident risk with a given driver skill level. It might reduce driver costs, or not, depending on union rules, and it might increase maintenance costs.

If the local base of AHS-capable vehicles builds up, this provides added incentive to build infrastructure.

9.7 GENERAL ISSUES AND CONSIDERATIONS

The questions listed in the outline are answered below.

What degree of automation is there in the navigation function?

The navigation function is done fully automatically by the vehicle, which must know the highway map at a gross level, and the desired exit.

What are the obvious failure modes for the concept?

GPS goes down. Vehicle-to-Vehicle Communications Airspace is jammed.

What major systems or subsystems can back one another up in case of failure?

Sensors and roadway markers can back up GPS/Comm-based navigation (and vice versa). Sensors on the whole set of vehicles can back up any one vehicle's sensor which goes out.

Under what circumstances (if any) is control passed to the driver?

Control is passed to the driver during check out. In the event of a total, system-wide shut-down (e.g., GPS goes down), control would eventually be passed to the driver. In general, the driver cannot take control during travel when in substantial traffic. a driver always has control, however, to the extent of being able to specify a new exit (including the next exit coming up).

How does the system sense limited visibility, or ice, water or snow on the roadway; what does it do with this information?

There may be ITS services, or sensors in the road which inform the infrastructure, either of which could inform the vehicles.

Vehicles sense traction, and thus, have some sense of poor road conditions, and can pass that information upstream. Limited sensor visibility is directly sensed by the inability to see the roadway markers. Note, this would be taken as an obstacle, and substantially shut the road down. (This suggests using an all-weather sensor, such as radar.)

What speed(s) would typical users travel at? How tailorable is this?

The maximum user speed is an open design issue, but could be very high. Once the maximum user speed is set, lower speed limits would be possible as local options. This would be very tailorable with Local Vehicle-to-Vehicle Communications Beacons. Speed limits could also be put in machine-readable format and read from passive markers, but the code would lead to a quantization limit of only a finite number of speeds.

What enhanced functions would a vehicle from this concept be able to perform on a conventional roadway?

These vehicles could always do adaptive cruise control when following other AHS vehicles. The vehicle specification could be extended so that these vehicles could always do adaptive cruise control. On roadways with the passive lane markers, the could also do automated lane keeping. (Note: these passive markers might be traditional reflective lane markers.)

When more than one of these vehicles are traveling within the vehicle-to-vehicle communications network length, they could communicate with each other. This communication could include local traffic patterns, and hazard, roadway and other information that would improve the safety of traveling. This network could carry many other possible secondary signals (e.g., Pong).

What assistance would this system provide to the traveler who is also using other modes (bus, rail, subway) of transportation?

Buses could run on the AHS lanes, gaining the same travel time benefits. AHS entry/exit points could be collocated with multi-mode transition points (airports, train terminals, park and rides, etc.). Greater throughput on AHS might slightly reduce the traveler load on other travel modes.

What additional services would the concept provide for freight carriers?

Much greater detail of truck activities could be monitored via ITS fleet management. The AHS equipment could also provide safety sensors (e.g., brake warning/adaptive cruise control) on non-automated highways. Convoys (groups of trucks traveling together) could interlink their traffic surrounds while on non-automated roads, which should greatly increase their aggregate safety.

What features of this concept will most contribute to increasing throughput over the present system?

The very detailed information on very local traffic, provided via redundant vehicle sources, will allow the vehicles to travel rapidly and at higher densities, while still maintaining safety.

What features of this concept will most contribute to increasing safety over the present system?

Enhanced situational awareness of surrounding traffic, including very rapid recognition of sudden changes in non-Line-of-Site vehicles.

What features of this concept will most contribute to making it cost-effective?

The vehicles exploit the ongoing historical trend in decreasing cost for performance.

What will be the required vehicle maintenance?

Repair/replacement of vehicle-to-vehicle communications and processor (should be very rare, solid-state device).

Regular maintenance of control/actuators.

Regular maintenance of forward looking sensor.

Continual inspection in use of AHS in vehicle equipment.

What will be the required infrastructure maintenance?

Continual maintenance on passive markers, replacing damaged/worn ones.

Pseudolites repair/replace damaged Pseudolites. (Including regular examination schedule, which can be drive-through.)

Roadside V-V Beacons, repair/replaced damage. Remote test. (Including regular examination schedule, which can be drive-through.)

General maintenance on any local "GPS" beacons.

What does this concept assume in the way of support from the external world (e.g., enforcement, safety checks, ...)?

It assumes periodic equipment checks on the vehicle. More significantly, it assumes that where a failure in use is identified, the vehicle is identified, and given a "fix it ticket." This ideally occurs primarily at Check-In.

Do you see any special categories of induced demand (i.e., are there particular classes of users who would take particular advantage of this AHS concept, increasing traffic from that class of user)?

Induced demand, comparable to that demand which would be induced if the highway was simply widened to the same level of capacity that AHS will offer. Special categories of induced demand are not currently foreseen.

10. CONCEPT 8B: ISACADO

This is a description of a design concept for the Automated Highway System. This particular concept is defined by:

- an infrastructure supported intelligence distribution,
- free agent vehicle separation architecture,
- dedicated lanes with continuous physical barriers,
- vehicles of the same class in a AHS lane,
- with dedicated entry/exit lanes, and
- comprehensive obstacle detection and avoidance.

This concept is given the mnemonic name *Isacado*.

10.1 OVERVIEW

The Isacado concept provides an outstanding solution for many urban traffic systems. Excellent throughput and a high level of safety is realized, while allowing regional specific implementation tailoring.

With dedicated lanes coupled to dedicated entry/exit access for single classes of vehicles, Isacado provides outstanding throughput. Vehicle flow can be optimized to the acceleration and braking characteristics of the single vehicle class, whether it be two axle automobiles; heavier, two axle busses or trucks; or heavy articulated vehicles.

The physical barriers, dedicated access, homogenous vehicle class, and obstacle sense and avoid approach provided by Isacado is the optimum combination of design architectures for safety. Physical barriers and dedicated access inhibit rogue vehicles and reduce the probability of random obstacles in the AHS lanes. The statistical distribution of vehicle control and responses, especially braking and steering, is small since all vehicles in a lane are of the same class. And finally, any obstacles that do encroach on the traffic flow are sensed and avoided without driver intervention.

The Isacado concept is adaptable to the urban traffic needs. Similar in design to many of the high occupancy vehicle (HOV) lanes used everyday in large cities, Isacado is a natural evolution. Isacado can be customized by the local implementing agency for time of day and direction of travel. Since the command, communication, and control intelligence (C^3I) is infrastructure supported, the implementation costs are lower than other infrastructure managed or infrastructure controlled designs.

10.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

The six concept dimensions are explored in the following paragraphs.

10.2.1 Distribution of Intelligence

The Isacado concept is based on cooperative vehicle intelligence supplemented by infrastructure information. The individual vehicles maintain lane keeping control; cooperatively, vehicles determine and maintain safe headway distance and perform merge maneuvers. The vehicles are provided traffic information, such as:

- congestion—slower traffic from mile 215 through mile 219, maximum speed 80 km/h;
- exit 211 at capacity, alternate exit 213 is open;
- lane damage at mile 212.5, slow to not greater than 70 km/h for bump;

10.2.2 Separation Policy

The Isacado concept is a “free agent” architecture. Safe headway spacing is a function of the class of vehicles in the lane, braking distance (a function of velocity and road condition), and the frequency, resolution, and accuracy of vehicle to vehicle communication (if any). The headway between vehicles can be minimized if the vehicles communicate with each other, rather than relying solely on sensing distance to the preceding vehicle.

10.2.3 Mixing of AHS and Non-AHS Vehicles in Same Lane

The Isacado concept is predicated on maintaining complete physical separation of non-AHS vehicles from the AHS vehicles. This can be satisfied by:

- continuous physical barriers, e.g. jersey barriers;
- physically separated roadway, e.g. elevated or below grade similar to some HOV lanes;
- specifically dedicated AHS roadway, e.g. new roadbed constructed in newly acquired or existing right-of-way, or dedication of existing roadway as an AHS highway.

10.2.4 Mixing of Vehicle Classes in a Lane

The Isacado concept is predicated on a single class of vehicles in a lane. Individual lanes must be provided to accommodate two or more classes of vehicles (traveling at the same time). The selection of which class, or classes, of vehicles to accommodate is a regional specific option.

10.2.5 Entry/Exit

Entry and exit to and from the AHS travel lanes for the Isacado concept is via dedicated lanes. The entry lanes include the vehicle inspection operation. In providing for higher throughput, increased safety, reduced emissions, and a favorable return on investment, the regional implementing agency will be encouraged to strategically locate entrance and exit lanes. It is expected that in order to make the AHS operate smoothly, the distance between access lanes cannot be as short as currently exists on some urban “expressways”, where some entrance/exits are separated by less than two kilometers.

10.2.6 Obstacle

The vehicles will sense and avoid hazardous obstacles. Each vehicle will sense the presence of obstacles, complemented by the cooperative communication between the vehicles. Additionally, if a change in traffic conditions occurs as a result of obstacle avoidance maneuvers, the supporting infrastructure intelligence will sense and inform approaching vehicles. However, the likelihood of encountering dangerous obstacles is relatively low for the Isacado concept, (as compared to many other concepts) given the physical segregation of traffic.

10.3 OPERATIONAL CONCEPT

The Isacado concept, an excellent bias of intelligence distribution (most intelligence within the vehicles), coupled with the closed nature of the system, is a deployable, operable system. The system is defined in three possible conditions: normal, degraded, or failed.

10.3.1 Normal Operating Condition

The Isacado design would operate almost exclusively in the normal condition.

10.3.1.1. Access

The Isacado AHS design concept provides safe and efficient traffic flow. Entrance lanes are instrumented and gated to inspect and permit, or prohibit, access to the AHS travel lanes. The driver passes gate one, entering a portal analogous to a man-trap. As the vehicle travels toward gate two, vehicle-infrastructure cooperative telemetry verifies the vehicle equipment meets the minimum operation conditions (sensors, communication, and controls working properly). Given satisfactory results to the interrogation, vehicle control is assumed by the AHS and the vehicle passes gate two and merged into the AHS traffic. If the vehicle fails the interrogation, the driver is advised that entrance to the AHS is denied (and given a reason), and instructed to drive the vehicle out of the access system (via a posted egress). Note that the gate designs must prevent vehicle passage; the specific solution could be something as unobtrusive as the tire puncture devices installed at car rental agencies and parking garages.

10.3.1.2. Exit

The Isacado design provides a simple and efficient exit operation. Given an indication from the driver of an exit preference, the vehicle will be guided from the travel lane to the dedicated exit lane—unless the vehicle has received a notification from the infrastructure that the exit is not available. The infrastructure monitors the travel and exit lane conditions and advises the vehicles of the availability of exits. Once in the exit lane, the vehicle enters a portal, similar to the access system described above; whereas for the exit portal, the release from the system is predicated by confirmation of the driver's ability to resume vehicle control. If the driver does not pass a competency screening, the AHS guides the car to a wayside station, and notifies highway authorities.

10.3.1.3. Normal Travel

> *"The building blocks of the Isacado concept are sufficiently flexible and modular to become the cornerstone of the national architecture. The implementation of the concept elements can be tailored to regional needs—while still maintaining configuration commonality."*

The vehicle, having been certified for the AHS and under autonomous control, is merged into the AHS travel lane. Through cooperative intelligence between the merging vehicle and the traveling vehicles (if any are in the vicinity coincident with the merge event), the vehicle accelerates and steers to a safe position between traffic in the travel lane. The vehicle travels along the highway as defined by the cooperative intelligence process, supplemented by traffic and roadway information through the infrastructure supported architecture. The vehicles, being of the same class, in a physically separated lane, can move at relatively high speeds, as compared to other design concepts. The speed limitation is driven by the class of vehicles, their performance characteristics (efficient operating speed, braking distances, handling characteristics), the roadway condition (type of pavement, condition of pavement, turn radius and bank), weather (rain, snow, wind), and system volume (number of vehicles, spacing between vehicles).

Incidences along the Isacado AHS are extremely rare. The high degree of containment: physical barriers separating the AHS traffic from other lanes, all vehicles cooperating, supported by infrastructure data, and all vehicles being with a class; reduces the likelihood of accidents to near zero.

10.3.2 Degraded AHS Condition

In the event of extreme weather, high congestion, roadway surface problems, vehicle accident, or AHS subsystem malfunctions, the AHS operates in a degraded mode. This mode may result in less than optimum throughput, and may require some driver participation. Note that since Isacado is an infrastructure *supported* design, and therefore not dependent on communication through the infrastructure for vehicle control, the likelihood of a degraded AHS as a result of an AHS subsystem or component malfunction is near zero (and may actually be shown to be zero, after design is complete and analyzed).

10.3.3 Failed AHS Condition

In the event of natural disaster, lane blockage, AHS failure, or other extreme event, the AHS will bring the vehicles to a safe transition to the driver. The driver may be instructed to exit the system or given some option to continue under manual control, depending on the nature of the problem. Note again, that since Isacado is an infrastructure *supported* design, and therefore not dependent on communication through the infrastructure for vehicle control, the likelihood of a failed AHS as a result of an AHS subsystem or component failure is near zero (and may actually be shown to be zero, after design is complete and analyzed).

10.4 FUNCTIONAL ALLOCATION

Table H.10.4-I defines the allocation of baseline functions for the Isacado design to vehicle, infrastructure, human, or combination. The allocation is presented as a distribution summing to 100%; i.e. check-in is shown to be allocated 75% to the vehicle, 25% to the infrastructure.

10.5 IMPLEMENTATIONS

In the Isacado design, the vehicles are sufficiently instrumented to cooperate a free agent separation policy supplemented with minimal infrastructure data.

10.5.1 Vehicle

The vehicle AHS subsystems include sensors to detect leading, following, and near adjacent vehicles and obstacles; processing logic to provide acceleration, braking and steering commands; communication equipment to communicate with neighboring vehicles, and actuation components to execute maneuver commands.

10.5.2 Infrastructure

The roadway supports vehicle lane keeping sensing with magnetic, optical, or other lane marking guides. The infrastructure also senses the access, exit and travel lane conditions to evaluate safe traveling speeds, prevent congestion, and support obstacle detection. The information is broadcast along the appropriate section of roadway; the vehicle operating systems respond accordingly.

10.5.2.1. Rural highway

The basic subsystems of the Isacado concept supports AHS applications in a rural environment. Assuming that rural agencies could not afford dedicated, physically segregated AHS travel and access lanes, the cooperative, fully instrumented vehicles required by the Isacado concept could also be operated in a rural environment where physical traffic segregation, both vehicle class and lane barriers, is nonexistent. The design concept dimensions for this application are:

- infrastructure supported, cooperative, or autonomous C^3I,
- free agent separation policy,
- full mixing of AHS and non-AHS traffic,
- transition lanes for entry and exit, and
- automatic sensing and avoidance of obstacles.

Note that the hand-off to/from manual and autonomous control and the merge process will differ from the Isacado concept for a rural application. Also, improvement in throughput will not be great; but, it is presumed that increasing throughput is not a significant need in a rural environment. The subsystems in the vehicles, supplemented by some form of lane marking guides, can provide substantial improvement in the safety and comfort of the rural traveler. The building blocks of the Isacado concept are sufficiently flexible and modular to become the cornerstone of the national architecture. The implementation of the concept elements can be tailored to regional needs—while still maintaining configuration commonality.

10.5.2.2. Urban Region

The Isacado concept is inherently envisioned for a urban region. Dedicated, physically separated access and travel lanes, providing segregated travel based on vehicle class, is a design specifically aimed at improving throughput and safety for congested urban traffic systems. The Isacado concept can be implemented for one, two, or more classes of vehicles. The regional transportation agency can designate lane use restrictions by time of day to certain classes of vehicles, or more likely, could establish AHS lanes for each class of vehicle warranted in a given area (e.g. one lane for busses, one for automobiles).

Table H.10.4-I. Allocation of Baseline Functions

Baseline Function	Vehicle (%)	Infrastructure (%)	Human (%)	Comment
Check-in	75	25		Infrastructure may facilitate inspection
Transition from Manual to Automatic	100			
Sensing of Roadway	100			
Sensing of Vehicles	70	30		Infrastructure senses vehicles to monitor traffic, facilitate flow control, identify availability of exits
Sensing of Obstacles	90	10		Infrastructure supports through monitoring traffic flow.
Lane Keeping	100			
Headway Keeping	100			Vehicles cooperative
Detection of Hazards				
Normal Maneuver Planning	100			Vehicles cooperative
Emergency Maneuver Planning	100			Vehicles cooperative
Maneuver Execution	100			
Transition from Automatic to Manual	90		10	Human acknowledges readiness to assume vehicle control
Check-Out	70	30		Infrastructure supports identification of availability of exits and may facilitate hand-off to driver.
Flow Control	50	50		
Malfunction Management	50	50		Infrastructure can broadcast advice to the vehicles

10.5.3 Deployment

The Isacado AHS design concept is a natural evolution for the traveling public, freight carriers, transit operators, and transportation management agencies. The vehicle subsystems are a natural evolution of the emerging intelligent vehicle components and the infrastructure requirements can be tailored to the region unique needs.

10.5.3.1. Vehicles

The vehicle is equipped with the necessary AHS instrumentation and controls. These vehicle unique components and subsystems are standard equipment on most automobiles, and readily available for buses and trucks. The ascendancy from cruise control, to adaptive cruise control, collision warning systems, et cetera, to the AHS equipment has been anticipated by the vehicle marketplace.

10.5.3.2. Infrastructure

The regional (national, state, county, urban authority) agencies modify their HOV lanes, where required, or establish new roadways, where desired, to provide dedicated entry/exit for physically segregated AHS traffic. The AHS lanes can be collocated with existing highways or constructed in other existing or acquired right-of -way.

10.6 GENERAL ISSUES AND CONSIDERATIONS

10.6.1 Implementation Flexibility

The Isacado concept, with dedicated lanes and access, does not have to be collocated to existing highway right-of-way. As in the Pittsburgh example, where railroad beds were acquired and converted for bus service, AHS lanes could be established in locations where right-of-way could be acquired for the lowest cost and would decrease motor vehicle congestion at existing highway and surface street intersections.

10.6.2 Cost

The Isacado concept has much lower infrastructure costs versus any infrastructure managed or infrastructure controlled designs. Given that the vehicles will need to provide sensors, processing and actuation systems for any concept, the additional costs for the infrastructure *supported* Isacado concept are relatively small: roadway sensors to monitor traffic, data processing equipment, and roadside beacons. Also, the Isacado concept could be modified to satisfy rural transportation needs (see 6.2.1), at even lower cost.

10.6.3 Freight Carriers

The Isacado design significantly reduces highway congestion, speeding the movement of freight. By improving traffic flow and reducing accidents, independent of whether a regional transportation agency has provided an AHS lane specifically for trailer truck rigs, the trip time will be improved for all highway users. And, of course, if a regional transportation agency dedicates a lane for freight class vehicles, trip time, trip time predictability and safety are improved; driver fatigue is eliminated.

11. CONCEPT 9: INFRASTRUCTURE SUPPORTED PLATOONING ON DEDICATED LANES, WITH MIXED CLASSES

11.1 OVERVIEW

Concept #9 considers *infrastructure supported platooning* of vehicles on the AHS while allowing *mixed vehicle classes in a lane*. The AHS and non-AHS lanes are separated with *continuous physical barriers* thereby requiring *dedicated entry-exit* facilities for the AHS lanes. We are considering this concept as it has the potential to achieve significant increase in capacity and safety of the AHS, by adding intelligence to both the vehicles and the roadside. Vehicles on the highway are organized into platoons. Platooning can be used to increase highway throughput, minimize the delta-velocity between vehicles within a platoon,[1] and use line-of-sight communication technology for control purposes. Infrastructure support allows for central coordination in the form of supervisory control.

11.1.1 Distinguishing features

- Use of platooning to increase throughput and minimize the delta-velocity between vehicles.
- Low level of reliance on infrastructure support. In the course of developing this concept we show that, to obtain the maximum benefits of infrastructure involvement, it is necessary to add a few special case features to the infrastructure other than those allowed by the definition of *infrastructure support*. The increased functionality will be required for two purposes: (i) entry/exit assistance which will be localized at the on-off ramps and (ii) vehicle specific communication capability used for dynamic routing and emergency notification.
- Distributed intelligence provides the opportunity to design an AHS that
  - optimizes system-wide performance via infrastructure-based controllers, and
  - provide for high levels of system availability: congestion due to faults/accidents avoided or eased through the use of infrastructure-based supervisory control.
- Infrastructure support can be used to broadcast safety-related information (e.g., reduced safe speed when it starts raining for example) to vehicles on specific sections of the automated highway.
- Dedicated lanes with continuous physical barriers mitigate hazards associated with intentional and unintentional mixing of vehicle types (i.e., manual and automated). However, continuous physical barriers also introduce hazards.
- Dedicated entry/exit ramps permits the hand-off-of-control in the presence of vehicles that are not equipped for automated vehicle control. If the queue of vehicles entering the dedicated entry ramp exceeds the ramp length, then the entry ramp will have a possibly negative impact on arterial roadway traffic flow. Similarly, if some interval of time the number of vehicles departing an automated lane via a dedicated exit ramp exceeds the capacity of the ramp, then some vehicles will be denied permission to exit until the next available exit ramp.

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[1] By minimizing the delta-velocity between vehicles, it is possible to reduce the severity of collisions between vehicles.

11.2 SELECTED ALTERNATIVES FROM EACH DIMENSION

11.2.1 Infrastructure Support

In this concept, infrastructure support is utilized to provide dynamic information to automated vehicles, such as:

- Suggesting lane changes and safe speeds.
- Announcing upcoming exit locations, lane drops, or hazards.
- Providing advice on entry/exit.

This type of infrastructure support is different from *infrastructure managed* since the information is relayed as a broadcast and is directed at platoon leaders.

Although the definition of *infrastructure supported* architecture rules out the possibility of communication to individual vehicle, it should be allowed for the purposes of emergency notification and dynamic routing so as to fully exploit the capabilities of roadside controllers. Relaying of vehicle specific information is also essential for achieving smooth entry/exit of automated vehicles.

11.2.1.1. Local Tailorability:

- Routing flexibility: Local authorities can influence the routing decisions taken by the infrastructure controller. For example, during construction or during a city marathon, local authorities can choose to close down sections of highway and divert traffic through other highways.
- Speed Control: Maximum speed limit can be set by local authority.
- Ramp Metering: Control over flow of vehicles entering AHS at various points.

11.2.2 Platooning With Mixed Vehicle Classes in a Lane

When automated vehicles of different classes are formed into platoons, the dynamics (e.g., maximum acceleration, rate of acceleration, speed, etc.) of each platoon is restricted by its slowest vehicle. From safety considerations, the intra-platoon separation should be picked according to the vehicle braking capability. Thus, passenger cars can be platted with a smaller intra-platoon separation than heavy vehicles such as trucks and buses. A mixed vehicle platoon may be created in following ways:

- Constant intra-platoon separation: The separation between any two successive vehicles is chosen to be the largest needed by a vehicle in the platoon. Introduction of one heavy vehicle in a platoon of passenger cars will increase intra-platoon separation thus, decreasing the throughput.
- Platoons with variable spacing: In this scheme, each vehicle follows its predecessor at the safe intra-platoon spacing for that vehicle. The performance of activities involving two platoons, such as joining and splitting of platoons as well as lane changes, will still be limited by the capabilities of the slower vehicles.

Local options for platooning are summarized as follows:

11.2.2.1. Local Tailorability (Platooning)

- Single vehicle platoons (free agents)
- Mixing of vehicle class in a platoon is allowed: This option can be executed in two ways as explained above. The choice of implementation should be left to the system designer rather than the local authorities.
- All vehicles in a platoon belong to a single class: results in homogeneous platoons. As the vehicles in a lane cannot exchange positions, formation of platoons of a single class depends on the percentage of vehicles of different class. With equal percentages for each class, this scheme can potentially degrade into free agents. A particular design may

force the vehicles to join the appropriate platoon at the time of entry requiring a large queuing space for each vehicle class at every on-ramp.

Regardless of the platooning strategy, the AHS throughput strongly depends on the types of vehicles present in each lane at the same time. Local authorities have the following choices in this regard.

11.2.2.2 Local Tailorability (Vehicle classes in a lane):

- Multiple vehicle classes per lane: The automated highway productivity can be significantly reduced due to a relatively small percentage of heavy vehicles such as trucks and buses. For example, a vehicle with reduced acceleration/braking capabilities and lower speed will slow down all the upstream vehicles in the same lane.
- Single vehicle class per lane: Needs at least two AHS lanes to implement this strategy and also provide access to AHS for all types of vehicle all the time. One lane can be reserved for passenger cars yielding high throughput and the other lane supporting heavy vehicles as well as passenger cars. In case of a single lane AHS, the AHS lane can be reserved for passenger cars during commute hour traffic and free for use by buses/trucks during off-peak hours. In fact, it can be exclusively used for trucks at night. The infrastructure support allows the local authorities to exercise such control depending on time of the day.

11.2.3 Dedicated Lanes with Continuous Physical Barriers

This option requires construction of barriers along the length of the AHS. The cost of construction will be offset by enhanced safety due to separation of AHS and non-AHS vehicles. This option with dedicated entry/exit allows the AHS operators to strictly enforce the above separation. Physical barriers also prevent accidents by manual vehicles spilling over to AHS and vice versa. On the other hand, the risk of collision with a stationary barrier requires tighter sensing and control of vehicle steering.

11.2.4 Dedicated Entry-Exit

This option results in a smooth flow of AHS and non-AHS traffic as the two streams use separate entry/exit facilities. However, the necessary construction of dedicated on/off ramps for AHS increases the cost of deployment and maintenance.

11.2.5 Automated Sensing Obstacles and Automatic Avoidance Maneuver If Possible

Humans are good at sensing of obstacles and making decisions but not as fast as an automated system. Automated sensing requires accurate (and probably costly) sensors to detect obstacles as small as a *shoe-box* with a minimal false alarm rate. These sensors should at least match the human sensing abilities. The design of an automated avoidance maneuver should at least match human intelligence.

Automated obstacle sensing and avoidance will be faster than its human counterpart and will eliminate some human driving errors, such as inattentiveness.

11.3 OPERATIONAL CONCEPT

Normal operation scenarios for this concept are as follows. The vehicle under manual control decides to enter the AHS by manually entering the dedicated AHS entry. At the beginning of the entry ramp the vehicle is checked into the AHS. The check-in can be done either manually or on-the-fly. In case of manual check-in, the driver is required to stop. The vehicle is then checked for AHS compatibility by the infrastructure and the vehicle monitoring systems. If this check is successful, then the vehicle is checked into the AHS. At this point the vehicle control systems take control of all the vehicle systems and sends a message requesting entry to the infrastructure. The infrastructure will have the capability to perform a ramp-metering type of function. Thus, based on overall system conditions it decides at some time to allow entry. Once permission is granted the vehicle moves towards the entrance of the highway. The vehicle has the capability to track velocity inputs, distance inputs and execute lane-change maneuvers. The vehicle then waits on the entrance ramp, and sends messages to the infrastructure requesting entry.

A feasible operational scenario for the entry process with minimal infrastructure involvement is as follows. The entry point infrastructure has detectors installed at a specified distance upstream from where the entering vehicle is waiting. These detectors determine the conditions in the entry zone. When the vehicle requests entry, the infrastructure checks the occupancy of the entry zone. If nothing is detected, the vehicle is allowed to enter. If a platoon is detected in the entry zone, the infrastructure has the means to sense the speed of the platoon and its distance from the entry point. If the speed and distance of the oncoming platoon allow safe entry, the infrastructure requests the platoon to allow entry. If the platoon acknowledges, it is required to decelerate to a specified entry speed. After the platoon receives confirmation from the oncoming platoon, it provides the waiting vehicle with its target speed and asks it to enter.

Once the vehicle enters the AHS by performing a successful entry maneuver, it decides, based on advice received from the infrastructure, whether it wishes to change into an inner lane. If so, the vehicle sends lane-change requests until a platoon communicates its willingness to admit the vehicle in front of it. The vehicle uses its sensors to detect if the minimum safe spacing and safe relative velocity with respect to the responding platoon exists in its target lane. If suitable conditions exist, it changes lanes. Otherwise, it co-ordinates with the adjacent lane platoon that has agreed to accept the vehicle in front of it. The assisting platoon slows down till the required gap becomes available. Then a lane-change maneuver is executed. If there is no platoon in the adjacent lane in the *safe lane change distance*, the vehicle changes lanes after confirming—through inter-vehicle communication—that no vehicle in the lane beyond the target lane (in case of a three lane AHS) wants to change in the same gap. The same process can be repeated again. If no further lane changes are required, the vehicle sensors are used to detect the presence of a platoon that is close enough ahead to join with. If such a platoon is detected, the vehicle, based on advice from the infrastructure may request a join maneuver. If the platoon ahead is not already in excess of the maximum platoon size broadcast by the infrastructure and if the platoon ahead is not already engaged in any other maneuver, the join maneuver is executed. Thus, the new vehicle accelerates to merge with the platoon ahead. If no such vehicle is detected within a specified range, the vehicle simply continues as a one car platoon. In this architecture, we allow each platoon to be engaged in only one maneuver at a time. This restriction is necessary to ensure basic safety while executing a maneuver. This ensures, for example, that during a join maneuver, another vehicle from an adjacent lane does not change lanes in between the two joining platoons. To maintain routing flexibility to individual vehicles, only free agents can change lanes in a multilane AHS. On the other hand, a follower in a platoon may exit without creating a separate platoon. The concept does allow lane change of an entire platoon in case of emergencies and faults. A decision to engage in a maneuver is taken by the leader of every platoon. The followers in a platoon can request their leaders to initiate a maneuver for them.

The infrastructure broadcasts approaching exits and advise vehicles to change lanes. For example, the infrastructure may suggest that vehicles in the innermost lane wishing to exit three exits downstream should execute one lane change maneuver. Since every vehicle knows its own exit, it processes the advice of the infrastructure and acts accordingly. The vehicle may also have autonomous capabilities to locate itself and take exit decisions. This is discussed further under degraded mode operation.

Once a vehicle decides to change lanes, it must check its platoon status. If it is in a platoon it must request a split. If it is a leader vehicle, it sends its split request to the vehicle immediately behind it. The vehicle behind reacts by assuming the role of platoon leader; it decelerates the entire platoon to create an inter-platoon gap. The original leader vehicle is now a one car platoon. If the vehicle was a follower vehicle, it must send its split request to the platoon leader who acknowledges the request by asking the vehicle to become a leader. Once the vehicle does so, it retards itself and all the vehicles behind it to create a safe inter-platoon gap. Thereafter it splits again like a platoon leader. Once the vehicle is a one-car platoon, it is allowed to request and execute lane change maneuvers. Platoons of larger size are not allowed to change lanes. Hereafter, lane changes proceed as above. Infrastructure based maneuver coordination, similar to entry maneuver is required for merging two streams of traffic.

Before discussing abnormal or degraded mode operation we review the functional capabilities of vehicle and infrastructure as assumed till this point. A vehicle is capable of tracking a given velocity input and tracking a longitudinal distance input that specifies its distance from the vehicle in front.[2] It is capable of sensing free spaces in adjacent lanes and executing automated lane change maneuvers. It is autonomous with respect to obstacle avoidance and detection. The vehicle possesses sufficient communication capabilities to receive distance, velocity setpoints and destination based lane change advice from the infrastructure. Vehicles also possess vehicle-to-vehicle communication capabilities as required during join, split, lane-change, and entry maneuvers.

The infrastructure, on the other hand, has the ability to meter entry to the AHS. It is aware of the AHS network topology, flow conditions (average speed, average density) on all parts of the AHS (This information will be obtained using roadside flow sensors such as loop detectors), and destination information collected at the point of entry. Based on this information about exits and network flow conditions, the infrastructure formulates lane change policies, velocity policies, platoon separation policies, to ensure good capacity utilization and timely exiting of vehicles. All this implies that, at all sections of the highway, the infrastructure has the ability to broadcast lane change advice, target platoon size, velocity and distance setpoints. The role of the infrastructure will still be limited as an advisory controller. The safe execution of maneuvers is handled by individual vehicle controllers. Moreover since the infrastructure participates in check-in and collects destination information at the point of entry, it has the ability to communicate with a single vehicle at its check-in stations.

We have not yet addressed the issue of vehicle routing. Since routing is dependent on network wide flow conditions, the infrastructure must be responsible at least for the collection and dissemination of network congestion information. ATIS equipped vehicles as per the ITS Architecture will have the ability to receive and process such information. We make the assumption that AHS vehicles also have the same capability. Thus, the infrastructure will support vehicles by providing dynamic travel time estimates for different links of the AHS, and relaying information about the transportation networks connected to the different AHS exits. It also provides non-AHS traffic management centers with information about traffic flow conditions within the AHS to support the management of AHS demand. Based on this information vehicles compute their own routes and choose their own exits. Thus, the infrastructure plays a supporting, rather than a controlling role, in the routing function! In order to accurately estimate the dynamically evolving state of the network, it is necessary to have the vehicles periodically broadcast

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[2] In a design based on this concept, the velocity input provided by the roadside controller will be used as a desired input and will be tracked if it is safe to do so, that is, maintaining safe distance from the platoon in front will have higher priority. Followers of the platoon will try to maintain safe distance from preceding vehicle while tracking its velocity. Inter-platoon distance will be typically constant-time separation or a small variation thereof whereas intra-platoon separation will typically be constant distance.

their planned exits to the infrastructure. Since the infrastructure requires only aggregate information, to protect the confidentiality the vehicles need not broadcast any unique identification with its destination.

Abnormal operating conditions arise either due to the loss of infrastructure or loss of vehicle functions. We start first with the infrastructure functions. We require that the vehicle have default values for all control setpoints, e.g., speed, intra and inter platoon distance setpoints, lane change distances etc., to be used if no inputs are received from the infrastructure for a specified period. These default values should ensure that in the sudden absence of infrastructure capabilities, the AHS continues to operate safely, though possibly with degraded productivity. For similar reasons, we also require that the vehicle have a default policy by which it moves out one lane per highway section as its exit approaches. Thus, even if infrastructure capabilities are lost a reasonable number of vehicles could be in the outermost lane by the time they reach the highway section containing their exit. However, this requires that the vehicle have the means of determining, without infrastructure support, its current global location to the extent that it knows its current section and how many sections away its exit is located. Such capabilities also ensure that, in the absence of infrastructure routing information, the vehicles are at least able to route themselves based on static information or according to passenger preference. If the infrastructure capabilities are lost at the check-in station, we require that the station be closed until check-in capabilities are restored. An AHS entry-point can not function without infrastructure control.

If a vehicle loses its vehicle-to-infrastructure communication capability, it must exit the AHS at the first available exit for the safety of surrounding vehicles, although it can safely coordinate maneuvers with other vehicles. The nearest platoon leader will communicate this exit information to the faulty vehicle or the faulty vehicle determines it by using its own emergency response system as described above.

If a vehicle loses its vehicle-vehicle communication capability, throttle control, brake control, automated lane changing, or automated lane keeping abilities it is required to come to a complete stop in its current lane. If its inter-vehicle communication capability is intact, it can be used to coordinate an emergency maneuver with neighboring platoons to assist the stop maneuver. Assistance from neighbors is particularly needed in case of brake failure as it takes much longer to stop without brakes. The faulty vehicle is required to communicate to the infrastructure the fact that it has stopped. It will then be removed by an emergency vehicle which will be dispatched to the section from which the message was received. It is required to emit some emergency signal detectable by the emergency vehicle (e.g., hazard lights).

One should limit the use of above mentioned stop maneuver to only severe faults as a stopped vehicle in a lane creates significant loss of throughput and large delays to travelers. Thus, in case of all other non-critical faults, the faulty vehicle should use its remaining capability along with help from neighboring platoons to exit AHS at the nearest exit. More failure specific maneuvers and control laws should be designed for that purpose.

Any vehicle that detects an obstacle on the highway is required to report the obstacle to the infrastructure. The infrastructure will be responsible for having the obstacle removed.

11.4 SYSTEM DIAGRAM

The system diagram is on the following page.

We assume that AHS users are also customers of various ITS Services. Thus, information flows both ways from all AHS vehicles to the various ITS Service providers. The AHS operations center also exchanges information with other non-AHS traffic operations centers. This allows both traffic operations centers to know about the state of each others networks and estimate or manage demand. AHS vehicles make decisions about their desired exits and routes based on information received by them from the AHS operations center and the ITS services they purchase (e.g. ATIS). The vehicles are required to convey their routing and exit choices to the AHS operations center. This may be done through the section controllers. This routing and exit information need only be in aggregate form since it is used by the AHS operations center to estimate demand.

The highway is divided into sections and each section has a section controller. The section controller receives information about average flow, speed, and density from roadway sensors placed at different points in the section. If the section has an AHS entry, then the entry port also has an entry controller. The section controller sends information about average speed, flow, and exiting traffic to the AHS operations center. The AHS operations center sends policies that regulate the average volume of entering traffic, exiting traffic, section flow and speed. The section controller sends the entry rates to all entry controllers in its section. The entry controllers are responsible for controlling free space and platoon speed in the entry zone and for co-ordinating the entry maneuver between the entering vehicle and the first upstream platoon, until the two detect each other and establish communications.

When emergencies occur, i.e. a vehicle experiences degraded control or communication capabilities then it is assumed that the infrastructure is able to send emergency communications to the vehicle in trouble.

Vehicles are organized in platoons. The desired platoon speed, inter platoon spacing, intra-platoon spacing for each section is broadcast by the section to all lead vehicles in the section. Vehicle-to-vehicle information flow pertains to that required for merge, split, lane change, entry and exit maneuvers. Vehicle-to-vehicle distance is sensed.

11.5 FUNCTIONAL ALLOCATIONS

11.5.1 Check-In

The human indicates his or her willingness to enter the AHS by driving onto the dedicated entry ramp. The vehicle senses that it has entered the dedicated entry ramp. The check-in may be performed either on-the-fly or manually. In case of manual check-in, the vehicle is required to stop at the check-in station. In case of on-the-fly check-in, the vehicle performs a diagnosis of its manual and automatic control system. The vehicle checks the ability of the human to perform the hand-off of control tasks. Depending on the results of the vehicle and human checks, the human will be advised by the vehicle to either initiate or abort the transition from manual to automated control. If the vehicle or human fails the checks, and the human or vehicle does not abort the transition process (e.g., due to human error or vehicle system malfunction), the infrastructure broadcasts to platoons entering the roadway segments in proximity to the entry ramp that a rogue vehicle might enter the automated lanes.

11.5.2 Transition from Manual to Automatic Control

The human relinquishes driving tasks to the vehicle control system. As each task is transferred, the vehicle acknowledges to the human that the transfer of control is complete and successful. If the transfer is complete and successful, the vehicle continues its journey onto the automated lanes under automatic control. The vehicle signals to the infrastructure that the transfer of control is complete and successful. The infrastructure broadcasts to platoons in proximity to the dedicated entry ramp the fact that a vehicle will enter the automated highway via the ramp.

If the transfer of control is incomplete or unsuccessful, in terms of human error or vehicle malfunction (e.g., failure to acknowledge transfer), the infrastructure broadcasts to platoons entering the roadway segments in proximity to the entry ramp that a rogue vehicle will enter the automated lanes.

11.5.3 Sensing of Roadway, Vehicles, and Obstructions

The vehicle performs all sensing tasks. The sensor data fusion task is shared by the vehicle and infrastructure. Fused data is transmitted to the infrastructure, which performs further fusion, yielding aggregate information regarding platoon position, location of obstruction, etc.

11.5.4 Lane and Headway Keeping

The vehicle performs all lane and headway keeping tasks. Vehicles communicate with each other, providing lane position, velocity, etc.

11.5.5 Detection of Hazards

Detection of hazards is performed by both the vehicle and infrastructure. The vehicle and infrastructure fuse sensor data, with the objective of distinguishing between hazards (e.g., rogue vehicle or roadway obstacle) and non-hazards (e.g., shallow puddle of water or newspaper blowing across the roadway).

11.5.6 Maneuver Planning

Vehicles within a platoon communicate with each other in order to prepare for a maneuver. When two or more platoons are involved in a maneuver, inter-vehicle communication is used for coordination purposes. The infrastructure provides aggregate vehicle and roadway information, which the vehicles utilize in planning maneuvers.

11.5.7 Maneuver Execution

Maneuver execution is performed by vehicles, according to the maneuver plans developed by platoons.

11.5.8 Transition from Automatic to Manual Control

Same as for transition from manual-to-automatic control, only in reverse order.

11.5.9 Check-Out

Same as for check-in, only in reverse order. The infrastructure will provide aggregate information regarding the status of arterials at the exit point (i.e., intersection of the dedicated exit ramp and arterial roadway).

11.5.10 Flow Control

The infrastructure provides aggregate roadway and vehicle status information. The vehicles receive this information and make local decisions (i.e., decision specific to one or more roadway segments) regarding control actions which affect local and global traffic flow. That is, the information provided by the infrastructure is in the form of recommendations rather than commands.

11.5.11 Malfunction Management

The platoons and infrastructure coordinate with each other in managing malfunctions. The infrastructure provides position and other platoon status information to platoons in the vicinity of a faulty vehicle or roadway infrastructure. If the malfunction is within the infrastructure, the management coordination relies on vehicle-to-vehicle communication, planning, and execution. If vehicle-to-vehicle communication fails, each vehicle within a platoon performs malfunction management as a free agent.

11.5.12 Handling Emergencies

The infrastructure provides global commands for stopping or restarting movement on the AHS lanes. Vehicles provide the infrastructure with their status.

11.6 IMPLEMENTATION

11.6.1 Vehicle

11.6.1.1. Roadway Sensing

Used for lateral and possibly longitudinal control (e.g., if vehicle communication fails, calculate spacing and relative speed from beacon data). Such technology includes all types of indirect[3] road reference systems (e.g., energy sources, reflectors, etc.).

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[3] By indirect we mean there is no physical link between the sensor and the marker: the signal processor is responsible for determining the distance between the sensor and the sensed marker.

11.6.1.2. Sensing Other Vehicles

Primarily for use in longitudinal control to maintain safe intra- and inter-platoon spacing, and in combined longitudinal and lateral control to coordinate maneuvers.

- Sensors to detect neighboring vehicles in the same lane and sensors to find distance and relative velocity from a preceding vehicle in the same lane, are needed. Possible choices are Doppler Radar, Sonar, two cameras mounted on the vehicle, etc. Sensing of the distance and relative velocity from the vehicle behind may also be needed/used in designing robust control laws and also during emergency situations.
- Sensors to detect neighboring vehicles in the adjacent lane.

11.6.1.3. Vehicle-to-Vehicle Communication

- *Control:* Infrared communication (e.g., on-off keying with clock encoding). However, the size and spacing of vehicles, radius of roadway curvature, height and reflectance of barriers, and so on affects the effectiveness, in terms of line-of-sight constraints for infrared communication devices.
- *Maneuver:* Pulse (i.e., frequency hopping spread spectrum) or WaveLAN (i.e., direct sequence spread spectrum) radio systems, along with the use of a mobile Internet protocol. FCC allocation of the frequencies for AHS remains an unresolved issue.
- *Advisory/Navigation:* Advisory and navigation information can be transmitted within and between platoons in a daisy-chain manner. Packet loss and delay of advisory and navigation information are non-critical. However, channel access is random in source, destination, and time, and communication distances are very long.

11.6.1.4. Vehicle-to-Infrastructure Communication

- *Control:* Broadcast communication medium. Cellular-based technologies are not a viable option since there will be more vehicles per 6 mi radius (effective range of cellular communication devices) than there are cellular channels to allocate. The infrastructure shall broadcast position information and each vehicle must provide an acknowledgment. The infrastructure provides the central coordination function. The technical questions to be answered are how to provide for position information and acknowledgments.
- *Maneuver:* Broadcast communication medium, for the same reason as described above. The same issues also apply here.
- *Advisory/Navigation:* Broadcast communication medium, for the same reason described above. The same issues also apply here.

11.6.1.5. Vehicle Identification Tag

One or more vehicle identification tags can be used for activities such as check-in, toll collection, and maneuver coordination.

11.6.2 Infrastructure

11.6.2.1. Low Level Modifications

- *Lateral Position Sensing:* Indirect road reference system (e.g., energy source, reflectors, etc.). Specific examples of this type of technology are acoustic resonance reflectors and magnets.
- *Barriers:* Barriers between the automated lanes and manual lanes.
- *Ramps:* Dedicated on and off ramps.
- *Macroscopic Traffic Condition:* Infrastructure-based sensors to collect traffic flow data (e.g., loop detectors).

- *Microscopic and Traffic Condition:* Infrastructure-based sensors to collect system performance data and determine the movements of individual vehicles.
- *Roadway Impediment Sensing:* Infrastructure-based sensors for detecting stationary or moving obstacles on the highway.

11.6.2.2. Intermediate-level modifications

- Short-range roadside transmitters that provide information to vehicles. The communication is in terms of radio broadcast (approximately one every 1.6-3.2 km.).
- Roadside controllers that get the flow data from roadside flow sensors as well as flow data from a few sections down the road to generate commands/ information to be passed on to vehicles
- Communication network between different sectional controllers.
- Communication network between TMC and each sectional controller.

These last two communication networks do need high bandwidth as the frequency of updates received from TMC will be of the order of 10's of minutes whereas the frequency of update of information to vehicles will be in the order of 1--2 minutes.

11.6.2.3. High Level Infrastructure modification

Network level TMC controller and two way communication between each sectional controller and the network controller.

11.6.3 Rural Highway

One possibility is to neither provide platooning nor transportation management center (TMC) services for routing.

11.6.4 Urban Highway

As described in Section 11.3.

