10.4.6 OBSTACLE MANAGEMENT ANALYSIS

Author, D.M. Briggs

Subtask B4 of Task C3

Obstacle Management consists of three distinct functions: Obstacle Exclusion (OE), Obstacle Detection (OD), and Obstacle Avoidance (OA). In addition, the Obstacle Characterization function is a cross-cutting activity, the results of which are useful to the other three functions.

It should be noted that two events in FY97 caused major hindrances to the progress of this activity. The first is the AHS Demo '97 that occurred in August. The monumental effort that was invested in preparing for the demo made many resources for the OM subtask unavailable. The second, and the most significant, event was the redirection of activities by the USDOT. It became apparent that if the driver is still engaged (contrary to what is assumed under full automation), then the requirements to be placed on the system would be very different. For example, if the driver is engaged in the driving task, the responsibility for finding obstacles (especially small objects at great distances) remains with the driver. Therefore, the OE and OD functions could be optimized for larger objects. The uncertainty associated with the redirection has caused much of the activity to cease until the future activities if the NAHSC become better defined.

While the AHS Demo and the USDOT redirection interfered significantly with the progress of the Obstacle Management subtask, some accomplishments can be documented:

- Members of the Bechtel team completed a study report describing various methods of preventing obstacles from entering the roadway from outside the roadway (see Appendix 10.4.8, Dedicated Lanes Analysis).
- A report on the types of obstacles encountered on existing freeways was completed by Steve Schuster of Hughes (see Appendix 10.4.4.1, Driving Environment Hazard and). This report lists, based on extensive analysis, the "Top Six" obstacle types that must be the focus of any automated system. The six obstacle types (in order of importance) are people, unknown object, tire, rollover, another vehicle, and metal scrap.

Future activities will be focused on providing requirements to the Obstacle Detection Technology Development activity, and to the Obstacle Exclusion activity. These requirements will depend on the direction established by the NAHSC leadership. If the direction is to continue developing technologies for a fully-automated system, the OE and OD requirements will be much more stringent than they would be if NAHSC moves toward systems that require the driver to remain engaged in the driving task.

10.4.7 MIXED TRAFFIC ANALYSES

Author, Carol Jacoby

10.4.7.1 INTRODUCTION

This section discusses analysis that has been submitted to the IEEE Conference on Intelligent Transportation Systems (Boston, November 9 - 12, 1997).

Probably the biggest issue in the definition of the national automated highway system (AHS) is whether or not the automated vehicles will be designed to share the road with manually driven vehicles, or whether they will require lanes or roads dedicated to the exclusive use of such vehicles. This section presents the current status of the issues and findings of the Mixed Traffic Team of the NAHSC. The goal of this team is to determine whether the major goals of mixed traffic can or should be met by an AHS.

Mixed traffic usually refers to fully automated vehicles sharing lanes with completely manually operated vehicles (standard vehicles as driven today). The discussion in this section applies also to any mix of vehicles with different levels of automated control, sharing a lane. The opposite is a dedicated lane, a lane that accepts only vehicles with at least a specified level of automated control. Dedicated lanes are discussed in Section 10.4.8.

While mixed traffic is complex and raises safety and other issues, as discussed below, it is attractive for several apparent reasons.

- The AHS may evolve naturally from driving aids such as cruise control.
- Construction costs may be minimized.
- Almost any freeway may become an AHS.
- All AHS roads may be available to most vehicles, avoiding elitism and low usage.

As it turns out, each of these motivations is tempered by constraints and conflicting motivations, and may not be achievable to the full extent. The issues are very complex and involve conflicting interests and priorities. There is much diversity of views on this question within the NAHSC. The next section summarizes the Task C2 work in this area, which was presented in "Issues of Automated Vehicles Operating in Mixed Traffic" at the 1997 annual meeting of ITS America.

10.4.7.2 SUMMARY OF RESULTS FROM C2

The NAHSC has defined measures of effectiveness for AHS and identified key issue areas. While these will not be discussed here, suffice it to say that they were considered relative to both mixed and dedicated lane approaches. This work was discussed in the C2 Final Report (Milestone 2 Report). Of the identified issues, four stood out as highlighting important distinctions between the two approaches.