11.6.5 Deployment

The minimum deployable system consists of the following:

- one or more automated lanes,
- physical barriers between the automated and non-automated lanes,
- at least one entry and one exit lane,
- check-in and check-out facilities at each entry and exit lane, respectively,
- full automation of vehicles, and
- partial automation of the infrastructure, including command, control, and communication capabilities

The degree to which command, control, and communication functions are shifted to the roadway infrastructure impacts the cost to develop, manufacture, and deploy automated vehicles. Too little or over reliance on infrastructure support can result in high-priced automated vehicles; for example, at either extreme, the complexity of the in-vehicle automation systems can be high and thus, costly to design, manufacture, and maintain.

There are some disincentives to deploying an this concept AHS. The more prominent disincentives are as follows:

- cost to build dedicated entry and exit lanes: these will have to be long enough to permit both small and large vehicles to accelerate or decelerate sufficiently to safely enter or exit the automated lane, and
- in some locales, no land is available—without razing existing structures, purchasing right-of-way, or having a significant environmental impact—for construction of dedicated entry and exit lanes

The incentives of such an architecture are that:

- dedicated entry and exit lanes and inter-lane barriers may be perceived by the public as necessary and sufficient safety features, and

- depending on the infrastructure design, in some cases it may be possible to upgrade the roadway infrastructure, especially in terms of communication, but less so for the physical roadway (e.g., resizing entry and exit ramps)

11.7 GENERAL ISSUES AND CONSIDERATIONS

11.7.1 Failure modes

As the intelligence is distributed between roadside and vehicle, the two types of control systems can back up each other. Different types of sensors and communication devices are used on the vehicle and the roadside to gather information of the world as well as for coordination. These systems can be used to back up other subsystems in case of a failure. Most of the vehicle failures (sensors, communication devices, etc.) will have a localized effect. Infrastructure failures will only result in reduced throughput and will not be safety critical. As the driver will not be able to drive in a platooned environment, the control should not be passed to the human driver while the vehicle is on AHS.

11.7.2 Sensing weather conditions

Adverse weather conditions such as limited visibility, snow, ice, etc. will be sensed by the on-board vehicle sensors and communicated to the infrastructure. They may also be sensed by roadside sensors placed at specific locations on the roadside for that purpose. The infrastructure communicates this information to the upstream traffic. The infrastructure may also advice the vehicles to slow down.

11.7.3 Vehicle functionality

Typical users will travel at the speed limit.[4] Due to infrastructure support functions, highway speeds are fully tailorable.

The vehicles equipped to drive in this AHS will be able to perform feet-off driving using Adaptive Cruise Control (ACC) capabilities on the conventional roads. They can also use most of the ATIS information for route selection.

11.7.4 Throughput and Safety

The *platooning* feature of this concept contributes most to increasing traffic flow. In fact, platooning allows one to realize maximum achievable increase in capacity. Infrastructure support is also critical in optimizing the traffic flow.

The safety of the system is increased because of automated obstacle detection and avoidance and due to distributed intelligence between infrastructure and vehicle.

11.7.5 Cost

As vehicles and infrastructure both have sensors, controllers and communication systems, regular maintenance of vehicles and infrastructure is required.

The dedicated entry/exit option requires construction of dedicated on-off ramps to the AHS.

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[4] Typically in the range of 65-70 MPH. Although one can design a system to operate at a higher speed such as 80-85 MPH. Beyond certain speed, the gain in throughput will be offset by the large inter-platoon spacing required for safety and the cost of associated sensors.

12. CONCEPT 10: INFRASTRUCTURE MANAGED FREE AGENTS ON DEDICATED LANES WITH GAPS

12.1 OVERVIEW

This concept is infrastructure-managed, has dedicated lanes with gaps in the barriers, mixed vehicle classes in the same lane, a transition lane, and no platooning. Unusual features of this concept are:

1) no direct vehicle-to-vehicle communication;
2) only one side-looking sensor;
3) Using the transition lane like a railroad siding to allow faster-moving traffic to pass slower-moving traffic.

12.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

- Distribution of intelligence—infrastructure managed
- Separation policy—free agent
- Mixing of AHS and non-AHS vehicles in the same lane—dedicated lanes with some gaps in physical barriers.
- Mixing of vehicle classes in a lane—Yes. When two or more AHS lanes are available, local options include limiting heavy vehicles to the right hand lane.
- Entry/exit—transition lane.
- Obstacles—automatic sensing and automatic avoidance maneuver if possible.

12.3 OPERATIONAL CONCEPT

The vehicle does autonomous lane-keeping and headway maintenance using on-board sensors. It performs obstacle detection using its forward-looking sensor, and position determination using its lane-keeping sensors (see Issues for more details). It senses velocity, computes acceleration, and measures range to any vehicles or objects ahead of it or to the right. The sensor on the right side of the vehicle is primarily for merging into the transition lane (which may have some non-AHS traffic) from the AHS lane(s), and for lane changes prior to stopping when communication with the roadside processor has failed. Vehicle position and dynamics, and range measured by the two sensors are periodically reported to the roadside processor.

The roadside processor tracks the position of vehicles within its area of responsibility, and orders speed changes for individual vehicles to manage traffic flow. It selects local routes for vehicles based on their destination, and orders lane changes as appropriate. It plans and executes any maneuvers needed to deal with unforeseen conditions. The roadside processor uses sensors in or on the roadway to monitor environmental conditions, and it validates the IDs of vehicles requesting entry into AHS. Reports of incidents and obstacles are forwarded to the TOC along with statistics on average traffic speed and throughput.

The Traffic Operations Center provides speed and route guidance information to the roadside processors to allow them to manage local traffic flow in a manner consistent with conditions in nearby regions. The TOC also manages all reported incidents. The master vehicle ID database is updated here before being sent to the roadside processors and high-level statistics on AHS performance are kept here.

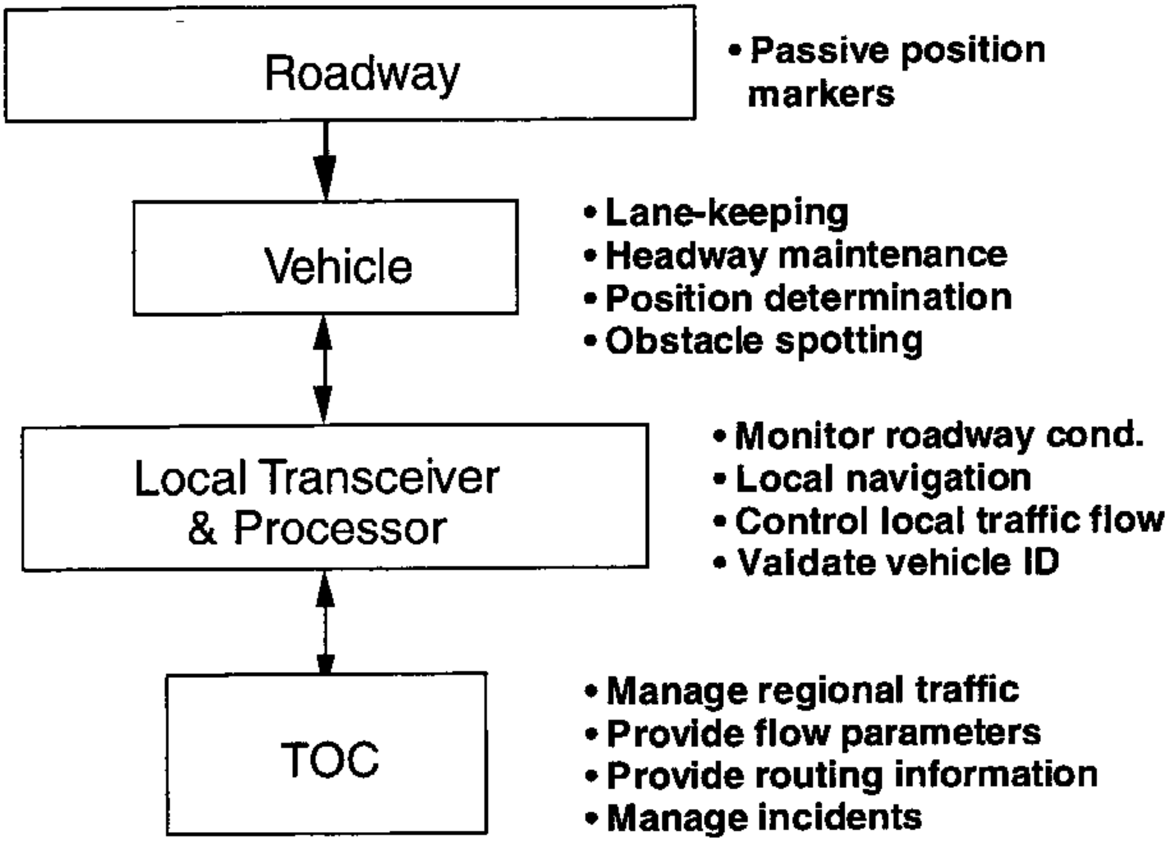

Figure H.12.3-1. Operational Concept

12.4 SYSTEM DIAGRAM

The system diagram is shown in Figure H.12.4-1. The vehicle coverage diagram is in Figure H.12.4-2.

12.5 FUNCTIONAL ALLOCATION

12.5.1 Check-In

An AHS-equipped vehicle in the transition lane requests permission to enter AHS. Local transceivers relay this request to the roadside processor, which checks the database, and queries (vehicle) on-board status indicators for vehicle status. If the vehicle is registered, and all systems are operating, the vehicle is signaled that it is logged into AHS.

12.5.2 Transition From Manual to Automatic Control

When an AHS vehicle traveling in the transition lane receives a "logged-in" signal, the driver pushes a button transferring control to AHS. If the driver fails to push the button within a certain time, the signal is repeated; if the driver still does not push the button, a message on the user interface instructs him on his options (including returning to manual operation in the conventional lanes). When the driver signals that he is ready to give up control of the vehicle, it is then automatically guided into the AHS lane. A vehicle crossing into the AHS lane under manual control triggers local alarms (bells, lights) from a sensor located on the lane divider, and a camera photographs the license and transmits the image to a dedicated roadside processor to relay to the TOC during a low demand time.

Concept #10 Data Flows

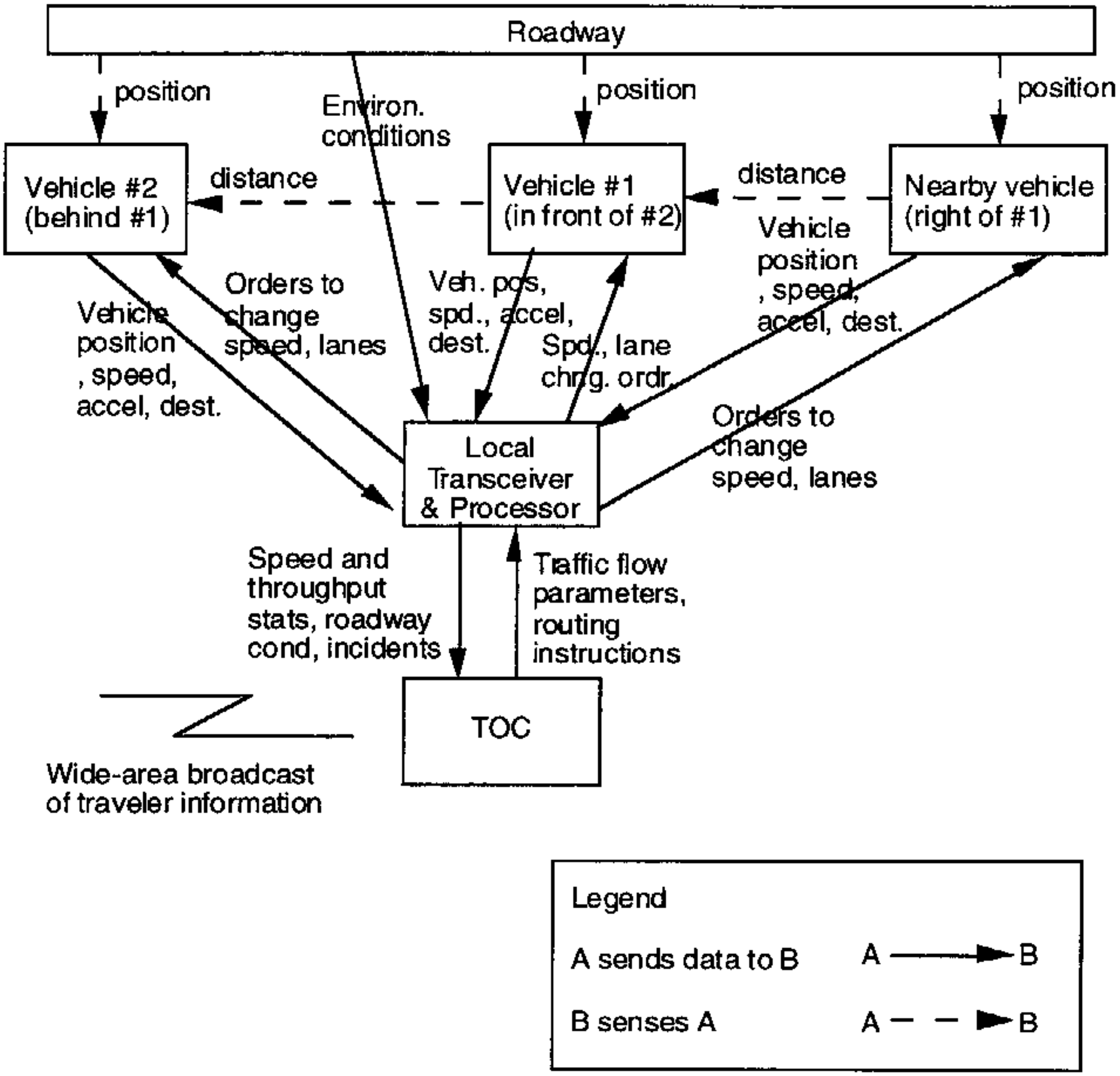

Figure H.12.4-1. Data Flows

12.5.3 Sensing of Roadway, Vehicles, and Obstructions

Other vehicles and large obstructions are sensed by the vehicle's forward-looking sensor. If technologically feasible, this is also used to spot all roadway hazards that can damage the vehicle. If this is not possible, it is necessary to add one of the following to this concept: 1) a second vehicle-mounted sensor optimized for obstacle detection; 2) roadway-mounted obstacle detection sensors; 3) use of the driver as a spotter for hazards and obstructions which the automatic sensor cannot pick up sufficiently far in advance (see Deployment for more on this). Roadway obstacles are reported to the roadside processor to divert traffic around them and forward the report to the TOC.

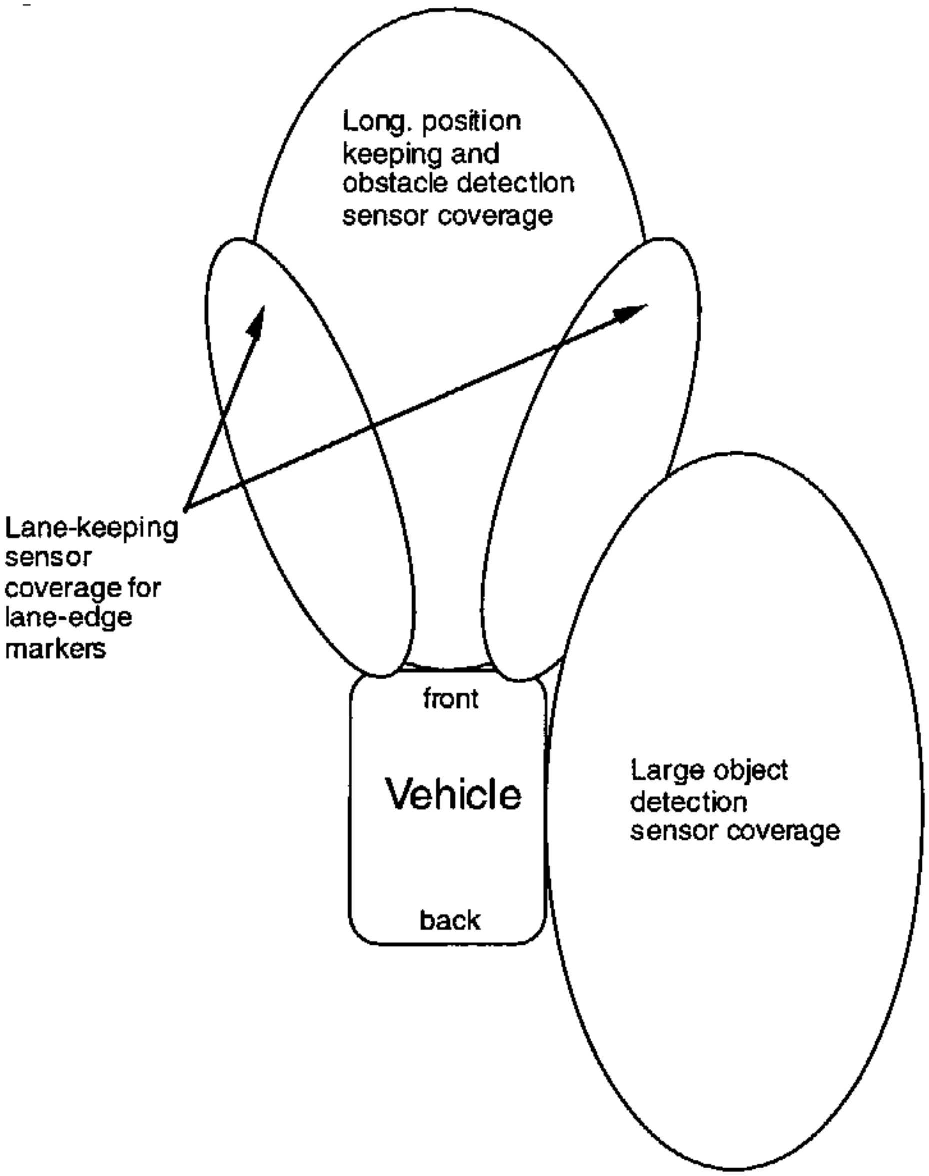

Figure 12.4-2. Vehicle Sensor Coverage

12.5.4 Lane and Headway Keeping

Lane-keeping and longitudinal positioning are vehicle-based. Lane-keeping is performed with reflective markers on both sides of the lane which will also be encoded with a sequence number used for positioning (see Issues). These markers may reflect visible light similar to the lane markers used on some interstate highways, or they may be radar reflective. The lane-keeping sensors measure range and can therefore estimate vehicle position relative to the markers. Vehicle speed is ordered by the roadside processor, but the vehicle can override this if needed to maintain an appropriate distance from the vehicle in front, judged by the forward-looking vehicle-based sensor.

12.5.5 Maneuver Planning

Lane change requests can originate with the driver ("I want to get a hamburger") or the infrastructure ("the middle lane is blocked ahead"); in either case, the roadside processor identifies the vehicles (if any) that must speed up or slow down to accommodate the lane change, and calculates speed changes for all vehicles concerned.

12.5.6 Maneuver Execution

The vehicles involved in the maneuver receive a command from the roadside processor to change speed or lane, and confirm receipt. The vehicles execute the command(s); the roadside processor can track the maneuver through the vehicle's regular position and speed updates.

12.5.7 Transition From Automatic To Manual Control

A vehicle preparing to exit AHS remains under automatic control until it is in the transition lane. The roadside processor signals the driver via the operator interface to take control, and the driver confirms that he is ready by pushing a sequence of buttons. If he fails to do this, he is instructed on his options via the user interface and asked to make a selection. If he fails to do so, the vehicle remains under AHS control until it can be stopped in a breakdown lane or area. The vehicle is checked out of AHS at the same time.

12.5.8 Check-Out

Check-out is performed at the same time as the transition from automatic to manual control. Fees are computed at this time by the roadside processor, and the vehicle is dropped from the list of those active in the region.

12.5.9 Flow Control

The infrastructure monitors traffic density and flow rate, and chooses routings which keep travel time low while taking overall traffic flow into consideration. The TOC does this at the global level, and passes traffic flow and speed parameters to the roadside controllers to optimize local traffic flow. In regions where only one lane can be dedicated to AHS, the transition lane is used like a railroad siding. If faster vehicles are being held up by slower vehicles (e.g., trucks ascending a grade), the infrastructure will order the slower (or perhaps faster) vehicles to switch to the transition lane at the next barrier opening. They remain under AHS control in the transition lane, and are ordered back onto the dedicated AHS lane once the faster traffic has passed.

12.5.10 Malfunction Management

If a vehicle does not respond properly to messages from the infrastructure, or does not report position and speed at appropriate intervals, the driver is notified and given the option of taking over manual control once the vehicle is in the transition lane. If the driver does not respond affirmatively to this, the vehicle will be kept under automatic control and shunted to a breakdown lane or area at the first opportunity. The vehicle processor is also programmed so that if no messages or confirmations are received from a roadside processor within a pre-determined time period, and no response to a special query is received, a communications failure will be assumed and the driver is alerted. He is given the option of taking over control of the vehicle; if he fails to do so, the vehicle will continue to move ahead and right, using on-board sensors, until it can be safely stopped in a breakdown lane or area. If the AHS senses a vehicle malfunction, other nearby vehicles are controlled to increase the spacing around (and in an emergency, avoid) the malfunctioning vehicle.

12.6 IMPLEMENTATIONS

12.6.1 Vehicle

- Processor,
- Short-range roadside to vehicle communication (2-way),
- Forward-looking sensor for range to vehicles and obstructions,
- Ranging sensor (for large objects) on right side only, and
- Lane-keeping sensors capable of reading encoded position information on specially designed reflectors, and measuring range to reflector.

12.6.2 Infrastructure

- Short-range roadside transceivers, sufficient density for continuous coverage,
- Traffic Operations Center spaced at pre-determined intervals,
- At least one dedicated AHS lane and one adjacent lane equipped with reflective lane markers compatible with the lane-keeping sensors,
- Physical barrier with gaps separating dedicated AHS lane(s) from transition lane,
- Breakdown lane (or areas) accessible from either the AHS lane or the transition lane. If not continuous, spaced at pre-determined intervals, and
- Cameras and unauthorized entry sensors at each entry zone.

12.6.2.1. Rural Highway

(See Flow Control for concept to allow mixed vehicle types on a single AHS lane.) Regular traffic lane can double as the AHS transition lane if this is dictated by cost or space limitations.

12.6.3 Deployment

If the lane-keeping sensors can be made compatible with existing rectangular reflectors, then a stepping-stone to implementing this concept could be installation of the on-board vehicle sensors, with no modifications to the infrastructure. The vehicle performs lane-keeping and longitudinal position-keeping under normal circumstances. The driver has the power to override when he desires, and is expected to take over under unusual circumstances. Driver monitoring techniques such as the one described in the next paragraph, are used to periodically check driver alertness.

If a satisfactory hazard detection sensor is not available at the time of initial AHS deployment, the driver can be used as a spotter for hazards and obstructions which the automatic sensor cannot pick up sufficiently far in advance. When the driver pushes an alert button, he also enters a code (roadway obstruction, fire, medical emergency, etc.). This information, along with the vehicle's position, is broadcast by the vehicle to a roadside receiver to relay to the TOC. If the driver pushes a button indicating a possible hazard in his lane, the roadside processor orders his vehicle and others near it to immediately slow and increases spacing in preparation for stopping or maneuvering. The driver must volunteer to perform this "spotter" function; reduced tolls represent a possible incentive. Where there are two or more dedicated AHS lanes a speed "bonus" could also be used as an inducement, with vehicles where the driver wants to read or sleep being limited to a lower speed in the right lane(s). Driver alertness and response time could be monitored by periodically projecting an image focused in the distance onto a windshield heads-up-display; the driver must respond by pushing a button within a prescribed time interval; if he fails several times, the vehicle is "demoted" to the lower speed right-hand lane.

12.7 ISSUES

12.7.1 Obstacle Detection Sensor

Obstacle detection could be performed a) by the vehicle-mounted headway sensor; b) by a separate vehicle-mounted sensor designed to detect small objects on the roadway; c) by sensors mounted on the roadway and designed for this purpose; d) by the headway sensor assisted by the driver (see previous paragraph). This is a technology issue that needs further investigation.

12.7.2 Vehicle Position Determination

This concept proposes that the vehicle calculate its position from a known position when it entered AHS, a count of the number of markers passed since entry, and measured range to the current markers. To do this the lane-keeping sensor must measure both range to the lane markers, and read a three to four bit sequence number encoded on the markers. These markers may reflect visible light similar to the lane markers used on some interstate highways, or they may be radar reflective. They are, however, spaced at regular intervals, machine-readable, and encoded with the sequence number of the marker. The vehicle counts markers, and uses the code on the marker as a check in case it misses a few. Where snow falls regularly, the markers must be designed or placed so that they are not damaged by snowplows. The feasibility of this position determination method is not critical to this concept; other methods can be substituted.

-13. CONCEPT 11: INFRASTRUCTURE MANAGED MIXED PLATOONING WITH TRANSITION LANES

13.1 OVERVIEW

This chapter is based on concept number 11 given in AHS concept matrix. That system is defined as infrastructure managed mixed platooning with transition entry/exit and dedicated physically barriered gaped lanes.

Among several concepts available in the AHS concept matrix, concept 11 has definite advantages over the others. This concept allows the use of existing freeway on and off ramps. The driver passes through non AHS lanes to reach AHS lane. This option is very cost effective as no new on and off ramps have to be designed and built. Building new on and off ramps is not only very expensive, but they take a long time to build.

Since mixing of different class of vehicles is allowed in this option, only one AHS lane is required to pass all kinds of traffic. Non mixing of different classes of traffic calls for either separate lanes or the system is only implemented for one class of traffic. Again this option is clearly a cost saver.

This concept restricts mixing of AHS and non AHS traffic by using a physical barrier between AHS and non AHS lanes. Since dedicated entry/exits are not allowed in this concept design, gaps are provided at certain distances for AHS traffic to merge/separate from AHS lane. Even though this lane is not allowed for non AHS users, there is a possibility of a rogue driver entering AHS lane. This likelihood is taken care of by the design and is discussed in section 13.5.1.2.3 of this report.

Allowing platooning in this option allows high throughput in a given time as traffic is more compact.

Infrastructure management creates a uniform signal structure, as every manufacturer has to comply with a single standard. Infrastructure management also streamlines the traffic since it can sense the traffic in a wider area than the vehicle itself.

13.2 TRADE OFFS

One of the very obvious feature of this report is that this concept calls for physical barriers with gaps to segregate the AHS lane from the non AHS lane. Jersey barriers or a permanent wall is required to achieve this concept. Gaps are required in these physical barriers in order to enable AHS vehicles to merge/separate form AHS lane. Existing freeways have to be modified in this fashion. AHS vehicles will use non AHS lanes and existing on/off ramps to access AHS lane.

Mixing of all classes of vehicles is allowed through the AHS lane. To achieve this local tailoring is not required to implement this trade off. This trade off is built in to this concept of AHS. Its implementation is described in section 3 of this report.

Platooning is called for in this concept. No local tailoring is required, as it is built in to this concept of AHS. This concept is described in section 5.1.2.1 of this report.

Roadside stations have to be installed along the freeway. To monitor roadside controllers, regional traffic management centers have to be erected. The implementation of roadside controllers and regional traffic management centers is discussed in section 6.2 of this report.

13.3 SYSTEM DIAGRAM

The AHS concept is shown in Figure H.13.3-1. Looking at the diagram one notices that there is no vehicle-to-vehicle or platoon-to-platoon communication. The only communication allowed is between the vehicle and roadside controller. A roadside controller is a bridge between traffic and regional traffic management center. Most of the traffic managing intelligence is located in the regional traffic management center. Even in case of roadside controller failure or complete destruction, local traffic will not be

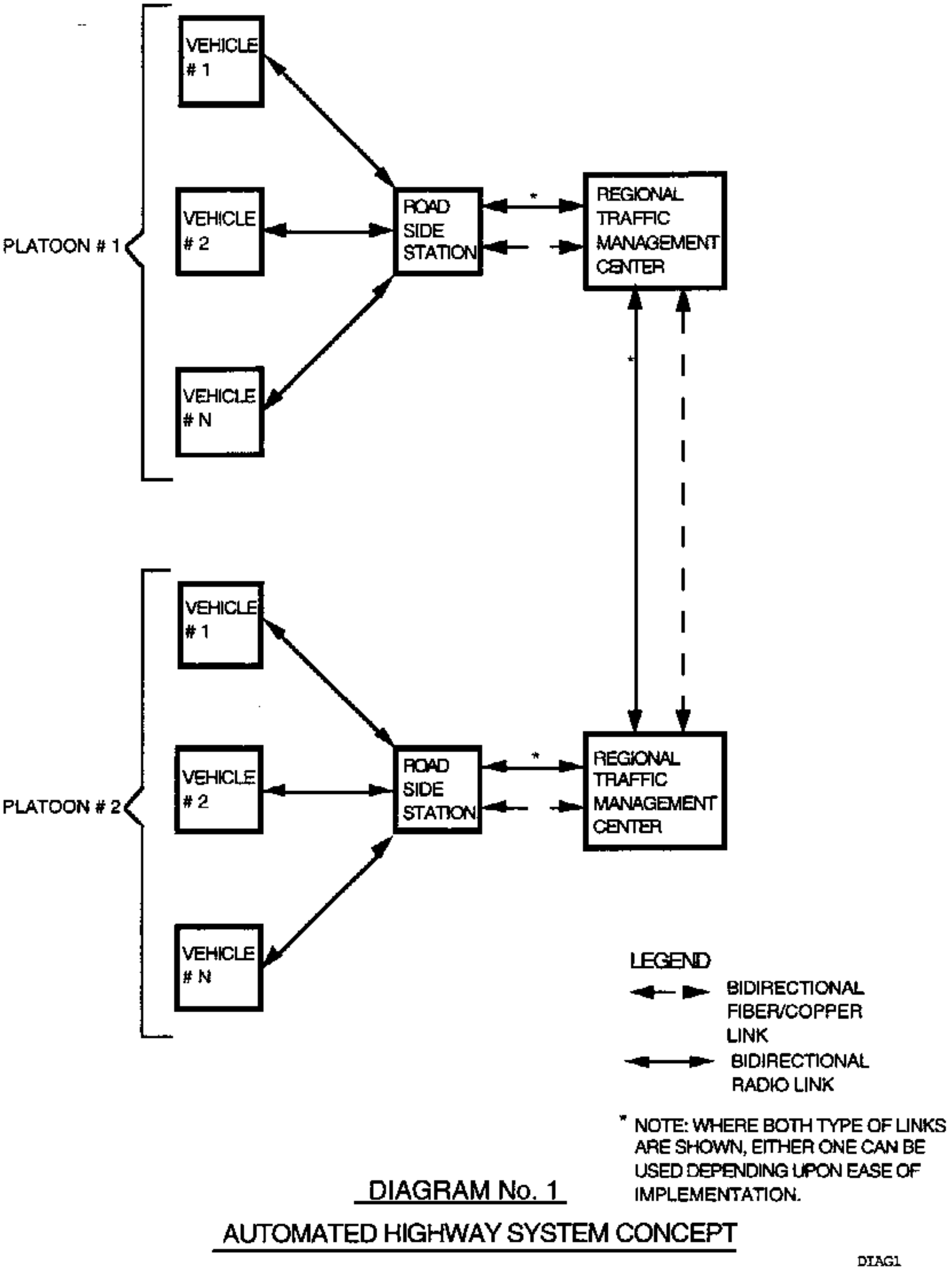

Figure H.13.3-1. Automated Highway System Concept

harmed and adjacent roadside controllers will take over the control.

Roadside controllers communicate with individual vehicles as well as regional traffic management centers simultaneously. The communication link between roadside controller and regional traffic management center shall either be a high speed radio or a fiber/copper link. Roadside controllers shall have the capability of collecting weather data and optional capability of video camera.

All these signals, if available, help personnel at the regional traffic management center to have better control over the traffic.

The regional traffic management center communicates with roadside controllers continuously. All the information about the traffic is passed to other regional traffic management centers to be shared. This distribution of information helps regional traffic management centers have better control over the traffic.

Figure H.13.3-2 shows vehicle on-board systems which are explained in detail in section 6 of this report.

13.4 OPERATIONAL CONCEPT

Before entering an AHS lane, each vehicle transmits its vehicle code, class identification code, and intention to merge into an AHS lane. The regional traffic management center registers this vehicle as a valid user. Vehicles are registered with the closest roadside controller. Each roadside controller has its operating zone based on its signal strength. As long as this vehicle remains in a zone, the roadside controller keeps all its information. Once the vehicle leaves a zone all the information is passed to the next roadside controller through the regional traffic management center. The regional traffic management center displays this information on a monitor.

After registering the vehicle, the regional traffic management grants or denies permission to enter the AHS lane. If permission is granted, the regional traffic management center sends speed and headway distance parameters. At this point the vehicle merges into the AHS lane. The merging procedure is discussed in section 5 of this report.

Allowing mixed classes calls for classification of vehicles. Vehicles are classified by their dynamic characteristics. Each vehicle is preprogrammed with a headway distance based on its class. Since heavy vehicles are slower in response (acceleration and braking) as compared to light vehicles, headway distance will vary for each class of vehicle. Heavy vehicles are preprogrammed with a higher headway distance then light vehicles.

Each segment of the AHS lane transmits speed and headway distance parameters to each vehicle. These parameters are weather and freeway condition dependent. The regional traffic management center computes these parameters and passes them to roadside controllers for a certain segment of freeway. Once a vehicle gets these parameters it maintains that speed in AHS lane. Headway distance is a slight different case. Since each vehicle is preprogrammed with a headway distance, the headway distance computed by the regional traffic management center is added by the vehicle on-board computer to preprogrammed headway distance.

In case the condition of the AHS lane is good, the regional traffic management center computes a higher speed and zero headway distance. In case of poor AHS lane conditions, the regional traffic management center computes a lower speed and a higher headway distance.

Each regional traffic management center handles up to a fixed number of roadside controllers. This creates a uniformity in design. Thus, rural areas end up with few regional traffic management centers with larger areas to cover since in rural areas roadside controllers can be installed with greater spacing.

In contrast, urban areas end up with more regional traffic management centers with smaller areas to cover since the number of roadside controllers per regional traffic management center is fixed. Roadside controllers in urban areas have low power transceivers to reduce interference between each other as the transceivers use the same frequency and bandwidth.

In normal conditions, AHS vehicles merge into the AHS lane by registering with roadside controllers. The roadside controller has the data about vehicle identification, vehicle class, number of vehicles in a platoon and their speeds. This data is given to the regional traffic management center for processing. When a vehicle enters a new zone it communicates with the roadside

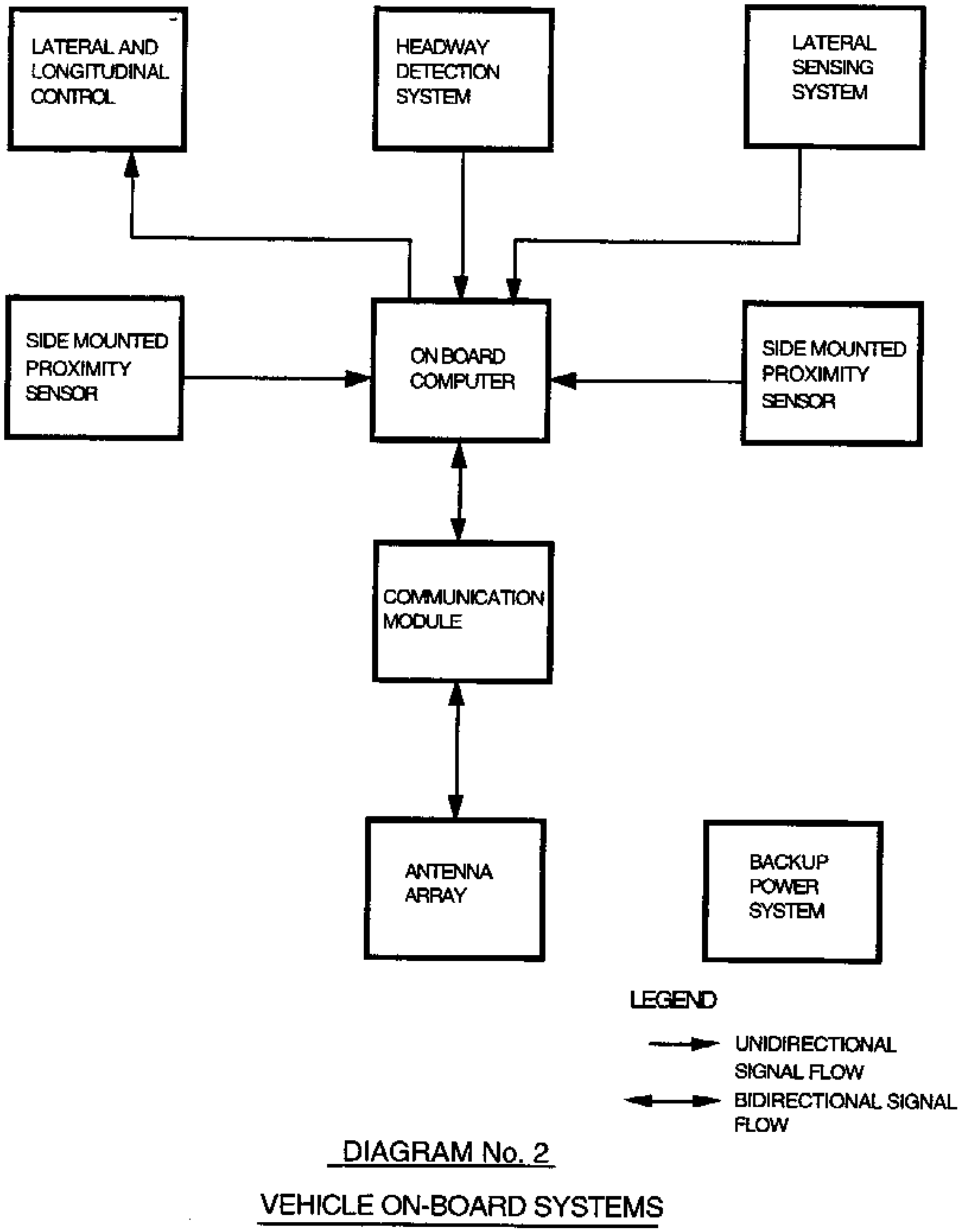

Figure H13.3-2. Vehicle On-board Systems

controller and all this data is given to the regional traffic management center for cross-checking against data provided by previous roadside controllers. Once a vehicle leaves, it informs the roadside controller and this data is again sent to the regional traffic management center to be processed and updated on the monitor.

The size of data communicated between vehicle and roadside controller is not more than a few hundred bytes. Also each vehicle communicates with the roadside controller only when it merges in an AHS lane or it enters a new zone. This does not burden the communication link between the vehicle and roadside controller. The update rate depends on speed and the distance between roadside controller and vehicle.

13.5 FUNCTIONAL ALLOCATION

This system allows communications between vehicles and roadside controllers only. Every request from the AHS vehicle is checked by the regional traffic management center. The regional traffic management center takes appropriate actions to manage the traffic. Roadside controllers serve as a bridge between AHS vehicles and regional traffic management centers.

13.5.1 Baseline Functions

Procedures for baseline functions are given below. Keep in mind that safety is the prime concern here.

13.5.1.1. Check-In

The driver uses an existing on-ramp to enter the freeway. After entering the freeway the driver transitions through non AHS lanes till he reaches the lane next to the AHS lane. The driver informs the infrastructure (roadside controllers) about his intention to enter the AHS lane by turning the AHS system ON. The on-board computer generates a signal and relays it to the nearest regional traffic monitoring center, through the roadside controller, requesting to enter the AHS lane. The regional traffic management center registers the vehicle as a valid user and grants permission to merge in the AHS lane. At this point, the vehicle is in a quasi automatic state. The on-board computer checks, using proximity sensors, for the physical barrier and for other vehicles in close proximity in the AHS lane. If the vehicle is passing by a gap in physical barriers and there are no vehicles present in close proximity in the AHS lane, the merging vehicle generates the proper lateral and longitudinal commands to merge in the AHS lane. After merging, the vehicle informs the roadside controller about its successful entry and engages the lateral and longitudinal control to follow the AHS lane (fully automatic mode).

13.5.1.2. Automatic mode of driving

Once the vehicle goes in the fully automatic mode, the on-board computer checks for the availability of any other vehicle in front using the front mounted headway detection system.

13.5.1.2.1. Joining the platoon

The regional traffic management center periodically checks a segment of the AHS lane for all the incomplete platoons. If there are any single vehicle platoons or incomplete platoons available, then the regional traffic management center manages the AHS vehicles to complete the platoons.

13.5.1.2.2. Separating from platoon

When the driver decides to separate from the platoon, he indicates this by entering a command on the key pad. The on-board computer generates commands to inform the regional traffic management center about the driver's intention. Permission is granted by the regional traffic management center to leave the platoon. The on-board computer uses proximity sensors to check a gap in the physical barrier and if there is no car in near proximity. Once both of the conditions are met, the on-board computer generates the proper lateral and longitudinal commands to leave the platoon and the AHS lane. After a successful exit from platoon the vehicle informs the roadside controller about its successful exit. The gap in this platoon is filled by the following cars as mentioned above until the platoon is full.

13.5.1.2.3. Sensing of roadway, vehicle and obstructions

Roadway sensing is done with a lateral sensing system. The system senses the roadway and processes this information using a dedicated CPU. All the processing is passed to an on-board computer for proper generation of lateral control commands.

The front mounted headway detection system computes the vehicle or platoon headway distance. The headway detection system has a dedicated CPU to process headway information. After this information is processed it is passed to the on-board computer for proper generation of longitudinal control commands.

Roadside controllers are equipped with surveillance equipment to monitor lane condition (oil spill, frost etc.) and any obstruction (dropped ladder, moving animal etc.) on the AHS lane. This information is passed to the regional traffic management center. In case of an unfavorable lane condition (oil spill, frost etc.), the regional traffic management center slows the AHS traffic speed and/or increases the headway distance. The regional traffic management center dispatches maintenance crews for cleanup. The case of obstruction on AHS lane is discussed in section 13.5.1.2.4

Roadside controllers check for any non AHS vehicles on the AHS lane. If a non AHS vehicle is detected on AHS lane, the regional traffic management center increases the distance between AHS and non AHS vehicle by either increasing/decreasing speed or increasing headway distance of AHS vehicles. The regional traffic management center also notifies the highway patrol to handle the situation.

13.5.1.2.4. Maneuver planning and execution

Normal maneuvering and execution was discussed above in sections 13.5.1.2.1 and 13.5.1.2.2.

Roadside stations detect any obstruction on AHS lane and relay this information to the regional traffic management center. This information is relayed by the regional traffic management center to all the previous roadside controllers, up to a specified distance. Roadside controllers relay this information to all cars and platoons within that specified distance from the obstruction. Roadside controllers also inform the on-board computer to leave the AHS lane and break the platoon. Once the vehicle exits the AHS lane, control is returned to the driver by the on-board computer, which also notifies the roadside controller about the successful exit of the vehicle from the AHS lane. Once AHS vehicles pass the obstructing point on AHS lane they are again given permission to merge in the AHS lane.

13.5.1.3. Check out

The checkout procedure is the reverse of the check-in procedure. The driver punches a command on the keypad to initiate the sequence. The on-board computer informs the roadside controller. The roadside controller relays this command to the regional traffic management center. The regional traffic management center grants permission to change the lane. At this point, the on-board computer uses the proximity sensors to check the feasibility of the lane change. If conditions are feasible (gap in physical barrier and no car in near proximity in the other lane), then the vehicle changes lane and goes into quasi-automatic mode. The driver is informed at this stage to take control and the roadside controller is informed of a successful lane change. After the driver takes control of the vehicle, the on-board computer can be switched off.

13.5.1.4. Malfunction management

Malfunctions are classified into two major classes:

- Vehicle malfunction, and
- Infrastructure malfunction

13.5.1.4.1. Vehicle malfunction

Before entering the AHS lane, the vehicle on-board computer goes through a self check. In case of a fault it prevents the driver from merging into the AHS lane by sounding an alarm. Also, if the driver still tries to merge into the AHS lane, the roadside controllers deny the request. The on-board computer never enters the quasi-automatic state, thereby preventing the driver from entering the AHS lane.

There is a possibility that a vehicle on-board system might malfunction while the car is moving in the AHS lane. The worst case scenario is computer malfunction. Since the on-board computer is the heart of the system, its failure (even though rare) causes tremendous problems to the driver. In such a case, the roadside controller detects this problem and relays this information to the regional traffic management center. The regional traffic management center treats this car as a non AHS vehicle. Handling of non AHS vehicles was discussed in section 5.1.2.3. The steering locks for few moments and an alarm sounds to inform the driver to take control of the vehicle. Also, the speed gradually decreases in order to break the platoon. The driver exits from the AHS lane by using the next gap available. The rest of the vehicles resume their journey after the departure of the malfunctioned vehicle from the AHS lane.

One hundred percent redundancy is provided by having a backup computer to take over in case the main on-board computer fails. Another way of solving this problem is to have a small computer that is programmed to take the vehicle out of the AHS lane only in case of such an emergency and that disengages after giving control to the driver.

13.5.1.4.2. Infrastructure malfunction

In this design, an infrastructure malfunction is not very critical as every stage has a backup to take control. In case of a roadside controller failure, the regional traffic management center detects it either by signal loss or data corruption. The regional traffic center shifts all the necessary parameters to adjacent roadside controllers to take control.

This backup management is on temporary basis and a maintenance crew is dispatched to replace/repair the defective controller component(s).

13.5.1.5. Emergency handling

In case of emergencies, the regional traffic management center relays global commands to all the AHS vehicles in that region to go to high safety mode. High safety mode is defined as shutting down the AHS functions by breaking the platoons slowly, reducing the speed, informing the drivers to change out of the AHS lane, etc. (i.e., the graceful degradation of the AHS system).

13.5.1.6. Flow control

Flow control is managed by roadside controllers in conjunction with regional traffic management centers. Roadside controllers inform the regional traffic management center about traffic conditions on the AHS lane (total number of cars passed in a certain time, average number of cars per platoon etc.). The regional traffic management center allows or disallows more AHS vehicles on the AHS lane. Regional traffic management centers have global traffic knowledge for an entire region. Regional traffic management centers share data with each other for better traffic flow control. Also, these centers are aware of any obstruction on an AHS lane, and so can redirect AHS traffic to non AHS lanes in advance.

13.6 IMPLEMENTATIONS

The implementation of this system depends on providing an array of electronic devices on-board the vehicle and enhancing the existing highway infrastructure. The success of this AHS concept relies on the speed and accuracy of on-board computers and instruments in conjunction with support provided by ground-based systems.

13.6.1 On-Board Vehicle Systems

The on-board vehicle systems consists of a(n):

- On-board computer,
- Headway detection system,
- Lateral sensing system,
- Side-looking proximity sensors,
- Lateral and longitudinal control subsystems,
- Communication module,
- Antenna array, and
- Backup power system.

Refer to diagram 2 for an overview of on-board vehicle systems and signal flows.

13.6.1.1. On-Board Computer

The on-board computer incorporates all necessary hardware, i.e., temporary and permanent storage devices, backlit LCD screen, keypad, and an adequate number of ports to communicate with all the on-board systems.

13.6.1.2. Headway detection system

The headway detection system consists of all essential hardware to provide range information to the on-board computer. The hardware includes a dedicated processor to relieve the on-board computer for other critical decisions.

13.6.1.3. Lateral sensing system

The lateral sensing system provides lateral guidance to the on-board computer. The lateral guidance employs a dedicated CPU to relieve the on-board computer for other critical decisions.

13.6.1.4. Side looking proximity sensors

Each vehicle is equipped with two side looking proximity sensors, one mounted on each side. These proximity sensors are the capacitive or inductive type and provide information about their presence to the on-board computer. Another option is to use a laser range finder as a proximity sensor. This way the on-board computer not only detects the presence of an object but also obtains range information. This option helps the on-board computer to make better decisions. These proximity sensors also help the on-board computer to avoid collisions through advanced warning when an object is too close.

13.6.1.5. Lateral and longitudinal control subsystems

The longitudinal control subsystem consists of throttling and braking control whereas the lateral control subsystem consists of steering control. The on-board computer generates the commands to control both subsystems. These subsystems have no intelligence of their own.

13.6.1.6. Communication module

The communication module contains radio modems and transceivers for the allocated frequencies. The communication module handles bi-directional, short range vehicle-to-roadside controller communications.

13.6.1.7. Antenna array

The antenna for short range communication between the vehicle and the roadside controller is a wide beam, low-gain unidirectional antenna.

13.6.1.8. Backup power system

A separate rechargeable battery is used to power the vehicle on-board systems and is charged by the vehicle battery charging system. A power flow monitor ensures that power only flows from the vehicle battery charging system to the separate rechargeable battery. A power monitor checks the battery and informs the on-board computer about its condition.

13.6.2 Infrastructure Modifications

In order for this system to work properly, infrastructure modifications are essential. This concept dictates regular maintenance and continuous vigilance over the dedicated lane condition.

Low-level modifications require that lane striping is maintained on a regular basis. Measurements are necessary to keep the AHS lane separated from non AHS lane. Gaps are provided at suitable intervals for the AHS traffic to merge and separate from the AHS lane.

Mid-level modifications are the roadside controllers and regional traffic management centers. The number of roadside controllers depends upon the number of obstacles (high rise buildings, trees, high tension lines etc.) as well as other radio frequency generating devices such as radio stations, cellular phone stations, and airports that are present in a particular area. Each regional traffic management center only handles a certain number of roadside controllers due to bandwidth constraints.

Roadside controllers are equipped with radio modem and transceivers to communicate with vehicles, local computers, surveillance equipment, weather sensing gear, and requisite hardware required to talk to regional traffic management centers such as fiber/copper link or radio modem and transceiver. Optional items are a camera with tilt and pan outfit. The camera has all the necessary hardware to communicate with the local computer.

The regional traffic management center is equipped with computers, high resolution monitors, and communication equipment such as a fiber/copper link or a radio modem and transceiver.

13.6.2.1. Rural highway implementation

Roadside controllers need power to run. Two possible providers exist. Power is provided by the local power company if they have an underground or overhead power line in the near vicinity. Alternatively, power is provided to roadside controllers by the highway department, who can lay an underground power line alongside the freeway. Laying an underground power line requires transformer stations at certain distances to maintain the original voltage level.

A separate conduit alongside the underground power line serves as a carrier for the fiber/copper link. This eliminates the use of expensive radio modem/transceiver combinations. Such a link between roadside controllers and regional traffic management centers is more reliable.

There is not much radio frequency interference in a rural area, so roadside controllers can have high power transceivers to communicate with vehicles. This eliminates the need to have roadside controllers close-by and permits design freedom in the installation of roadside controllers at larger distances.

13.6.2.2 Urban region implementation

Urban region implementation is totally opposite to rural region implementation. Urban regions have access to power at almost all locations. The available power is generally of good quality and is very reliable.

Radio frequency interference is much greater in urban areas and the chance of having obstacles such as high rise buildings, trees, and high tension power lines is much greater. This requires more roadside controllers, which in turn require low power transceivers so there is no interference with each other or with other nearby radio equipment.

Urban areas have access to phone lines and dedicated lines leased from local phone companies. Leasing a dedicated line eliminates the need to have a radio modem/ transceiver combination in each roadside controller to communicate with the regional traffic management center. This greatly reduces the cost per roadside controller.

13.6.3 Deployment

A minimal deployable system consists of vehicle mounted lateral and longitudinal control and minimal infrastructure support. Infrastructure support is limited to lane maintenance only. A vehicle equipped with such a system assists the driver in keeping the car under better control by maintaining the distance between the vehicle in front and by keeping the car in the middle of the lane. This is a quasi-automatic system, giving the driver the option to override anything the driver does not like. The driver must still stay alert, but this is less stressful than having full control over the car.

With full system in operation, the driver not only drives in a stress free environment, but has time to do other work while traveling in an AHS vehicle.

14. CONCEPT 12A: INFRASTRUCTURE MANAGED MIXED FREE AGENTS

14.1 OVERVIEW

This chapter describes in detail the operational, functional and implementation issues involved in the AHS Concept "Infrastructure Managed Mixed Free Agents".

Concept #12a is one of four infrastructure managed AHS concepts that call for complete separation of AHS and non-AHS traffic, thereby leading to a dual highway system in the country. Among these four concepts (#12a, #12b, #13, #19), one (#19) calls for manual avoidance of obstacles, thereby depending upon the driver for an extremely important maneuver. The other three concepts, including #12a, do not expect the driver to do any maneuvering from the point of entry to the point of exit. They call for completely hands-off driving. These three concepts all share the feature of automatic sensing and avoidance of obstacles.

Two of these three concepts (#12b, #13) divide the highway system even further, on the basis of vehicle class. No mixing of vehicle classes is envisioned, even at the point of entry/exit and for transition purposes. This leads to a tiered AHS system, each tier catering only to certain classes.

Concept #12b allows mixing of vehicle classes in AHS lanes, at least for transitional, highway interchange and entry/exit purposes. It opens up the possibility that conventional highway structures can be modified slightly to prepare them for the AHS system. At the same time, it calls for free agents instead of platoons as the primary units of longitudinal and lateral control.

This concept represents the possibility that the most cost-effective way of achieving maximum throughput is by allowing the vehicle classes to mix in transition areas, thereby eliminating the need for special exits and interchanges, and by taking the middle path in both vehicle-based intelligent control and infrastructure based control. The infrastructure is expected to be an intelligent agent that monitors every vehicle but does not control any unless requested under normal circumstances; this keeps the cost low. The vehicle is expected to be intelligent enough to keep its lane and sense its immediate surroundings, but is not expected to accomplish lane changes or manage initial placement without infrastructure help.

The distinguishing feature of this concept is the maximum achievable throughput without using platooning and medium cost infrastructure. Complete vehicle automation and global traffic flow management are going to be the important factors in achieving that goal. Infrastructure setup investment is mainly in the setting up traffic management centers and communication networks.

14.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

	Concept Characteristic	Dimension Alternative
1	Distribution of Intelligence	Infrastructure managed
2	Separation Policy	Free Agent
3	Mixing of AHS and non-AHS Vehicles in the Same Lane	Dedicated lanes with physical barriers
4	Mixing of Vehicle Classes in a Lane	Mixed
5	Entry/Exit	Dedicated
6	Obstacle Avoidance	Automatic sensing and automatic maneuver if possible

1. The intelligent agents reside both on the vehicle and on the infrastructure. The driver is the highest-level decision maker inside the vehicle, though he, necessarily, transfers full control to the vehicle. The vehicle uses on-board intelligent control systems mainly for longitudinal control and possibly for lateral control. The main mode of

infrastructure operation is a request-response type. Each vehicle's requests are processed and appropriate commands are sent to the appropriate vehicles to respond to that request. The infrastructure takes a more pro-active role in monitoring traffic flow, broadcasting traffic flow messages, advising lane changes to individual vehicles, and the other usual ITS functions. The infrastructure is also capable of highly intelligent functions. This means taking over complete control of any individual vehicle, i.e., the infrastructure can completely substitute for a vehicle's intelligence and assume longitudinal, lateral and navigational control. However, it might not have enough resources to control more than just a fraction of vehicles on the road at a time. The local officials may opt for an infrastructure that takes over the vehicle only in case the vehicle (or the driver) authorizes such a transfer of control. Such a practice might be limited to off-peak hours.

2. The longitudinal separation policy is based upon the assumption that the traffic is composed of vehicles driven as free agents. The longitudinal separation between two free agent vehicles, though not quite as little as within a platoon, is still appreciably lesser than that in the conventional highways because of the intelligent longitudinal control system. Therefore maximum throughput of the system is expected to be somewhere between that of AHS system with extensive platooning and conventional highways.
3. Only those vehicles that have fully functioning AHS capabilities are allowed to enter the AHS. Moreover non-AHS vehicles are separated by physical barriers from AHS vehicles. The only way a non-AHS vehicle can make its way to an AHS lane is either by trespassing at the entry point, or if its AHS capabilities fail during travel. The local tailorability is minimal in this regard, as the system is jeopardized if many non-AHS vehicles find their way to AHS lanes. It implies a dual highway system in which the AHS system is completely independent of the non-AHS system.
4. Each AHS lane can, in principle, be used by vehicles of all classes. The AHS system is geared to handle mixed traffic in all lanes. However, the characteristic is highly tailorable according to local requirements. In a more typical scenario, the local officials may bar the heavy vehicles from the lane of lighter vehicles, but let the light vehicles use the lane reserved for heavier vehicles, especially for transition purposes at entry/exit points and highway-to-highway interchanges. Though mixing of vehicle classes is permitted, each lane may still be denoted for main use by certain classes of vehicles. A more detailed protocol of lane usage is left for the local authorities. As compared to the no-mixing option, the mixing option is much easier to implement as far as the physical highway structure is concerned. Conventional highways can be upgraded gradually to function as AHS highways. However, maximum throughput in the mixing option is significantly less, though still greater than with conventional highways.
5. Entry/Exit structure is driven by the two concept characteristics discussed above, i.e., AHS and non-AHS traffic separated by physical barriers, and mixing of vehicle classes in a lane. Entries and exits to AHS are composed of fully dedicated lanes, i.e., at no time does AHS traffic mix with non-AHS traffic. Since mixing of vehicle classes is permitted in a lane, one lane per entry/exit suffices. Local officials may opt for more lanes per entry/exit, each possibly catering to a different AHS lane and a different set of vehicle classes.
6. Obstacles of nearly every size, stationary or moving, are sensed and detected by the non-human intelligent agents, both on-board the vehicle and the ones in the infrastructure. The response depends upon the situation. An automatic maneuver to avoid the obstacle would be made, if considered possible. Possible

maneuvers include fast lane changing, swerving around the obstacle, driving over the obstacle, and emergency braking. The response considers obstacle size and type. The safety of the vehicle in question and the others around it is the supreme concern. At no stage is human involvement expected, except possibly in the sensing of the obstacle. Any human input regarding a possible obstacle is processed first by the non-human agents before being used for detection or maneuvering. Any temporary or permanent non-AHS vehicle on the highway is considered an obstacle.

14.3 OPERATIONAL CONCEPT

Two different point of views are considered to illustrate the operational design of the system, that of the driver of each vehicle and that of the vehicle. The emphasis is limited to the normal operating conditions.

Before these point of views are presented, it is illustrative to consider the four modes of operation a vehicle can have based on who is in charge. The intelligent agent in charge makes high level decisions that are executed by agents lower in the control hierarchy.

- The vehicle is in charge through the use of an array of intelligent control systems.
- The vehicle (and in exceptional circumstances the driver) authorizes the infrastructure to take charge, for example during the lane changes, entry/exit, and emergencies.
- The infrastructure wrests control from the vehicle.
- The driver of the vehicle is in charge under emergency conditions.

In any case, once the vehicle is no longer in control, it is unable to get it back on its own; the infrastructure has to reinstate control. Whenever a transfer of control takes place from the infrastructure to the vehicle, the vehicle has to actively take over control and convince the infrastructure it is aware of the transfer. If the vehicle fails to respond in the right fashion, the infrastructure retains control. Similarly, once the driver transfers control to the vehicle, he is unable to get it back on his own. The vehicle has to reinstate control; this normally happens only at exit. The driver has to convince the vehicle that he is aware of the transfer. If the driver fails to respond in the right fashion, the vehicle retains control.

14.3.1 Driver Point of View

A driver decides to enter the AHS and picks the entry point for its vehicle classes, in case there are multiple entry points. The driver logs in the vehicle class and trip description, possibly without ever stopping. Permission to enter might be denied at this point, if the vehicle fails the AHS-capability tests. The driver is given a suggested route to the destination. Under normal circumstances, the driver is expected to be a passive observer until exit. Under emergency conditions, full control may be passed to the driver who then assumes manual control of the vehicle.

The only operation a driver can possibly perform is the change of exit.

1. Change of Exit: The driver registers a change of exit with the vehicle, which then informs the infrastructure.

14.3.2 Vehicle Point of View

The vehicle is guided to one of the AHS lanes (decided upon by the infrastructure to optimize the traffic flow). This may involve automatic lane merging, lane changing, acceleration, and deceleration. When the lane-positioning is complete, the vehicle control is given to the vehicle.

Once a vehicle is in a lane in charge of itself, it can be involved in various operations. All of the following operations are initiated by the vehicle. Some of these can be redundant if a navigational subsystem is in place.

1. Lane Following: The vehicle oversees lane following procedures. The intelligent headway and speed maintenance mechanisms, which are located on-board, control the vehicle longitudinally.
2. Request Lane Change: The vehicle decides to change lane and registers a

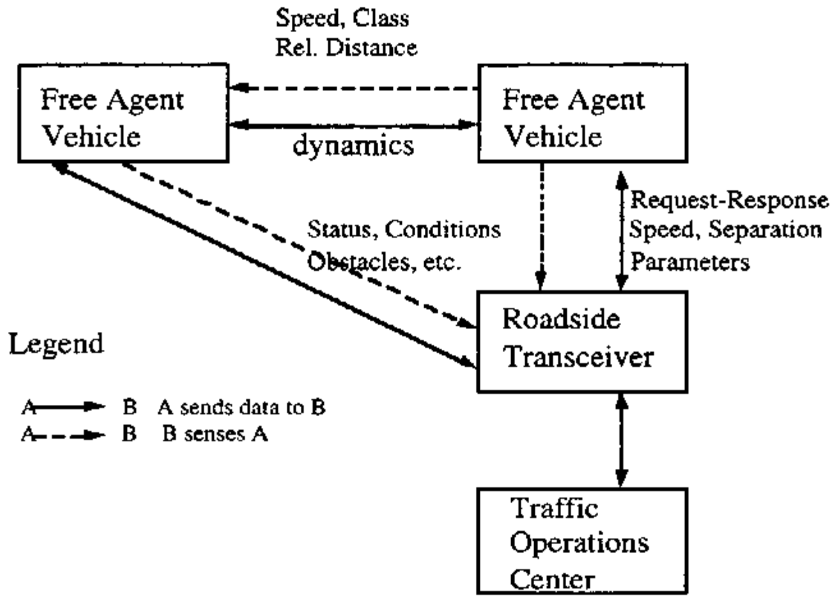

Figure H.14.3-1. System Diagram

request with the infrastructure. A lane change request can also be initiated by the navigational system or certain other intelligent non-human agents aboard the vehicle. The request cannot normally be denied unless it leads to an unusual disturbance in the normal operations. Once the request is granted, the vehicle is informed and taken out of the control loop until the lane has been automatically changed. Control passes to the vehicle from the infrastructure when the vehicle is stably located in the new lane.

3. Request Exit: The vehicle is informed of the approaching destination exit or the driver decides to make an early exit or the navigation system senses the approaching exit. In any case, a request is registered with the infrastructure. The request is granted under normal circumstances, unless the requested exit is congested, or is not available for some other reasons. If the request is granted, the vehicle is taken out of the loop, a series of automatic lane changes occur, and the vehicle is guided to the exit lane, where control is passed back to the driver.
4. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the vehicle may decide to take avoidance maneuvers without the help of the infrastructure. Automatic maneuvers are performed to avoid a collision. They include fast lane changing, swerving around the obstacle, driving over the obstacle, and emergency braking.

Certain operations are not initiated by the vehicle. The infrastructure, after informing the vehicle, takes control and performs these operations. These are the operations that can appear unexpectedly to the driver.

1. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the infrastructure may decide to take charge of the vehicle and perform automatic maneuvers to avoid a collision. Such maneuvers include fast lane changing, swerving around the obstacle, driving over the obstacle, and emergency braking.
2. Automatic Acceleration/Deceleration: The above operations are performed to create room for vehicles that are attempting a lane change.
3. Automatic Rerouting: Automatic rerouting is done by the infrastructure to optimize the overall traffic flow from the point of view of throughput and congestion.

14.4 SYSTEM DIAGRAM

Information and control commands and parameters flow among "free agent" vehicles, and between "free agent" vehicles and the infrastructure.

The vehicle to vehicle data communication is related to maneuver coordination, position, velocity, acceleration data, and vehicle dynamics. The vehicle-to-infrastructure data communication consists mostly of requests, e.g., lane change request, entry/exit request, etc., as well as vehicle status information. In addition, vehicles transmit information regarding obstacles detected by the sensors on the vehicle.

The infrastructure-to-vehicle data communication consists mainly of responses to vehicle requests, e.g., commands for lane changes, exit, lane positioning etc. There is additional non-response type data flow regarding the position of obstacles, routing commands, traffic flow information etc. While the exact content of the communicated messages has not yet been defined, it is estimated and expected that a medium bandwidth communications channel will suffice. At this time, rough estimates of the magnitude of the message size, update rate and range are given below.

The bulk of the communication takes place between vehicles. Based on prior experiments, it is estimated that messages of up to 100 bytes with a repetition rate of 1/10th of a second are used. This requires a channel with 9600 bps capacity and a variable duty cycle. That is, the communication channel may not always need to transmit the maximum possible message size. Vehicles that are at some distance apart are not likely to have a need to communicate, as their dynamics and trajectories do not affect each other. At the same time it is desirable to minimize the transmitting power and range of vehicle to vehicle communication to minimize interference to other vehicles and to allow for efficient spectrum reuse. At this time, a 1/4 mile maximum range seems sufficient and reasonable.

Similarly, to simplify the complexity of the infrastructure control requirements it seems reasonable that such control be localized. Each roadside transceiver only communicates with a finite and limited number of vehicles. The optimal numbers need to be computed after a careful analysis. At this time, only a rough estimate is possible. It is also a good idea to make it possible for two adjacent roadside transceivers to receive vehicle-to-infrastructure communications for purposes of redundancy and reliability, which requires doubling the range of communication from the vehicle-to-roadside as opposed to the other way around. The roadside-to-vehicle communications are made reliable by on-vehicle redundancies. However, it would be desirable for one, and only one, roadside transceiver to attempt to communicate with each vehicle. The hand-over of the vehicle from one roadside transceiver to the next can be handled by the Traffic Operations Center.

To summarize the requisite communication:

- Vehicle in front to Vehicle in Back: Message Content: Position, Velocity, Acceleration, Braking force, operational status, emergency ahead. Also communicated at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, and estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 9600 bps channel, 75% duty cycle, 1/4 mile maximum range.
- Vehicle in front to Vehicle in Back: Passive reflection of the radar sensor beam from the Vehicle in Back permits this vehicle to detect relative position and relative speed.
- Vehicle in back to Vehicle in Front: Message Content: Position, Velocity, operational status. Also communicated but at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 960 bps channel, 25% duty cycle, 1/4 mile maximum range.
- Infrastructure to Vehicle: Message Content: Command and control requests,

speed and separation parameters, road surface condition advisories, notification of location and nature of emergencies. 1000 byte "packets", 1 sec repetition rate, 960 bps channel, 25% duty cycle, 1 mile maximum range.

- Vehicle to Infrastructure: Message Content: Position, Velocity, Acceleration, operational status, road surface condition, detected obstacles. 1000 byte "packets", 1 sec repetition rate, 960 bps channel, 5% duty cycle, 2 mile maximum range.
- Infrastructure to ANY vehicle (Broadcast): Message Content: Broadcast location identification, road surface condition advisories, traffic condition advisories, notification of location and nature of emergencies. 1200 byte packets, 10 sec repetition rate, 1200 bps channel, 100% duty cycle, 4 mile maximum range.

Furthermore, there is a need for the infrastructure to be able to sense the presence, position and velocity of vehicles within the range of authority of its Traffic Operations Center. While most of that information will be provided by the vehicles themselves through the vehicle-to-infrastructure communications channel, the infrastructure should have an independent way to obtain the same information for the purpose of reliability through redundancy and to allow the identification of non-equipped or malfunctioning vehicles. The interval of installation of roadside sensors is equal to the roadside transceiver distance from each other and the bandwidth of the communication channel between roadside sensors and TOC is roughly equal to that of the vehicle to infrastructure data channel times the maximum number of vehicles that may have to be supervised at once.

14.5 FUNCTIONAL ALLOCATION

14.5.1 Baseline Functions

14.5.1.1. Check-in

Allocated to the vehicle in combination with the infrastructure. The function is performed in coordination with the infrastructure after the vehicle passes operational test. Equipped vehicles are coordinated and assisted in merging. Non-equipped or non-fit vehicles are not allowed to enter. Sequence of events description: The driver decides to enter the AHS and selects an entry point that is appropriate for his vehicle class. Once the vehicle reaches the entry point, an operational test is performed. Some operational status data may have been collected during normal driving before reaching the entry point while other data may be collected on the spot. These results are communicated to the infrastructure. The infrastructure makes the go/no-go decision regarding the operability of the vehicle. A traffic light with arrows directs the driver towards the AHS lanes if the result is "go" or towards the manual lanes if the result is "no-go" As soon as the "go" condition is given and the vehicle approaches the AHS lane it's velocity control is assumed by the infrastructure in order to coordinate its motion in preparation for merging.

14.5.1.2. Transition from manual to automatic control

Allocated to the vehicle. The transition is contingent upon successful check in. Sequence of events description: Velocity control is assumed by the automatic controller first. If the vehicle velocity responds to the infrastructure commands as intended, lateral control is subsequently assumed by the automatic controller. If a failure is detected at this time, the driver is immediately notified to continue driving the vehicle as a manual vehicle and directed towards the manual lanes or emergency lane.

14.5.1.3. Automated Sensing of roadway, vehicles and obstacles

Allocated to the vehicle. Sequence of events description: Electronic sensors mounted on the vehicle perform the sensing and detection functions continuously or with a repetition frequency adequate for the required bandwidth of the on-vehicle automatic controllers.

14.5.1.4. Longitudinal sensing

Vehicle sensors sense the presence of other vehicles and obstacles in the space ahead of the vehicle.

14.5.1.5. Lateral sensing

Vehicle sensors sense the presence of other vehicles and obstacles in the space on each side of the vehicle.

14.5.1.6. Obstacle sensing

Vehicle sensors are able to sense at least some kinds of obstructions other than vehicles.

14.5.1.7. Vehicle longitudinal position sensing

Both absolute (medium high accuracy) and relative to the vehicle in front (very high accuracy).

14.5.1.8. Vehicle lateral position sensing

Both absolute (high accuracy) and relative to the vehicles on each side (medium accuracy).

14.5.1.9. Automated Sensing of vehicles and obstacles

Allocated to the infrastructure. Roadway sensors belonging to the infrastructure collect information about obstacles and pass this information to the vehicle. Sequence of events description: The infrastructure employs video cameras, radar, inductive loops, and other sensors to sense as accurately as possible the location position and velocity of vehicles in the AHS lanes. Disabled vehicles are classified as obstacles. Detection of other obstacles (foreign objects, stray animals etc.) may be possible but of limited success.

14.5.1.10. Collision avoidance

Information from the vehicle sensors and the infrastructure is passed to the Longitudinal Velocity Controller, which acts as a longitudinal collision avoidance system. Sequence of events description: All the information collected by the on-vehicle sensors is correlated with the information provided by the vehicle in front as well as the information provided by the infrastructure. If the information is deemed consistent, it is used as input to the Longitudinal Velocity Controller. If minor inconsistencies are found, the worst case scenario is assumed by the controller and the infrastructure is notified via the status report. If major inconsistencies are found, an emergency is declared and the driver is notified that he may have to resume manual control. At the same time, the infrastructure and other vehicles in the vicinity are also notified and requested to increase their distance from the malfunctioning vehicle. If the information from all sensors is consistent and indicates that the vehicle is in a collision path with another vehicle or a newly identified obstacle, the Longitudinal Velocity Controller attempts to reduce the velocity by applying emergency braking. A change lane request may also be generated by the vehicle and transmitted to the infrastructure.

14.5.1.11. Automated headway keeping

Allocated to the vehicle. Vehicle sensors measure relative position and relative speed to the vehicle in front. The controller can control the velocity and headway of the vehicle down to zero velocity, including stop and go situations. Sequence of events description: All the information collected by the on-vehicle sensors is correlated with the information provided by the vehicle in front as well as the information provided by the infrastructure. If deemed consistent, this information becomes the input to the Longitudinal Controller, which applies throttle or brake as necessary to maintain the headway that is recommended by the infrastructure. The headway recommendation of the infrastructure is adjusted by the vehicle controller depending on information from the vehicles in front and in the back and also according to the road surface conditions. The infrastructure is notified of any changes.

14.5.1.12. Automated Lateral Controller. (Lane Keeping)

Vehicle based, but is likely to require the presence of "markers" or other aids from the infrastructure. Sequence of events description: The on-vehicle sensors detect the position of the vehicle in absolute terms and also relative to the lane boundaries and other vehicles on adjacent lanes. The information is used to control the steering angle so that the vehicle follows a smooth trajectory near the center of its assigned traffic lane.

14.5.1.13. Detection of hazards

Vehicle-based or in combination with the infrastructure. The vehicle may use the longitudinal and lateral sensors. The infrastructure may assist by transmitting to all vehicles the exact location of known hazards. Sequence of events description: The longitudinal and lateral sensors on the vehicle pass the information collected to the controller. The information is correlated to the information received via communications from other vehicles and the infrastructure. Any objects detected by the vehicle sensors that do not coincide with any objects known to the infrastructure are automatically classified as potential hazards and the infrastructure is immediately notified of their presence. Furthermore, if the position of the hazards appears to be in the path of the vehicle, the collision avoidance procedures are automatically initiated.

14.5.1.14. Normal Maneuver planning

Allocated to the vehicle in combination with the infrastructure and is executed by the vehicle based on information from the sensors and the infrastructure. Sequence of events description: Based on the desired destination declared by the driver, the vehicle navigation controller employs information provided by the infrastructure to implement the vehicle travel plan. The plan is submitted to the infrastructure for approval. Depending on local conditions the infrastructure may opt to alter the travel plan and may request additional maneuvers at any time.

14.5.1.15. Emergency Maneuver planning

Allocated to the vehicle, possibly in combination with the infrastructure. In some cases, it might be managed by the infrastructure. Sequence of events description: It is assumed that the most likely implementation is for the vehicle controller to assume the responsibility of "self-preservation" during emergencies. Infrastructure involvement may be necessary even during emergencies to avoid the possibility of chaotic behavior when individual vehicles begin attempting emergency maneuvering on their own. This is an area that bears further investigation.

14.5.1.16. Normal Maneuver execution

Allocated to the vehicle and is executed by the on-board controller. Sequence of events description: The on-vehicle controller applies the throttle brake and steering actuators as necessary to implement the desired maneuvers.

14.5.1.17. Emergency Maneuver execution

Allocated to the Vehicle and is executed by the on-board controller, though in some cases, the driver may be called in to take control. An exact scenario to be followed is subject to debate. Sequence of events description: The on-vehicle controller applies the throttle brake and steering actuators as necessary to implement the desired maneuvers. The driver may have the option to intervene, but his intervention power may be limited or his intervention power may depend on the situation. That is, certain scenarios may allow more driver input than others. This appears to be a very problematic issue with respect to the eventual deployment of AHS.

14.5.1.18. Transition from automatic to manual control

Allocated to the vehicle, driver or infrastructure. Sequence of events description: It is requested by the driver, the infrastructure, or enforced by the vehicle as a failure response fallback mode. This normally happens immediately after check-out. A likely scenario is: The vehicle relinquishes partial control to the driver who is notified and expected to apply certain corrections to the vehicle velocity and path by applying a moderate amount of braking and steering. By doing so, he effectively verifies his alertness and readiness to resume full manual control. If he fails to perform the required actions within the allocated time, the vehicle controller declares that the driver is unfit and resumes fully automatic vehicle control. In this case the vehicle is driven automatically to a designated exit that has been designed for the accommodation of "sleeping" drivers and brought to a complete stop. A human operator approaches the vehicle and investigates the condition of the driver. If he has suffered death or loss of senses, he is taken to a hospital. If he is found to be under the influence of drugs or alcohol, he is taken to jail. If he is sleeping he is awakened. If he is playing games, i.e., testing the system, he is cited for a traffic violation.

14.5.1.19. Check out

Allocated to any one of the vehicle, driver or infrastructure. Sequence of events description: Check-out may be requested by the driver, the infrastructure, or enforced by the vehicle as a failure response option. In most cases the vehicle is self guided towards the exit ramp and a transition from automatic to manual control is initiated.

14.5.1.20. Flow control

Allocated to the infrastructure. The infrastructure manages and controls the traffic flow. The sequence of events description: The infrastructure measures the volume and the velocity of the traffic at different sections along the AHS. A central controller at the Traffic Operations Center decides on optimal velocity, spacing and traffic routing to control and optimize traffic flow.

14.5.1.21. Malfunction management

Allocated to the vehicle, infrastructure and possibly the driver, in combination. In most cases it is cooperative between the vehicle and infrastructure. Sequence of events description: If the malfunction is identified to be on the vehicle, it is fully or partially compensated by redundancy and the vehicle is requested to check-out at the earliest opportunity. If the malfunction is identified to be on the vehicle but is not covered by redundancy, the driver is notified and requested to resume full manual control. If the malfunction is identified to be on the infrastructure, the vehicle and the driver are notified of the exact nature and the extent of the loss of functionality and the AHS continues operating in a degraded fashion, is shut down, or is temporarily converted to manual operation.

14.5.1.22. Handling of emergencies

Normally allocated to the vehicle or to the vehicle and the driver in combination. Sequence of events description: The most likely implementation is for the vehicle controller to assume the responsibility of "self-preservation" during emergencies. Infrastructure involvement may be necessary even during emergencies to avoid the possibility of chaotic behavior when individual vehicles begin attempting emergency maneuvering on their own. In at least some cases, it may become necessary to pass control responsibility to the driver, who would be expected to assume manual control of the vehicle.

14.6 IMPLEMENTATION

In this section, one possible implementation concept is described. This is not the only possible implementation or even the most recommended one. It is only a representative example of an implementation that permits visualization of the magnitude and complexity of the problems involved and the intricate relations and interdependencies between system components.

14.6.1 Vehicle

The vehicle requires the following functions and subsystems:

Fail-proof longitudinal control system. The longitudinal control system serves the function of velocity and headway maintenance. The requirement for fail-proof operation of the longitudinal controller under all conditions imposes the need for extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.

1. Fail-proof lateral control system. The lateral control system serves the function of lane keeping and lane changing. The requirement for fail-proof operation of the lateral position controller under all conditions imposes the need for extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.
2. Accurate longitudinal position sensing. The longitudinal position of the vehicle is known in absolute terms and in terms of relative position to other vehicles. The absolute position is for navigation and trip destination control purposes and the relative position for velocity and headway maintenance and control, as well as for collision avoidance.
3. Accurate lateral position sensing and lane position identification. The lateral position of the vehicle is known in absolute terms and in relative position to other vehicles. The absolute position is for lane keeping, lane changing and navigation purposes and the relative position is mostly for collision avoidance especially during lane changing.
4. Collision avoidance based on obstacle sensing in combination with vehicle-to-vehicle and vehicle-to-infrastructure communications. Vehicle sensors are not adequate and do not guarantee collision avoidance with any kind of obstacle or even with another vehicle. Therefore, the collision avoidance control logic requires additional information that can only be supplied by other vehicles and by the infrastructure.
5. Maneuver coordination between vehicles. Every aspect of the motion of the vehicle, especially lane changes, is orchestrated and coordinated by a control authority at a higher level than each vehicle itself. This control authority is distributed collectively among vehicles or it is assigned to the infrastructure. Most likely, a local decision affects the assignment of this control authority. In urban regions, the authority is exclusive to the infrastructure. In rural regions, the authority is distributed among vehicles and in every case it is dynamically distributed among the vehicles and the infrastructure by means of appropriate maneuver protocols.
6. Automatic route guidance based on navigation computers and interaction with the infrastructure.
7. Supervisory controller which monitors everything and alerts the driver of any single point failure. Malfunction management is one of the more complicated issues facing AHS system designers. It is desirable, if not essential, that every part of the automation be covered by multiple redundancies so that no single point failure affects the operation of the system. At the same time, any failure must be immediately detectable and the driver must become aware of it as soon as possible to assume partial or full control of the vehicle if necessary.

14.6.1.1. Required vehicle components

Two longitudinal range and range rate sensors. based on Forward looking Doppler radar, FMCW radar, infrared laser ranging system, optical recognition method or combination of the above are required.

Side looking vehicle and obstacle sensors based on very low power radar, sonar, or infrared light are required.

Redundant lateral lane position sensors are required. These same sensors provide absolute longitudinal position information. The sensing method includes Differential GPS and the use of lane markers, which requires a potentially large investment in the infrastructure. Candidate lane marking methods include magnetic nails, magnetic lane marking paint, corner reflectors for radar, optical patterns, and others. A single method with optimal performance cannot be identified at this time. Each system has potential merits and a number of shortcomings and limitations.

A transceiver for vehicle-to-vehicle communications is required. Communication includes, but is not limited to, velocity, acceleration and braking force. Also required is a communication ability with cars in adjacent lanes for cooperation in merging.

A lateral collision warning coupled with the steering actuator for assistance in checking in and out is required.

Environmental conditions sensors are required. The primary purpose of these sensors is to sense and/or estimate road surface conditions and friction coefficients for cornering and braking.

Driver status monitors and diagnostics are required. Although the driver is not involved in the control of the vehicle when traveling in an AHS environment, his readiness status and alertness are essential in case of detected failures in some part of the redundant controllers and needed before and during the check-out stage.

Supervisory controller monitors the performance and functionality of every part of the system, including every redundant part of the controllers, sensors and actuators, the communications systems, and driver status. The supervisory controller has the responsibility to reassign responsibilities among system parts based on a well-defined priority system. The supervisory controller attempts to detect and recover any detectable failure. In doing so it reassigns actuator responsibilities to different parts of the system when actuator malfunctions are detected. Control responsibilities are reassigned to different controllers when control malfunctions are detected, i.e. to the infrastructure and eventually to the driver. Sensing responsibilities are reassigned to different sensors when sensing malfunctions are detected, i.e. to alternative sensors first, then to the infrastructure and eventually to the driver.

14.6.1.2. Vehicle implementation issues and considerations

In considering acceptable versus unacceptable failures of vehicle components, two independent ways of controlling the throttle, brake and steering are needed to accommodate any single point failure in the sensor, controller or actuator.

Furthermore, no single point failure of any subsystem should escape diagnosis or lead to loss of control. Care must be taken to avoid common mode failures such as loss of power to both parts of a redundant controller simultaneously.

14.6.2 Infrastructure

Required infrastructure components:

1. Low-level infrastructure components:

   Markers must be provided to assist the vehicles in performing the lane keeping function. These markers must be unambiguous and extremely reliable under all traffic, lighting, weather and temperature conditions. It is not expected that different type sensors are needed in rural versus urban sections of the highways.

   Physical barriers have to be provided to separate the AHS system from the non-AHS part of the highways. For cost considerations it might be considered as an option not to have those barriers in rural sections of the highways, though a safe alternative is unknown.

Mixing of vehicle classes is allowed. Therefore, no separate entry/exit ramps and highway interchanges are needed.

2. Intermediate-level infrastructure components

   Low bandwidth communication (broadcasting) must be provided to all vehicles within the authority of the infrastructure and may contain "traveler information" type data. The roadside transmitters of broadcast type information are allocated as a dual redundant station with a range of 4 miles located every 6 to 8 miles in rural highway sections. In urban sections of the highways it might be preferable to employ lower power transmitters more closely spaced, e.g., 1 mile range transmitters located every 2 miles.

3. High-level infrastructure components

   Medium bandwidth bi-directional communication with individual vehicles is required. Vehicles must be individually identifiable and individually addressable both by the infrastructure controllers and by the communication transceivers. This requirement is the same in both rural and urban sections of the highways.

   Sensing of traffic flow speed and flow density, under all traffic, lighting, weather and temperature conditions is required. The accuracy requirements may be slightly relaxed in sparsely traveled rural highways, but the sensing requirements are basically the same as in urban highways.

   Sensing of individual vehicle position and velocity under all traffic, lighting, weather and temperature conditions is required. This is required in urban highway sections but may not have to be implemented in sparsely traveled rural highway sections.

   The Traffic Operations Centers must be present along the roadside at intervals that are determined based on the typical and expected traffic density. The location and the distance between those TOCs will be different for rural and urban sections of the highways.

14.6.2.1. <u>Rural Highway</u>

In a rural highway environment, the necessary infrastructure may be different to some extent. It may be more cost efficient to cover larger areas with fewer traffic control stations. Those sparsely spaced traffic control stations must cover a larger number of vehicles over extended distances. If the distance between the infrastructure equipment and the vehicle is extended, long range communications, medium to high capacity communication channels, and reliable backup equipment are required. In rural environments, infrastructure sensing may be limited to flow rate and average velocity every few miles.

14.6.2.2. <u>Urban Highway</u>

In an urban highway environment it is likely more efficient to employ short range communications, high capacity communication channels, and closely spaced traffic control stations. Knowledge of individual vehicle position coordinates may be required at each infrastructure Traffic Operations Center site.

14.6.3 Deployment

The minimal deployable system has a longitudinal controller (maintain velocity or headway) and a lateral controller (maintain lane position) on the vehicle as well as an infrastructure system to manage the flow of traffic by providing commands and information to the vehicle.

The longitudinal controller needs a longitudinal sensor, an actuator system. and the controller hardware and software.

The lateral controller needs a lateral sensor, an actuator, and the lateral controller hardware and software.

The required communication needs a medium to high bandwidth communication transceiver on the vehicle and a communication system built into the infrastructure.

Some way for the infrastructure to monitor the traffic flow is also essential.

The incentive to buy a vehicle so equipped is that an automated vehicle driven on an automated highway offers the potential for shorter travel times and a major improvement in the comfort of the driver and passengers.

The incentive for the roadway operator to deploy an AHS roadway is the potential for reduced highway travel times, reduced pollution and most important the postponement of the need to build more highway lanes if the existing ones can be used more efficiently.

14.7 GENERAL ISSUES AND CONSIDERATIONS

What degree of automation is there in the navigation function?
The system has the capability for fully automatic navigation for any individual vehicle though it is not included as a specific requirement in the architecture. What is a characteristic of the baseline model is monitoring of each vehicle that enters the AHS, which is the most important element of a navigational system. Such information is used by infrastructure-based agents or on-board agents to navigate the vehicle automatically. The communication load on the infrastructure grows dramatically if all the vehicles are navigated by its agents. In a more reasonable scenario, the infrastructure performs the specific navigation function of initial route selection and leaves the rest of the navigation to the agents aboard an individual vehicle.

What are the obvious failure modes for the concept?
The system consists of so many subsystems that a variety of failure modes are possible. The primary failure modes can be classified into the following categories. Each category is illustrated by examples.

Sensory Failures
Vehicle cannot sense its own position:

Vehicle cannot sense the presence of other vehicles ahead,

Vehicle cannot sense the presence of obstacles ahead,

Vehicle cannot sense the presence of other vehicles aside,

Vehicle cannot sense the presence of obstacles aside, and

Vehicle cannot sense the weather conditions around.

Longitudinal Control
Vehicle cannot maintain velocity,

Vehicle cannot maintain the desired headway Lateral Control Failures, and

Vehicle cannot maintain lateral trajectory.

Communication Failures
Vehicle cannot receive communication from other vehicles,

Vehicle cannot receive communication from other infrastructure,

Vehicle cannot transmit to other vehicles, and

Vehicle cannot transmit to the infrastructure.

Entry/Exit Function Failures
Vehicle fails the check-in procedure.

Vehicle (or driver) fails the check-out procedure.

Control Transfer Failure
Vehicle cannot switch between operating modes.

What major systems or subsystems can back one another up in case of failure?
None, unless explicitly designed for the purpose. Dual redundancy is required for most automation subsystems to guarantee fail-safe operation. Triple redundancy is required on the most critical subsystems. If designed properly, degradation of the

system, in case of failure, occurs in a fashion so that if the infrastructure is unable to control a particular vehicle, it should pass control to the vehicle. In case the vehicle is unable to control itself, it is able to pass control to the driver. Each has multiple redundancy in their control systems to reduce the chances of breakdown. But if the breakdown does take place, at no time is the vehicle out of proper control.

The feasibility of such a design, however, is far from a settled issue.

Under what circumstances (if any) is control passed to the driver?
The driver has no control, except the high-level navigational one, e.g., choice of the destination, during normal operations on the AHS, which include lane keeping, lane following, lane-changes, automatic obstacle avoidance maneuvers.

The only circumstances in which the driver might get the control are exceptional ones. In a malfunctioning system, the infrastructure may perceive the manual option to be the safest one. In such a case it alerts the drivers and pass over the control to the drivers. Malfunctions could be of various types. If the control and execution mechanisms on the vehicle breakdown, and it renders the vehicle uncontrollable, then there is no choice but to give control to the driver. If the vehicle is functioning well, but the infrastructure manager breaks down, then the vehicle takes over the infrastructure responsibilities and still manages to keep the driver out of the loop. The performance is naturally degraded.

How does the system sense limited visibility, or ice, water or snow on the roadway; what does it do with this information?
The infrastructure constantly senses the highway environs for weather conditions, like visibility, temperature and precipitation. Some of these conditions might be localized, e.g., ice on a bridge, water collected on the inside lane, and some other might be characteristic to a larger area. The system senses the two kind of conditions in different fashion.

The weather parameters, like temperature and wind speed, are measured on a regional basis using standard technology. Precipitation is monitored for both type and quantity, also on a regional basis.

Some weather-related conditions are measured more locally. All the bridges are monitored for icy conditions under near-zero weather conditions. The snow level on a road during or after a snowstorm, water level if it tends to log in certain locations, are measured at regular distances in each lane and at known trouble spots.

The infrastructure uses sensors that are on each vehicle to sense localized trouble spots. The vehicle passes the relevant information to the infrastructure, which can alert the on-coming traffic of the trouble spots. Vision-based systems coupled with image processing hardware may be able to discriminate some of these conditions. Local visibility, pools of water, icy patches, and friction coefficients are examples of weather elements that might be sensed by the vehicles.

Some of the weather-related information gathered by the infrastructure is directly passed on to the vehicles, who add that information to the knowledge they already possess from their own sensors or some other prior information. The weather parameters play a very important role in the functioning of the control mechanisms in adverse conditions. Certain other information is first processed by the infrastructure to generate warnings, advisories, and commands for vehicles in specific areas and lanes. It is possible for the same piece of information to result in different courses of action for different vehicles depending upon their location, class, and lane.

What speed(s) would typical users travel at? How tailorable is this?
These are conflicting requirements. A low typical velocity hurts efficiency and performance. A high typical velocity hurts fuel economy and generates potentially dangerous conditions in case of malfunctions. The risks increase

exponentially with speed. The exact figures must be analyzed. An estimate is that the typical maximum speed will be 20% higher than the current speed limits. Lower typical speeds will be necessary in many cases. The typical speed needs to be tailorable to local conditions, but the maximum speed probably does not.

What enhanced functions would a vehicle from this concept be able to perform on a conventional highway?
Except for basic speed and headway control, a vehicle is not currently able to perform other enhanced functions on conventional highways. However, a low-level infrastructure modification like magnetic nails and exit sensors, opens various possibilities. A vehicle, with capabilities of this concept, can possibly perform a variety of enhanced functions on these slightly modified highways. Longitudinal control functions, e.g., sophisticated lane keeping and lane following functions can be performed by such a vehicle. The technology needed to accurately sense the surroundings of a vehicle are improving. A dynamic map of the surroundings can form the basis of lateral control functions, like lane changing and even elementary obstacle avoidance. Further analysis is needed to estimate the quality of such localized lateral control. Enhanced functions that seem to be definitely out of the reach of even intelligent vehicles, in the absence of intermediate or high-level infrastructure, are advanced obstacle avoidance, global traffic flow control, route selection, and other traffic management functions.

What assistance would this system provide to the traveler who is also using other modes (bus, rail, subway) of transportation?
No special assistance to public transportation is expected, unless explicitly provided for in the design, e.g., direct excess to subway, rails from the AHS system. In fact, faster speeds and more throughput means that roads will be more widely used than ever. As history has told us in the past, more capacity means more drivers.

What additional services would the concept provide for freight carriers?
The drivers of the freight carriers would benefit from this concept probably more than the driver of any other class of vehicles. Their attention to actual driving operations will be of a very high-level, infrequent type. On long trips, which is often the norm for freight carriers, the drivers can indulge in other job-related tasks while in the carrier. Human-less freight carriers can also be envisioned within this concept, though mixing of vehicle classes in a lane makes it a uphill task. The infrastructure has to constantly monitor the vehicle (the on-board agents still perform the micro-control), so the additional cost can be justifiably passed on to the freight carrier.

What features of this concept will most contribute to increasing throughput over the present system?
The variety of intelligent agents present aboard the vehicle or on the infrastructure most contribute to increasing throughput.

The most important are the agents aboard the vehicles which, with sophisticated longitudinal control, enable small separation between vehicles at higher speeds thereby leading to increase in throughput. Spontaneous platooning is not part of the baseline model under this concept. Even if it included as part of the concept, but not supported by the infrastructure, it is not expected to lead to significant throughput increase.

The second most important feature is the traffic flow management of the infrastructure. Since the infrastructure monitors each and every vehicle, it sets global flow parameters to maximize throughput. The specific infrastructure tasks that influence the throughput in a significant fashion are the initial placement of the vehicle in a lane, routing the vehicle to the destination, the control over the lane changing, control over exit inflow, the capability to shut down an exit temporarily, and setting localized speed limits. Each one of these is a tool in the infrastructure hands to increase throughput of the system.

The feature of mixing vehicle classes in a lane adversely affects the throughput in a significant fashion. Vehicles of similar performance level and size can safely travel closer to each other than vehicles of different classes. Moreover, the lighter vehicles can travel at a speed significantly higher than that of the heavier vehicles, since they have a lane of their own. The two factors directly result in lesser throughput.

What features of this concept will most contribute to increasing safety over the present system?
Almost every feature contributes to the safety of the vehicles operating on AHS. It is assumed that the features function as designed all the time. Reliability, which is often the most important one to evaluate safety, is not considered at this time.

The features which lead to fewer accident situations in the first place are listed below.

Automatic Headway Maintenance
"Rear-ends" are frequent cause of accidents in the present system. These are avoidable if a headway is maintained automatically. The control mechanism needed is the least sophisticated and most reliable among the set needed to implement this concept.

Automatic Lane-Keeping
Automatic lane-keeping enables vehicles to stay in their own lanes at all times and leads to fewer side collisions.

Automatic Lane-Changing
Many accidents in the current system occur during the process of lane changing, the reason being that the driver has to be aware of the traffic in front, side and, to some extent, back of the vehicle at the same time. All these duties are shared by different sensors under the concept implementation, therefore enabling a better decision to be taken by the intelligent agent. Moreover, the infrastructure has a control over the involved vehicles during the lane-changing process which means that there are no surprises during the process.

Automatic Obstacle Detection
Likely obstacles are detected early to give more time to the agents on-board and on the infrastructure to plan a avoidance maneuver.

Traffic Flow Management
The features like localized speed control and knowledge of traffic conditions ahead of time are important factors in improving system safety.

The features that lead to lesser injuries to limb and property in an accident situation are listed below.

Automatic Obstacle Avoidance
The maneuvers of the vehicles are coordinated to avoid the impending obstacles so that the obstacle is completely avoided or only minimal impact and injuries to limb and property occur.

Physical Barriers: The high-speed AHS traffic is separated from the non-AHS traffic using physical barriers. No manually driven vehicle is allowed to stray into the AHS lanes. An accident in low-speed lanes does not have a spill-over effect on the high-speed AHS lanes.

On the other hand, the features that lead to more accident situations are listed below.

High Speeds
The vehicles travel at much higher speeds with reduced reaction times. The chances of an accident increase in direct proportion.

Separation Policy
Vehicles are separated by smaller distances so there is a greater chance of an accident. Mixing of vehicle classes, although a feature of the present system, is not a critical factor today because of the low speeds. At high speed, mixing together with close separation can lead to more accidents.

Multitude of Electronic Control Mechanisms
Each control mechanism alone is designed to operate at levels that are safer than those of human beings. However, the sheer number of control mechanisms involved raises the question of system reliability.

Heavy redundancy and multiple backup systems can improve the reliability of the system. extent and at what cost remains to be studied.

What features of this concept will most contribute to making it cost-effective?
The costs involved in the implementation, operation and maintenance of this concept are tremendous. Instead of trying to list these, consider the relative benefits which accrue out of this concept.

As far as the user is concerned, the principal benefit is the reduced average travel-time. Even the cost of spending time in the vehicle goes down because the driver is relatively free to perform non-driving and perhaps work-related tasks. Increased comfort level and safety level are the other two major benefits. Automatic navigation is a relatively intangible benefit to the user.

The principal cost to the user is the increased cost of the vehicle, and the user fees of the system.

The features that most increase throughput are also the features that most make it cost-effective.

What will be the required vehicle maintenance?
Most electronic subsystems added to the vehicle to enable automation can be designed to be sufficiently reliable. The wear out mechanisms for electronic components have an occurrence rate in the order of a few tens of years. Random failures do occur, but maintenance cannot alter random failure rate.

It is predicted that required vehicle maintenance will only be necessary for mechanical subsystems that are subject to wear, just like with the current generation of vehicles. However, the control systems need tighter performance from the engine and the transmission. This leads to the need of more regular required check-ups and maintenance.

What will be the required infrastructure maintenance?
Infrastructure maintenance is expected to be most severe for the hardware embedded in the roads, like lane markers. Communication equipment, being key to numerous functions of the AHS, will require careful maintenance. Since the AHS cannot be stopped or taken off-line, the maintenance has to be done in a continuous fashion.

What does this concept assume in the way of support from the external world (e.g., enforcement, safety checks, ...)?
Tight enforcement has to form the backbone of this concept. A non-AHS vehicle in a AHS lane is a safety hazard. Even a momentary lapse in the AHS capabilities of a vehicle jeopardizes the well-being of it and its neighboring vehicles. To avoid this situation, a number of enforcements must be in place. Some of them are yearly safety checks while others are enforced every time the vehicle enters an AHS system. Control systems/sensors/communication devices and other electronic components must be designed to have multiple levels of redundancy and be easily testable for malfunctions. Physical parts like brakes and throttles, keys for vehicle safety, must also be checked on a regular basis.

Technically, the driver is not in the control loop as soon as the vehicle enters the system. Therefore, any problems that arise and result in an accident are not the fault of the driver. The vehicle is the responsible agent. In order for this to work as a legal argument, responsibility for the well-functioning of the vehicle must be assumed by someone. The only way the driver could be held responsible in this regard is through a system of certified checks a vehicle has to go through on regular basis. Only those cars that have the required checks are expected to enter the system. The certificates could be checked electronically every time the vehicle enters the AHS, or it could be an implicit requirement.

Do you see any special categories of induced demand (i.e., are there particular classes of users who would take particular advantage of this AHS concept, increasing traffic from that class of user)?
Increased speeds and reduced travel time imply that more working people of all types and classes would take to the roads. Cities

will sprawl even more, as people can afford to live further away from work. Small distance commuter flights would be less attractive as compared to using the AHS. In fact, all means of public transportation would be less attractive because of increased speeds and throughput. Have you thought about the user view?

Could you describe how the AHS operates, and the personal driving experience, from the point of view of a naive user who knows how to operate the system, but doesn't know how it works?
For a user of the AHS system under this concept, the driving experience could be compared to taking a train-ride except that you have a personalized bogey when you reach the station; you can actually drive the bogey home.

A well functioning AHS system under this concept has relatively few lane changes and lane-keeping and lane-following are so uniform that the user feels that his vehicle is just a part of a big and long procession.

In a malfunctioning AHS system, where control is passed to the driver, the driving would return to the usual non-AHS experience.

The users feel out of control in the event of automatic obstacle avoidance. Jerky, non-uniform maneuvers made by the vehicle to avoid the obstacle would appear somewhat akin to being in the seat next to the driver in the event of an accident in the current system.

The user will not feel comfortable closely following bigger vehicles. Even if mixing is allowed, the modern protocol of bigger vehicles on the right should be observed on AHS. Mixing should be used only for the transition purposes.

The users will feel strangest when driving manually in AHS lanes, if and when they have to do that (e.g., in case of breakdown of AHS capabilities of the vehicle). It is difficult to imagine how that experience would seem. The high speeds involved would make the user feel unsafe under manual control. The transition from automatic to manual control would be a nervous experience for some drivers.

15. CONCEPT 12B: CONCEPT #12B: INFRASTRUCTURE MANAGED UNMIXED FREE AGENTS

15.1 OVERVIEW

This chapter describes in detail the operational, functional and implementation issues involved in the AHS Concept "Infrastructure Managed Unmixed Free Agents".

Concept #12b is one of four infrastructure managed AHS concepts that call for complete separation of AHS and non-AHS traffic, thereby leading to a dual highway system in the country. Among these four concepts (#12a, #12b, #13, #19), one (#19) calls for manual avoidance of obstacles, thereby depending upon the driver for an extremely important maneuver. The other three concepts, including #12b, do not expect the driver to do any maneuvering from the point of entry to the point of exit. They call for completely hands-off driving. These three concepts all share the feature of automatic sensing and avoidance of obstacles.

Two of these three concepts (#12b, #13) divide the highway system even further, on the basis of vehicle class. No mixing of vehicle classes is envisioned, even at the point of entry/exit and for transition purposes. This leads to a tiered AHS system, each tier catering only to certain classes.

Concept #12b is one of the two tiered concepts. It differs from the other one in the regard that it calls for free agents instead of platoons as primary units of longitudinal and lateral control.

This concept represents the possibility that the most cost-effective way of achieving maximum throughput is by separating each vehicle class in its own lane and by taking the middle path in both vehicle-based intelligent control and infrastructure based control. The infrastructure is expected to be an intelligent agent which monitors every vehicle but does not control any unless requested under normal circumstances, keeping the cost low. The vehicle is expected to be intelligent enough to keep its lane and sense its immediate surroundings, but not expected to accomplish lane changes, or manage the initial placement without the infrastructure's help.

The distinguishing feature of this concept is the maximum achievable throughput without using platooning. Complete vehicle automation, global traffic flow management and no mixing of vehicle classes are going to be the important factors in achieving that goal. However, infrastructure setup investment is the single most important cost. Because of the tiered nature of AHS, complex and expensive interchanges and exits are required to implement this concept.

15.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

	Concept Characteristic	Dimension Alternative
1	Distribution of Intelligence	Infrastructure managed
2	Separation Policy	Free Agent
3	Mixing of AHS and non-AHS Vehicles in the Same Lane	Dedicated lanes with physical barriers
4	Mixing of Vehicle Classes in a Lane	Not Mixed
5	Entry/Exit	Dedicated
6	Obstacle Avoidance	Automatic sensing and automatic maneuver if possible

1. The intelligent agents reside both on the vehicle and on the infrastructure. The driver is the highest-level decision maker inside the vehicle, though he, necessarily, gives over full control to the vehicle. The vehicle uses on-board intelligent control systems mainly for longitudinal control and also possibly for lateral control. The main mode of operation of the infrastructure is a request-response type. Each vehicle's requests are processed and appropriate commands are sent to the appropriate vehicles to respond to that request. Infrastructure takes a more pro-active role in monitoring traffic flow, broadcasting traffic flow messages, advising lane changes to individual vehicles and the other usual ITS functions. The infrastructure is also capable of highly intelligent functions like taking over complete control of any individual vehicle, i.e., infrastructure can completely substitute for a vehicle's intelligence and assume longitudinal, lateral and navigational control. However, it might not have enough resources to control more than just a fraction of vehicles on the road at a time. The local officials may opt for an infrastructure that takes over the vehicle only in case the vehicle (or the driver) authorizes such a transfer of control. Such a practice might be limited to off-peak hours.
2. Longitudinal separation policy is based upon the assumption that the traffic is composed of vehicles driven as free agents. The longitudinal separation between two free agent vehicles, though not quite as little as within a platoon, is still appreciably less than that in the conventional highways because of the intelligent longitudinal control system. Therefore maximum throughput of the system is expected to be somewhere between that of AHS system with extensive platooning and the conventional highways.
3. Only those vehicles that have fully functioning AHS capabilities are allowed to enter the AHS. Moreover, non-AHS vehicles are separated by physical barriers from AHS vehicles. The only way a non-AHS vehicle can make its way to an AHS lane is either by trespassing at the entry point, or if its AHS capabilities fail during travel. The local tailorability is minimal in this regard as the system is jeopardized in case a lot of non-AHS vehicles find their way to AHS lanes. It implies a dual highway system in which the AHS system is completely independent of the non-AHS system.
4. Each AHS lane is meant for use by only certain classes of vehicles. No mixing is allowed. The heavy vehicles are naturally barred from the lane of lighter vehicles. The light vehicles also can not use the lane reserved for heavy vehicles, not even for transition purposes. The local tailorability is minimal since any modification would classify as a different concept, e.g., Concept #11, or #19. It implies a tiered AHS system, each tier catering to a different set of vehicle classes. There is little interaction between the tiers; therefore highway-to-highway interchanges would be tiered making its design highly complicated. A separate entry/exit would be required for each tier. Such a design is perhaps suitable for city commute traffic which is often composed of similar vehicle classes.
5. Entry/Exit structure is driven by the two concept characteristics discussed above, i.e., AHS and non-AHS traffic separated by physical barriers, and no mixing of vehicle classes in a lane. Entries and exits to AHS are composed of fully dedicated lanes. Since there is no mixing of vehicle classes in a lane under this concept, a separate entry/exit lane is provided for each class of vehicles. The incoming vehicles access the correct AHS lane directly without first passing through a transition area. Similarly, vehicles do not transition through lanes of other vehicle classes before exiting.
6. Obstacles of nearly every size, stationary or moving, are sensed and detected by the non-human intelligent agents, both

on-board the vehicle and the ones in the infrastructure. The response depends upon the situation. An automatic maneuver to avoid the obstacle is made, if possible. Possible maneuvers include fast lane changing, swerving around the obstacle, driving over the obstacle, and emergency braking. The response takes into account the size and type of the obstacle. The safety of the vehicle in question, and the others around it, are the supreme concern. At no stage, is human involvement expected, except possibly in the sensing of the obstacle. Any human input regarding a possible obstacle is processed first by the non-human agents before being used for detection or maneuvering. Any temporarily or permanent non-AHS vehicles on the highway are considered obstacles.

15.3 OPERATIONAL CONCEPT

Two different point of views are considered to illustrate the operational design of the system, that of the driver of each vehicle and that of the vehicle. The emphasis is limited to the normal operating conditions.

Before these point of views are presented, it is illustrative to look at four modes of operation a vehicle can be under from the point of view of who is in charge. The intelligent agent in charge makes the high level decisions, which are executed by the agents further down in the control hierarchy.

The vehicle is in charge through the use of an array of intelligent control systems.

1. Vehicle (and in exceptional circumstances the driver) authorizes infrastructure to take charge, for example during the lane changes, entry/exit and emergencies.
2. Infrastructure wrests control away from the vehicle. The driver of the vehicle is in charge under emergency conditions.

In any case, once the vehicle loses the charge, it is unable to get it back on its own. The infrastructure has to reinstate the charge. Whenever a transfer of control takes place from infrastructure to the vehicle, the vehicle has to actively take over the control and convince the infrastructure that it is aware of the transfer. If the vehicle fails to respond in the right fashion, the infrastructure retains the control. Similarly, once the driver loses the charge to the vehicle, he is unable to get it back on his own. The vehicle has to reinstate the charge; this normally happens only at exit. The driver has to convince the vehicle that he is aware of the transfer. If the driver fails to respond in the right fashion, the vehicle retains the control.

15.3.1 Driver Point of View

A driver decides to enter the AHS and picks the right entry point for its vehicle classes, in case there are multiple entry points. He logs in the vehicle classes and the trip description, possibly without ever stopping. Permission to enter might be denied at this point, if the vehicle fails the AHS-capability tests. The driver is given a suggested route to the destination. The driver is expected to be a passive observer until exit under normal circumstances. Under emergency conditions, full control may be passed to the driver, who then assumes manual control of the vehicle.

The only operation a driver can possibly perform is the following:

1. Change of Exit: The driver registers a change of exit with the vehicle, which then informs the infrastructure.

15.3.2 Vehicle Point of View

The vehicle is guided to one of the AHS lanes (decided upon by the infrastructure to optimize the traffic flow). It may involve automatic lane merging, lane changing, acceleration, and deceleration. When the lane-positioning is complete, the vehicle control is given to the vehicle.

Once a vehicle is in a lane in charge of itself, it can be involved in various operations. All of the following operations are initiated by the vehicle. Some of these can be redundant if a navigational subsystem is in place.

1. Lane Following: The vehicle oversees lane following procedures. The intelligent headway and speed maintenance mechanisms, which are

located on-board, control the vehicle longitudinally.

2. Request Lane Change: The vehicle decides to change lane and registers a request with the infrastructure. A lane change request can also be initiated by the navigational system or certain other intelligent non-human agent aboard the vehicle. The request cannot normally be denied unless it leads to an unusual disturbance in the normal operations. Once the request is granted, the vehicle is informed and taken out of the control loop until the lane has been automatically changed. Control passes to the vehicle by the infrastructure when the vehicle is stably located in the new lane.
3. Request Exit: The vehicle is informed of the approaching destination exit or the driver decides to make an early exit or the navigation system senses the approaching exit, in any case a request is registered with the infrastructure. The request is granted under normal circumstances, unless the exit requested is congested, or is not available for some other reasons. If the request is granted, the vehicle is taken out of the loop, a series of automatic lane changes occur and the vehicle is guided to the exit lane, where control is passed back to the driver.
4. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the vehicle may decide to take avoidance maneuvers without the help of infrastructure. Automatic maneuvers are performed to avoid a collision. They include fast lane changing, swerving around the obstacle, driving over the obstacle and emergency braking.

Certain operations are not initiated by the vehicle. The infrastructure, after informing the vehicle, takes over the control and performs these operations. These are the operations that can appear unexpected to the driver.

1. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the infrastructure may decide to take charge of the vehicle, and automatic maneuvers are performed to avoid a collision. They include fast lane changing, swerving around the obstacle, driving over the obstacle and emergency braking.
2. Automatic Acceleration/Deceleration: The above operations are performed to create room for vehicles that are attempting a lane change.
3. Automatic Rerouting: Automatic rerouting is done by the infrastructure to optimize the overall traffic flow from the point of view of throughput and congestion.

15.4 SYSTEM DIAGRAM

Information and control commands and parameters flow between "free agent" vehicles, and between "free agent" vehicles and the infrastructure.

The vehicle to vehicle data communication is related to maneuver coordination, position, velocity, acceleration data and vehicle dynamics. The vehicle-to-infrastructure data communication consists mostly of requests, e.g., lane change request, entry/exit request, etc. as well as vehicle status information. In addition, vehicles transmit information regarding obstacles detected by the sensors on the vehicle.

The infrastructure-to-vehicle data communication consists mainly of responses to vehicle requests, e.g., commands for lane changes, exit, lane positioning etc. There is additional non-response type data flow regarding the position of obstacles, routing commands, traffic flow information etc.

While the exact content of the communicated messages has not been defined yet, it is estimated and expected that a medium bandwidth communications channel will suffice. At this time, rough estimates of the magnitude of the message size, update rate and range are the following.

The bulk of the communication probably takes place between vehicles. Based on prior experiments, it is estimated that messages of up to 100 bytes with a repetition rate of 1/10th of a second will be

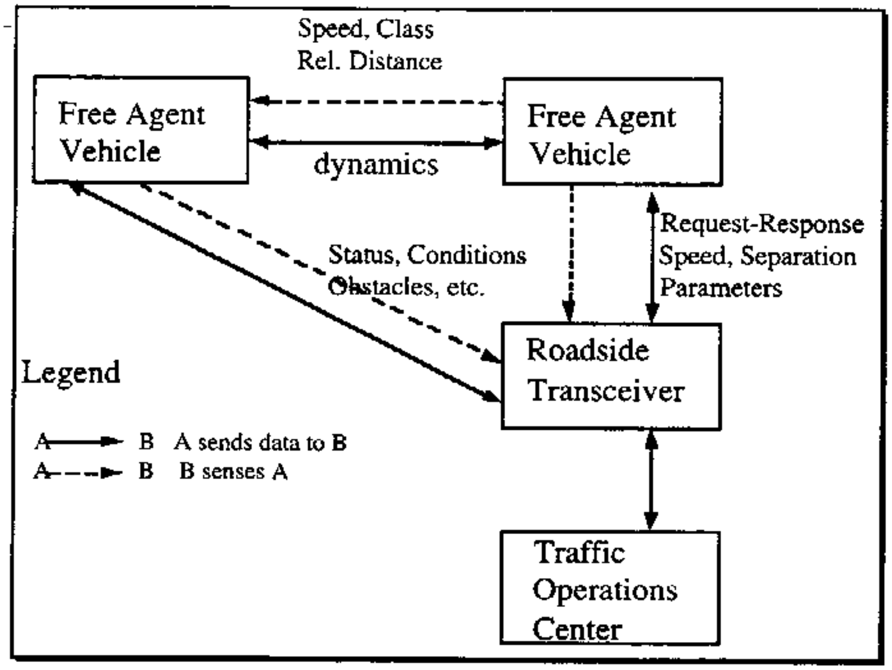

Figure H.15.4-1. System Diagram

used. This requires a channel with 9600 bps capacity and a variable duty cycle, i.e. the communication channel may not always need to transmit the maximum possible message size. Vehicles that are at some distance apart are not likely to have a need to communicate as their dynamics and trajectories do not affect each other. At the same time it is desirable to minimize the transmitting power and range of vehicle to vehicle communication to minimize interference to other vehicles and to allow for efficient spectrum reuse. At this time, a 1/4 mile maximum range seems sufficient and reasonable.

Similarly, to simplify the complexity of the infrastructure control requirements it seems reasonable that such control should be localized. Each roadside transceiver should only have to communicate with a finite and limited number of vehicles. The optimal numbers must be computed after a careful analysis. It is a good idea to make it possible for two adjacent roadside transceivers to be receiving the vehicle to infrastructure communications, for purposes of redundancy and reliability. Therefore double the range of communication from the vehicle to the roadside is allowed, compared to the other way around. The roadside to vehicle communications can be made reliable by on-vehicle redundancies, but it would be desirable for one and only one roadside transceiver to be attempting to communicate with each vehicle. The handover of the vehicle from one roadside transceiver to the next can be handled by the Traffic Operations Center.

So, to summarize:
Vehicle in front to the Vehicle in Back: Message Content: Position, Velocity, Acceleration, Braking force, operational status, emergency ahead. Also communicated but at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 9600 bps channel, 75% duty cycle, 1/4 mile maximum range.

Vehicle in front to the Vehicle in Back: Passive reflection of the radar sensor beam from the Vehicle in Back, permits the vehicle on back to detect relative position and relative speed.

Vehicle in back to the Vehicle in Front: Message Content: Position, Velocity, operational status. Also communicated but at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 9600 bps channel, 25% duty cycle, 1/4 mile maximum range

Infrastructure to Vehicle: Message Content: Command and control requests, speed and separation parameters, road surface condition advisories, notification of location and nature of emergencies. 1000 byte "packets", 1 sec repetition rate, 9600 bps channel, 25% duty cycle, 1 mile maximum range

Vehicle to Infrastructure: Message Content: Position, Velocity, Acceleration, operational status, road surface condition, detected obstacles. 1000 byte "packets", 1 sec repetition rate, 9600 bps channel, 5% duty cycle, 2 mile maximum range

Infrastructure to ANY vehicle (Broadcast): Message Content: Broadcast location identification, road surface condition advisories, traffic condition advisories, notification of location and nature of emergencies. 1200 byte packets, 10 sec repetition rate, 1200 bps channel, 100% duty cycle, 4 mile maximum range

Furthermore, the infrastructure must sense the presence, position and velocity of vehicles within the range of authority of its Traffic Operations Center. While most of that information is provided by the vehicles themselves through the vehicle to infrastructure communications channel, the infrastructure should have independent means of obtaining the same information for the purpose of reliability through redundancy and to allow the identification of non-equipped or malfunctioning vehicles. The interval of installation of roadside sensors equals the roadside transceiver distance from each other, and the bandwidth of the communication channel between roadside sensors and TOC is roughly equal to that of the vehicle to infrastructure data channel times the maximum number of vehicles that have to be supervised at once.

15.5 FUNCTIONAL ALLOCATION

15.5.1 Baseline functions

Check-in: Allocated to vehicle in combination with the infrastructure. Function performed in coordination with the infrastructure after vehicle passes operational test. Equipped vehicles are coordinated and assisted in merging. Non-equipped or non-fit vehicles are not allowed to enter. Sequence of events description: The driver decides to enter the AHS and selects an entry point that is appropriate for his vehicle class. Once the vehicle reaches the entry point an operational test is performed. Some operational status data may have been collected during normal driving before reaching the entry point while other data may be collected on the spot. The results are communicated to the infrastructure. The infrastructure makes the go/no-go decision regarding the operability of the vehicle. A traffic light with arrows directs the driver towards the AHS lanes if the result is "go" or towards the manual lanes if the result is "no-go" As soon as the "go" condition is given and the vehicle approaches the AHS lane it's velocity control is assumed by the infrastructure in order to coordinate its motion in preparation for merging.

Transition from manual to automatic control: Allocated to the vehicle. The transition is contingent upon successful check in. Sequence of events description: Velocity control is assumed by the automatic controller first. If the vehicle velocity responds to the infrastructure commands as intended, lateral control is subsequently assumed by the automatic controller. If a failure is detected at this time, the driver is immediately notified to continue driving the vehicle as a manual vehicle and to direct it towards the manual lanes or an emergency lane.

Automated Sensing of roadway, vehicles and obstacles: Allocated to the vehicle. Sequence of events description: Electronic sensors mounted on the vehicle perform the sensing and detection functions continuously or with a repetition frequency adequate for the required bandwidth of the on-vehicle automatic controllers.

Longitudinal sensing: Vehicle sensors sense the presence of other vehicles and obstacles in the space ahead of the vehicle. Lateral sensing: Vehicle sensors sense the presence of other vehicles and obstacles in the space on each side of the vehicle. Obstacle sensing: Vehicle sensors are able to sense at least some kinds of obstructions other than vehicles.

Vehicle longitudinal position sensing: Both absolute (medium high accuracy) and relative to the vehicle in front (very high accuracy). Vehicle lateral position sensing: Both absolute (high accuracy) and relative to the vehicles on each side (medium accuracy).

Automated Sensing of vehicles and obstacles: Allocated to the infrastructure. Roadway sensors belonging to the infrastructure collect information about obstacles, and the information is passed from the infrastructure to the vehicle. Sequence of events description: The infrastructure employs video cameras, radar, inductive loops and other sensors to sense as accurately as possible the location position and velocity of vehicles in the AHS lanes. Disables vehicles automatically get classified as obstacles. Detection of other obstacles (foreign objects, stray animals etc.) may be possible but of limited success.

Collision avoidance: Information from the vehicle sensors and the infrastructure is passed to the Longitudinal Velocity Controller, which acts as a longitudinal collision avoidance system. Sequence of events description: All the information collected by the on-vehicle sensors is correlated with the information provided by the vehicle in front as well as the information provided by the infrastructure. If the information is deemed consistent it is used as input to the Longitudinal Velocity Controller. If minor inconsistencies are found the worst case scenario is assumed by the controller and the infrastructure is notified via the status report. If major inconsistencies are found an emergency is declared and the driver is notified that he may have to resume manual control. At the same time the infrastructure and other vehicles in the vicinity are notified and requested to increase their distance from the malfunctioning vehicle. If the information from all sensors is consistent and indicates that the vehicle is in a collision path with another vehicle or a newly identified obstacle, the Longitudinal Velocity Controller attempts to reduce the velocity by applying emergency braking. A change lane request may also be generated by the vehicle and transmitted to the infrastructure.

Automated headway keeping: Allocated to the vehicle. Vehicle sensors measure relative position and relative speed to the vehicle in front. The controller can control the velocity and headway of the vehicle down to zero velocity, including stop and go situations. Sequence of events description: All the information collected by the on-vehicle sensors is correlated with the information provided by the vehicle in front as well as the information provided by the infrastructure. If deemed consistent, this information becomes the input to the Longitudinal Controller, which applies throttle or brake as necessary to maintain the headway that is recommended by the infrastructure. The headway recommendation of the infrastructure can be adjusted by the vehicle controller depending on information from the vehicles in front and in the back and also according to the road surface conditions and the infrastructure notified of any changes.

Automated Lateral Controller. (Lane Keeping): Vehicle based, but it most likely will require the presence of “markers” or other aids from the infrastructure. Sequence of events description: The on-vehicle sensors detect the position of the vehicle in absolute terms and also relative to the lane boundaries and relative to any other vehicles on adjacent lanes. The information is used to control the steering angle such that the vehicle follows a smooth trajectory near the center of its assigned traffic lane.

Detection of hazards: Vehicle-based or in combination with the infrastructure. The vehicle may use the longitudinal and lateral sensors. The infrastructure may assist by transmitting to all vehicles the exact location of known hazards. Sequence of events description: The longitudinal and lateral sensors on the vehicle pass the information collected to the controller. The information is correlated to the information received via communications from other vehicles and the infrastructure. Any objects detected by the vehicle sensors that do not coincide with any objects known to the infrastructure are automatically classified as potential hazards and the infrastructure is immediately notified of their presence. Furthermore, if the position of the hazards appears to be in the path of the vehicle, the collision avoidance procedures is initiated automatically as well.

Normal Maneuver planning: Allocated to the vehicle in combination with the infrastructure. Executed by the vehicle based on information from the sensors and the infrastructure Sequence of events description: Based on the desired destination declared by the driver, the vehicle navigation controller employs information provided by the infrastructure to implement the vehicle travel plan. The plan is submitted to the infrastructure for approval. Depending on local conditions the infrastructure may opt to alter the travel plan and may request additional maneuvers at any time.

Emergency Maneuver planning: Allocated to the vehicle, possibly in combination with the infrastructure. In some cases it might be managed by the infrastructure. Sequence of events description: This is a very sensitive problem. It is assumed that the most likely implementation is for the vehicle controller to assume the responsibility of "self-preservation" during emergencies. Infrastructure involvement may be necessary even during emergencies to avoid the possibility of chaotic behavior when individual vehicles begin attempting emergency maneuvering on their own.

Normal Maneuver execution: Allocated to the Vehicle. Executed by the on-board controller. Sequence of events description: The on-vehicle controller applies the throttle brake and steering actuators as necessary to implement the desired maneuvers.

Emergency Maneuver execution: Allocated to the Vehicle. Executed by the on-board controller but in some cases the driver may be called in to take over control. The exact scenario to be followed is subject to debate. Sequence of events description: The on-vehicle controller may apply the throttle brake and steering actuators as necessary to implement the desired maneuvers. The driver may have the option to intervene but his intervention power may be limited or his intervention power may depend on the situation, i.e. certain scenarios may allow more driver input than others. This is likely to be one of the thorniest issues regarding the eventual deployment of AHS.

Transition from automatic to manual control: Allocated to any one of the vehicle, driver or infrastructure. Sequence of events description: It may be requested by the driver, requested by the infrastructure, or enforced by the vehicle as a failure response fallback mode and normally happens immediately after check out. A likely scenario is as follows: The vehicle relinquishes partial control to the driver who is notified and expected to apply certain corrections to the vehicle velocity and path by applying a moderate amount of braking and steering. By doing so, he effectively verifies his alertness and readiness to resume full manual control. If he fails to perform the required actions within the allocated time, the vehicle controller declares the driver unfit and resumes fully automatic vehicle control. In this case the vehicle is driven automatically to a designated exit that has been designed for the accommodation of "sleeping" drivers and brought to a complete stop. A human operator will approach the vehicle and investigate the condition of the driver. If he has suffered death, loss of senses and such he is taken to a hospital. If he is found to be under the influence of drugs or alcohol he is taken to jail. If he is found to be sleeping he is rudely awakened. If he is found to be playing games i.e. testing the system, he is cited for a traffic violation.

Check out: Allocated to any one of the vehicle, driver or infrastructure. Sequence of events description: Check-out may be requested by the driver, requested by the infrastructure, or enforced by the vehicle as a failure response option. In most cases the vehicle self guides towards the exit ramp and a transition from automatic to manual control is initiated.

Flow control: Allocated to the infrastructure. The infrastructure manages and controls the traffic flow. Sequence of events description: The infrastructure measures the volume and the velocity of the traffic at different sections along the AHS and a central controller at the Traffic Operations Center makes the decisions on optimal velocity, spacing and traffic routing in order to control and optimize the flow.

Malfunction management: Allocated to the vehicle, infrastructure and possibly the driver, in combination. In most cases it is cooperative between vehicle and infrastructure. Several different scenarios exist. Sequence of events description: If the malfunction is identified to be on the vehicle, it is assumed that it can be fully or partially compensated by redundancy and the vehicle is requested to check-out at the earliest opportunity. If the malfunction is identified to be on the vehicle but it is not covered by redundancy, the driver is notified and requested to resume full manual control. If the malfunction is identified to be on the infrastructure, the vehicle and the driver are notified of the exact nature and the extent of the loss of functionality and the AHS either continues operating at a degraded mode of operation or shuts down or temporarily converts to manual operation.

Handling of emergencies: Normally allocated to the vehicle or to the vehicle and the driver in combination. Sequence of events description: It is assumed that the most likely implementation is for the vehicle controller to assume the responsibility of "self-preservation" during emergencies. Infrastructure involvement may be necessary even during emergencies to avoid the possibility of chaotic behavior when individual vehicles begin attempting emergency maneuvering on their own. In at least some cases, it may become necessary to pass control responsibility to the driver, who would be expected to assume manual control of the vehicle.

15.6 IMPLEMENTATION

In this section we describe one possible implementation of the concept. This is by no means the only possible implementation or even the most recommended one. It is only a representative example of an implementation that allows visualization of the magnitude and complexity of the problems involved and the intricate relations and interdependencies between the components of the system.

15.6.1 Vehicle

The vehicle requires the following functions and subsystems:

Fail-proof longitudinal control system. The longitudinal control system serves the function of velocity and headway maintenance. The requirement for fail-proof operation of the longitudinal controller under all conditions imposes extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.

Fail-proof lateral control system. The lateral control system serves the function of lane keeping and lane changing. The requirement for fail-proof operation of the lateral position controller under all conditions imposes extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.

Accurate longitudinal position sensing. The longitudinal position of the vehicle is known in absolute terms and in relative position to other vehicles. The absolute position is for navigation and trip destination control purposes and the relative position is for velocity and headway maintenance and control as well as for collision avoidance.

Accurate lateral position sensing and lane position identification. The lateral position of the vehicle is known in absolute terms and in relative position to other vehicles. The absolute position is for lane keeping, lane changing and navigation purposes and the relative position is mostly for collision avoidance especially during lane changing.

Collision avoidance based on obstacle sensing in combination with vehicle to vehicle and vehicle to infrastructure communications. Vehicle sensors are not adequate and do not guarantee collision avoidance with any kind of obstacle or even with another vehicle. Therefore the collision avoidance control logic requires additional information that can only be supplied by other vehicles and by the infrastructure.

Maneuver coordination between vehicles. Every aspect of the motion of the vehicle and especially lane changes is orchestrated and coordinated by a control authority at a higher level than the each vehicle itself. This control authority is distributed collectively among vehicles or is assigned to the infrastructure. It is most likely that a local decision affects the assignment of this control authority. In urban regions the authority may be exclusive to the infrastructure. In rural regions the authority is distributed among vehicles and in every case it is dynamically distributed among the vehicles and the infrastructure by means of appropriate maneuver protocols.

Automatic route guidance based on navigation computers and interaction with the infrastructure.

Supervisory controller that monitors everything and alerts the driver of any single point failure. Malfunction management is one of the more complicated issues facing the designers of the AHS system. It is very desirable if not essential that every part of the automation is covered by multiple redundancies so that no single point failure affects the operation of the system. At the same time, any failure must be immediately detectable and the driver must become aware of it as soon as possible. If necessary the driver is required to assume partial or full control of the vehicle.

15.6.1.1 Required vehicle components

Two longitudinal range and range rate sensors based on Forward looking Doppler radar, FMCW radar, infrared laser ranging system, optical recognition method or combination of the above are required.

Side looking vehicle and obstacle sensors based on very low power radar, sonar, or infrared light are required.

Redundant lateral lane position sensors are required. These same sensors provide absolute longitudinal position information. The sensing method includes Differential GPS and the use of lane markers, which requires a potentially large investment in the infrastructure. Candidate lane marking methods include magnetic nails, magnetic lane marking paint, corner reflectors for radar, optical patterns, and others. A single method with optimal performance cannot be identified at this time. Each system has potential merits and a number of shortcomings and limitations.

A transceiver for vehicle-to-vehicle communications is required. Communication includes, but is not limited to, velocity, acceleration and braking force. Also required is a communication ability with cars in adjacent lanes for cooperation in merging.

A lateral collision warning coupled with the steering actuator for assistance in checking in and out is required.

Environmental conditions sensors are required. The primary purpose of these sensors is to sense and/or estimate road surface conditions and friction coefficients for cornering and braking.

Driver status monitors and diagnostics are required. Although the driver is not involved in the control of the vehicle when traveling in an AHS environment, his readiness status and alertness are essential in case of detected failures in some part of the redundant controllers and needed before and during the check-out stage.

Supervisory controller monitors the performance and functionality of every part of the system, including every redundant part of the controllers, sensors and actuators, the communications systems, and driver status. The supervisory controller has the responsibility to reassign responsibilities among system parts, based on a well-defined priority system. The supervisory controller attempts to detect and recover any detectable failure. In doing so it reassigns actuator responsibilities to different parts of the system when actuator malfunctions are detected. Control responsibilities are reassigned to different controllers when control malfunctions are detected, i.e. to the infrastructure and eventually to the driver. Sensing responsibilities are reassigned to different sensors when sensing malfunctions are detected, i.e. to alternative sensors first, then to the infrastructure and eventually to the driver.

15.6.1.2. Vehicle implementation issues and considerations

In considering acceptable versus unacceptable failures of vehicle components, two independent ways of controlling the throttle, brake and steering are needed to accommodate any single point failure in the sensor, controller or actuator.

Furthermore, no single point failure of any subsystem should escape diagnosis or lead to loss of control. Care must be taken to avoid common mode failures such as loss of power to both parts of a redundant controller simultaneously.

15.6.2 Infrastructure

Required infrastructure components:

1. Low-level infrastructure components:

   Markers must be provided to assist the vehicles in performing the lane keeping function. These markers must be unambiguous and extremely reliable under all traffic, lighting, weather and temperature conditions. It is not expected that different type sensors are needed in rural versus urban sections of the highways.

   Physical barriers have to be provided to separate the AHS system from the non-AHS part of the highways. For cost considerations it might be considered as an option not to have those barriers in rural sections of the highways, though a safe alternative is unknown.

   Mixing of vehicle classes is allowed. Therefore, no separate entry/exit ramps and highway interchanges are needed.

2. Intermediate-level infrastructure components

   Low bandwidth communication (broadcasting) must be provided to all vehicles within the authority of the infrastructure and may contain "traveler information" type data. The roadside transmitters of broadcast type information are allocated as a dual redundant station with a range of 4 miles located every 6 to 8 miles in rural highway sections. In urban sections of the highways it might be preferable to employ lower power transmitters more closely spaced, e.g., 1 mile range transmitters located every 2 miles.

3. High-level infrastructure components

   Medium bandwidth bi-directional communication with individual vehicles is required. Vehicles must be individually identifiable and individually addressable both by the infrastructure controllers and by the communication transceivers. This requirement is the same in both rural and urban sections of the highways.

   Sensing of traffic flow speed and flow density, under all traffic, lighting, weather and temperature conditions is required. The accuracy requirements may be slightly relaxed in sparsely traveled rural highways, but the sensing requirements are basically the same as in urban highways.

   Sensing of individual vehicle position and velocity under all traffic, lighting, weather and temperature conditions is required. This is required in urban highway sections but may not have to be implemented in sparsely traveled rural highway sections.

   The Traffic Operations Centers must be present along the roadside at intervals that are determined based on the typical and expected traffic density. The location and the distance between those

TOCs will be different for rural and urban sections of the highways.

15.6.2.1. Rural Highway

In a rural highway environment, the necessary infrastructure may be different to some extent. It may be more cost efficient to cover larger areas with fewer traffic control stations. Those sparsely spaced traffic control stations must cover a larger number of vehicles over extended distances. If the distance between the infrastructure equipment and the vehicle is extended, long range communications, medium to high capacity communication channels, and reliable backup equipment are required. In rural environments, infrastructure sensing may be limited to flow rate and average velocity every few miles.

15.6.2.2. Urban Highway

In an urban highway environment it is likely more efficient to employ short range communications, high capacity communication channels, and closely spaced traffic control stations. Knowledge of individual vehicle position coordinates may be required at each infrastructure Traffic Operations Center site.

15.6.3 Deployment

The minimal deployable system has a longitudinal controller (maintain velocity or headway) and a lateral controller (maintain lane position) on the vehicle as well as an infrastructure system to manage the flow of traffic by providing commands and information to the vehicle.

The longitudinal controller needs a longitudinal sensor, an actuator system. and the controller hardware and software.

The lateral controller needs a lateral sensor, an actuator, and the lateral controller hardware and software.

The required communication needs a medium to high bandwidth communication transceiver on the vehicle and a communication system built into the infrastructure. Some way for the infrastructure to monitor the traffic flow is also essential.

The incentive to buy a vehicle so equipped is that an automated vehicle driven on an automated highway offers the potential for shorter travel times and a major improvement in the comfort of the driver and passengers.

The incentive for the roadway operator to deploy an AHS roadway is the potential for reduced highway travel times, reduced pollution and most important the postponement of the need to build more highway lanes if the existing ones can be used more efficiently.

15.7 GENERAL ISSUES AND CONSIDERATIONS

What degree of automation is there in the navigation function?
The system has the capability for fully automatic navigation for any individual vehicle though it is not included as a specific requirement in the architecture. What is a characteristic of the baseline model is monitoring of each vehicle that enters the AHS, which is the most important element of a navigational system. Such information is used by infrastructure-based agents or on-board agents to navigate the vehicle automatically. The communication load on the infrastructure grows dramatically if all the vehicles are navigated by its agents. In a more reasonable scenario, the infrastructure performs the specific navigation function of initial route selection and leaves the rest of the navigation to the agents aboard an individual vehicle.

What are the obvious failure modes for the concept?
The system consists of so many subsystems that a variety of failure modes are possible. The primary failure modes can be classified into the following categories. Each category is illustrated by examples.

Sensory Failures
Vehicle cannot sense its own position:

Vehicle cannot sense the presence of other vehicles ahead,

Vehicle cannot sense the presence of obstacles ahead,

Vehicle cannot sense the presence of other vehicles aside,

Vehicle cannot sense the presence of obstacles aside, and

Vehicle cannot sense the weather conditions around.

Longitudinal Control
Vehicle cannot maintain velocity,

Vehicle cannot maintain the desired headway Lateral Control Failures, and

Vehicle cannot maintain lateral trajectory.

Communication Failures
Vehicle cannot receive communication from other vehicles,

Vehicle cannot receive communication from other infrastructure,

Vehicle cannot transmit to other vehicles, and

Vehicle cannot transmit to the infrastructure.

Entry/Exit Function Failures
Vehicle fails the check-in procedure.

Vehicle (or driver) fails the check-out procedure.

Control Transfer Failure
Vehicle cannot switch between operating modes.

What major systems or subsystems can back one another up in case of failure?
None, unless explicitly designed for the purpose. Dual redundancy is required for most automation subsystems to guarantee fail-safe operation. Triple redundancy is required on the most critical subsystems. If designed properly, degradation of the system, in case of failure, occurs in a fashion so that if the infrastructure is unable to control a particular vehicle, it should pass control to the vehicle. In case the vehicle is unable to control itself, it is able to pass control to the driver. Each has multiple redundancy in their control systems to reduce the chances of breakdown. But if the breakdown does take place, at no time is the vehicle out of proper control.

The feasibility of such a design, however, is far from a settled issue.

Under what circumstances (if any) is control passed to the driver?
The driver has no control, except the high-level navigational one, e.g., choice of the destination, during normal operations on the AHS, which include lane keeping, lane following, lane-changes, automatic obstacle avoidance maneuvers.

The only circumstances in which the driver might get the control are exceptional ones. In a malfunctioning system, the infrastructure may perceive the manual option to be the safest one. In such a case it alerts the drivers and passes over the control to the drivers. Malfunctions could be of various types. If the control and execution mechanisms on the vehicle breakdown, and it renders the vehicle uncontrollable, then there is no choice but to give control to the driver. If the vehicle is functioning well, but the infrastructure manager breaks down, then the vehicle takes over the infrastructure responsibilities and still manages to keep the driver out of the loop. The performance is naturally degraded.

How does the system sense limited visibility, or ice, water or snow on the roadway; what does it do with this information?
The infrastructure constantly senses the highway environs for weather conditions, like visibility, temperature and precipitation. Some of these conditions might be localized, e.g., ice on a bridge, water collected on the inside lane, and some other might be characteristic to a larger area. The system senses the two kind of conditions in different fashion.

The weather parameters, like temperature and wind speed, are measured on a regional basis using standard technology.

Precipitation is monitored for both type and quantity, also on a regional basis.

Some weather-related conditions are measured more locally. All the bridges are monitored for icy conditions under near-zero weather conditions. The snow level on a road during or after a snowstorm, water level if it tends to log in certain locations, are measured at regular distances in each lane and at known trouble spots.

The infrastructure uses sensors that are on each vehicle to sense localized trouble spots. The vehicle passes the relevant information to the infrastructure, which can alert the on-coming traffic of the trouble spots. Vision-based systems coupled with image processing hardware may be able to discriminate some of these conditions. Local visibility, pools of water, icy patches, and friction coefficients are examples of weather elements that might be sensed by the vehicles.

Some of the weather-related information gathered by the infrastructure is directly passed on to the vehicles, who add that information to the knowledge they already possess from their own sensors or some other prior information. The weather parameters play a very important role in the functioning of the control mechanisms in adverse conditions. Certain other information is first processed by the infrastructure to generate warnings, advisories, and commands for vehicles in specific areas and lanes. It is possible for the same piece of information to result in different courses of action for different vehicles depending upon their location, class, and lane.

What speed(s) would typical users travel at? How tailorable is this?
These are conflicting requirements. A low typical velocity hurts efficiency and performance. A high typical velocity hurts fuel economy and generates potentially dangerous conditions in case of malfunctions. The risks increase exponentially with speed. The exact figures must be analyzed. An estimate is that the typical maximum speed will be 20% higher than the current speed limits. Lower typical speeds will be necessary in many cases. The typical speed needs to be tailorable to local conditions, but the maximum speed probably does not.

What enhanced functions would a vehicle from this concept be able to perform on a conventional highway?
Except for basic speed and headway control, a vehicle is not currently able to perform other enhanced functions on conventional highways. However, a low-level infrastructure modification like magnetic nails and exit sensors, opens various possibilities. A vehicle, with capabilities of this concept, can possibly perform a variety of enhanced functions on these slightly modified highways. Longitudinal control functions, e.g., sophisticated lane keeping and lane following functions can be performed by such a vehicle. The technology needed to accurately sense the surroundings of a vehicle are improving. A dynamic map of the surroundings can form the basis of lateral control functions, like lane changing and even elementary obstacle avoidance. Further analysis is needed to estimate the quality of such localized lateral control. Enhanced functions that seem to be definitely out of the reach of even intelligent vehicles, in the absence of intermediate or high-level infrastructure, are advanced obstacle avoidance, global traffic flow control, route selection, and other traffic management functions.

What assistance would this system provide to the traveler who is also using other modes (bus, rail, subway) of transportation?
No special assistance to public transportation is expected, unless explicitly provided for in the design, e.g., direct excess to subway, rails from the AHS system. In fact, faster speeds and more throughput means that roads will be more widely used than ever. As history has told us in the past, more capacity means more drivers.

What additional services would the concept provide for freight carriers?
The drivers of the freight carriers would benefit from this concept probably more than the driver of any other class of vehicles. Their attention to actual driving operations will be of a very high-level, infrequent type.

On long trips, which is often the norm for freight carriers, the drivers can indulge in other job-related tasks while in the carrier. Human-less freight carriers can also be envisioned within this concept, though mixing of vehicle classes in a lane makes it a uphill task. The infrastructure has to constantly monitor the vehicle (the on-board agents still perform the micro-control), so the additional cost can be justifiably passed on to the freight carrier.

What features of this concept will most contribute to increasing throughput over the present system?
The variety of intelligent agents present aboard the vehicle or on the infrastructure most contribute to increasing throughput.

The most important are the agents aboard the vehicles which, with sophisticated longitudinal control, enable small separation between vehicles at higher speeds thereby leading to increase in throughput. Spontaneous platooning is not part of the baseline model under this concept. Even if it included as part of the concept, but not supported by the infrastructure, it is not expected to lead to significant throughput increase.

The second most important feature is the traffic flow management of the infrastructure. Since the infrastructure monitors each and every vehicle, it sets global flow parameters to maximize throughput. The specific infrastructure tasks that influence the throughput in a significant fashion are the initial placement of the vehicle in a lane, routing the vehicle to the destination, the control over the lane changing, control over exit inflow, the capability to shut down an exit temporarily, and setting localized speed limits. Each one of these is a tool in the infrastructure hands to increase throughput of the system.

The feature of mixing vehicle classes in a lane adversely affects the throughput in a significant fashion. Vehicles of similar performance level and size can safely travel closer to each other than vehicles of different classes. Moreover, the lighter vehicles can travel at a speed significantly higher than that of the heavier vehicles, since they have a lane of their own. The two factors directly result in lesser throughput.

What features of this concept will most contribute to increasing safety over the present system?
Almost every feature contributes to the safety of the vehicles operating on AHS. It is assumed that the features function as designed all the time. No serious attempt is include into consideration the reliability point of view, which is often the most important one to evaluate safety.

The features which lead to fewer accident situations in the first place are listed below.

Automatic Headway Maintenance
"Rear-ends" are frequent cause of accidents in the present system. These are avoidable if a headway is maintained automatically. The control mechanism needed is the least sophisticated and most reliable among the set needed to implement this concept.

Automatic Lane-Keeping
Automatic lane-keeping enables vehicles to stay in their own lanes at all times and leads to fewer side collisions.

Automatic Lane-Changing
Many accidents in the current system occur during the process of lane changing, the reason being that the driver has to be aware of the traffic in front, side and, to some extent, back of the vehicle at the same time. All these duties are shared by different sensors under the concept implementation, therefore enabling a better decision to be taken by the intelligent agent. Moreover, the infrastructure has a control over the involved vehicles during the lane-changing process which means that there are no surprises during the process.

Automatic Obstacle Detection
Likely obstacles are detected early to give more time to the agents on-board and on the infrastructure to plan a avoidance maneuver.

Traffic Flow Management
The features like localized speed control and knowledge of traffic conditions ahead of time are important factors in improving system safety.

The features that lead to lesser injuries to limb and property in an accident situation are listed below.

Automatic Obstacle Avoidance
The maneuvers of the vehicles are coordinated to avoid the impending obstacles so that the obstacle is completely avoided or only minimal impact and injuries to limb and property occur.

Physical Barriers: The high-speed AHS traffic is separated from the non-AHS traffic using physical barriers. No manually driven vehicle is allowed to stray into the AHS lanes. An accident in low-speed lanes does not have a spill-over effect on the high-speed AHS lanes.

On the other hand, the features that lead to more accident situations are listed below.

High Speeds
The vehicles travel at much higher speeds with reduced reaction times. The chances of an accident increase in direct proportion.

Separation Policy
Vehicles are separated by smaller distances so there is a greater chance of an accident. Mixing of vehicle classes, although a feature of the present system, is not a critical factor today because of the low speeds. At high speed, mixing together with close separation can lead to more accidents.

Multitude of Electronic Control Mechanisms
Each control mechanism alone is designed to operate at levels that are safer than those of human beings. However, the sheer number of control mechanisms involved raises the question of system reliability. Heavy redundancy and multiple backup systems can improve the reliability of the system. The extent and at what cost remains to be studied.

What features of this concept will most contribute to making it cost-effective?
The costs involved in the implementation, operation and maintenance of this concept are tremendous. Instead of trying to list these, consider the relative benefits which accrue out of this concept.

As far as the user is concerned, the principal benefit is the reduced average travel-time. Even the cost of spending time in the vehicle goes down because the driver is relatively free to perform non-driving and perhaps work-related tasks. Increased comfort level and safety level are the other two major benefits. Automatic navigation is a relatively intangible benefit to the user.

The principal cost to the user is the increased cost of the vehicle, and the user fees of the system.

The features that most increase throughput are also the features that most make it cost-effective.

What will be the required vehicle maintenance?
Most electronic subsystems added to the vehicle to enable automation can be designed to be sufficiently reliable. The wear out mechanisms for electronic components have an occurrence rate in the order of a few tens of years. Random failures do occur, but maintenance cannot alter random failure rate.

It is predicted that required vehicle maintenance will only be necessary for mechanical subsystems that are subject to wear, just like with the current generation of vehicles. However, the control systems need tighter performance from the engine and the transmission. This leads to the need of more regular required check-ups and maintenance.

What will be the required infrastructure maintenance?
Infrastructure maintenance is expected to be most severe for the hardware embedded in the roads, like lane markers. Communication equipment, being key to numerous functions of the AHS, requires careful maintenance. Since the AHS cannot be stopped or taken off-line, the maintenance has to be done in a continuous fashion.

Tight enforcement has to form the backbone of this concept. A non-AHS vehicle in a AHS lane is a safety hazard. Even a momentary lapse in the AHS capabilities of a vehicle jeopardizes the well-being of it and its neighboring vehicles. To avoid this situation, a number of enforcements must be in place. Some of them are yearly safety checks while others are enforced every time the vehicle enters an AHS system. Control systems/sensors/communication devices and other electronic components must be designed to have multiple levels of redundancy and be easily testable for malfunctions. Physical parts like brakes and throttles, keys for vehicle safety, must also be checked on a regular basis.

Technically, the driver is not in the control loop as soon as the vehicle enters the system. Therefore, any problems that arise and result in an accident are not the fault of the driver. The vehicle is the responsible agent. In order for this to work as a legal argument, responsibility for the well-functioning of the vehicle must be assumed by someone. The only way the driver could be held responsible in this regard is through a system of certified checks a vehicle has to go through on regular basis. Only those cars that have the required checks are expected to enter the system. The certificates could be checked electronically every time the vehicle enters the AHS, or it could be an implicit requirement.

Do you see any special categories of induced demand (i.e., are there particular classes of users who would take particular advantage of this AHS concept, increasing traffic from that class of user)?
Increased speeds and reduced travel time imply that more working people of all types and classes would take to the roads. Cities will sprawl even more, as people can afford to live further away from work. Small distance commuter flights would be less attractive as compared to using the AHS. In fact, all means of public transportation would be less attractive because of increased speeds and throughput. Have you thought about the user view?

Could you describe how the AHS operates, and the personal driving experience, from the point of view of a naive user who knows how to operate the system, but doesn't know how it works?
For a user of the AHS system under this concept, the driving experience could be compared to taking a train-ride except that you have a personalized bogey when you reach the station; you can actually drive the bogey home.

A well functioning AHS system under this concept has relatively few lane changes and lane-keeping and lane-following are so uniform that the user feels that his vehicle is just a part of a big and long procession.

In a malfunctioning AHS system, where control is passed to the driver, the driving would return to the usual non-AHS experience.

The users feel out of control in the event of automatic obstacle avoidance. Jerky, non-uniform maneuvers made by the vehicle to avoid the obstacle would appear somewhat akin to being in the seat next to the driver in the event of an accident in the current system.

The user will not feel comfortable closely following bigger vehicles. Even if mixing is allowed, the modern protocol of bigger vehicles on the right should be observed on AHS. Mixing should be used only for the transition purposes.

The users will feel strangest when driving manually in AHS lanes, if and when they have to do that (e.g., in case of breakdown of AHS capabilities of the vehicle). It is difficult to imagine how that experience would seem. The high speeds involved would make the user feel unsafe under manual control. The transition from automatic to manual control would be a nervous experience for some drivers.

16. CONCEPT 13: INFRASTRUCTURE MANAGED UNMIXED PLATOONING

16.1 OVERVIEW

This document describes in detail the operational, functional and implementation issues involved in the AHS Concept "Infrastructure Managed Unmixed Platooning".

Concept #13 is one of four infrastructure managed AHS concepts that call for complete separation of AHS and non-AHS traffic, thereby leading to a dual highway system in the country. Among these four concepts (#12a, #12b, #13, #19), one (#19) calls for manual avoidance of obstacles, thereby depending upon the driver for an extremely important maneuver. The other three concepts, including #13, do not expect the driver to do any maneuvering from the point of entry to the point of exit and call for completely hands-off driving. These three concepts all share the feature of automatic sensing and avoidance of obstacles.

Two of these three concepts (#12b, #13) divide the highway system even further, on the basis of vehicle class. No mixing of vehicle classes is envisioned, even at the point of entry/exit and for transition purposes. This leads to a tiered AHS system, each tier catering only to certain classes.

Concept #13 is one of the two tiered concepts. It differs from the other one in that it calls for platoons instead of free agents as the primary units of longitudinal and lateral control.

This concept represents the possibility that the safest, and possibly most cost-effective, way of achieving maximum throughput is by making platoons the basic unit of traveling on roads. This boosts road capacity and takes a middle path in infrastructure-based control. The infrastructure is expected to be an intelligent agent that monitors every vehicle, but, under normal circumstances, does not control any vehicle unless requested. This keeps the cost low. The vehicle is expected to be intelligent enough to keep its lane, sense its immediate surroundings, and perform platooning functions, but is not expected to accomplish lane changes, or manage the initial placement after entry without the infrastructure's help.

The distinguishing feature of this concept is the maximum achievable throughput. Platooning, complete vehicle automation, global traffic flow management and no mixing of vehicle classes are important factors in achieving that goal. However, infrastructure investment is an important cost. Because of the tiered nature of AHS, complex and expensive interchanges and exits are required to implement this concept.

Selected Alternative from Each Dimension

16.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

Concept Characteristic	Dimension Alternative
1 Distribution of Intelligence	Infrastructure managed
2 Separation Policy	Platooning
3 Mixing of AHS and non-AHS Vehicles in the Same Lane	Dedicated lanes with physical barriers
4 Mixing of Vehicle Classes in a Lane	Not Mixed
5 Entry/Exit	Dedicated
6 Obstacle Avoidance	Automatic sensing and automatic maneuver if possible

1. The intelligent agents reside both on the vehicle and on the infrastructure. The driver is the highest-level decision maker inside the vehicle, though he, necessarily, passes full control to the vehicle. The vehicle uses on-board intelligent control systems mainly for longitudinal control and platooning functions, but may possibly use them for lateral control. The main mode of operation of the infrastructure is a request-response type. Each vehicle's requests are processed and appropriate commands are sent to the appropriate vehicles/platoons, which respond to that request. Infrastructure takes a more pro-active role in monitoring traffic flow; it broadcasts traffic flow messages, advises lane changes to individual vehicles and performs other typical ITS functions. The infrastructure is also capable of highly intelligent functions; it takes complete control of any individual vehicle, i.e., infrastructure can completely substitute for a vehicle's intelligence and assumes longitudinal, lateral and navigational control. However, it might not have enough resources to control more than a fraction of the vehicles on the road at any time. Local officials may opt for an infrastructure that controls the vehicle only in case the vehicle (or the driver) authorizes such a transfer of control. Such a practice might be limited to off-peak hours.

2. The longitudinal separation policy is based upon platooning requirements. Extensive use of platooning is supported by the system. When used properly, it should lead to a dramatic increase in the throughput of the highway. In the baseline system, every vehicle that enters the AHS immediately becomes a candidate for platooning. Local authorities may elect to offer every individual the choice of joining a platoon or driving as a free agent. In a more likely scenario, local authorities may offer this only during light traffic conditions, e.g., during the off-peak hours of the day in a city environment, or on a sparsely used highway.

3. Only those vehicles that have fully functioning AHS capabilities are allowed to enter the AHS. Moreover, non-AHS vehicles are separated by physical barriers from AHS vehicles. The only way a non-AHS vehicle can make its way to an AHS lane is either by trespassing at the entry point, or if its AHS capabilities fail during travel. The local tailorability is minimal in this regard, as the system is jeopardized if many non-AHS vehicles find their way to AHS lanes. It implies a dual highway system in which the AHS system is completely independent of the non-AHS system.

4. Each AHS lane is meant for use by only certain classes of vehicles. No mixing is allowed. The heavy vehicles are naturally barred from the lane of lighter vehicles. The light vehicles also can not use the lane reserved for heavy vehicles, not even for transition purposes. The local tailorability is minimal since any modification would classify as a different concept, e.g., Concept #11, or #19. It implies a tiered AHS system, with each tier catering to a different set of vehicle classes. There is little interaction between the tiers; therefore, highway-to-highway interchanges would be tiered making its design highly complicated. A separate entry/exit would be required for each tier. Such a design is perhaps suitable for city commute traffic, which is often composed of similar vehicle classes.

5. Entry/Exit structure is driven by the two concept characteristics discussed above, i.e., AHS and non-AHS traffic separated by physical barriers, and no mixing of vehicle classes in a lane. Entries and exits to AHS are composed of fully dedicated lanes. Since there is no mixing of vehicle classes in a lane with this concept, a separate entry/exit lane is provided for each class of vehicles. The incoming vehicles can access the correct AHS lane directly without first passing through a transition area. Similarly, vehicles do not transition through lanes of other vehicle classes before exiting.

6. Obstacles of nearly every size, stationary or moving, are sensed and detected by the non-human intelligent agents, both on-board the vehicle and in the infrastructure. The response depends upon the situation. An automatic maneuver to avoid the obstacle would be made, if considered possible. Possible maneuvers include fast lane changing, swerving around the obstacle, driving over the obstacle, emergency braking. The response takes into account the size and the type of the obstacle. The safety of the vehicle in question, and the others around it, are of supreme concern. At no stage, is human involvement expected, except possibly in the obstacle sensing. Any human input regarding a possible obstacle is processed first by the non-human agents before being used for detection or maneuvering. Any temporarily or permanent non-AHS vehicles on the highway are considered obstacles.

16.3 OPERATIONAL CONCEPT

Three different point of views are considered to illustrate the operational design of the system, that of the driver of each vehicle, that of the vehicle and that of a platoon. The emphasis is limited to the normal operating conditions.

Before these point of views are presented, it is illustrative to look at four modes of operation a vehicle can be under from the point of view of who is in charge. The intelligent agent in charge makes the high level decisions, which are executed by the agents further down in the control hierarchy.

The vehicle is in charge through the use of an array of intelligent control systems. The vehicle (and in exceptional circumstances the driver) authorizes the infrastructure to take charge, for example during the lane changes, platooning, deplatooning, entry/exit and emergencies. A platoon is in charge of the vehicle. The platoon leadership can be collective or individual, depending upon the implementation. Infrastructure wrests the charge away from the vehicle or the platoon. The driver of the vehicle is in charge under emergency conditions.

In any case, once the vehicle loses the charge, it is unable to get it back on its own. The infrastructure has to reinstate the charge. Whenever a transfer of control takes place from infrastructure to the vehicle, the vehicle has to actively take control and convince the infrastructure that it is aware of the transfer. If the vehicle fails to respond in the right fashion, the infrastructure retains the control. Similarly, once the driver loses the charge to the vehicle, he is unable to get it back on his own. The vehicle has to reinstate the charge; this normally happens only at exit. The driver has to convince the vehicle that he is aware of the transfer. If the driver fails to respond in the right fashion, the vehicle retains the control.

16.3.1 Driver Point of View

A driver decides to enter the AHS and picks the right entry point for its vehicle classes, in case there are multiple entry points. He logs in the vehicle classes and the trip description, possibly without ever stopping. Permission to enter might be denied at this point, if the vehicle fails the AHS-capability tests. The driver is given a suggested route to the destination. The driver is expected to be a passive observer from now on under normal circumstances. Under emergency conditions, the full control may be passed over to the driver, who then assumes manual control of the vehicle.

The only operation a driver can possibly perform is the following:

1. Change of Exit: The driver registers a change of exit with the vehicle, which informs the infrastructure. Request Deplatooning: The driver may be free to make this request under the implementation where platooning is not uniformly enforced but only encouraged. If the permission is granted, the platoon breaks at one or two places to make the vehicle a free agent. Full control is passed to the vehicle.

16.3.2 Vehicle Point of View

The vehicle is guided to a position in one of the AHS lanes (decided upon by the infrastructure to optimize the traffic flow). It may involve automatic lane merging, lane changing, acceleration, deceleration, platoon formation and platoon modification. When the lane-positioning is complete, vehicle control is transferred to the vehicle. Under the baseline model, the vehicle at this point is part of a platoon, and so has very limited authority. The platoon operates as a unit. If the vehicle is a free agent, it might be expected to initiate the process of joining a platoon at this point.

Once a vehicle is in a lane in charge of itself but not a member of a platoon, it can be involved in various operations. All of the following operations are initiated by the vehicle. Some of these are redundant if a navigational subsystem is in place.

1. Lane Following and Lane Keeping: The vehicle oversees lane following procedures. The intelligent headway and speed maintenance mechanisms, which are located on-board, control the vehicle longitudinally.
2. Request Lane Change: The vehicle decides to change lane and registers a request with the infrastructure. A lane change request can also be initiated by the navigational system or certain other intelligent non-human agent aboard the vehicle. The request is not normally denied unless it leads to an unusual disturbance in the normal operations. Once the request is granted, the vehicle is informed and the infrastructure takes charge of the vehicle. The high level decisions regarding lane changes are passed on to the from the infrastructure until the lane has been automatically changed. Control passes to the vehicle from the infrastructure when the vehicle is stably located in the new lane.
3. Request Exit: The vehicle is informed of the approaching destination exit or the driver decides to make an early exit or the navigation system senses the approaching exit, in any case a request is registered with the infrastructure. The request is granted under normal circumstances, unless the exit requested is congested, or is not available for some other reasons. If the request is granted, the vehicle is taken out of the loop, a series of automatic lane changes occur and the vehicle is guided to the exit lane, where control is passed back to the driver.
4. Platooning Request: The vehicle (or the driver) may have to make this request in the implementation where platooning is not uniformly enforced, but encouraged using other incentives. Otherwise, the infrastructure commands the vehicle to join a platoon. The infrastructure selects a platoon that is suitably located for the vehicle to join, takes control of the vehicle, and sends control commands to navigate the vehicle to the platoon. Once in position to join the platoon, the control is passed to the platoon. The platoon performs the necessary control actions to incorporate the new vehicle. The platoon retains the high level control of the vehicle as long as the vehicle is a member.
5. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the vehicle may decide to take avoidance maneuvers without the help of infrastructure. Automatic maneuvers are performed to avoid a collision and include fast lane changing, swerving around the obstacle, driving over the obstacle and emergency braking.
6. Certain operations are not initiated by the vehicle. The infrastructure, after informing the vehicle, takes control and performs these operations. These are the operations that may appear unexpected to the driver.
7. Automatic Obstacle Avoidance Maneuvering: Once an obstacle is sensed, the infrastructure may decide to take charge of the vehicle. Automatic maneuvers are then performed to avoid a collision and include fast lane changing, swerving around the obstacle, driving over the obstacle and emergency braking. Automatic Deplatooning: Automatic Acceleration/Deceleration:

The above operations are performed to create room for vehicles that are attempting a lane change. Automatic Rerouting: Automatic rerouting is done by the infrastructure to optimize the overall traffic flow from the point of view of throughput and congestion.

The limited high level operations a vehicle is able to do as a member of the platoon are the following.

1. Request Exit: The vehicle is informed of the approaching destination exit or the driver decides to make an early exit. In any case, a request is registered both with the infrastructure and the platoon. The request is granted under normal circumstances, unless the exit requested is overflowing or is not available for some other reasons. If the request is granted, the platoon breaks at one or two places to make the exiting vehicle a one vehicle platoon that is still under the control of the infrastructure. A series of automatic lane changes occur and the vehicle is guided to the exit lane, where the control is returned to the vehicle. Request Deplatooning: The driver may be free to make this request under the implementation where platooning is not uniformly enforced, but only encouraged. If permission is granted, the platoon breaks at one or two places to make the vehicle a free agent. Full control is passed to the vehicle.

16.3.3 Platoon Point of View

A platoon as an entity is created by the infrastructure but is not controlled by it. The intelligent agents behind it reside on the member vehicles. One particular member of a platoon is usually denoted as the leader of the platoon. Once formed, it has a life and a death. During its life it can perform many operations, some akin to a free agent vehicle and others quite different from those of a free agent vehicle.

1. Lane Following and Lane Keeping: The platoon does lane following, with assistance from an assortment of intelligent control mechanisms, to maintain speed or headway or for lane-keeping. Request Lane Change: The platoon can request a lane change for the entire platoon. It is not expected to be a frequent request as it is a very expensive maneuver from the communication point of view. The infrastructure has control of the platoon during the lane change. Removal of a Vehicle: Once a platoon gets a request from a member vehicle to deplatoon, the platoon first isolates the vehicle and then requests the infrastructure to change its lane. The broken platoon may be merged as one again afterwards. Addition of a Vehicle or a Platoon: The platoon receives a request from the infrastructure to add a suitably positioned vehicle. The platoon takes control of the vehicle and maneuvers it to join the platoon.

16.4 SYSTEM DIAGRAM

Information and control commands and parameters flow between individual vehicles, vehicles and the platoon entity, between vehicles and the infrastructure and between the platoon entity and the infrastructure. The vehicle-to-vehicle data communication is related to maneuver coordination, platooning parameters and vehicle dynamics. The vehicle-to-infrastructure data communication consists mostly of requests, e.g., lane change request, platooning requests, entry/exit request, etc. There is some additional non-request type data flow regarding obstacles detected by the sensors on the vehicle. The infrastructure to vehicle data communication consists mainly of responses to the vehicle requests, e.g., commands for lane changes, exit, lane positioning etc. There is additional non-response type data flow regarding the position of obstacles, routing commands, traffic flow information etc.

While the exact content of the communicated messages has not been defined yet, it is estimated and expected that a medium bandwidth communications channel will suffice. At this time, rough estimates of the magnitude of the message size, update rate and range are the following.

The bulk of the communication will probably take place between vehicles.

Based on prior experiments, it is estimated that messages of up to 100 bytes with a repetition rate of 1/10th of a second will be used. This requires a channel with 9600 bps capacity. A variable duty cycle is estimated, i.e. the communication channel may not always need to transmit the maximum possible message size. Vehicles that are some distance apart are not likely to need to communicate since their dynamics and trajectories do not affect each other. At the same time, it is desirable to minimize the transmitting power and range of vehicle-to-vehicle communication to minimize interference with other vehicles and to permit an efficient spectrum reuse. At this time, a 1/4 mile maximum range seems sufficient and reasonable.

Similarly, to simplify the complexity of the infrastructure control requirements it seems reasonable that such control should be localized. Each roadside transceiver only needs to communicate with a finite and limited number of vehicles. The optimal numbers must be computed after a careful analysis. At this time, only a rough estimate is possible. For reliability through redundancy, it is a good idea to make it possible for two adjacent roadside transceivers to receive the vehicle-to-infrastructure communications. Therefore, twice the range of communication from the vehicle to the roadside, as opposed to the other way around, should be allowed. The roadside-to-vehicle communications is made reliable by on-vehicle redundancies, but it would be desirable for one and only one roadside transceiver to attempt to communicate with each vehicle. The handover of the vehicle from one roadside transceiver to the next is handled by the Traffic Operations Center.

So, to summarize:
Vehicle in front-to-Vehicle in Back: Message Content: Position, Velocity, Acceleration, Braking force, operational status, emergency ahead. Also communicated but at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 9600 bps channel, 75% duty cycle, 1/4 mile maximum range.

Vehicle in front to the Vehicle in Back: Passive reflection of the radar sensor beam from the Vehicle in Back permits the vehicle on back to detect relative position and relative speed.

Vehicle in back to the Vehicle in Front: Message Content: Position, Velocity, operational status. Also communicated but at a lower repetition rate: Vehicle mass, maximum acceleration, maximum deceleration, estimated stopping distance according to current road surface conditions. 100 byte "packets", 0.1 sec repetition rate, 9600 bps channel, 25% duty cycle, 1/4 mile maximum range

Infrastructure-to-Vehicle: Message Content: Command and control requests, speed and separation parameters, road surface condition advisories, notification of location and nature of emergencies. 1000 byte "packets", 1 sec repetition rate, 9600 bps channel, 25% duty cycle, 1 mile maximum range

Vehicle-to-Infrastructure: Message Content: Position, Velocity, Acceleration, operational status, road surface condition, detected obstacles. 1000 byte "packets", 1 sec repetition rate, 9600 bps channel, 5% duty cycle, 2 mile maximum range

Infrastructure-to-ANY-Vehicle (Broadcast): Message Content: Broadcast location identification, road surface condition advisories, traffic condition advisories, notification of location and nature of emergencies. 1200 byte packets, 10 sec repetition rate, 1200 bps channel, 100% duty cycle, 4 mile maximum range

Furthermore, there is a need for the infrastructure to be able to sense the presence, position and velocity of vehicles, within the range of authority of its Traffic Operations Center. Most of that information is provided by the vehicles themselves, through the vehicle to infrastructure communications channel. However, for reliability through redundancy, the infrastructure should have an independent way to obtain the same information. This also allows the identification of non-equipped or malfunctioning vehicles. The installation interval for roadside sensors is approximately equal to the roadside transceiver distance from each other. The bandwidth of the communication channel between roadside sensors and the TOC is roughly equal to that of the vehicle-to-infrastructure data channel times the maximum number of vehicles that may need supervision at once.

16.5 FUNCTIONAL ALLOCATION

16.5.1 Baseline Functions

Check-in: Allocated to vehicle in combination with the infrastructure. Function performed in coordination with the infrastructure after vehicle passes operational test. Equipped vehicles are coordinated and assisted in merging. Non-equipped or non-fit vehicles are not allowed to enter. Sequence of events description: The driver decides to enter the AHS and selects an entry point that is appropriate for his vehicle class. Once the vehicle reaches the entry point, an operational test is performed. Some operational status data has been collected during normal driving before reaching the entry point, while other data must be collected on the spot. The results are communicated to the infrastructure. The infrastructure makes the go/no-go decision regarding the operability of the vehicle. A traffic light with arrows directs the driver towards the AHS lanes, if the result is "go", or towards the manual lanes, if the result is "no-go" As soon as the "go" condition is given and the vehicle approaches the AHS lane, its velocity control is assumed by the infrastructure to coordinate its motion in preparation for merging into traffic.

Transition from manual to automatic control: Allocated to the vehicle. The transition is contingent upon a successful check in. Sequence of events description: Velocity control is assumed by the automatic controller first. If the vehicle velocity responds to the infrastructure commands as intended, lateral control is subsequently assumed by the automatic controller. If a failure is detected at this time, the driver is immediately notified to continue driving the vehicle as a manual vehicle and to direct it towards the manual lanes or an emergency lane.

Automated Sensing of roadway, vehicles and obstacles: Allocated to the vehicle. Sequence of events description: Electronic sensors mounted on the vehicle perform the sensing and detection functions continuously or with a repetition frequency adequate for the required bandwidth of the on-vehicle automatic controllers.

Longitudinal sensing: Vehicle sensors sense the presence of other vehicles and obstacles in the space ahead of the vehicle. Lateral sensing: Vehicle sensors sense the presence of other vehicles and obstacles in the space on each side of the vehicle. Obstacle sensing: Vehicle sensors are able to sense at least some kinds of obstructions, other than vehicles.

Vehicle longitudinal position sensing: Both absolute (medium high accuracy) and relative to the vehicle in front (very high accuracy). Vehicle lateral position sensing: Both absolute (high accuracy) and relative to the vehicles on each side (medium accuracy).

Automated Sensing of vehicles and obstacles: Allocated to the infrastructure. Roadway sensors belonging to the infrastructure collect information about obstacles, and the information is passed from the infrastructure to the vehicle. Sequence of events description: The infrastructure employs video cameras, radar, inductive loops and other sensors to sense as accurately as possible the location position and velocity of vehicles in the AHS lanes. Disabled vehicles are automatically classified as obstacles. Detection of other obstacles (foreign objects, stray animals etc.) may be possible but of limited success.

Collision avoidance: Information from the vehicle sensors and the infrastructure is passed to the Longitudinal Velocity Controller which acts as a longitudinal collision avoidance system. Sequence of events description: All the information collected by the on-vehicle sensors is correlated with the information provided by the vehicle in front as well as the information provided by the infrastructure. If the information is deemed consistent it is used as input to the Longitudinal Velocity Controller. If minor inconsistencies are found the worst case scenario is assumed by the controller and the infrastructure is notified via the status report. If major inconsistencies are found, an emergency is declared and the driver is notified that he may have to resume manual control. At the same time the infrastructure and other vehicles in the vicinity are notified and requested to increase their distance from the malfunctioning vehicle. If the information from all sensors is consistent and indicates that the vehicle is in a collision path with another vehicle or a newly identified obstacle, the Longitudinal Velocity Controller attempts to reduce the velocity by applying emergency braking. A change lane request may also be generated by the vehicle and transmitted to the infrastructure.

Automated headway keeping: Allocated to the vehicle. Vehicle sensors measure relative position and relative speed to the vehicle in front. The controller can control the velocity and headway of the vehicle down to zero velocity, including stop and go situations. Sequence of events description: All the information collected by the on-vehicle sensors is correlated with the information provided by the vehicle in front as well as the information provided by the infrastructure. If deemed consistent, this information becomes the input to the Longitudinal Controller, which applies throttle or brake as necessary to maintain the headway that is recommended by the infrastructure. The headway recommended of the infrastructure can be adjusted by the vehicle controller depending on information from the vehicles in front and back and also according to the road surface conditions. The infrastructure is notified of any changes.

Automated Lateral Controller. (Lane Keeping): Vehicle based, but it most likely will require the presence of "markers" or other aids from the infrastructure. Sequence of events description: The on-vehicle sensors detect the position of the vehicle in absolute terms and also relative to the lane boundaries and relative to any other vehicles on adjacent lanes. The information is used to control the steering angle so that the vehicle follows a smooth trajectory near the center of its assigned traffic lane.

Detection of hazards: Vehicle-based or in combination with the infrastructure. The vehicle may use the longitudinal and lateral sensors. The infrastructure assists by transmitting to all vehicles the exact location of known hazards. Sequence of events description: The longitudinal and lateral sensors on the vehicle pass the information collected to the controller. The information is correlated to the information received via communications from other vehicles and the infrastructure. Any objects detected by the vehicle sensors that do not coincide with any objects known to the infrastructure are automatically classified as potential hazards and the infrastructure is immediately notified of their presence. Furthermore, if the position of the hazards appears to be in the path of the vehicle, the collision avoidance procedures are automatically initiated as well.

Normal Maneuver planning: Allocated to the vehicle in combination with the infrastructure. Executed by the vehicle based on information from the sensors and the infrastructure Sequence of events description: Based on the desired destination declared by the driver, the vehicle navigation controller employs information provided by the infrastructure to implement the vehicle travel plan. The plan is submitted to the infrastructure for approval. Depending on local conditions the infrastructure may opt to alter the travel plan and may request additional maneuvers at any time.

Emergency Maneuver planning: Allocated to the vehicle, possibly in combination with the infrastructure. In some cases it may be managed by the infrastructure. Sequence of events description: It is assumed that the most likely implementation is for the vehicle controller to assume the responsibility of "self-preservation" during emergencies. Infrastructure involvement may be necessary even during emergencies to avoid the possibility of chaotic behavior when individual vehicles begin attempting emergency maneuvering on their own.

Normal Maneuver execution: Allocated to the Vehicle. Executed by the on-board controller. Sequence of events description: The on-vehicle controller applies the throttle brake and steering actuators as necessary to implement the desired maneuvers.

Emergency Maneuver execution: Allocated to the Vehicle. Executed by the on-board controller but in some cases the driver may be called in to take over control. The exact scenario to be followed is subject to debate. Sequence of events description: The on-vehicle controller applies the throttle brake and steering actuators as necessary to implement the desired maneuvers. The driver has the option to intervene but his intervention power is limited or depends on the situation, i.e., certain scenarios allow more driver input than others. This is likely to be one of the thorniest issues regarding the eventual deployment of AHS.

Leading a platoon: Allocated to the vehicle in combination with the infrastructure. Sequence of events description: The leader and/or the infrastructure decides the speed, inter-vehicle spacing and other parameters of the platoon. The parameters are communicated to the member vehicles who generate their local control commands (micro-commands) using those parameters.

Transition from free agent vehicle to platoon control: Allocated to the vehicle and the platoon and possibly to the infrastructure as well. Sequence of events description: The platoon receives a request from a new vehicle that wants to join-in. The infrastructure is notified, and when the infrastructure approves, the vehicle is given the appropriate commands to maneuver and join the platoon.

Transition from platoon to free agent vehicle control: Allocated to the vehicle and the platoon. Sequence of events description: The platoon receives a request from a vehicle for deplatooning, isolates the vehicle, slowly transfers control to the vehicle and breaks into two separate platoons. If the vehicle changes the lane immediately, the two platoons may rejoin.

Transition from automatic to manual control: Allocated to any one of the vehicle, driver or infrastructure. Sequence of events description: It may be requested by the driver, requested by the infrastructure, or enforced by the vehicle as a failure response fallback mode. This normally happens immediately after check out. A likely scenario is as follows: The vehicle relinquishes partial control to the driver who is notified and expected to apply certain corrections to the vehicle velocity and path through the application of a moderate amount of braking and steering. By doing so he effectively verifies his alertness and readiness to resume full manual control. If he fails to perform the required actions within the allocated time, the vehicle controller declares that the driver is unfit and resumes fully automatic vehicle control. In this case, the vehicle is driven automatically to a designated exit that has been designed for the accommodation of "sleeping" drivers and brought to a complete stop. A human operator will approach the vehicle and investigate the condition of the driver. If he has suffered death, loss of senses, and such he is taken to a hospital. If he is found to be under the influence of drugs or alcohol he is taken to jail. If he is found to be sleeping he is awakened. If he is found to be playing games i.e., testing the system, he is cited for a traffic violation.

Check out: Allocated to any one of the vehicle, driver or infrastructure. Sequence of events description: Check-out may be requested by the driver, requested by the infrastructure, or enforced by the vehicle as a failure response option. In most cases, the vehicle is self guided towards the exit ramp and a transition from automatic to manual control is initiated.

Flow control: Allocated to the infrastructure. The infrastructure manages and controls the traffic flow. Sequence of events description: The infrastructure measures the volume and the velocity of the traffic at different sections along the AHS and a central controller at the Traffic Operations Center makes the decisions on optimal velocity, spacing and traffic routing in order to control and optimize the flow.

Malfunction management: Allocated to the vehicle, infrastructure and possibly the driver, in combination. In most cases it is cooperative between vehicle and infrastructure. Several different scenarios exist. Sequence of events description: If the malfunction is identified to be on the vehicle, it is assumed that it can be fully or partially compensated by redundancy and the vehicle will be requested to check-out at the earliest opportunity. If the malfunction is identified to be on the vehicle but it is not covered by redundancy, the driver is notified and requested to resume full manual control. If the malfunction is identified to be on the infrastructure, the vehicle and the driver are notified of the exact nature and the extent of the loss of functionality and the AHS either continues operating in a degraded mode, shuts down or it is temporarily converted to manual operation.

Handling of emergencies: Normally allocated to the vehicle or to the vehicle and the driver in combination. Sequence of events description: It is assumed that the most likely implementation is for the vehicle controller to assume the responsibility of "self-preservation" during emergencies. Infrastructure involvement may be necessary even during emergencies to avoid the possibility of chaotic behavior when individual vehicles begin attempting emergency maneuvering on their own. In at least some cases, it may become necessary to pass control responsibility to the driver, who would be expected to assume manual control of the vehicle.

16.6 IMPLEMENTATION

In this section one *possible* implementation of the concept is described. This is by no means the only possible implementation or even the most recommended one. It is only a representative example of an implementation that allows visualization of the magnitude and complexity of the problems involved and the intricate relations and interdependencies between the components of the system.

16.6.1 Vehicle

The vehicle requires the following functions and subsystems:

Fail-proof longitudinal control system. The longitudinal control system serves the function of velocity and headway maintenance. The requirement for fail-proof operation of the longitudinal controller under all conditions imposes the need for extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.

Fail-proof lateral control system. The lateral control system serves the function of lane keeping and lane changing. The requirement for fail-proof operation of the lateral position controller under all conditions imposes the need for extensive redundancies in every part of the controller architecture. This includes the sensors, the actuators and the control logic hardware and software.

Accurate longitudinal position sensing. The longitudinal position of the vehicle must be known both in absolute terms and in terms of relative position to other vehicles. The absolute position must be known for navigation and trip destination control purposes and the relative position must be known for velocity and headway maintenance and control as well as for collision avoidance.

Accurate lateral position sensing and lane position identification. The lateral position of the vehicle must be known both in absolute terms and in terms of relative position to other vehicles. The absolute position must be known for lane keeping, lane changing and navigation purposes and the relative position must be known mostly for collision avoidance especially during lane changing.

Collision avoidance based on obstacle sensing in combination with vehicle to vehicle and vehicle to infrastructure communications. It is anticipated that vehicle sensors will not be adequate and will not guarantee collision avoidance with any kind of obstacle or even with another vehicle. Therefore the collision avoidance control logic requires additional information that can only be supplied by other vehicles and by the infrastructure.

Maneuver coordination between vehicles. Every aspect of the motion of the vehicle and especially lane changes has to be orchestrated and coordinated by a control authority at a higher level than the each vehicle itself. This control authority is distributed collectively among vehicles or is assigned to the infrastructure. It is most likely that a local decision will affect the assignment of this control authority. In urban regions the authority may be exclusive to the infrastructure. In rural regions the authority may be distributed among vehicles and in every case it may be dynamically distributed among the vehicles and the infrastructure by means of appropriate maneuver protocols.

Automatic route guidance based on navigation computers and interaction with the infrastructure.

Supervisory controller, which monitors everything and alerts the driver of any single point failure. Malfunction management will be one of the most complicated issues facing the designers of the AHS system. It is very desirable if not absolutely essential that every part of the automation be covered by multiple redundancies such that no single point failure can affect the operation of the system. At the same time, any failure must be immediately detectable and the driver should become aware of it as soon as possible. If necessary the driver is required to assume partial or full control of the vehicle.

16.6.1.1. Required vehicle components

Two longitudinal range and range rate sensors. They are based on Forward looking Doppler radar, FMCW radar, infrared laser ranging system, optical recognition method or combination of the above.

Side looking vehicle and obstacle sensors. They are based on very low power radar, sonar, or infrared light.

Redundant lateral lane position sensors. The same sensors provide absolute longitudinal position information. The sensing method will include Differential GPS and the use of lane markers, which requires a potentially large investment in infrastructure. Candidate lane marking methods include magnetic nails, magnetic lane marking paint, corner reflectors for radar, optical patterns and others. A single method with optimal performance cannot be identified at this time. Each system has potential merits and a number of shortcomings and limitations at the same time.

Transceiver for vehicle to vehicle communications. Communication includes but is not limited to velocity, acceleration and braking force. Also required is communication ability with cars in adjacent lanes for cooperation in merging.

Platooning protocol controller. Requires extended bandwidth longitudinal and lateral controllers, as well as high precision sensors and actuators.

Lateral collision warning coupled with the steering actuator for assistance in checking in and out.

Environmental conditions sensors. The primary purpose of these sensors is to sense and/or estimate road surface conditions and especially friction coefficients for cornering and braking.

Driver status monitors and diagnostics. Although the driver is not involved in the control of the vehicle when traveling in an AHS environment, his readiness status and alertness are essential pieces of information in case of detected failures of some part of the redundant controllers, as well as before and during the check out stage.

Supervisory controller. The supervisory controller monitors the performance and functionality of every part of the system, including every redundant part of the controllers, sensors and actuators, the communications systems and also driver status. The supervisory controller has the responsibility of reassigning responsibilities among parts of the system based on a well defined system of priorities. The supervisory controller attempts to detect and recover any detectable failure. In doing so it reassigns actuator responsibilities to different parts of the system when actuator malfunctions are detected. Control responsibilities are reassigned to different controllers when control malfunctions are detected, i.e. to the infrastructure and eventually to the driver. Sensing responsibilities are reassigned to different sensors when sensing malfunctions are detected, i.e. to alternative sensors first, then to the infrastructure and eventually to the driver.

16.6.1.2. Vehicle implementation issues and considerations

In considering acceptable versus unacceptable failures of vehicle components, two independent ways of controlling the throttle, brake and steering must be provided to accommodate any single point failure in the sensor, controller or actuator.

Furthermore, no single point failure of any subsystem must escape diagnosis or lead to loss of control. Care must be taken to avoid common mode failures such as loss of power to both parts of a redundant controller simultaneously.

16.6.2 Infrastructure

Required low-level infrastructure components
Markers must be provided to assist the vehicles in performing the lane keeping function. The markers must be unambiguous and extremely reliable under all traffic, lighting, weather and temperature conditions. It is not expected that different type sensors will be needed in rural versus urban sections of the highways.

Physical barriers must be provided to separate the AHS system from the non-AHS part of the highways. For cost considerations it might be considered as an option not to have those barriers in rural sections of the highways, although a safe alternative at this time is not known.

No mixing of vehicle classes is allowed. This implies that separate entry/exit ramps and highway interchanges are needed to accommodate more than one vehicle class. Again this may be the subject of a cost versus benefit analysis on sparsely traveled rural highways.

Required intermediate-level infrastructure components
Low bandwidth communication (broadcasting) to all vehicles within the authority of the infrastructure. May contain "traveler information" type data. The roadside transmitters of broadcast type information are allocated as a dual redundant station with a range of 4 miles located every 6 to 8 miles in rural highway sections. In urban sections of the highways, it might be preferable to employ lower power transmitters more closely spaced. For example, 1 mile range transmitters located every 2 miles.

Required high-level infrastructure components
Medium bandwidth bi-directional communication with individual vehicles is required. Vehicles must be individually identifiable and individually addressable, both by the infrastructure controllers and by the communication transceivers. This requirement is the same in both rural and urban sections of the highways.

Sensing of traffic flow speed and flow density, under all traffic, lighting, weather and temperature conditions must be possible. The accuracy requirements may be slightly relaxed in sparsely traveled rural highways, but the sensing requirements are basically the same as in urban highways.

Sensing of individual vehicle position and velocity under all traffic, lighting, weather and temperature conditions. This is required in urban highway sections but may not have to be implemented in sparsely traveled rural highway sections.

Traffic Operations Centers are required to be present along the roadside at intervals to be determined based on the typical and the expected traffic density. The location and the distance between those TOCs will be different for rural and urban sections of the highways.

16.6.2.1. Rural Highway

In a rural highway environment the necessary infrastructure will probably be different to some extent. It may be more cost efficient to cover larger areas with fewer traffic control stations. Those sparsely spaced traffic control stations must cover a larger number of vehicles over extended distances. If the distance between the infrastructure equipment and the vehicle is extended, long range communications, medium to high capacity communication channels, and reliable backup equipment are needed. In rural environments, infrastructure sensing may be limited to flow rate and average velocity every few miles.

16.6.2.2. Urban Highway

In an urban highway environment, it is likely more efficient to employ short range communications, high capacity communication channels, and closely spaced traffic control stations. Knowledge of individual vehicle position coordinates may be required at each infrastructure Traffic Operations Center site.

16.6.3 Deployment

The minimal deployable system requires a longitudinal controller (maintain velocity or headway) and a lateral controller (maintain lane position) on the vehicle as well as an infrastructure system to manage the flow of traffic by providing commands and information to the vehicle.

For the longitudinal controller a longitudinal sensor, an actuator system, and the controller hardware and software are needed.

For the lateral controller a lateral sensor, an actuator and the lateral controller hardware and software are needed.

For the communication required a medium to high bandwidth communication transceiver on the vehicle and a communication system built into the infrastructure are needed.

Some way for the infrastructure to monitor the traffic flow is essential.

The incentive for the buyer to obtain a vehicle so equipped is that an automated vehicle driven on an automated highway offers the potential for shorter travel times and a major improvement in the comfort of the driver and passengers.

The incentive for the roadway operator to deploy an AHS roadway is the potential for reduced highway travel times, reduced pollution and most important the postponement of the need to build more highway lanes if the existing ones can be used more efficiently.

16.7 GENERAL ISSUES AND CONSIDERATIONS

What degree of automation is there in the navigation function?
The system has the capability for fully automatic navigation for any individual vehicle though it is not included as a specific requirement in the architecture. What is a characteristic of the baseline model is monitoring of each vehicle which enters the AHS. That is, however, the most important element of a navigational system. Such information can be used by infrastructure-based agents or on-board agents to navigate the vehicle automatically. The communication load on the infrastructure would grow dramatically if all the vehicles are being navigated by its agents. In a more reasonable scenario, the infrastructure performs the specific navigation function of initial route selection and leaves the rest of the navigation to the agents aboard an individual vehicle.

What are the obvious failure modes for the concept?
The system consists of so many subsystems that it will have a variety of failure modes. The primary failure modes can be classified into the following categories. Each category is illustrated by examples.

Sensory Failures
Vehicle cannot sense it's own position.

Vehicle cannot sense the presence of other vehicles ahead.

Vehicle cannot sense the presence of obstacles ahead.

Vehicle cannot sense the presence of other vehicles aside.

Vehicle cannot sense the presence of obstacles aside.

Vehicle cannot sense the weather conditions around.

Longitudinal Control Failures
Vehicle cannot maintain velocity.

Vehicle cannot maintain the desired headway.

Lateral Control Failures
Vehicle cannot maintain lateral trajectory.

Communication Failures
Vehicle cannot receive communication from other vehicles.

Vehicle cannot receive communication from other infrastructure.

Vehicle cannot transmit to other vehicles.

Vehicle cannot transmit to the infrastructure.

Platooning Function Failures
Vehicle cannot coordinate its maneuvers with the platoon.

Entry/Exit Function Failures
Vehicle fails the check-in procedure.

Vehicle (or driver) fails the check-out procedure.

Control Transfer Failure
Vehicle cannot switch between operating modes.

What major systems or subsystems can back one another up in case of failure?
None, unless explicitly designed for the purpose. Dual redundancy will be required for most automation subsystems to guarantee fail-safe operation. Triple redundancy will be required on the most critical subsystems. If designed properly, degradation of the system, in case of failure, occurs in a fashion so that if the infrastructure (or a platoon) is unable to control a particular vehicle then it should pass down the control to the vehicle; in case the vehicle is unable to control itself, it is able to pass down the control to the driver. Each of these infrastructure, platoon, vehicle has multiple redundancy in their control systems to reduce the chances of breakdown. But if the breakdown does take place, at no time is the vehicle out of proper control.

The feasibility of such a design, however, is far from a settled issue. If a platoon looses control of a member vehicle, it is unlikely that vehicle has enough time to take over the control without colliding with the neighboring vehicles. It implies that platoon functions should be designed such that each vehicle is always under control of itself as much as it is feasible within the concept of a platoon. The control subsystems have to be intelligent enough to recognize and differentiate the impending failures of other subsystems.

Under what circumstances (if any) is control passed to the driver?
The driver has no control, except the high-level navigational one, e.g., choice of the destination, during normal operations on the AHS which include lane keeping, lane following, lane-changes, automatic obstacle avoidance maneuvers.

The only circumstances in which the driver might get the control are exceptional ones. In a malfunctioning system, the infrastructure may perceive the manual option to be the safest one. In such a case it will alert the drivers and pass over the control to the drivers. Malfunctions could be of various types. If the control and execution mechanisms on the vehicle breakdown, and it renders the vehicle uncontrollable, then there is no choice but to give over the control to the driver. If the vehicle is functioning well but the infrastructure manager breaks down, then the vehicle could take over the infrastructure responsibilities and still manage to keep the driver out of the loop. The performance will be naturally degraded.

How does the system sense limited visibility, or ice, water or snow on the roadway; what does it do with this information?
The infrastructure constantly senses the highway environs for weather conditions, like visibility, temperature and precipitation. Some of these conditions might be localized, e.g., ice on a bridge, water collected on the inside lane, and some other might be

characteristic to a larger area. The system senses the two kind of conditions in different fashion.

The weather parameters like temperature and wind speed are measured on regional basis using the standard technology. The precipitation is monitored for both type and quantity also on a regional basis.

Some weather-related conditions are measured more locally. All the bridges are constantly monitored for icy conditions under near-zero weather conditions. The snow level on road during or after a snowstorm, water level if it tends to log in certain locations are measured at regular distances in each lane and at the known trouble spots.

The infrastructure may use the sensors which are on each vehicle for sensing localized trouble spots. The vehicle passes on the relevant information to the infrastructure which can alert the on-coming traffic of the trouble spots. Vision based systems coupled with image processing hardware may be able to discriminate some of these conditions. Local visibility, pools of water, icy patches, and friction coefficients are examples of weather elements which might be sensed by the vehicles.

Some of the weather related information gathered by the infrastructure is directly passed on to the vehicles, who add that information to the knowledge they already possess from their own sensors or some other prior information. The weather parameters play a very important role in functioning of the control mechanisms in the adverse conditions. Certain other information is first processed by the infrastructure to generate warnings, advisories and commands for vehicles in specific areas and lanes. Same piece of information can result into different course of action for different vehicles depending upon their location, class, and lane.

What speed(s) would typical users travel at? How tailorable is this?
There are conflicting requirements. A low typical velocity will hurt efficiency and performance. A high typical velocity will hurt fuel economy and may generate potentially dangerous conditions in case of malfunctions. The risks increase exponentially with speed. The exact figures will have to be analyzed. A ball-park figure is that the typical maximum speed will be 20% higher than the current speed limits. Lower typical speeds will be necessary in many cases. The typical speed will have to be tailorable to local conditions, but the maximum speed probably not.

What enhanced functions would a vehicle from this concept be able to perform on a conventional highway?
Except for basic speed and headway control, no other enhanced functions would a vehicle be able to perform on conventional highways of today. However, a low-level infrastructure modification like magnetic nails and exit sensors, could open up various possibilities. A vehicle, with capabilities of this concept, can possibly perform a variety of enhanced functions on these slightly modified highways. Longitudinal control functions, e.g., sophisticated lane keeping and lane following functions can be performed by such a vehicle. Platooning is also within reach of these vehicles. The technology needed to accurately sense the surroundings of a vehicle are improving day-by-day. A dynamic map of the surroundings can form the basis of lateral control functions, like lane changing and even elementary obstacle avoidance. Further analysis is needed to estimate the quality of such localized lateral control. The enhanced functions which seem to be definitely out of the reach of even intelligent vehicles, in the absence of intermediate or high-level infrastructure, are advanced obstacle avoidance, global traffic flow control, route selection, and other traffic management functions.

What assistance would this system provide to the traveler who is also using other modes (bus, rail, subway) of transportation?
No special assistance to public transportation is expected, unless explicitly provided for in the design, e.g., direct excess to subway, rails from the AHS system. In fact, faster speeds and more throughput means that more will use the roads than

ever, as history has told us in the past, more capacity means more drivers.

What additional services would the concept provide for freight carriers?
The drivers of the freight carriers would benefit from this concept probably more than the driver of any other class of vehicles. The attention they need to give to actual driving operations will be of very high-level infrequent type. On long trips, which is often the norm for freight carriers, the drivers can indulge in other job-related tasks while in the carrier. Human-less freight carriers can also be envisioned within this concept. The infrastructure will have to constantly monitor the vehicle (the on-board agents still perform the micro-control), therefore the additional cost can be justifiably passed on to the freight carrier. No mixing of vehicle classes in a lane further enable the possibility of a platoon of human-less freight carriers, just like cargo trains. With no fear of incursion of small vehicles in their lanes, the automation of freight carriers is much easier to carry out.

What features of this concept will most contribute to increasing throughput over the present system ?
The variety of intelligent agents present aboard the vehicle or on the infrastructure will most contribute to increasing throughput.

The most important feature is platooning. It is estimated that extensive platooning can quadruple the capacity of the present system, even if the speed stays the same. The platooning is enabled by the agents aboard the vehicles. They, with sophisticated longitudinal control, enable small separation between vehicles at higher speeds thereby leading to increase in throughput.

The feature of not mixing vehicle classes in a lane is second most important factor. Vehicles of similar performance level and size can safely travel closer to each other than vehicles of different classes. Moreover, the lighter vehicles can travel at a speed significantly higher than that of the heavier vehicles, since they have a lane of their own. The two factors directly result in more throughput.

The third most important feature is the traffic flow management of the infrastructure. Since the infrastructure monitors each and every vehicle, it can set global flow parameters to maximize throughput. The specific infrastructure tasks that influence the throughput in a significant fashion are the initial placement of the vehicle in a lane, routing the vehicle to the destination, the control over the lane changing, control over exit inflow, the capability to shut down an exit temporarily, and setting localized speed limits. Each one of these is a tool in the infrastructure hands to increase throughput of the system.

What features of this concept will most contribute to increasing safety over the present system ?
Almost every feature contributes to the safety of the vehicles operating on AHS. It is assumed that the features provided function as designed all the time. No serious attempt is include into consideration the reliability point of view, which is often the most important one to evaluate safety.

The features which lead to fewer accident situations in the first place are listed below.

Automatic Headway Maintenance: "Rear-ends" are frequent cause of accidents in the present system. It can be avoided if a headway is maintained automatically. The control mechanism needed is least sophisticated and most reliable among the set needed to implement this concept. Automatic Lane-Keeping: Automatic lane-keeping enables vehicles to stay in their own lanes at all times leading to fewer side collisions. Automatic Lane-Changing: A lot of accidents in the current system occur during the process of lane changing, the reason being that the driver has to be aware of the traffic in front, side and, to some extent, back of the vehicle at the same time. All these duties will be shared by different sensors under the concept implementation, therefore enabling a better decision to be taken by the intelligent agent. Moreover, the infrastructure has a control over the involved vehicles during the lane-changing process which means that there are no surprises during the process. Automatic Obstacle Detection: Likely obstacles are detected early thereby giving more time to the agents on-board and on the infrastructure to plan a avoidance maneuver. Traffic Flow Management: The features like localized speed control and knowledge of traffic conditions ahead of time are important factors in improving safety of the system. No Mixing of Vehicle Classes: Each lane contains vehicles of only the same class. A tighter longitudinal control is possible resulting into safer operations.

The feature which lead to lesser injuries to limb and property in an accident situation are listed below.

Automatic Obstacle Avoidance: The maneuvers of the vehicles are coordinated to avoid the impending obstacles thereby leading to completely avoiding the obstacle or minimal impact and injuries to limb and property. Physical Barriers: The high-speed AHS traffic is separated from the non-AHS traffic using physical barriers. No manually driven vehicle is allowed to stray into the AHS lanes. An accident in low-speed lanes does not have a spill-over effect on the high-speed AHS lanes.

On the other hand, the features which lead to more accident situations are listed below.

High Speeds: The vehicles travel at much higher speeds with reduced reaction times. The chances of an accident increase in direct proportion. Separation Policy: The platooning policy is fraught with dangers of serious accidents because of the small separation between the vehicles. Multitude of Electronic Control Mechanisms: Each control mechanism alone is designed to be operate at levels which are safer than those of human beings. However, the sheer number of control mechanisms involved raises the question of reliability of such a system. Heavy redundancy and multiple backup systems can improve the reliability of the system but to what extent and at what cost remains to be studied.

What features of this concept will most contribute to making it cost-effective?

The costs involved in the implementation, operation and maintenance of this concept are obviously tremendous. Instead of trying to list these, we look at the relative benefits which accrue out of this concept. The features which most increase the throughput are also the features which most make it cost-effective.

As far as the user is concerned the principal benefit is the reduced average travel-time. Even the cost of spending time in the vehicle goes down because the driver is relatively free to perform non-driving and perhaps work-related tasks. Increased comfort level and safety level are the other two major benefits. Automatic navigation has an associated relatively intangible benefit to the user.

The principal cost to the user is the increased cost of the vehicle, and the user fees of the system.

What will be the required vehicle maintenance?

Most electronic subsystems that will be added on the vehicle to enable automation can be designed to be sufficiently reliable. The wear out mechanisms for electronic components have an occurrence rate in the order of a few tens of years. Random failures do occur but maintenance cannot alter the random failure rate.

It is predicted that required vehicle maintenance will only be necessary for mechanical subsystems that are subject to wear, just like with the current generation of vehicles. However, the control systems needs tighter performance from the engine and the transmission. This leads to the need of more regular required check-ups and maintenance.

What will be the required infrastructure maintenance?

Infrastructure maintenance is expected to most severe for the hardware embedded in the roads, like lane markers. Communication equipment, being key to numerous functions of the AHS, will require careful maintenance. Since the AHS cannot be stopped or taken off-line, the maintenance has to be done in a continuous fashion. What does this concept assume in the way of support from the external world (e.g., enforcement, safety checks,...) ?

Tight enforcement will have to form the backbone of this concept. A non-AHS vehicle in a AHS lane is a safety hazard. Even a momentary lapse in the AHS capabilities of a vehicle can jeopardize the well-being of it and its neighboring vehicles. To avoid this situation, a number of enforcement have to be put into place. Some of them would be yearly safety checks while others would be enforced every time the vehicle enters a AHS system. Control systems/sensors/communication devices and other electronic components have to be designed so that they have multiple levels of redundancy and they are easily testable for malfunctions. Physical parts like brakes, throttle which are key for vehicle safety have to be also checked on a very regular basis.

Technically, the driver is not in the control loop as soon as the vehicle enters the system. Therefore, any problems which might come up and result into an accident are not the fault of the driver. The vehicle is the responsible agent. In order for this to work as a legal argument, somebody has to take responsibility for well-functioning of the vehicle. The only way the driver could be held responsible in this regard is through a system of certified checks a vehicle has to go through on regular basis. Only those cars which have the required checks are expected to enter the system. The certificates could be checked electronically every time the vehicle enters the AHS, or it could be an implicit requirement.

Do you see any special categories of induced demand (i.e., are there particular classes of users who would take particular advantage of this AHS concept, increasing traffic from that class of user) ?
Increased speeds and reduced travel time imply that more working people of all types and classes would take to the roads. Cities will sprawl even more, as people can afford to live further away from work. Small distance commuter flights would be less attractive as compared to using the AHS. In fact, all means of public transportation would be less attractive because of increased speeds and throughput. Have you thought about the user view? Could you describe how the AHS operates, and the personal driving experience, from the point of view of a naive user who knows how to operate the system, but doesn't know how it works?

For a user of the AHS system under this concept, the driving experience could be compared to taking a train-ride except that you have a personalized bogey and when you reach the station, you can actually drive the bogey home.

A well functioning AHS system under this concept will have relatively few lane changes and the lane-keeping and lane-following would be so uniform that the user will feel that his vehicle is just a part of a big and long procession and once in a while the vehicle changes lanes and joins another train of vehicles. Platooning will make the experience even more like that of a train.

In a malfunctioning AHS system, where the driver is passed over the control, the driving would be back to the usual non-AHS experience.

The users will feel out of control in the event of automatic obstacle avoidance. Jerky, non-uniform maneuvers made by the vehicle to avoid the obstacle would appear somewhat akin to being in the seat next to the driver in the event of an accident in the current system.

The users will feel the strangest driving manually in AHS lanes, if and when they have to do that, e.g., in case of breakdown of AHS capabilities of the vehicle. It is difficult to imagine how that experience would seem. The high speeds involved would make the user feel unsafe under manual control. The transition from automatic to manual control would be a nervous experience for some drivers.

17. CONCEPT 14: INFRASTRUCTURE SUPPORTED PLATOONS WITH GAPS IN PHYSICAL BARRIERS

17.1 OVERVIEW

Concept #14 considers *infrastructure supported platooning* of vehicles on the AHS while allowing *mixed vehicle classes in a lane*. AHS and non-AHS vehicles have *dedicated lanes with some gaps in the physical barrier*. Entry-exit to the AHS is organized using a *transition lane* structure.

We are considering this concept as it has the potential to achieve significant increase in capacity and safety of the AHS, by adding intelligence to both the vehicles and the roadside.

Traffic on the highway is organized in groups of tightly spaced vehicles, named platoons. It is clear that packing of vehicles in platoons results in increased capacity. What may be more surprising is that this can be done without a negative impact on passenger safety. By having the vehicles within a platoon follow each other with a small intra-platoon separation, we can show that if there is a failure and an impact is unavoidable, the relative speed of the vehicles involved in the collision will be small, hence, the damage will be minimized.

Close separation within platoon also allows use of low-cost inter-vehicle communication for control purposes. The inter-platoon separation, on the other hand, will be large (usual safe separation) to physically isolate the platoons from each other. The infrastructure support allows for the traffic flow to achieve its global optimum.

We now list the distinguishing features of this concept.

17.1.1 Distinguishing Features

- Platooning implies maximum achievable throughput without compromising safety of the vehicles.
- Limited infrastructure involvement implies low cost computing and communications infrastructure.

In the course of developing this concept we show that, to obtain the maximum benefits of infrastructure involvement, it is necessary to add a few special features to the infrastructure other than those allowed by the definition of *infrastructure support*. The increased functionality will be required for two purposes; entry/exit assistance which will be localized at the on-off ramps, and, vehicle specific communication capability used for dynamic routing and emergency notification.

Distributed Intelligence implies:

- Capability to optimize global measures using the roadside controllers, and
- Enhanced fault tolerant operation: The ensuing congestion due to faults/accidents can be eased by infrastructure based flow control.
- Infrastructure support can be used to relay common safety critical information for the entire section {Such as reduced safe speed when it starts raining for example}, resulting in increased safety.
- Entry/exit using transition lane eliminates construction/maintenance cost for dedicated ramps.

17.2 SELECTED ALTERNATIVES FROM EACH DIMENSION

17.2.1 Infrastructure Support

In this concept, infrastructure support is utilized to provide dynamic information to automated vehicles such as suggesting lane changes, safe speeds, informing upcoming exit locations, upcoming lane drops or hazards and facilitating entry/exit. This type of infrastructure support is different from *infrastructure managed* since the information is relayed as a broadcast and is directed at platoon leaders.

Although the definition of *infrastructure supported* architecture rules out the possibility of communication to individual vehicle, it should be allowed for the purposes of emergency notification and dynamic routing so as to fully exploit the capabilities of roadside controllers. Relaying of vehicle specific information is also essential for achieving smooth entry/exit of automated vehicles.

17.2.1.1. Local Tailorability:

- Routing flexibility: Local authorities can influence the routing decisions taken by the infrastructure controller. For example, during construction or during a city marathon, local authorities can choose to close down sections of highway and divert traffic through other highways.
- Speed Control: Maximum speed limit can be set by local authority.
- Ramp Metering: Control over flow of vehicles entering AHS at various points.

17.2.2 Platooning With Mixed Vehicle Classes in a Lane

When automated vehicles of different classes are formed into platoons, the dynamics (such as maximum acceleration, rate of acceleration, speed, etc.) of each platoon is restricted by its slowest vehicle. From safety considerations, the intra-platoon separation should be picked according to the vehicle braking capability. Thus, passenger cars can be platooned with a smaller intra-platoon separation than heavy vehicles such as trucks and buses. A mixed vehicle platoon may be created in following ways:

- Constant intra-platoon separation: The separation between any two successive vehicles is chosen to be the largest needed by a vehicle in the platoon. Introduction of one heavy vehicle in a platoon of passenger cars will increase intra-platoon separation thus, decreasing the throughput.
- Platoons with variable spacing: In this scheme, each vehicle follows its predecessor at the safe intra-platoon spacing for that vehicle. The performance of activities involving two platoons, such as joining and splitting of platoons as well as lane changes, will still be limited by the capabilities of the slower vehicles.

Local options for platooning are summarized as follows:

17.2.2.1. Local Tailorability (Platooning)

- Single vehicle platoons (free agents)
- Mixing of vehicle class in a platoon is allowed: This option can be executed in two ways as explained above. The choice of implementation should be left to the system designer rather than the local authorities.
- All vehicles in a platoon belong to a single class: results in homogeneous platoons. As the vehicles in a lane cannot exchange positions, formation of platoons of a single class depends on the percentage of vehicles of different class. With equal percentages for each class, this scheme can potentially degrade into free agent following. A particular design may force the vehicles to join the appropriate platoon at the time of entry requiring large queuing space for each vehicle class at every on-ramp.

Regardless of the platooning strategy, the AHS throughput strongly depends on the types of vehicles present in each lane at the same time. Local authorities have the following choices in this regard.

17.2.2.2. Local Tailorability (Vehicle classes in a lane)

- Multiple vehicle classes per lane: The automated highway productivity can be significantly reduced due to a relatively small percentage of heavy vehicles such as trucks and buses. For example, a vehicle with reduced acceleration/braking capabilities and lower speed will slow down all the upstream vehicles in the same lane.

- Single vehicle class per lane: Needs at least two AHS lanes to implement this strategy and also provide access to AHS for all types of vehicle all the time. One lane can be reserved for passenger cars yielding high throughput and the other lane supporting heavy vehicles as well as passenger cars. In case of a single lane AHS, the AHS lane can be reserved for passenger cars during commute hour traffic and free to use by buses/trucks during off-peak hours. In fact in can be exclusively used for trucks at night. The infrastructure support allows the local authorities to exercise such a control depending on time of the day.

17.2.3 AHS and Non-AHS Lanes Separated By Physical Barriers With Some Gaps For Entry/Exit

Requires construction of barriers along the length of the AHS. The cost of construction will be offset by enhanced safety due to separation of AHS and non-AHS vehicles.

17.2.4 Transition Lane Entry/Exit

This option has negative impact on throughput of both the AHS and non-AHS traffic. To enter the AHS lanes, vehicle have to weave through the manual lanes creating disturbance and loss of throughput for the manual lanes. Similarly high density of traffic on manual lanes can create a bottleneck at the AHS exit causing backups on the automated lanes. This option also takes away the capacity of the transition lane as the transition lane can not be used for through travel. If the entrances and exits to the AHS are close to each other (typical in an urban area), an entire lane next to the AHS will be converted into transition lane and can not be used by manual traffic. In a rural area, sections of this lane close to entry/exit is reserved for automation equipped vehicles and the other parts of the lane can be used by manual traffic. An advantage of this option is that it does not need construction of dedicated ramps.

17.2.5 Automated Sensing Obstacles and Automatic Avoidance Maneuver If Possible

Humans are good at sensing of obstacles and making decisions but not as fast as an automated system. Automated sensing requires accurate (and probably costly) sensors to detect obstacles as small as a *shoe-box* and to keep down the false alarm rate. These sensors should at least match the human sensing abilities. Design of automated avoidance maneuver should at least match the human intelligence.

Automated obstacle sensing and avoidance will be faster than its human counterpart and will eliminate some of the human driving errors such as inattentiveness.

17.3 OPERATIONAL CONCEPT

Normal operation scenarios for this concept are as follows. The vehicle under manual control first enters the manual highway using the manual on-ramp. To enter the AHS, this vehicle manually enters the transition lane.

At the beginning of the entry (the length of the transition lane needed for the entry maneuver is called entry section. The entry section ends at the gap between the barriers which is used for AHS entry) the vehicle is checked into the AHS.

The check in can be done either manually or on-the-fly.

In case of manual check-in, the driver is required to stop. The vehicle is then checked for AHS compatibility by the infrastructure and the vehicle monitoring systems. If this check is successful then the vehicle is checked into the AHS. If the check-in fails, the vehicle is denied entry into the AHS and it should re-enter the manual lane. At the successful completion of check-in, the vehicle control systems take control of all the vehicle systems and sends a message requesting entry to the infrastructure. The infrastructure should have the capability to ensure that transition lane blockage does not spill over into the manual lanes, both to preserve the capacity of the manual lanes and for the safety of high-speed oncoming traffic in the manual lanes. The infrastructure will have the capability to perform a ramp-metering type function. Thus, based on overall system conditions it decides at some time to allow entry. Once permission is granted the vehicle moves ahead towards the entrance of the highway. The vehicle has the capability to track velocity inputs, distance inputs and execute lane-change maneuvers. The vehicle then waits on the entrance ramp, and sends messages to the infrastructure requesting entry.

A feasible operational scenario for the entry process with minimal infrastructure involvement is as follows. The entry point infrastructure has detectors installed at a specified distance upstream of the point at which the entering vehicle is waiting. These detectors are used to determine the conditions in the entry zone. When the vehicle requests entry the infrastructure checks the occupancy of the entry zone. If nothing is detected then the vehicle is allowed to enter. If a platoon is detected in the entry zone then the infrastructure will have the means to sense the speed of the platoon and its distance from the entry point. If the speed and distance of the oncoming platoon are such as to allow safe entry the infrastructure will request the platoon to allow entry. If the platoon acknowledges it will be required to decelerate to a specified entry speed. After the platoon receives confirmation from the oncoming platoon it will provide the waiting vehicle with its target speed and ask it to enter.

Once the vehicle enters the AHS by performing a successful entry maneuver, it decides, based on advice received from the infrastructure, whether it wishes to change into an inner lane. If it wishes to do so then the vehicle will send lane-change requests until a platoon communicates its willingness to admit the vehicle in front of it. The vehicle will use its sensors to detect if the minimum safe spacing and safe relative velocity with respect to the responding platoon exists in its target lane. If suitable conditions exist then it will change lanes. Otherwise, it will co-ordinate with the adjacent lane platoon that has agreed to accept the vehicle in front of it. The assisting platoon will slow down till the required gap becomes available. Then a lane-change maneuver will be executed. If there is no platoon in the adjacent lane in the *safe lane change distance*, the vehicle will change lane after confirming—through inter-vehicle communication—that no vehicle in the lane beyond the target lane (in case of a three lane AHS) wants to change in the same gap.

The same process can be repeated again. If no further lane changes are required then the vehicle sensors will be used to detect the presence of a platoon that is close enough ahead to join with. If such a platoon is detected then the vehicle, based on advice from the infrastructure may request a join maneuver. If the platoon ahead is not already in excess of the maximum platoon size broadcast by the infrastructure and if the platoon ahead is not already engaged in any other maneuver, then the join maneuver will be executed in which the new vehicle will accelerate to merge with the platoon ahead. If no such vehicle is detected within a specified range then the vehicle simply continues as a one car platoon. In this architecture, we allow each platoon to be engaged in only one maneuver at a time. This restriction is necessary to ensure basic level of safety while executing a maneuver. This will ensure, for example, that during a join maneuver, another vehicle from adjacent lane will not change lane in between the two joining platoons. To maintain routing flexibility to individual vehicles, we also require that only free agents can change lane in a multilane AHS. On the other hand, a follower in a platoon is allowed to exit without creating a separate platoon. The concept does allow lane change of an entire platoon in case of emergencies and faults. A decision to engage in a maneuver is taken by the leader of every platoon. The followers in a platoon can request their leaders to initiate a maneuver for them.

The infrastructure will broadcast approaching exits and advise vehicles to change lanes. For example the infrastructure may suggest that vehicles in the innermost lane wishing to exit three exits downstream should execute one lane change maneuver. Since every vehicle knows its own exit it will process the advice of the infrastructure and act accordingly. The vehicle may also have autonomous capabilities to locate itself and take exit decisions. This is discussed further under degraded mode operation.

Once a vehicle decides to change lanes it must check its platoon status. If it is in a platoon it must request a split. If it is a leader vehicle it sends its split request to the vehicle immediately behind it. The vehicle behind reacts by assuming the role of platoon leader. It then decelerates the entire platoon to create an inter-platoon gap. The original leader vehicle is now a one car platoon. If the vehicle was a follower vehicle then it must send its split request to the platoon leader which then acknowledges the request by asking the vehicle to change mode and become a leader. Once the vehicle changes mode it retards itself and all the vehicle behind it to create a safe inter-platoon gap. Thereafter it splits again like a platoon leader. Once the vehicle is a one-car platoon it is allowed to request and execute lane change maneuvers. Platoons of larger size are not allowed to change lanes. Hereafter the lane changes would go exactly as before.

The automated vehicle exits from AHS into the transition lane. At this time, the transition lane may contain automation equipped vehicles which are driven either manually or automatically. Infrastructure based maneuver coordination is needed for safe execution of this exit maneuver. Once on the transition lane, the control is transferred to the driver. If for some reason, the driver is unable to take over control, the vehicle under automatic control is taken to a parking lot adjacent to the AHS. Upon transfer of control, the exiting vehicle enters the *leftmost* or the *fast* manual lane and continues its journey on the manual highway.

Infrastructure based maneuver coordination, similar to entry maneuver is required for merging two streams of traffic.

Before discussing abnormal or degraded mode operation we review the functional capabilities of vehicle and infrastructure as assumed till this point. A vehicle is capable of tracking a given velocity input and tracking a longitudinal distance input that specifies its distance from the vehicle in front.[5] It is capable of sensing free spaces in adjacent lanes and executing automated lane change maneuvers. It is autonomous with respect to obstacle avoidance and detection. The vehicle possesses sufficient communication capabilities to receive distance, velocity setpoints and destination based lane change advice from the infrastructure. Vehicles also posses vehicle to vehicle communication capabilities as required during join, split, lane-change, entry maneuvers.

The infrastructure on the other hand has the ability to meter entry to the AHS. It is aware of the AHS network topology, flow conditions (average speed, average density) on all parts of the AHS (This information will be obtained using roadside flow sensors such as loop detectors), and destination information collected at the point of entry. Based on this information about exits and network flow conditions the infrastructure formulates lane change policies, velocity policies, platoon separation policies, that help ensure good capacity utilization and timely exiting of vehicles. All this implies that at all sections of the highway the infrastructure has the ability to broadcast lane change advice, velocity and distance setpoints. The role of the infrastructure will still be limited as an advisory controller and the safe execution of maneuvers will be handled by individual vehicle controllers.

Moreover since the infrastructure participates in check-in and collects destination information at the point of entry,

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[5] In a design based on this concept, the velocity input provided by the roadside controller will be used as a desired input and will be tracked if it is safe to do so. i.e., maintaining safe distance from the platoon in front will have higher priority. Followers of the platoon will try to maintain safe distance from preceding vehicle while tracking its velocity. Inter-platoon distance will be typically constant-time separation or a small variation thereof whereas intra-platoon separation will typically be constant distance

it has the ability to communicate with a single vehicle at its check-in stations.

We have not yet addressed the issue of vehicle routing. Since routing is dependent on network wide flow conditions, the infrastructure must be responsible at least for the collection and dissemination of network congestion information. ATIS equipped vehicles as per the ITS Architecture will have the ability to receive and process such information. We make the assumption that AHS vehicles also have the same capability. Thus, the infrastructure will support vehicles by providing dynamic travel time estimates for different links of the AHS, and relaying information about the transportation networks connected to the different AHS exits. It will also provide non-AHS traffic management centers with information about traffic flow conditions within the AHS to support the management of AHS demand. Based on this information vehicles will compute their own routes and choose their own exits. Thus, the infrastructure plays a supporting rather than a controlling role in the routing function! In order to accurately estimate the dynamically evolving state of the network it is necessary to have the vehicles periodically broadcast their planned exits to the infrastructure. Since the infrastructure requires only aggregate information, to protect the confidentiality the vehicles need not broadcast any unique identification with its destination.

Abnormal operating conditions can arise either due to the loss of infrastructure or vehicle functions. We start first with the infrastructure functions. We require that the vehicle have default values for all control setpoints, e.g., speed, intra and inter platoon distance setpoints, lane change distances etc., to be used if no inputs are received from the infrastructure for a specified period. These default values should ensure that in the sudden absence of infrastructure capabilities, the AHS continues to operate safely though possible with degraded productivity. For similar reasons, we also require that the vehicle have a default policy by which it moves out one lane per highway section as its exit approaches. Thus, even if infrastructure capabilities are lost a reasonable number of vehicles could be in the outermost lane by the time they reach the highway section containing their exit. However, this requires that the vehicle have the means of determining, without infrastructure support, its current global location to the extent that it knows its current section and how many sections away its exit is located. Such capabilities also ensure that, in the absence of infrastructure routing information, the vehicles are at least able to route themselves based on static information or the preference of the passengers. If the infrastructure capabilities are lost at the check-in station, we require that the station be closed until check-in capabilities are restored. An AHS entry-point can not function without infrastructure control.

If a vehicle loses its vehicle to infrastructure communication capability it must exit the AHS at the first available exit for the safety of surrounding vehicles, although it can safely coordinate maneuvers with other vehicles. The nearest platoon leader will communicate this exit information to the faulty vehicle or the faulty vehicle can figure it out using its own emergency response system as described above.

If a vehicle loses its vehicle-vehicle communication capability, throttle control, brake control, automated lane changing, or automated lane keeping abilities it is required to come to a complete stop in its current lane. If its inter-vehicle communication capability is intact, it can be used to coordinate an emergency maneuver with neighboring platoons to assist the stop maneuver. Assistance from neighbors is particularly needed in case of brake failure as it takes much longer to stop without brakes. The faulty vehicle is required to communicate to the infrastructure the fact that it has stopped. It will then be removed by an emergency vehicle which will be dispatched to the section from which the message was received. It is required to emit some emergency signal detectable by the emergency vehicle (e.g., hazard lights).

One should limit the use of above mentioned stop maneuver to only severe faults as a stopped vehicle in a lane creates significant loss of throughput and large delays to travelers. Thus, in case of all other non-critical faults, the faulty vehicle should use remaining capability along with help from neighboring platoons to get out of the AHS at the nearest exit. More failure specific maneuvers and control laws should be designed for that purpose.

Any vehicle that detects an obstacle on the highway is required to report the obstacle to the infrastructure. The infrastructure will be responsible for clearing the obstacle.

17.4 SYSTEM DIAGRAM

The diagram is in Figure 17.4-1.

We assume that AHS users are also customers of various ITS Services. Thus, information flows both ways from all AHS vehicles to the various ITS Service providers. The AHS operations center also exchanges information with other non-AHS traffic operations centers. This allows both traffic operations centers to know about the state of each others networks and estimate or manage demand. AHS vehicles make decisions about their desired exits and routes based on information received by them from the AHS operations center and the ITS services they purchase (e.g. ATIS). The vehicles are required to convey their routing and exit choices to the AHS operations center. This may be done through the section controllers. This routing and exit information is only required to be in aggregate form since it is required by the AHS operations center to estimate demand.

The highway is divided into sections and each section has a section controller. The section controller receives information about average flow, speed, and density from roadway sensors placed at different points in the section. If the section has an AHS entry then the entry port also has an entry controller. The section controller sends information about average speed, flow, and exiting traffic to the AHS operations center. The AHS operations center sends policies that regulate the average volume of entering traffic, exiting traffic, section flow and speed. The section controller sends the entry rates to all entry controllers in its section. The entry controllers are responsible for controlling free space and platoon speed in the entry zone and for co-ordinating the entry maneuver between the entering vehicle and the first upstream platoon, until the two detect each other and establish communications.

When emergencies occur, i.e. a vehicle experiences degraded control or communication capabilities then it is assumed that the infrastructure is able to send emergency communications to the vehicle in trouble.

Vehicles are organized in platoons. The desired platoon speed, inter platoon spacing, intra-platoon spacing for each section is broadcast by the section to all lead vehicles in the section. Vehicle to vehicle information flow pertains to that required for merge, split, lane change, entry and exit maneuvers. Vehicle to vehicle distance is sensed.

17.5 FUNCTIONAL ALLOCATIONS

17.5.1 Check-In

The human indicates his or her willingness to enter the AHS by driving onto the transition lane. The vehicle senses that it has entered the entry section.

The check-in may be performed either on-the fly or manually. In case of manual check-in, the vehicle is required to stop at the check-in station. In case of on-the-fly check-in, the vehicle performs a diagnosis of its manual and automatic control system. The vehicle checks the ability of the human to perform the hand-off of control tasks. Depending on the results of the vehicle and human checks, the human will be advised by the vehicle to either initiate or abort the transition from manual to automated control. If the vehicle or human fails the checks, and the human or vehicle does not abort the transition process (e.g., due to human error or vehicle system malfunction), then the infrastructure will broadcast to platoons entering the roadway segments in proximity to the entry gap that a rogue vehicle might enter the automated lanes.

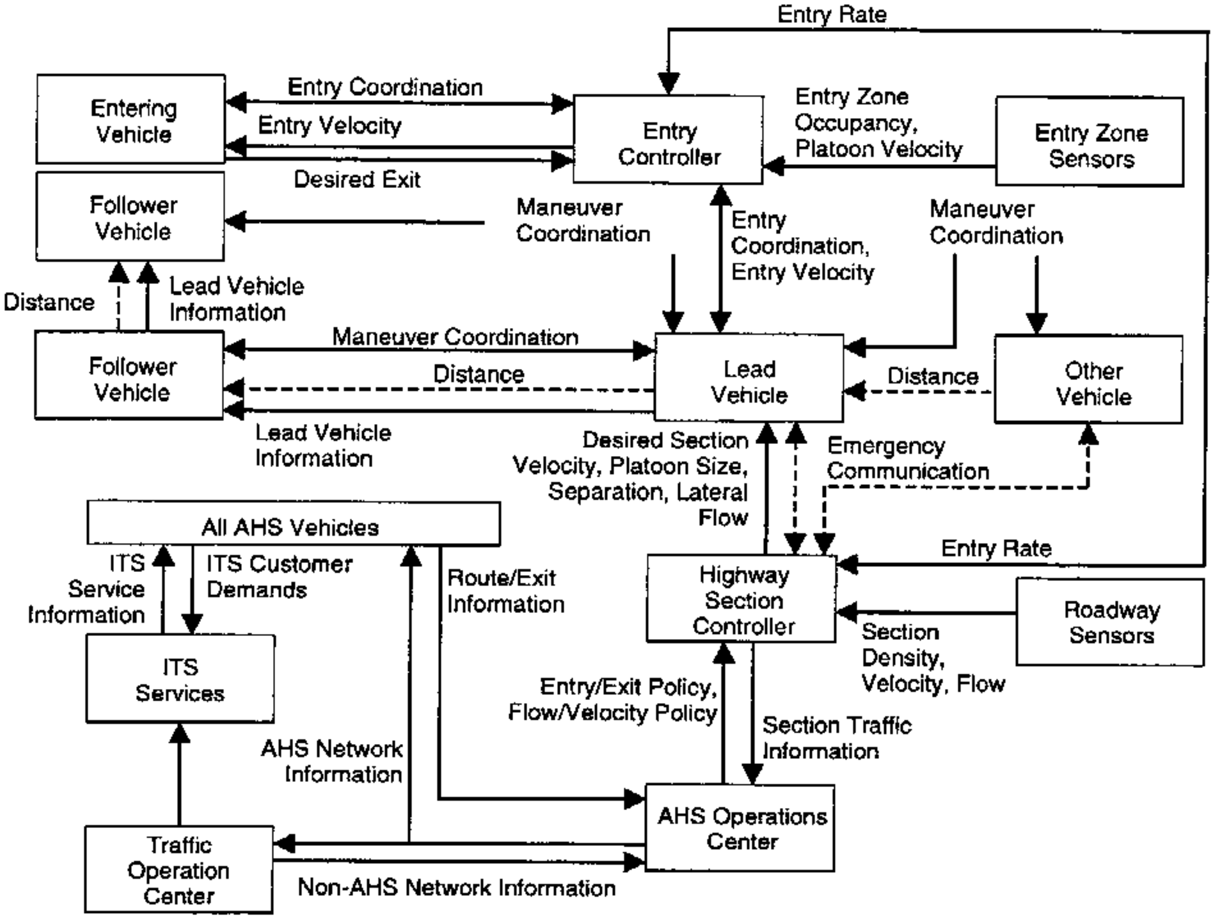

Figure 17.4-1. System Diagram

17.5.2 Transition from Manual to Automatic Control

The human relinquishes driving tasks to the vehicle control system. As each task is transferred, the vehicle acknowledges to the human that the transfer of control is complete and successful. If the transfer is complete and successful, the vehicle continues its journey onto the automated lanes under automatic control. The vehicle signals to the infrastructure that the transfer of control is complete and successful. The infrastructure, in turn, broadcasts to platoons in proximity to the entry gap the fact that a vehicle will enter the automated highway via the ramp.

If the transfer of control is incomplete or unsuccessful, in terms of human error or vehicle malfunction (e.g., failure to acknowledge transfer), then the infrastructure will broadcast to platoons entering the roadway segments in proximity to the entry gap that a rogue vehicle will enter the automated lanes.

17.5.3 Sensing of Roadway, Vehicles, and Obstructions

The vehicle performs all sensing tasks. The sensor data fusion task is shared by the vehicle and infrastructure. Fused data is transmitted to the infrastructure, which performs further fusion, yielding aggregate information regarding platoon position, location of obstruction, etc.

17.5.4 Lane and Headway Keeping

The vehicle performs all lane and headway keeping tasks. Vehicles communicate with each other, providing lane position, velocity, etc.

17.5.5 Detection of Hazards

Detection of hazards is performed by both the vehicle and infrastructure. The vehicle and infrastructure fuse sensor data, with the objective of distinguishing between hazards (e.g., rogue vehicle or roadway obstacle) and non-hazards (e.g., shallow puddle of water or newspaper blowing across or along the roadway).

17.5.6 Maneuver Planning

Vehicles within a platoon communicate with each other in order to prepare for a maneuver. When two or more platoons are involved in a maneuver, inter-vehicle communication takes plan for coordination purposes. The infrastructure provides aggregate vehicle and roadway information, which the vehicles utilize in planning maneuvers.

17.5.7 Maneuver Execution

Maneuver execution is performed by vehicles, according to the maneuver plans developed by platoons.

17.5.8 Transition from Automatic to Manual Control

Same as for transition from manual to automatic control, only in reverse order.

17.5.9 Check-Out

Same as for check-in, only in reverse order. The infrastructure will provide aggregate information regarding the status of manual highway and arterials at the exit point.

17.5.10 Flow Control

The infrastructure will provide aggregate roadway and vehicle status information. The vehicles receive this information and make local decisions (i.e., decision specific to one or more roadway segments) regarding control actions which will affect local and global flow of traffic. That is, the information provided by the infrastructure is in the form of recommendations rather than commands.

17.5.11 Malfunction Management

The platoons and infrastructure coordinate with each other in managing malfunctions. The infrastructure provides position and other platoon status information to platoons in the vicinity of a faulty vehicle or roadway infrastructure. If the malfunction is within the infrastructure, the management coordination will have to rely on vehicle-to-vehicle communication, planning, and execution. If vehicle-to-vehicle communication fails, then each vehicle within a platoon will perform malfunction management as a free agent.

17.5.12 Handling Emergencies

The infrastructure will provide global commands for stopping or restarting movement on the AHS lanes. Vehicles will provide the infrastructure with their status.

17.6 IMPLEMENTATION

17.6.1 Vehicle

17.6.1.1. Roadway Sensing

Used for lateral and possibly longitudinal control (e.g., if vehicle communication fails, calculate spacing and relative speed from beacon data). Such technology includes all types of indirect road reference systems (by indirect we mean there is no physical link between the sensor and the marker: the signal processor is responsible for determining the distance between the sensor and the sensed marker, e.g., energy sources, reflectors, etc.).

17.6.1.2. Sensing Other Vehicles

Primarily for used in longitudinal control to maintain safe intra- and inter-platoon spacing, and in combined longitudinal and lateral control to coordinate maneuvers.

- Sensors to detect neighboring vehicles in the same lane. Sensors to find distance and relative velocity from preceding vehicle in the same lane is needed. Possible choices are Doppler Radar, Sonar, Two cameras mounted on the vehicle, etc. Sensing of the distance and relative velocity from the vehicle behind may also be needed/used in designing robust control laws and also during emergency situations.

- Sensors to detect neighboring vehicles in adjacent lanes, including the transition lane.

17.6.1.3. Vehicle-to-Vehicle Communication

- *Control*: Infrared communication (e.g., on-off keying with clock encoding). However, the size and spacing of vehicles, radius of roadway curvature, height and reflectance of barriers, and so on will affect the effectiveness, in terms of line-of-sight constraints, of infrared communication devices.
- *Maneuver*: Pulse (i.e., frequency hopping spread spectrum) or WaveLAN (i.e., direct sequence spread spectrum) radio systems, along with the use of a mobile Internet protocol. FCC allocation of the frequencies for AHS is an unresolved issue.
- *Advisory/Navigation*: Advisory and navigation information can be transmitted within and between platoons in a daisy-chain manner. Packet loss and delay of advisory and navigation information are non-critical. However, channel access is random in source, destination, and time, and communication distances are very long.

17.6.1.4. Vehicle-to-Infrastructure Communication

- Control: Broadcast communication medium. Cellular-based technologies are not a viable option since there will be more vehicles per 6 mi radius (effective range of cellular communication devices) than there are cellular channels to allocate. The infrastructure shall broadcast positional information and each vehicle must provide an acknowledgment. The infrastructure provides the central coordination function. The technical questions to be answered are how to provide for positional information and acknowledgments.
- *Maneuver*: Broadcast communication medium, for the same reason as described above. The same issues also apply here.
- *Advisory/Navigation*: Broadcast communication medium, for the same reason described above. The same issues also apply here.

17.6.1.5. Vehicle Identification Tag

One or more vehicle identification tags can be used for activities such as check-in, toll collection, and maneuver coordination.

17.6.2 Infrastructure

17.6.2.1. Low Level Modifications

- *Lateral Position Sensing*: Indirect road reference system (e.g., energy source, reflectors, etc.). Specific examples of this type of technology are acoustic resonance reflectors and magnets.
- *Barriers*: Barriers between the automated lanes and manual lanes; gaps in barriers for egress and ingress.
- *Transition Lanes*: Transition lanes.
- *Macroscopic Traffic Condition*: } Infrastructure-based sensors to collect traffic flow data (e.g., loop detectors).
- *Microscopic and Traffic Condition*: Infrastructure-based sensors to collect system performance data and determine the movements of individual vehicles.
- *Roadway Impediment Sensing:* Infrastructure-based sensors for detecting stationary or moving obstacles on the highway.

17.6.2.2. Intermediate-level modifications

- Short-range roadside transmitters shall provide information to vehicles. The communication will be in terms of radio broadcast. Approximately one every 1.6-3.2 km.

- Roadside controllers that get the flow data from roadside flow sensors as well as flow data from a few sections down the road to generate commands/information to be passed on to vehicles
- A communication network between different sectional controllers.
- A communication network between TMC and each sectional controller.

There last two communication networks do need high bandwidth as the frequency of updates received from TMC will be of the order of 10s of minutes whereas the frequency of update of information to vehicles will be of the order of 1-2 minutes.

17.6.2.3. <u>High Level Infrastructure modification</u>

Network level TMC controller and two way communication between each sectional controller and the network controller.

17.6.3 Rural Highway

One possibility is to neither provide platooning nor transportation management center (TMC) services for routing.

17.6.4 Urban Highway

As described in Section 17.3.

17.6.5 Deployment

The minimum deployable system consists of the following:

- one or more dedicated automated lanes some gaps in the inter-lane barriers
- at least one transition lane for use in entry exit, with the transition lane length proportional to the design speed and size of the length of the barrier gaps such that vehicles can safely enter and exit through the gaps
- check-in and check-out facilities at each entry and exit point, respectively
- full automation of vehicles
- partial automation of the infrastructure, including command, control, and communication capabilities

The degree to which command, control, and communication functions are shifted to the roadway infrastructure will have an impact on the cost to develop, manufacture, and deploy automate vehicles. Too little or over reliance on infrastructure support can result in high-priced automated vehicles; for example, at either extreme, the complexity of the in-vehicle automation systems can be high and thus, costly to design, manufacture, and maintain.

There are some disincentives to deploying an this concept AHS. The more prominent disincentives are as follows:

- cost and complexity of automated systems which allow vehicles to precisely execute maneuvers through gaps in barriers
- public perception of risks associated with shared transition lanes
- cost and complexity of transition-lane-based check-in and check-out technology and ability of the system to deter rogue vehicles from entering the automated highway

The incentives of such an architecture are as follows:

- depending on the infrastructure design, in some cases it may be possible to upgrade the roadway infrastructure, especially in terms of communication, but less so for the physical roadway (e.g., resizing entry and exit ramps)
- it is possible to use existing manual lanes as transition lanes

17.7 GENERAL ISSUES AND CONSIDERATIONS

17.7.1 Failure modes

As the intelligence is distributed between roadside and vehicle, the two types of control systems can back up each other. Different types of sensors and communication devices are used on the vehicle and the roadside to gather information of the world as well as for coordination. These systems can be used to back up other subsystems in case of a failure. Most of the vehicle failures—in sensors, communication devices, and so on—will have a localized effect. Infrastructure failures will only result in reduced throughput and will not be safety critical. As the driver will not be able to drive in a platooned environment, the control should not be passed to the human driver while the vehicle is on AHS.

17.7.2 Sensing Weather Conditions

Adverse weather conditions (e.g., limited visibility, snow, ice, etc.) will be sensed by the on-board vehicle sensors and then communicated to the infrastructure. They may also be sensed by roadside sensors placed at specific locations on the roadside for that purpose. The infrastructure communicates this information to the upstream traffic. The infrastructure may also advice the vehicles to slow down.

17.7.3 Vehicle Functionality

Typical users will travel at the speed limit (typically in the range of 65-70 mph. Although one can design a system to operate at a higher speed such as 80-85 MPH. Beyond certain speed, the gain in throughput will be offset by the large inter-platoon spacing required for safety and the cost of associated sensors). Due to infrastructure support functions, highway speeds are fully tailorable.

The vehicles equipped to drive in this AHS will be able to perform feet-off driving using Adaptive Cruise Control (ACC) capabilities on the conventional roads. They can also use most of the ATIS information for route selection.

17.7.4 Throughput and Safety

The *platooning* feature of this concept will most contribute to increasing traffic. In fact, platooning allows one to realize maximum achievable increase in capacity. Infrastructure support is also critical in optimizing the traffic flow.

Entry/exit via transition lane will create serious problems during heavy traffic. This option requires the traffic entering AHS to weave through manual lanes before reaching the transition lane thereby reducing manual highway throughput. On the other hand, traffic exiting AHS, has to enter the fast manual lane creating problem with respect to safety as well as capacity.

The safety of the overall system will be increased compared to current system because of automated obstacle detection and avoidance and due to distributed intelligence between infrastructure and vehicle.

17.7.5 Cost

As vehicles and infrastructure both have sensors, controllers and communication systems, regular maintenance of vehicles and infrastructure will be required.

18. CONCEPT 15: INFRASTRUCTURE MANAGED FULL MIXING

18.1 OVERVIEW

This concept represents a full mixture of AHS and non-AHS vehicles operating on the same infrastructure that will be managed mainly by the infrastructure on the existing roadway. This concept considers a mixture of both AHS and non-AHS vehicles classes on existing infrastructure and each AHS vehicle considered to be a free agent and individually will be controlled and managed.

The transition of AHS vehicles status from manual to automatic and back to manual at the entry and exit locations will take place in a transition lane (this is further discussed in the operation section).

Obstacles on the roadway are automatically detected by AHS vehicles and/or the infrastructure (based on their location) and are managed by the infrastructure to automatically execute the proper maneuver to avoid them.

In this concept obstacles are automatically sensed by the AHS vehicles and infrastructure can be upgraded to be used by both existing non-automated vehicles and AHS vehicles. By doing so, there will not be a need for dedicated AHS right-of-way until all the vehicles are AHS equipped. While in evolutionary path toward full automation, the potential capacity of the existing facilities equipped with the AHS can be maximized. Finally, the system will reach its maximum capacity when all the vehicles on the system are fully automated.

This concept offer an opportunity of transition from existing infrastructure management system currently in operation to future upgraded version to manage the AHS vehicles.

18.2 SELECTED ALTERNATIVE DIMENSIONAL DESCRIPTION

18.2.1 Distribution of Intelligence—Infrastructure Managed

The choice of infrastructure management system is desirable since the existing freeway systems are such and the addition of AHS system only could complement that.

The infrastructure managed system can be utilized to operate as mixed traffic (AHS and non-AHS vehicles operating simultaneously) or as a non-AHS system when needed (during off-peak hours in those locations that operation of AHS is not economically feasible).

18.2.2 Separation Policy—Free Agent

In this option each AHS vehicle is considered as a separate entity and a platoon will be composed of many entities following each other in a minimum allowable gap (function of vehicles speed and maximum or desirable deceleration rates).

This option seems to be superior over the platooning option since there could be other non-AHS vehicles included within the platoon that the system does not have any control over their movements. Also, even though the system does not control non-AHS vehicles, it can always sense each individual vehicle's location and speed and based on that make proper adjustment to manage the AHS vehicles.

18.2.3 Mixing of AHS and non-AHS Vehicles in Same Lane—Full Mixing

This option will allow the local operators to maximize the wage of their existing infrastructure with the lease amount of

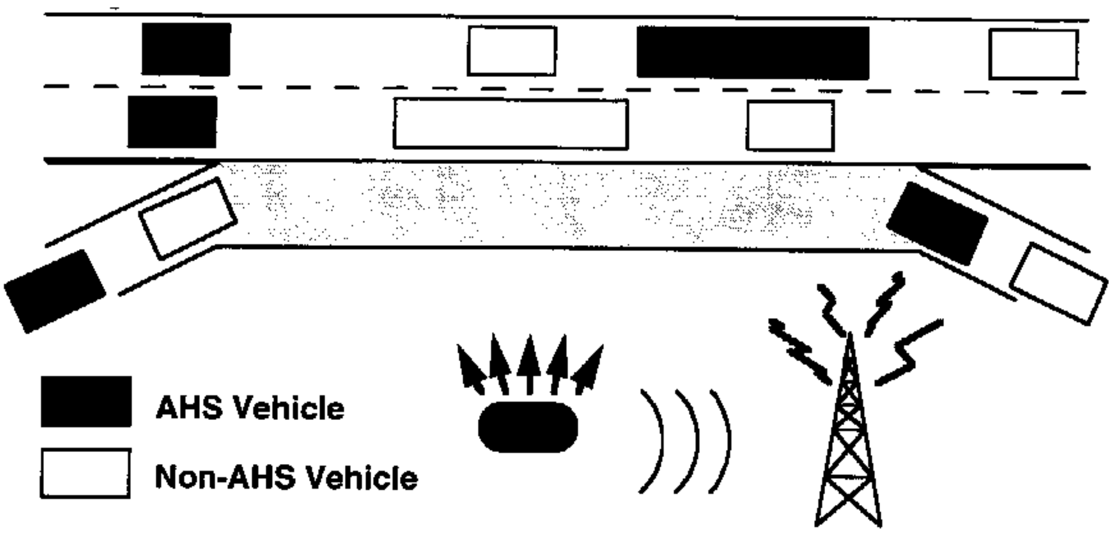

Figure H.18-1.

modifications needed. Also, in the event of system malfunctions or during off-peak hours where operating AHS is not economically feasible, this option will allow the local authorities to operate the system as non-AHS.

18.2.4 Mixing of Vehicle Classes in a Lane—Mixed

In this concept, different classes of AHS and non-AHS vehicles are operating together on the same roadway. Managing the operation of this mixture of vehicles will not be as easy as it would be with all AHS vehicles, since, in addition to variety of different vehicles' functions (such as acceleration and deceleration rates), lack of control over the non-AHS vehicles plays an important role in designing the system.

In this option, local authorities can provide some types of limitation on the use of left lane by non-AHS vehicles (such as only be used for passing maneuver when it is feasible).

18.2.5 Entry/Exit—Transition

In this option, the existing entry and exit will be shared by the AHS vehicles. This will take place on a transitional basis where AHS and non-AHS vehicles enter and exit the system from the same locations. The possible locations for drivers to request the change of status from manual to automated operation or vice versa (transitional area) are:

1) Along the roadway section
2) Along the entrance and exit ramps
3) Along the acceleration and deceleration lanes provided for entrance and exit ramps.

18.2.6 Obstacle Sensing and Avoidance—Automatic Sensing & Automatic Avoidance Maneuver

In this option, obstacle are detected by either infrastructure or AHS vehicles' sensors (where it will be reported to the infrastructure). AHS vehicles are given the proper direction to follow to avoid the obstacle and the information is routed to the Traffic Operation Center (TOC) where through the use of Intelligent Transport System (ITS) features non-AHS vehicles can also be informed of the location of the obstacle. At this time, TOC will further analyze and make the proper decision on the needed actions to be taken to remove the obstacle.

18.3 OPERATIONAL CONCEPT

The operation of this concept is more complex than other concepts since two separate entities (AHS and non-AHS vehicles) must be managed together.

The operation of this concept can be conducted in three levels of command, control, and communication.

At vehicle level, individual AHS vehicles can sense where they are relative to other surrounding vehicles. This level relies on computer software and hardware technologies.

Local infrastructure is where the bulk of traffic operation and management will take place. Its majority of functions will concern sending, receiving and interpreting signals. This level of operation acts as a funnel through which commands travel from the TOC to individual vehicles and through which status and feedback are sent back to TOC from each vehicle. Also, at this level, data from the local infrastructure, infrastructure to vehicle, and infrastructure to infrastructure communication technologies.

The TOC must know in aggregate the traffic status in real time. It receives aggregate data from local controllers, analyze the data and then provide appropriate command. The type of technology needed at this level will be mainly information/computing and communication technologies. Also, a high order of intelligence will be required at this level as the system needs to make complex decisions concerning traffic operations and incident management.

18.4 SYSTEM DIAGRAM

The system diagram showing data flows and sensing between vehicles and infrastructure is shown below:

18.5 FUNCTIONAL ALLOCATION

18.5.1 Check-In

The request to change the status to automated will be transmitted from the vehicle to the infrastructure. Next the infrastructure will check the AHS capabilities after approving the status, local controller will admit the vehicle as an AHS and will change its status. Next, the vehicle's parameters needed to be controlled (i.e., maximum deceleration and acceleration rate) are tagged along to the vehicle in order to be able to automatically control its movements.

18.5.2 Transition from Manual to Automatic Control

Transition will be controlled by the infrastructure are few possibilities as of where the transition could take place. Three of which are listed below:

1) If the metering of entrance to the roadway is of interest, then, the status of vehicle will be checked prior to entering to the roadway. Next, based on the availability of gaps and unused capacity of roadway (and other factors such as level of air and noise pollution and environmental conditions) vehicles will be queued and in turn enter the roadway.
2) If the metering is not a concern, the AHS vehicle can operate manually and enter the roadway. Next while traveling, the request to change the status could be checked by the infrastructure (such as local controllers) and if feasible the status will be changes.
3) The acceleration lane can be used as a transitional lane to grant the automated status to approved AHS vehicles.

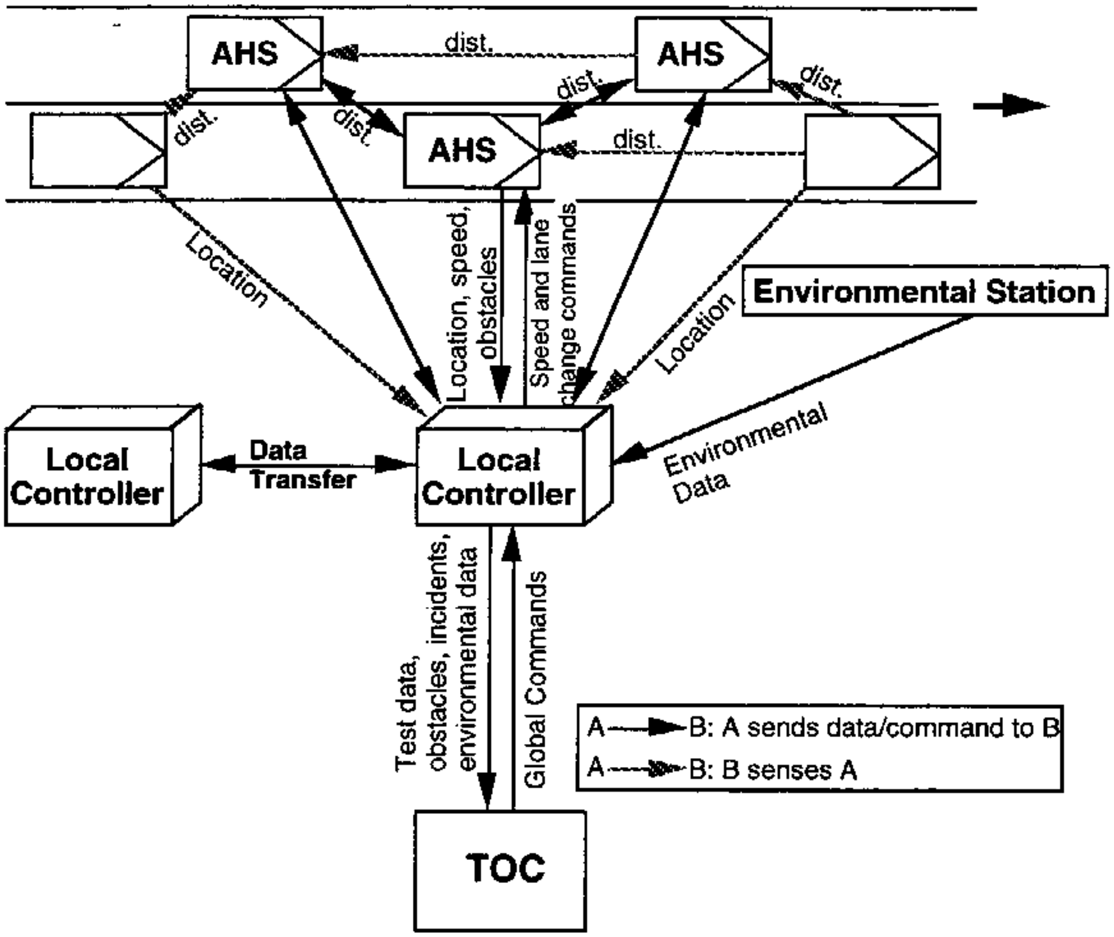

Figure H.18-2.

18.5.3 Automated Driving

18.5.3.1. Sensing of Roadway, Vehicles, and Obstructions

Sensing of roadway, vehicles, and obstructions while driving will be conducted by the AHS vehicles. Infrastructure will be capable of sensing the obstructions and providing the automated vehicles and the TOC with the needed information. Infrastructure can also sense the location of all types and classes of vehicles on the roadway in order to make proper decisions.

18.5.3.2. Lane and Headway Keeping

Lane and Headway keeping are conducted by the AHS vehicles equipped with longitudinal and lateral sensors. The TOC will determine the allowable speed and spacing between vehicles and the command funnel through the local controller and transmitted to AHS vehicles. Infrastructure will only govern the allowable speed and spacing between vehicles.

18.5.3.3. Detection of Hazards

Hazards are located by vehicles and the infrastructure. If an AHS becomes disable, automatically, its location and status will be reported to the local controller and the TOC and the proper respond maneuvers to be executed will be send to the AHS and non-AHS vehicles will be informed via other means (such as in-vehicle computer). If the disable vehicle is a non-AHS vehicle, the infrastructure and/or AHS vehicles will be able to detect and report the condition to each other and TOC. Other hazards can be detected by both AHS vehicles and the infrastructure.

18.5.3.4. Maneuver Planning

The local controller will be the one allowing the vehicle to make the needed maneuver any time during the automated driving. If the AHS vehicle detects a hazard, it can only notify the local controller and take the proper action to stop, the lane changing maneuver will only take place when the local controller decides there is sufficient gap to do so.

18.5.3.5. Maneuver Execution

After the needed maneuver is scheduled by the infrastructure, the execution of it will be conducted by the AHS vehicle following the proper command from the local controller.

18.5.4 Transition from Automatic to Manual Control

As the AHS vehicle reaches the destination, the infrastructure will check to make sure the driver is ready to accept the manual control of the vehicle. In the event of possible response, at the proper transition place the control of vehicle will be granted to the driver and the status of the AHS vehicle will be changed to manual. The infrastructure will update the database and send the needed data to the TOC. There are few possibilities as of where the transition could take place. Three of which are listed below:

1) On the off-ramp where if the driver did not verify its readiness it could be routed to the storage area.
2) Any location along the roadway where driver can request and be granted.
3) Along the deceleration ramp to the exit entrance.

18.5.5 Check-out

As the AHS vehicle goes through the change of status and returns to its manual mode, the infrastructure will update its database and the vehicle no longer will be controlled by the system.

18.5.6 Control of Traffic Flow

This will be conducted by the local controllers where they follow the global decisions set by the TOC (refer to the section 18.5.7). Traffic data such as; number of vehicles within the system, portion of the automated vehicles, unused capacity of the system, level of air and noise pollution, weather conditions, occurrence of incidents, will be collected and transmitted to the TOC where proper global parameters will be determined and communicated back to local controller for execution.

18.5.7 Global Decisions

The ability of TOC to adjust global parameters dynamically will allow the effect of specific changes in the system to be evaluated and the optimized performance of the system to be achieved. Global parameters include items such as headway, system speeds, access metering rates and overall volume on the system. Small changes in one or combinations can be evaluated and used in the further refinement of the overall system and development of guidelines for future expansion of the system.

TOC can set control parameters by regulating the traffic ingress to optimize system service levels. It can also process environmental data to determine how many users can be on the system to keep the level of pollution under control and respectively, change the metering rates.

18.5.8 Status Monitoring

The AHS should be monitored for system performance. Monitoring allows the TOC the ability to lay a proactive role in the success of the system. The quicker the system can recognize and respond to problems, the better the system user can be served. The TOC and local controllers will provide continuous evaluation of all devices in the system, reports of the status, and related information about maintenance and construction.

18.5.9 Vehicle Malfunction Management

Vehicle malfunction management will be conducted by both the AHS vehicles and the infrastructure. If a vehicle is malfunctioning, it will report its status to the local controller and request exit or assistance. If the vehicle is not capable of exiting the system or its malfunction will effect the performance of other vehicles, the infrastructure will inform other vehicles of the existence of an obstacle ahead and provide them with proper action to take.

18.5.10 Incident Management (Handling of Emergency)

The automatic deployment of the incident management will become of vital importance in the area of handling public safety and liability concern. Incident management includes incident detection verification and response procedures.

Early remote detection and verification of an incident can be conducted by AHS vehicles and the infrastructure. The automated incident response management will be conducted by the TOC. These responses can include speed regulation, alternate route assignments, and advisory signs in addition to informing proper authorities to take the needed actions to remove the incident as early as possible.

18.6 GENERAL ISSUES AND CONSIDERATIONS

Although one of the major advantages of this concept is that it flows with the existing traffic patterns and does not cause major disruption to the existing infrastructure and current traffic demand, still, it needs to deal with the non-AHS vehicles. As a result, issues such as safety, societal and institutional impacts, and traffic non-AHS vehicles should be of concern.

The existing traffic operation is impacted by mixture of different classes of vehicles on the same infrastructure (i.e., impact of heavy vehicles on passenger vehicles operation). Introduction of a new generation of AHS vehicles along with its own classes will magnify this problem and needs to be further analyzed.

Management of non-AHS vehicles may be required for a safe and efficient system. Therefore, the management task of this concept could be horrendous.

Currently, multi-jurisdictional interactions are among important issues that need to be resolved. Coordinating of TOCs and multi-jurisdictional interaction of the AHS will only magnify the problem and the proper solution needs to be identified.

Since non-AHS vehicles operate on the same infrastructure as AHS vehicles, the control of traffic operation will be some how limited and types of malfunctions and incidents unpredictable.

Since one of the advantages of this concept is the economical feasibility of it, this concept should be given appropriate consideration and its viability issues should be further investigated.

Since the operating speed of AHS vehicles may require to follow the general flow of traffic (namely, non-AHS vehicles' speed), this may be considered as a deficiency of the system.

Even though, during the inclement weather conditions, infrastructure can properly manage the AHS vehicles in the system by using the input from weather monitoring stations, the lack of capabilities of non-AHS vehicles will reduce the efficiency of the system.

Each possibility of the location for transition of the status of AHS vehicles from automated to manual and manual to automated will carry along its own issues which needs to be further studied.

The possibility of this concept to follow an evolutionary path needs to be further analyzed and the fact that it could be the most feasible and economical solution to the AHS needs to be further investigated.

19. CONCEPT 16: FREE AGENT ON MIXED-CLASS DEDICATED LANES WITH VIRTUAL BARRIERS

19.1 OVERVIEW

This concept features the operation of mixed-class Automatically Controlled Vehicles (ACVs) as free agents (i.e. ACVs following each other at safe distances) and using one or more dedicated AHS lane that are separated from the manually driven lane or lanes by a virtual barrier (i.e. pavement markings, magnetic tapes along-side of the AHS lane, etc.). The highway infrastructure will be equipped to support the operation of the ACVs through the provision of non-vehicle specific information such as speed, merge demerge instructions, lane availability, etc.

This concept offers a deployable AHS system that satisfies the general objectives of the National AHS Program and that is :

- Compatible with the existing national freeway system
- Amenable to being deployed in transitional stages with minor disruption to existing freeway operation.
- Upgradeable to higher levels of technological sophistication.
- Relatively low cost of public expenditure for ultimate deployment.
- Deployable in urban as well as rural environment.

The primary advantage of this concept is the combination of low cost and ease of deployment.

19.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

19.2.1 Free Agent in a Mixed Vehicle-Class Environment

The combination of free agent operation with mixing various classes of vehicles in one dedicated AHS lane would limit the practical throughput of the AHS lane and thus, its efficient operation. Available options would include:

- dedicating more than one lane to AHS operation. Such an option would only be practical in urban applications. It would allow slower moving vehicles to operate on one lane with faster moving vehicles on the other.
- restricting the operation of slow vehicles to off-peak hours only.
- using the transition lane as a passing lane in case of a one dedicated-AHS-lane operation.

19.2.2 Distribution of Intelligence: Infrastructure Supported

This dimension assumes that acceleration, deceleration and possibly maneuver data concerning adjacent vehicles in a local area is available to the single vehicle coordination unit. The infrastructure supported dimension provides infrastructure monitoring of global events such as traffic flow and incidents. The infrastructure communicates pertinent information to vehicles within its local zone. Data is expected to include general parameters such as assigned travel speed, headway, or roadway geometry.

Vehicle control loop commands are generated by the vehicle. The vehicle control loop can use local zone information generated by the infrastructure to improve maneuver planning. Individual vehicles are not responsible for roadway condition or environment sensing, allowing vehicle sensors to focus on obstacle detection and headway measurement. The reduced responsibility in terms of vehicle sensors is balanced by an increase in infrastructure instrumentation to support sensing and communications between the vehicle and the infrastructure.

19.2.3 Separation Policy: Free Agent

The separation policy specifies that individual vehicles operate as the coordination unit for AHS maneuvers such as merge and separation to and from the automated lane. The vehicle separation is determined by an infrastructure controller at the zone or regional level and communicated to the vehicles at check-in or enroute. The vehicles maintain their own headway through sensing of adjacent vehicles and generation of acceleration, deceleration, and turning control loop commands. Vehicles may cooperate by sharing speed and acceleration/deceleration data with adjacent vehicles, allowing coordination of non-emergency maneuvers within a local zone.

19.2.4 Transition Lane and Location of the Virtual Barrier

The transition lane will be used by Automatically Equipped Vehicles (AEVs) driven under manual control as well as by Automatically Controlled Vehicles (ACVs) ready to transition to the dedicated AHS lane or lanes. To prevent manually controlled vehicles from encroaching on the transition lane, the virtual barrier may be placed between the transition lane and the manually driven lane or lanes. This location would also be recommended in case the transition lane is used as a by-pass AHS-controlled lane as discussed above.

The transition lane could be continuous alongside the entire length of the AHS-dedicated lane or lanes, or it could be discontinuous allowing its use by manually driven vehicles on non-transition segments. The first option may be applicable to urban applications where interspacing between interchanges are relatively short, while the second option may be appropriate for rural applications where interspacing between interchanges are relatively long.

19.2.5 Obstacle: Automated Sensing and Avoidance Maneuver

Obstacle detection is performed by the vehicle. Vehicle detection of obstacles can be shared cooperatively with adjacent vehicles. Acceleration, deceleration, and maneuver commands are generated by single vehicle units based on internal information and data obtained cooperatively.

19.2.6 Infrastructure Messages

This concept calls for the infrastructure to provide AEVs and ACVs with informational, advisory, cautionary, and other types of messages. Depending on the placement and medium of transmitting these messages, it may be advisable to combine these messages with other messages intended for the manually driven lanes and manually driven vehicles as well.

19.2.7 Check-in Procedure

A vehicle-based intelligence, an infrastructure-based intelligence, or a combination of both would be required to clear AEVs to operate on the AHS facility.

19.3 OPERATIONAL CONCEPT

19.3.1 Check-In

As AEVs approach an AHS facility, they would be checked-in for operability on the AHS System. Check-in options would be vehicle-based, see 3.6 for discussion. The check-in function should be accomplished prior to entering the freeway facility in order to give the driver the opportunity to react to the results without impinging on the normal operation of the freeway. AEVs that pass the check-in testing would use common on-ramps to access the freeway equipped with an AHS operation.

19.3.2 Transition to Automated Control

As the AEV merges into the freeway, it would operate in a completely manual mode maneuvering its way to the transition lane of the AHS system. Once on the transition lane, the AEV would communicate its position to ACVs on the dedicated AHS lane or lanes. While still on the transition lane, the AEV would transition from manual operation to automatic operation. At the proper time, it would merge into the AHS facility and operate as a free agent with other ACV's of various classes of vehicles.

19.3.3 Automated Driving

The ACV's operation on the AHS lane should proceed in a normal fashion communicating with other vehicles for longitudinal and lateral positioning. Some of the alternatives discussed above, if implemented, would use the transition lane as a by-pass lane (to pass a slow-moving vehicle or to avoid an obstacle on the AHS lane). In this case, an infrastructure message may be required to signal the acceptability of such use.

19.3.4 Check-Out and Transition to Manual Operation

The exiting process is initiated by the trip planning function through which the vehicle and the driver are notified that they are approaching the desired exit or the terminus of the AHS system. In this concept, such notification would be vehicle-based and supported by infrastructure messages. Check-out would be processed through vehicle-based instruments that would insure that both the vehicle and the driver are capable of operating in a manual mode. The vehicle would then communicate its intention of exiting the system to adjacent vehicles and proceed to move to the transition lane, still under automatic control. The driver would then assume manual control of the vehicle and maneuver into the manually-driven lanes and to the desired exit ramp.

19.3.5 Communications to Support Maneuver Coordination

Maneuvers such as lane change, entry, and exit will be automated in this concept. The infrastructure supported definition of intelligence distribution assumes cooperative sharing of acceleration, deceleration, turning, and position data between adjacent vehicles. Wireless technologies can be used to implement communications among a group of vehicles. The steady-state message channel is expected to consist of small packets of information. The channel activity is expected to be on the order of one packet per second, and delivery of non-emergency maneuver information is not time-critical. Connectivity among a group of vehicles will require pairs of vehicles to exchange information without requiring them to be directly adjacent to one another. Infrared links require direct line of sight for reliable data transfer. A broadcast RF method of communications may be best suited to the maneuver coordination function, using global addressing to uniquely identify the sources of data.

19.3.6 Communications to Support Check-In and Check-Out Advisories and Traffic Flow Information

The majority of the intelligence in this concept is located within the vehicle. The vehicle could monitor on-board diagnostics prior to entry to the AHS. The vehicle will initiate entry to the AHS if the check-in procedure is successful with no verification from the infrastructure. A similar procedure could be performed prior to exit. The vehicle would initiate a series of self-tests and transfer control to the driver without verification from the infrastructure. Communications between the vehicle and the infrastructure is not supported.

Traffic advisories, route planning, and road conditions are provided by the infrastructure. The infrastructure monitors sensors and generates advisory messages. The messages can be addressed to vehicles in a local zone but are not expected to be addressed to individual vehicles. The method of communications is expected to be broadcast RF. The infrastructure transmitters can be linked along the infrastructure to a central traffic management center using leased lines, fiber optic, or microwave links. These are implementation options and can be tailored to the specific location.

19.4 FUNCTIONAL ALLOCATION

19.4.1 Position Control

The position control function is performed in the vehicle. Free agent spacing will require sensing of adjacent vehicles to maintain headway and land parameters to maintain lateral position. The individual vehicle is also responsible for obstacle detection and avoidance. The position control function receives absolute position and speed data from on-board vehicle sensors. This function receives commands to change position and speed from the maneuver coordination function. The position control function generates throttle, brake, and steering signals and implements longitudinal and lateral changes to maintain headway and lane keeping, and in response to maneuver commands as required.

19.4.2 Maneuver Coordination

The maneuver coordination function is performed in the vehicle. The maneuver coordination function receives zone and regional roadway information from the flow control function, hazard warnings concerning local obstacles from the hazard management function, and malfunction warnings concerning vehicles or operator detected failures from the malfunction management function.

The maneuver coordination function receives acceleration, deceleration, and turning information from adjacent vehicles allowing maneuvers to be planned in terms of local vehicle motion. This function generates commands to change speed or lane position based on information received from the infrastructure regarding current travel conditions and from adjacent vehicles regarding their position and speed.

The maneuver coordination function receives a message from the check-in function when a vehicle is prepared to access the automated lane and control has been transferred from manual to automated. The maneuver coordination function responds by generating speed and lane change commands which allow the vehicle to move into the automated lane.

The maneuver coordination function receives a message from the check-out function when a vehicle is prepared to exit the automated lane. In the case of exit, control is transferred from automated to manual after the vehicle has moved into the transition lane. The maneuver coordination function generates speed and lane change commands which allow the vehicle to move out of the automated lane. Control is transferred to the operator while the vehicle is traveling in the transition lane.

The maneuver coordination function responds to hazard and malfunction warnings by generating commands to change speed or lane position which allow vehicles to mitigate malfunctions or avoid hazards in a safe manner. This function transmits the control signals addressed to the vehicle in the affected slot. The maneuver coordination function provides notification to the operator interface of merge, demerge, or emergency ,maneuvers. Notification to the operator interface will be coordinated with the maneuver to prepare the driver for unexpected changes in vehicle speed or position.

19.4.3 Hazard Management

The hazard management function is performed in the vehicle. The hazard management function detects obstacles and adjacent vehicles using on-board vehicle sensors. The hazard management function generates a hazard warning message when an obstacle or vehicle enters a specified control zone, and it is passed to the maneuver coordination function for appropriate action.

19.4.4 Malfunction Management

The malfunction management function is performed in the vehicle. This function receives vehicle system status information from on-board vehicle diagnostics, and operator input regarding system conditions or hazards. The malfunction management function generates a malfunction warning message which is passed to the maneuver coordination function for appropriate action based on processing of vehicle and operator data. This function provides vehicle or system failure information to the traffic operations center and provides status messages to the operator.

19.4.5 Flow Control

The flow control function is performed in the infrastructure. The flow control function monitors infrastructure sensors at the zone level and provides information regarding roadway conditions and local incidents to the maneuver coordination function. This function monitors traffic flow at the regional level and provides operating information to the maneuver coordination function such as congestion at entry/exit points, travel speed, and lane or route closures.

19.4.6 Operator Interface

The operator interface function is performed in the vehicle. The operator interface receives inputs from the operator concerning entry and exit requests and generates requests to enter and exit the automated lanes for the check-in and check-out functions. This function processes inputs from the operator concerning system operating conditions, including hazards or malfunctions and generates messages to the malfunction management function indicating a detected hazard or malfunction.

The operator interface provides sensory notification to the driver to indicate impending maneuvers based on messages received from the maneuver coordination function. This function also provides status to the operator concerning ongoing vehicle and system operating conditions. The operator interface will generate messages which provide status and instructions regarding entry or exit procedures.

19.4.7 Check-In

The check-in function is performed in the vehicle. This function receives operator requests to enter the automated system and initiates the check-in process. The check-in function processes vehicle condition information received from the malfunction management function concerning the integrity of the automated control subsystems. This function verifies the ability to perform the transition from manual to automated control safely and generates a message to the maneuver coordination function to initiate entry to the automated lane. The transfer of control from manual to automated takes place in the transition lane prior to entry to the automated lane.

Vehicles which fail the check-in process will be denied access to the automated lane. A message will be generated to the operator interface function which indicates the status of the check-in results and notifies the driver that the vehicle will remain in manual control and will not maneuver to the automated lane.

19.4.8 Check-Out

The check-out function is performed in the vehicle. This function receives operator requests to exit the automated system and initiates the check-out process. This function verifies the ability to perform the transition from automated to manual control safely and generates a message to the maneuver coordination function to initiate exit from the automated lane.

The check-out function will generate a message to the operator interface function which will allow the transition of control to occur. The operator interface will pass a message back to the check-out function when the operator has performed the required tasks successfully. The operator will be prompted to resume manual control prior to transfer from automated to manual control.

Vehicles which fail the check-out process will remain in automated control and will be moved to a safe location. A message will be generated to the operator interface function which indicates the status of the check-out results and initiates the process for exiting under automated control.

19.5 IMPLEMENTATION

19.5.1 Infrastructure

19.5.1.1. <u>Rural Highway</u>

This concept would require at least one dedicated AHS lane plus one transition lane that should be dedicated to AHS operations intermittently; e.g. at entrance ramps, at exit ramps, and for automatically-controlled passing maneuvers. The manual operation of the highway would require at least one dedicated manual lane plus the use of the transition lane (at segments not dedicated to AHS operation) for passing slow-moving vehicles. Since most of our rural highways have only two lanes in each direction, the deployment of this AHS concept would necessitate the addition of one lane in each direction.

19.5.1.2. Urban Region

This concept can be deployed in an urban environment without significant modifications or lane additions to many existing urban freeways. Since inter-spacing between interchanges on urban freeways are relatively short, it appears that the transition lane will have to be dedicated to AHS operation. Therefore, a minimum of two lanes would be required for AHS operation. Since a minimum of two lanes would also be necessary for manual operation, the minimum number of lanes required for the deployment of this concept in an urban environment would be four.

Careful analysis will have to be performed of the throughput of AHS-equipped freeways considering the above lane allocation and the constant maneuvering in and out of manually-driven lane to access or egress the AHS system. AHS operation may have to be suspended at freeway to freeway interchanges subject to confirmation by site-specific analysis.

19.5.3 Deployment

The deployment of any AHS system will have to be staged in several transitional phases until there are sufficient number of automatically-equipped vehicles to justify full deployment of the system. This concept is particularly adaptable to such transitional deployment.

19.6 GENERAL ISSUES AND CONSIDERATIONS

Concept Limitations

- Unless more than one dedicated AHS lane is provided, mixed operation on one lane would restrict ACV's to the slowest moving vehicle. One solution would be to restrict use of the AHS system to certain classes of vehicles, permanently or during certain operating periods.
- The absence of physical barriers between AHS lanes (dedicated and transition) and manually-operated lanes would invite manually-driven vehicles to encroach on the AHS lanes particularly during congested periods on the manually-driven lanes. Even during periods of normal operation, the absence of physical barriers between the two systems would cause inconvenience and anxiety to manual drivers.
- Since the entry/exit maneuvering in and out of the AHS system would consume (in some urban locations) one to two miles of driving in a manual/transition mode, automated driving may only make sense for a minimum trip length. This may preclude the use of the system by certain segment of the traveling public.
- It may be necessary to restrict access to and egress from the AHS lane(s) to certain locations along the length of the transition lane. This may preclude the use of certain on and off ramps by AEVs.

20. CONCEPT 17: COOPERATIVE PLATOONING WITH VIRTUAL LANES

20.1 OVERVIEW

This is one of two cooperative concepts with platooning, and the only platooning concept in which the dedicated AHS lanes are not protected by physical barriers. It is therefore a test case both for cooperative platooning, and for platooning without physical isolation of the AHS lane(s). Unusual features of this concept are 1) two-way communication between the vehicle and the roadside (unusual for a cooperative concept); 2) the use of the transition lane like a railroad siding to allow faster-moving traffic to pass slower-moving traffic.

20.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

Distribution of intelligence—cooperative.

Separation policy—platooning. Local options include excluding the right-hand AHS lane from platooning where two or more lanes are available, and setting a maximum platoon size.

AHS/non-AHS mixing—dedicated lanes with virtual barriers.

Mixing of vehicle classes in the same lane—yes. Where two or more AHS lanes are available, heavy vehicles and non-platooning vehicles will be limited to the right-hand lane. Where only one lane is available, local options include restricting the use of AHS by heavy vehicles to specified hours.

Entry/exit—transition lane. Local options include minimum speed and sharing this lane with HOV's.

Obstacle—automatic sensing and automatic avoidance maneuver.

20.3 OPERATIONAL CONCEPT

In this cooperative concept, the vehicle does autonomous lane-keeping and headway maintenance using a suite of on-board sensors which maintains a current picture of objects in a 270 degree sector centered around the vehicle velocity vector (see System Diagram for a sensor coverage map). It performs obstacle detection using its forward-looking sensor, and position determination using its lane-keeping sensors (see Issues for more details). It senses velocity, computes acceleration, and measures range to any vehicles or objects ahead of it or to either side. The vehicle's processor will use on-board sensor inputs to calculate required heading and speed changes. The processor will use position and speed broadcasts by nearby vehicles to identify vehicles in the sensor blind spot, and roadway obstructions. If an obstruction is identified, the vehicle will broadcast a warning to nearby vehicles and the roadside processor.

20.4 SYSTEM DIAGRAM

Platoons will be formed under this concept by vehicles advertising their position and destination to other nearby vehicles or platoons. Vehicles (or lead vehicles of platoons which can accept more vehicles) with compatible destinations will reply with an invitation to link up unless the driver has issued a "no platooning" command. When a vehicle(s) which is part of a platoon approaches its exit, or the driver wishes to leave the platoon, the departing vehicle(s) will notify the lead vehicle, which will issue commands to all platoon vehicles creating a gap before and after the departing vehicle(s). The departing vehicle(s) will then change lanes.

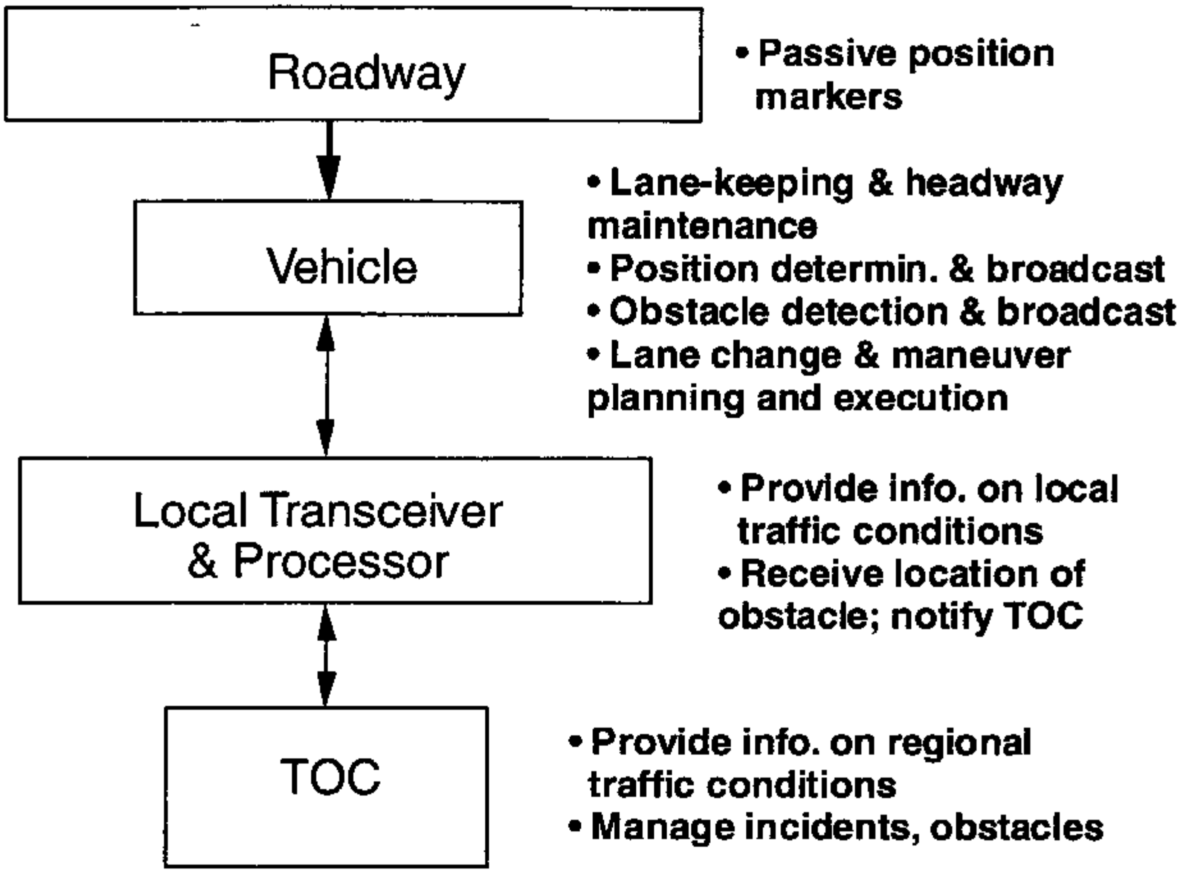

Figure H.20-1.

This is a cooperative concept in which the role of the roadside processor and the TOC is quite limited. The TOC sends regional traffic conditions to the roadside processor which in turn transmits that information to vehicles in the area. The roadside processor monitors traffic density, speed, and environmental conditions using sensors in or on the roadway. It also monitors reports of obstacles and incidents broadcast by vehicles; all this information is forwarded to the TOC.

20.5 FUNCTIONAL ALLOCATION

20.5.1 Check-In

"Check-in" is limited to vehicle self-test of on-board AHS systems.

20.5.2 Transition From Manual To Automatic Control

This is a manual operation performed in motion in the transition lane. Prior self-test of AHS systems is required. The driver throws a switch on the console; visual/auditory confirmation is given if the vehicle processor can take control of the vehicle. Visual/auditory warning is given if the vehicle processor cannot take control. The driver can also select a semi-automated mode for non-AHS roadways. Once in automatic mode, the vehicle will begin broadcasting its availability for platooning and its destination to nearby vehicles.

20.5.3 Sensing of Roadway, Vehicles, And Obstructions

Other vehicles and large obstructions are sensed by the vehicle's forward-looking sensor. If technologically feasible, this will also be used to spot all roadway hazards which can damage the vehicle. If this is not possible, it will be necessary to add one of the following to this concept: 1) a second vehicle-mounted sensor optimized for obstacle detection; 2) use the driver as a spotter for hazards and obstructions which the automatic sensor cannot pick up sufficiently far in advance (see Deployment for more on this). The vehicle processor will compare the range estimates of the forward and side-looking sensors with the broadcast positions of nearby AHS vehicles. Any objects which do not broadcast their position and are detected by the sensors will be assumed to be obstacles unless they are moving within the lines of the transition lane; then they will be assumed to be non-AHS vehicles. Any vehicle detecting an

Concept #17 Data Flows

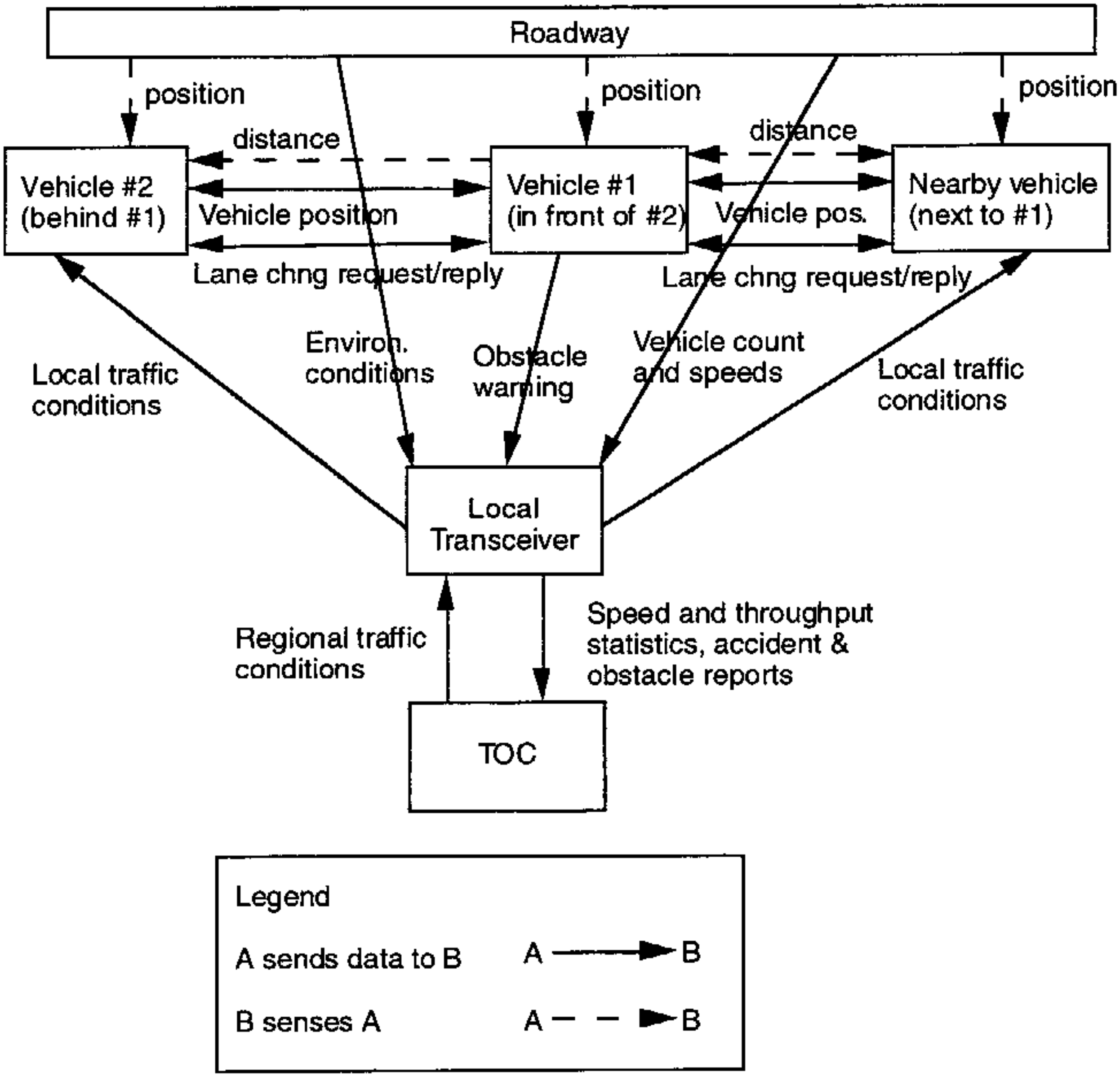

Figure H.20-2.

obstacle will broadcast a warning to nearby vehicles and to the roadside processor, which will forward the report to the TOC. The driver will also have an Alert button, and the ability to enter a limited number of codes for incidents such as request non-emergency communication, report emergency, etc.

20.5.4 Lane and Headway Keeping

Lane-keeping and longitudinal positioning are vehicle-based. Lane-keeping is performed with reflective markers on both sides of the lane which will also be encoded with a sequence number used for positioning (see Issues). These markers may reflect visible light similar to the lane markers used on some interstate highways, or they may be radar reflective. The lane-keeping sensors measure range and can therefore estimate vehicle position relative to the markers. Longitudinal position-keeping is done based on a recommended speed for the region broadcast by the roadside processor, and on inputs from the forward-looking sensor.

20.5.5 Maneuver Planning

The vehicle may make route guidance-based lane change decisions (e.g., lane ends, change lanes for exit or interchange) using in-vehicle routing, or the vehicle may determine the need for an immediate maneuver based on received and sensed vehicle/obstacle positions. Lane change decisions can also be made by the driver, and requested via the user interface. Nearby vehicles will be requested to accelerate/decelerate to make the needed space; if their cooperation is confirmed by return message, the maneuver is executed. Otherwise, an alternative direction is chosen and the process is repeated.

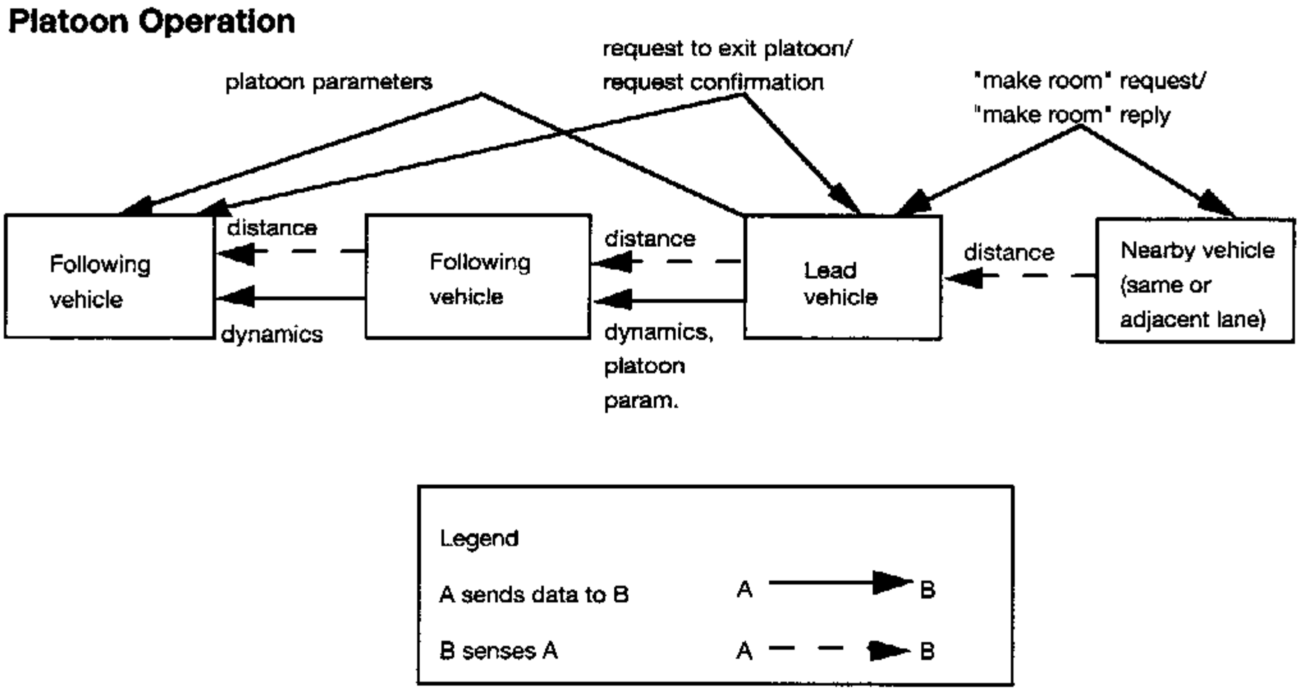

Figure H.20-3.

20.5.6 Maneuver Execution

As maneuver progresses, the vehicle uses its on-board sensors to re-evaluate its relative position and recompute maneuver parameters.

20.5.7 Transition From Automatic To Manual Control

This happens after the vehicle has left the AHS lane(s) under automatic control and is traveling in the transition lane; it can also occur in the case of catastrophic failure of hardware or software. The vehicle signals the driver to resume control, the driver confirms that he is able by pushing a sequence of buttons. If the driver fails to respond correctly within a specified time, he is prompted a second time; if he still does not respond appropriately, the processor brings the vehicle to a stop in the breakdown lane or nearest breakdown area.

20.5.8 Flow Control

In regions where only one lane can be dedicated to AHS, the transition lane can be used like a railroad siding. If faster vehicles are being held up by slower vehicles (e.g., trucks ascending a grade), the faster vehicle can switch to the reflector-equipped transition lane in an attempt to pass without surrendering automatic control of the vehicle. The vehicle will remain under AHS control in the transition lane, and will switch back to the dedicated AHS lane once it has had a chance to pass the slower traffic, or has failed to do so in a certain time interval.

20.5.9 Malfunction Management

The vehicle will have subsystem redundancy for longitudinal position-keeping and lane-keeping. Lane-keeping will be done primarily by sensing reflective markers, and backed up by dead-reckoning. Longitudinal position-keeping will be done primarily by the vehicle-based sensors, backed up by the vehicle's position estimated from lane marker codes, and other vehicles' positions similarly estimated and broadcast.

20.5.10 Handling of Emergencies

If the vehicle's AHS monitoring functions sense hardware or software failures with potentially serious impact, they will broadcast a warning to nearby vehicles, which will respond by increasing spacing and decreasing speed. They will also request the driver to take over manual control, and will bring the vehicle to a halt if he does not (see Transition from automatic to manual control, above).

20.6 IMPLEMENTATION

20.6.1 Vehicle

- Processor
- Short-range vehicle to vehicle communication (2-way)
- Forward-looking sensor for vehicles and obstructions
- Lane-keeping sensors capable of reading encoded position information on specially designed reflectors
- Short-range lateral sensors capable of sensing nearby vehicles

20.6.2 Infrastructure

- Short-range roadside receivers, sufficient density for continuous coverage and accompanying processors
- Traffic Operations Centers at some density
- At least one dedicated AHS lane and one adjacent lane equipped with reflective lane markers compatible with the lane-keeping sensors
- Breakdown lane (or areas) accessible from either the AHS lane or the transition lane. If not continuous, spaced periodically.

20.6.3 Rural Highway

See Flow Control

20.6.4 Deployment

If the lane-keeping sensors can be made compatible with existing rectangular reflectors, then a stepping-stone to implementing this concept could be installation of the on-board vehicle sensors and controllers, but with no capability to plan or execute lane changes, and no modifications to the infrastructure. The vehicle would perform lane-keeping and longitudinal position-keeping under normal circumstances. The driver would have the power to override when he desired, and would be expected to take over under unusual circumstances. Driver monitoring techniques such as the one described in the next paragraph, could be used to periodically check driver alertness.

If a satisfactory hazard detection sensor is not available at the time of initial AHS deployment, the driver can be used as a spotter for hazards and obstructions which the automatic sensor cannot pick up sufficiently far in advance. When the driver pushes an alert button, he can also enter a code (roadway obstruction, fire, medical emergency, etc.). This information, along with the vehicle's position, is broadcast by the vehicle to nearby vehicles and the roadside receiver, which relays the information to the TOC. If the driver pushes a button indicating a possible hazard in his lane, other vehicles near it will begin to slow and increase spacing in preparation for stopping or maneuvering. The driver must volunteer to perform this "spotter" function; reduced tolls represent a possible incentive. Where there are two or more dedicated AHS lanes a speed "bonus" could also be used as an inducement, with vehicles where the driver wants to read or sleep being limited to a lower speed in the right lane(s). Driver alertness and response time could be monitored by periodically projecting an image focused in the distance onto a windshield heads-up-display; the driver must respond by pushing a button within a prescribed time interval; if he fails several times, the vehicle is "demoted" to the lower speed right-hand lane.

20.7 ISSUES

20.7.1 Obstacle Detection Sensor

Obstacle detection could be performed 1) by the vehicle-mounted headway sensor; 2) by a separate vehicle-mounted sensor designed to detect small objects on the roadway; 3) by the headway sensor assisted by the driver (see previous paragraph). This is a technology issue which needs further investigation.

20.7.2 Vehicle Position Determination

This concept proposes that the vehicle calculate its position from a known position when it entered AHS, a count of the number of markers passed since entry, and measured range to the current markers. To do this the lane-keeping sensor must measure both range to the lane markers, and read a three to four bit sequence number encoded on the markers. These markers may reflect visible light similar to the lane markers used on some interstate highways, or they may be radar reflective. They will, however, be spaced at regular intervals, be machine-readable, and encoded with the sequence number of the marker. The vehicle counts markers, and uses the code on the marker as a check in case it misses a few. Where snow falls regularly, the markers will need to be designed or placed so that they are not damaged by snowplows. The feasibility of this position determination method is not critical to this concept, however; other methods can be substituted.

21. CONCEPT 18: COOPERATIVE VEHICLES ON DEDICATED LANES

21.1 OVERVIEW

In this concept, autonomous vehicles utilize inter-vehicular communications for coordinated lane changes and simple platooning of like-vehicle-classes. There is minimal infrastructure intelligence, indicating that traffic flow optimization will not be performed by a global support network. This concept utilizes uni-directional dedicated lanes with physical barriers and dedicated entry and exit ports. Obstacle detection will be performed automatically, however obstacles will either be manually avoided or the vehicle automatically stopped in order to avoid a collision.

21.2 SELECTED ALTERNATIVE FROM EACH DIMENSION

Distribution of Intelligence: Cooperative vehicles (autonomous vehicles with inter-vehicular communication) with minimal infrastructure intelligence Separation Policy: Free agent vehicle. Traffic flow is not optimized by a global support network or organized platoons.

Mixing of Vehicles: AHS vehicles will travel on dedicated lanes with continuous physical barriers.

Mixing of Vehicle Classes: Full mixing of all vehicle classes on the AHS lanes will occur.

Entry/Exit: There will be dedicated entry/exit points onto the AHS lanes.

Obstacle: Automatic sensing of obstacles will lead to manual maneuvering or automated stopping in order to avoid colliding with the obstacle.

Region Specific Options:

1. Each region will need to determine the optimal entry/exit ports onto the AHS lanes in order to maximize throughput and minimize the impact to surrounding streets.
2. Each local region will be responsible for determining which roadways will benefit by installation of an AHS dedicated lane. This may involve simple retrofitting of existing HOV lanes, utilizing existing manual land for AHS use, or the creation of new AHS lanes.
3. Each region will need to determine if AHS dedicated lanes must also be used as HOV lanes.

21.3 OPERATIONAL CONCEPT

21.3.1 Communications

Communications, in this concept, is not limited to "command" information. One aspect of the potential communications architecture is a vehicle beacon which provides steady-state information to surrounding vehicles. This beacon identifies the vehicle as being AHS-equipped and provides a performance indicator for the vehicle. This will allow vehicles to calculate safe stopping distances given the performance of surrounding vehicles. Emergency vehicles will have an additional indicator on the vehicle beacon. When the lights and sirens are used, the beacon will also activate an emergency signal. This information will be used by vehicles in the surrounding area to "make way" for this vehicle. All vehicles will be constantly querying the surrounding vehicles (within a short range) for performance data and will be continually updating the braking profile given the characteristics of surrounding vehicles. This proactive braking calculation will provide a deceleration value that can be used immediately in an emergency situation. Decreased headways will be obtained because of this communications capability. This will result in higher throughputs while continuing to maintain reasonable gap sizes.

21.3.2 Check In

The AHS-equipped vehicle will pull into the dedicated entry point for the AHS. A systems check will be performed by the on-board software to verify that all hardware and software is in proper working order. The AHS computer will have the capability of determining the required fuel loading for the trip and will notify the driver if an earlier exit will have to be taken. The driver will be responsible for ensuring that tire inflation is proper, and that the car is working within the performance measures assigned to that vehicle. This measure of personal responsibility is required for a system without a heavy infrastructure emphasis. Drivers can be discouraged from providing poor maintenance by the use of heavy fines if avoidable breakdowns occur on the AHS lanes. The entry point may require police support to ensure that vehicles that are not AHS-designated do not enter the AHS lanes. This would be necessary due to the fact that infrastructure is minimized in this concept.

Once the vehicle has passed the systems check, the vehicle will assume control. It will be responsible for merging into the AHS lanes and traveling with the flow of traffic. A spacing policy will be required that enables AHS vehicles to merge into the lane without the use of a long transition ramp. At this point, the driver of the vehicle indicates what exit or what approximate distance of travel is desired. This can be achieved through a keypad or voice-based system where the vehicle queries the driver. An on-board, regional-specific database would be required to confirm destination points, and suggestions may be made by the computer for an exit if the number or name is not known by the driver. This will also require that a system be developed to uniquely identify exit numbers throughout the country (for example: PA-79-01A would indicate the Pennsylvania section of I-79, exit 1A). Depending on the amount of available on-board disk space, database loading stations may be required at rest stops along AHS travel routes. This will allow vehicles traveling from one region to another to update the on-board information. This will also minimize infrastructure requirements by updating the database slowly, rather than in real-time.

21.3.3 Normal Operations, Including Obstacle Detection

The vehicle will determine its location on the highway either through vision data or GPS used in conjunction with an on-board database. The vehicle will be able to determine the number of lanes on the freeway and which lane the vehicle is in. The vehicle has 360 degree obstacle detection sensors that detect other vehicles and obstacles. The vehicle will also be capable of detecting the relative velocity of these objects. The on-board logic uses the above information to maneuver the vehicle so that it travels with the flow of the traffic and maintains a safe distance from other vehicles.

A gain in throughput and flowrate is achieved because intelligent vehicles can use shorter headways due to the automated reactions to received information. In the event that the AHS vehicle is closing on an object, the AHS system will signal the driver that a collision may occur. The driver will be required to either manually avoid the object or to indicate to the vehicle that the object is inconsequential. If no action is taken by the driver or if the reaction time would be unacceptable, the vehicle will brake so as to avoid a collision. One of several potential technologies used to detect the relative motion of surrounding objects is Doppler Radar. Sensed information from radar, IR, or vision systems will be integrated with communicated data. These data will feed into the maneuvering and braking algorithms on-board which in turn command the vehicle. Vehicles will have the logic to automatically create a space for a vehicle in another lane that has communicated its intention to merge into its own lane.

The backwards looking sensors will be continually scanning for vehicles which are approaching with a problematic delta v. The vehicle can signal the approaching vehicle by signaling the vehicle via the communications link. If this signaling is unsuccessful due to a hardware failure and a collision is imminent, the AHS vehicle will maneuver out of the lane to avoid a collision.

21.3.4 Check Out

In order to regain manual control, a graceful transition period is required. This will be done outside of the AHS lane in a transition lane that is dedicated to a particular exit. When the transition ramp for the selected exit becomes available, the vehicle will automatically exit. If there are surrounding vehicles in the transition lane, all vehicle headways will be increased for safe manual driving. Transition of control to the driver will be achieved through an alertness test which may involve transition acceleration control first, then braking and maneuvering. If the system has indications that the driver is incapacitated, it will pull into a safe area.

It is important that side-street traffic flow is well coordinated with AHS exiting requirements so that local congestion does not "back up" into the AHS transition lane (and hence, the AHS lane as well). This may require a regional study to ensure that all traffic flow is maximized.

21.3.5 Use of AHS Technology for Rural and Inner-City Driving

Certain features of the AHS system, such as lane-keeping and headway maintenance, can be used independent of other features. This will provide additional safety benefits during inner-city driving as well as rural roadway driving. Partial-use of AHS features will be terminated manually.

21.4 FUNCTIONAL ALLOCATION

In this concept, all intelligence is assigned to the vehicle. No infrastructure changes have been implemented to support AHS. Additional functional allocation information is summarized under "3.0 Operational Concept."

21.5 IMPLEMENTATION

Implementation of intelligence is strictly placed in the vehicle. No infrastructure support will be required.

21.5.1 Vehicle

The following technologies will be examined in order to achieve this concept:

- Forward and backward looking Doppler Radar
- GPS
- Side looking proximity sensors
- Infrared technology
- Vision system technology

Various communications possibilities exist, all of which are to be explored.

21.5.2 Infrastructure

There will be no infrastructure support in this concept other than already existing GPS infrastructure. No TOC will be necessary or available.

21.5.3 Deployment

This system will have tremendous appeal because of the safety advantages, early implementation of technology, and wide applicability of technology. Vehicles can be equipped with AHS technology as soon as it is proven and prior to infrastructure upgrades for dedicated lanes. AHS capability can not only be utilized on freeways but can also be used, at least partially, in the city and on rural roadways. This provides significant and immediate benefit to the consumer.

21.6 GENERAL ISSUES AND CONSIDERATIONS

It was determined that the requirement for manual obstacle avoidance is insupportable technically. Given that the vehicle has autonomous capability, obstacle avoidance is built into the system design and should be fully utilized.

22. CONCEPT 19: INFRASTRUCTURE MANAGED PLATOONS WITH AUTOMATIC SENSING, STOP, AND MANUALLY AVOID

22.1 OVERVIEW

This system implements a highly centralized and controlled system which is managed directly by the infrastructure. Mixed classes of vehicles operate together in dedicated and physically separated lanes. Vehicles operate in platoons for optimal throughput and fuel efficiency, and are allocated a position at the dedicated entry control station.

This concept can provide a highly optimized and efficient system because of its centralized nature. Traffic flow can be optimized although it does require a complex central software system. Growth is very efficient and controlled because all changes can be made at one location irrespective of growth or evolution in vehicle models.

22.2 SELECTED ALTERNATIVE DIMENSIONAL DESCRIPTION

22.2.1 Distribution of Intelligence—Infrastructure Managed

The infrastructure monitors individual vehicles and commands vehicles on an exception basis, including entry and exit. The infrastructure senses obstacles and sends commands to the vehicles; if the vehicle senses an obstacle the infrastructure missed, it requests an emergency stop (to allow the other platooned vehicles to respond simultaneously). Local position keeping is granted to individual vehicles, but there is no communication between vehicles; all platoon level parameters are set by the infrastructure.

22.2.2 Separation Policy—Platooning

Vehicles are required to run in platoons (A single vehicle would still be treated as a platoon). The separation within a platoon is set by the infrastructure as a function of the worst minimum stopping velocity of the vehicles in the platoon. This data is acquired at check-in, is forwarded to consecutive roadside beacons/controllers, and is also maintained by the lead vehicle. All vehicles brake at the same delta velocity upon command of the infrastructure (roadside controllers).

Note there are two other possible separation policies consistent with this option. These are presented here but are not considered in the ensuing discussion:

a) vehicles can maintain their own available delta v and adjust their separation distance as a function of the allocated platoon speed; or

b) the infrastructure controller could develop customized spacings (even smaller) that are a function of each vehicle and the vehicle ahead (for the lead vehicle, the sensing range).

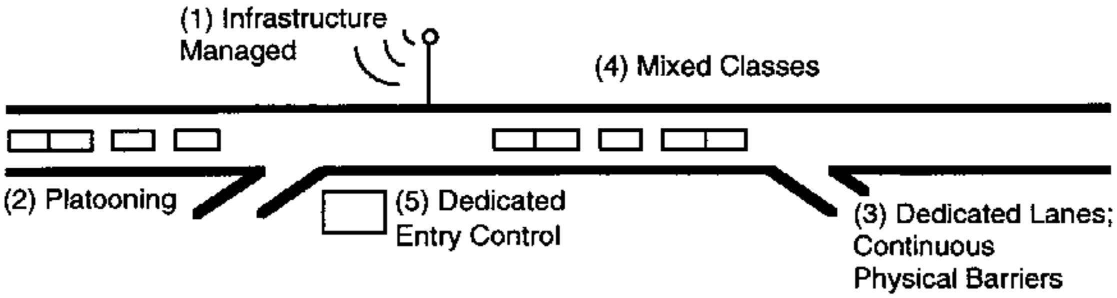

Figure H.22.1-1. System Overview

These variations on the basic alternative can be selected/modified by the local governing agency by simple software modification.

22.2.3 Mixing of AHS and non-AHS Vehicles—Dedicated Lanes with Continuous Physical Barriers

Continuous physical barriers are used with dedicated entry points so that non-AHS vehicles do not operate with AHS vehicles.

22.2.4 Mixing of Vehicle Classes in a Lane—Mixed

Different vehicle classes may be mixed in any platoon arrangement. The infrastructure takes individual vehicle control parameters into account when setting up platoons and platoon operating parameters. The ensuing description (§3 through §7) presumes that platoon spacing and velocity parameters are set as the worst case of the vehicles in the platoon. For example the platoon would maintain common spacing which would be a function of the slowest available negative acceleration (stopping capability) and the desired speed (a function of maximum vehicle acceleration (engine and weight) and hill grades over the highway segment). Each vehicle would maintain this common spacing; thus, platoons would operate at the lowest common denominator of the different classes represented in the platoon.

Note there are two other possible platooning policies consistent with this option wherein the entry station and/or assigning roadside controller sort incoming vehicles into different platoons. These are presented here but are not considered in the ensuing discussion:

a) platoons may be homogeneous with different classes of platoons for each class of vehicle (this reduces control complexity, but also reduces overall throughput); or

b) platoons may be sorted on (throughput affecting) parameters to increase performance at the cost of a slight increase in complexity.

These variations on the basic alternative can be selected/modified by the local governing agency by simple software modification.

22.2.5 Entry/Exit—Dedicated

Entry/exit points are dedicated access points which are located at openings in the continuous physical barrier in conjunction with the AHS check-in function; entry/exit at intermediate points in the roadway is not available.

22.2.6 Obstacle Sensing and Avoidance—Automatic Sensing, and Stop or Manually Avoid

Obstacles are automatically detected by a combination of vehicle and infrastructure. The only allowed response is for the vehicles (platoons) to stop. A human must release the blocked condition, either by driving around or by requesting assistance via the roadside beacon. Two types of response are defined. For infrastructure detected obstacles, the system knows the location and approach vector. Thus, the system can modulate the platoon velocity to bring the platoon to a gradual stop at the correct point. If a (lead) vehicle detects an (unknown) obstacle, it first sends the information to the local roadside beacon which then commands all vehicles to simultaneously come to a stop at a given stopping velocity. Note that if a response is not received by the lead vehicle from the beacon within a specified time, the vehicle can begin braking itself. Subsequent vehicle braking is initiated and controlled by each vehicle's longitudinal controller. The available maximum delta v is a function of the platoon control algorithm and may be less than the available stopping velocity because of platoon stability issues.

22.3 OPERATIONAL CONCEPT

The environment for this concept is highly defined and controlled: the AHS lanes are dedicated and have continuous physical barriers; Check-in is highly controlled at entry points; control of the platoons and vehicle commands are generated by local roadside beacons and is coordinated by a central TOC. Information may also be sent to an overlapping TOC for informational and planning purposes.

Entry into the dedicated lane is controlled at the check-in point. In addition to verifying the readiness of the vehicle, the check-in station gathers vehicle information such as maximum stopping velocity and front sensor range to be used for platoon control. This information is sent to the infrastructure control manager to request insertion into or at the end of a platoon. The infrastructure control manager then grants a request to enter, or form, a platoon. Information maintained on each platoon includes number of vehicles, vehicle IDs, maximum forward sensing range, and worst minimum stopping velocity.

Control of the platoon is governed by the infrastructure. Roadside beacons send commands to the platoon for velocity, etc. based on platoon information, the upcoming highway, upcoming traffic conditions, weather conditions, and infrastructure sensed obstacles. Overall control, governed by a TOC, is aided by the roadside beacons forwarding platoon information to the next beacon.

Control within the platoon is governed by the common set of parameters sent to the vehicles such as velocity. Nominal adjustments (increases/decreases) in speed are commanded and executed by the individual vehicle controllers. In case of the lead vehicle sensing an obstacle, the roadside beacon is alerted which then asserts a defined stopping velocity. Note that one of the parameters that is sent with the platoon is the worst maximum stopping velocity.

Centralized Control and Computing is provided at the Traffic Operations Center (TOC). The communications lines linking the roadside beacons/controller must be highly reliable.

22.4 SYSTEM DIAGRAM

The system block diagram is shown in Figure H.22.4-1. Data rates are defined in §6. Dashed lines indicate sensed information. Solid lines indicate communication links.

Shaded lines indicate the solid physical barriers. The Traffic Operations Center (TOC) provides traffic coordination.

22.5 FUNCTIONAL ALLOCATION

22.5.1 Check-In

Check-in is allocated to the infrastructure at a dedicated entry point. The vehicle state is analyzed to ensure AHS capability, and some dynamic parameters are collected to be passed to the platoon control function. This information would include maximum stopping velocity (=f(weight, tires, brakes)), maximum range and resolution of forward obstacle sensor, and vehicle ID. The check-in station then requests an insertion on to the dedicated lane which may be at the end of an existing platoon, a new platoon, or if in heavy traffic into the middle of a platoon. The request to the roadside controller for entry includes the dynamic information.

22.5.2 Transition from Manual to Automatic Control

Control of transition to automatic driving is allocated to the infrastructure. Once the vehicle is verified to be ready to enter the dedicated AHS lane, the infrastructure controller selects a platoon for the vehicle to join and sends a merge profile to the vehicle. When the vehicle is in the platoon and within a nominal spacing of the forward vehicle, it assumes longitudinal control and maintains its distance given the nominal platoon velocity.

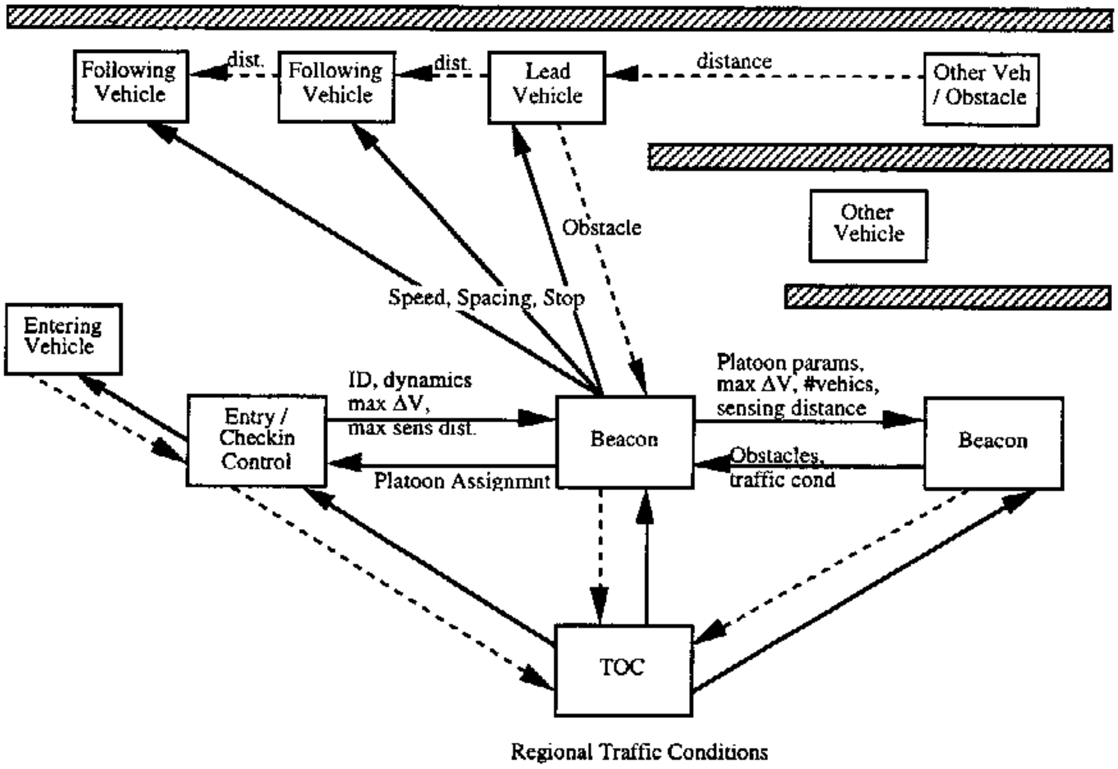

Figure H.22.4-1. System Block Diagram

22.5.3 Automated Driving

22.5.3.1. Sensing of roadway, vehicles, and obstructions

Dynamic sensing of the roadway, vehicles, and obstacles is allocated to the vehicle. Down road obstacles that are sensed by the infrastructure fixed sensors are communicated to the correct roadside beacon which uses the location data to adjust platoon velocities and eventually, at the correct physical coordinates, to come to a simultaneous commanded stop.

22.5.3.2. Lane and headway keeping

Lane and headway keeping are allocated to the individual vehicles. A nominal velocity and spacing is commanded by the roadside beacon; the vehicle then maintains the correct distance by adjusting its velocity around the set point.

22.5.3.3. Detection of hazards

Detection of hazards is allocated to both the vehicle and the infrastructure. The role of the infrastructure is to keep obstacles out of the dedicated lane with continuous physical barriers. If a vehicle becomes disabled its location is transmitted upstream as a local traffic condition. The vehicle sensing role applies only to the lead vehicle of a platoon and is to detect any non-predefined obstacles. Upon identification of the obstacle the vehicle sends a request to the local roadside beacon to request a stop. The command to stop is sent broad band to all vehicles so they may commence braking nearly simultaneously.

22.5.3.4. Maneuver planning

Maneuver planning (both normal and emergency) is allocated to the infrastructure. The only allowed reaction of a vehicle to an obstacle is to stop and this must first be requested to the local roadside controller. The vehicle can begin braking on its own accord if no response is received within a nominal time (~100ms).

22.5.3.5. Maneuver execution

Maneuver execution is allocated to the vehicle.

22.5.4 Transition from Automatic to Manual Control

Transition from automatic to manual control is allocated to a combination of the vehicle and the infrastructure. The vehicle, upon operator request, verifies its readiness to exit to manual control. The vehicle then requests an exit from the AHS lane. The local control system grants the request and also sends any additional instructions necessary to the rest of the platoon.

22.5.5 Check-Out

Checkout functions are allocated to a combination of the vehicle and the infrastructure. The vehicle, upon operator request, verifies its readiness to exit to manual control. The vehicle then requests an exit from the AHS lane. The local control system grants the request and also sends any additional instructions necessary to the rest of the platoon.

22.5.6 Flow Control

Flow control is allocated to the infrastructure. This is divided between the local control beacons and the TOC. Local speed control and platoon forming and braking are under the control of the local beacon. Traffic management is performed at the TOC as a function of inputs supplied by the local controllers.

22.5.7 Malfunction Management

Malfunction management is allocated to a combination of the vehicles and the infrastructure. If a vehicle fails and becomes unable to continue as an AHS capable system, it requests an exit. If the vehicle is unable to reach an exit, the local control beacon notes its location, sends a signal to the TOC, and then forwards the obstacle information upstream to earlier local beacons to give platoons correct instructions on what action to take (such as slowing through incremental speed steps to stop at a particular GPS location).

22.5.8 Handling of Emergencies

Handling of emergencies is the same as Malfunction Management. It is allocated to a combination of the vehicle and infrastructure. If a vehicle fails and becomes unable to continue as an AHS capable system, it requests an exit. If the vehicle is unable to reach an exit, the local control beacon notes its location, sends a signal to the TOC, and then forwards the obstacle information upstream to earlier local beacons to give platoons correct instructions on what action to take (such as slowing through incremental speed steps to stop at a particular GPS location).

22.6 IMPLEMENTATIONS

22.6.1 Vehicle

Below is a coarse comparison of hardware implementation costs compared with other possible concepts. Use of the word 'same' implies that this is an independent choice and is not specifically affected by the selection of this particular concept.

Actuators	same
Communication	minimal
Health Monitoring	same
Obstacle Detection	same
CPU	minimal
Lane Keeping	same
Headway Control	same

22.6.2 Infrastructure

Below is a coarse comparison of hardware implementation costs compared with other possible concepts. Use of the word 'same' implies that this is an independent choice and is not specifically affected by the selection of this particular concept.

Communication	higher bandwidth
Obstacle Sensors	needed
Check-in	same
Roadside Controllers	greater CPU reqs
TOC	more software

22.6.2.1. Rural highway

Some special considerations for implementing this concept for a rural system are discussed below.

The assumption of continuous physical barriers implies a slightly higher cost for installation of the infrastructure and might restrict access somewhat. However, as the main benefit of this method is increased safety, it may be worthwhile. For instance, it would be a distinct advantage if installed on major interstate trucking routes.

The need for active roadside infrastructure control seems to imply a need for a large number of roadside controllers and communications. However, this issue is easily sidestepped by having the lead vehicle in a platoon carry the pertinent platoon information forward to the next interchange or exit point. This is reasonable since the infrastructure control is only for non-steady-state adjustments which would not occur between activity points.

22.6.2.2. Urban region

Some special considerations for implementing this concept for an urban system are discussed below.

Urban implementations are ideal for this concept. The level of infrastructure required is a perfect match for the required functionality in a complex urban environment. Additional goals and objectives can be met for user incentives as well as real-time throughput and routing adjustments by the TOC and linked roadside controllers.

Multiple lane implementations (when the demand gets high enough) would be simple software modifications. For instance lane switching would require the ability to "open" platoons. However this is the same software needed for vehicle entry. This software would simply be transferred to the roadside controllers, and a request for a lane change would simply be a special case of existing software.

22.6.3 Deployment

The minimum deployable system requires all of the infrastructure and software to be installed up front. This makes the initial funding requirements greater. However, subsequent investments would be minimal. Note that once the first system is up and running, all software is developed (only requires adaptation), and the subsequent infrastructure capitalization costs revert to the same level required for the infrastructure by any other implementation concept

The incentive for people to buy AHS capable vehicles is the low delta cost. This concept would require the fewest components on the vehicle.

Cities and other metropolitan transit authorities should prefer this system because they can use the centralized control to adjust usage policies for their particular region.

22.7 GENERAL ISSUES AND CONSIDERATIONS

Some coarse subjective evaluations relative to the AHS System Goals and Objectives are discussed below. Use of the word 'same' implies that this is an independent choice and is not specifically affected by the selection of this particular concept.

Table H.22.7-I.

Goal/ Objective	Parameter or Alternative	Relative Performance	Notes
Safety	Obstacle Sensing	safer	use of both vehicle and infrastructure is better than one
	Physical Barriers	much safer	
	Unexpected Intrusion	safer	Especially from other nearby vehicles.
Throughput	Platooning	very high	Two additional modes for even more throughput.
	No Non-AHS vehicles	undefined	less vehicles are allowed on but this may increase through put because it enables better platooning
	Traffic Management	very high	Global Optimization is enabled
Cost	Barriers	more	
	Vehicles Electronics	less	minimal cpu required
	Infrastructure Computer & S/W	more	roadside beacons / controllers need more software and elec
	Capitalization	more	Higher up front costs for infrastructure
	Operations	saves money	
Modularity and Growth	Maintenance	easy, centralized	less vehicle maintenance
	Evolution	easy upgrades	upgrades are generally S/W, no vehicle mods needed
	Expansion	no difference	
	Interoperability	no difference	conjunction of regional systems still problematic
Other	Communications Needs	Higher bandwidth; flexible packet routing	No new technology
	User Friendliness		no special attributes

23. CONCEPT 20: AUTOMATED SENSING, STOP AND MANUALLY AVOID WITHOUT CLASS MIXING

23.1 OVERVIEW

This concept was selected to be an AHS concept with as little technical risk as possible. It does not require that the AHS be able to maneuver around all obstacles.

23.2 CONCEPT DIMENSIONS

23.2.1 Infrastructure Supported

Selected as a mainstream option. More infrastructure support may offer more of a challenge and more risk. Less infrastructure support may make the task for vehicles too difficult.

23.2.2 Free Agent

Vehicles maneuver independently, with no effort to form into tight platoons. Vehicles do not communicate with each other, and thus, they must drive allowing extra space as a margin for uncertainty.

23.2.3 Dedicated Lanes With Continuous Physical Barrier

Only AHS vehicles are allowed on the AHS roadway, and this segregation is maintained by physically separating AHS vehicles for the duration of their journey.

A major goal of the physical highway architecture is to minimize hazards and obstacles of all types, as they will severely disrupt traffic flow in this architecture.

A continuous breakdown lane is a necessity. Beyond functioning as a breakdown lane, it provides a space where vehicles can manually be driven around obstacles. On automated highways carrying two classes of traffic in separated lanes, these lanes could share a common breakdown lane between them.

23.2.4 Vehicle Classes Not Mixed in Lanes

Ordinary operations presume that all vehicles in the same lane are of the same class.

As a local option, a highway could allow mixed class vehicles, but in this case all long-stopping-distance vehicles would have to follow using very large headways, under the presumption that they may be following a fast-braking vehicle. Traffic density and total throughput would suffer as a result. Vehicles would be informed during check-in of this exception on such an automated highway.

23.2.5 Dedicated Entry and Exit

Vehicles must pass ordinary check-in to enter an automated roadway.

Note, however, that there is a second kind of entry and exit into AHS operations. When the vehicle comes across an obstacle in the roadway, it stops automated operations and reverts to manual control. This is a check out. Once around the obstacle, the vehicle resumes automated operations. This is a check in. All vehicles must be able to accomplish this simpler level of check-out and check-in at any point on the highway.

23.2.6 Automatic Sensing, Stop, and Manual Avoidance

This is the largest departure from most AHS concepts. When a vehicle comes across a substantial obstacle or hazard, rather than trying to automatically navigate around it, the vehicle stops, notifies the driver, and the driver manually drives the vehicle around the obstacle.

23.3 OPERATIONAL CONCEPT

In steady state, a vehicle is traveling in a lane, maintaining headway using an on-board forward looking sensor, and staying in the lane by relying on passive, machine readable markings in the roadway. If the vehicle comes across an obstacle, it stops and notifies the driver.

23.4 FUNCTIONAL ALLOCATION

23.4.1 Check-In

Performed by the vehicle, in conjunction with the driver and roadway.

The AHS-equipped vehicle will pull into the dedicated entry point for the AHS, and stop. A systems check will be performed by the on-board software to verify that all hardware and software is in proper working order. This will be verified by the infrastructure at the check-in station, using the vehicle communications. The AHS computer will have the capability of determining the required fuel loading for the trip and will notify the driver if an earlier exit will have to be taken. Once the vehicle has passed the systems check, the vehicle will assume control. It will be responsible for merging into the AHS lanes and traveling with the flow of traffic.

23.4.2 Transition from Manual to Automatic Control

Occurs in the vehicles, while they are stopped.

23.4.3 Automated Driving

23.4.3.1. Sensing of roadway, vehicles, and obstructions

Roadway is sensed indirectly, by sensing of standardized, machine-readable markings. Vehicles and large obstructions ahead are sensed using forward looking sensor which measures range and range-rate on large objects. Vehicles are cooperatively marked. Smaller obstacles ahead are sensed using on-board sensors, and if suspicious, lead to stopping the vehicle and being sensed manually by the driver.

23.4.3.2. Lane and headway keeping

Lane keeping is accomplished using machine-readable roadway marking to indicate lanes, and an on-board sensor. The control loop is within the vehicle. Headway keeping is managed using a forward-looking sensor and closing the loop within the vehicle.

23.4.3.3. Detection of hazards

Detection of hazards is handled by individual vehicles, using on-board sensors. Once detected, the vehicle stops and control passes to the manual driver, who is responsible for watching the hazard until it is safely cleared.

23.4.3.4. Maneuver planning (normal or emergency)

A normal lane change is planned by a vehicle.

The emergency maneuver is to come to a stop and transfer control to the manual driver. This is implicitly pre-planned into the control algorithms.

23.4.3.5. Maneuver execution

Accomplished by the vehicles.

In the case of lane changes, the vehicle waits until its proximity sensor indicates that the immediate side it wishes to merge into is clear, and uses the short range LOS communications to inform that it is making a merge. If it receives no objection, then it merges. Vehicles which receive a request to merge are to slow down, and let the vehicle merge in.

23.4.4 Transition from Automatic to Manual Control

Vehicle maneuvers to a stop under automatic control, and is then driven away under manual control.

23.4.5 Check-Out

A vehicle exits the AHS lane by moving through a dedicated transition ramp to an empty space at a check-out station at the desired exit. Communications with the station may tell the vehicle to not take this exit, but the vehicle may request an emergency exit in any case, if it is low on fuel. Once stopped, the vehicle transitions to manual control, and informs the driver, who then drives off.

23.4.6 Flow Control

Flow control is managed by the infrastructure.

23.4.7 Malfunction Management

Vehicle monitors internal state, and takes next exit if possible if it notes a discrepancy. If unable to make the exit, move into the breakdown lane, and make a Mayday call (using ITS).

23.4.8 Handling of emergencies

Standard panic mode for an emergency is to come to a rapid stop, and transition control to manual driver.

23.5 IMPLEMENTATIONS

The following is a notional implementation.

23.5.1. Vehicle

- Forward looking Doppler radar
- Passive marker sensor (may also be forward looking sensor, or side looking sensor)
- Side looking proximity sensors
- GPS
- On-board processor
- Short range, directional, Line of Sight communications

23.5.2 Infrastructure

Passive markers to indicate lanes, AHS traffic rules, other special, static information. Continuous physical barrier, or totally separate roadway, isolating AHS from other traffic.

Widely spaced entry/exit stations. These have spaces to stop for transition to/from automatic control, and simple communications to support check in and check out.

As a local option, traditional traffic control sensors, and TOC control the traffic flow of the AHS

23.5.2.1. Rural highway

Rural highway might use isolated lane, rather than building a continuous barrier.

23.5.2.2. Urban region

Urban region would use continuous, physically isolated lanes, generally on pre-existing highway. Entry and exit stations would be sited where space for large adjacent parking was already available (e.g., airports, shopping malls).

23.5.3 Deployment

Possible first applications: Dedicated transit roadways; Dedicated interstate Trucking roadway; Part of a "shortcut" tollway corridor

23.6 ISSUES

One key issue is "how does the system operate so that a stall in the fast lane does not grow into a massive shutdown of AHS for that vehicle class?"