- The role of the driver
- Progressive deployment
- Safety
- Roadway capacity

The team found that all of these center around providing safety for the automated vehicles. This is especially true in the case of the role of the driver and evolutionary deployment, as discussed below. Because of this, the team has emphasized in C3 the safety requirements, in particular an analysis of the functional requirements to design safety into the system.

10.4.7.2.1 The Role of the Driver and evolutionary deployment

It is the deployment sequence issue that has generated the most interest in mixed traffic operations. The wish is to facilitate the transition from driver aids such as adaptive cruise control to full automation. Another way to look at the issue is the "chicken and egg" problem of whether the roads will be built first, motivating people to equip their vehicles, or whether the vehicles will be equipped first, motivating communities to instrument roadways to support them. The latter approach will require mixing with manual traffic at least in the early stages. There is also increasing interest in near-term applications of AHS technologies to warning and partial control systems, which will generally be used in mixed traffic. While this section focuses on the requirements of full automation, the results have applicability to these systems as well.

There are more than just the two extremes -- automated vehicles freely mixing with manual vehicles on any roadway, and strictly controlled lanes on which only automated vehicles are allowed. In fact, there is a continuum of approaches, such as mixed traffic only on certain, controlled roadways, or automated vehicles allowed to mix only with specially equipped or semi-automated vehicles. In fact, early AHS systems may be mixed operation on "designated" or "protected" lanes, strictly controlled and barriered lanes that support both automated and manual or partially automated vehicles. In this section the term "dedicated" is reserved for lanes that are for automated use only.

So there are actually two evolutionary paths to mixed traffic AHS. The first is the allowing of automated or partially automated vehicles access to certain areas of the interstate system. In other words, the path involves initially opening a limited number of roadway segments to mixed traffic AHS, and gradually expanding the road segments that support it. Some areas of the country are better suited than others for initial mixed traffic operation, and in addition they can be specially equipped and protected. The other track is the growth in the degree of autonomy of the vehicle, with changes in the role of the driver.

The reason mixed traffic is difficult is that automated and manually driven vehicles have different characteristics. Automated vehicles are good at precise control, fast response and consistency, but poor in unexpected situations. Manual drivers, on the other hand, are good at image interpretation, situation assessment and situation prediction, but slow to react and sometimes distracted. The fact that drivers and automated systems excel at different facets of vehicle operation suggests that the solution may be a combination of driver and computer, with the computer doing the precise and repetitive, and the driver watching for and reacting to the unusual.

The potential, and very serious, problem with this approach is the underlying assumption that the driver will maintain at least the same level of involvement in the tasks he continues to perform. But several human factors studies suggest that humans do not reliably monitor situations that they do not control. In particular, they will drop out from watching for hazards and unusual situations once the vehicle takes over second-by-second control of steering, brakes and throttle, and may start dropping out before that time. Drivers normally do a continual situation assessment of the vehicle, the roadway and the surrounding vehicles. This important function, which is very difficult to automate, will not get done. The role of the driver is discussed in greater detail in Section 10.4.5.

The implication is that it is not safe to provide the public with fully automated lane and distance keeping without also providing some provision for responding to anomalies, such as obstacles, merges, sudden stops and other sorts of aberrant driver behavior. While these constitute a very small percentage of driving activities, they contribute to the vast majority of safety threats, as we will see. Thus any vehicle that is short of full automation must be carefully designed from a human factors standpoint to keep the driver involved to the necessary extent and clear on his role. One possibility is to add resistance to inappropriate driver actions, while allowing the driver to override if necessary.

Similarly, any vehicle that does not keep the driver appropriately involved must be fully automated, and as such must respond safely to the expected range of hazardous situations within its environment. So a complete understanding of the mixed traffic driving environment is essential to the design of a safe, fully automated highway system.

10.4.7.3 SAFETY

10.4.7.3.1 Background

Since humans cannot be expected to perform effectively if only monitoring, fully automated vehicles in mixed traffic must react, without driver assistance, to any emergency. Debris will fall off other vehicles and other drivers will drive erratically or worse. The system cannot control the actions of these other drivers, and in fact such actions are difficult to predict. One reason is that there is a wide range of driver conditions, skills, and styles. Further research into driver behavior is necessary to design an automated system that can recognize and react to the possible worst case scenarios that could arise from any given situation.

The safety question centers on a model of the driving environment, including both normal and unusual behavior of the surrounding vehicles, especially the manually driven ones. Accident statistics are one way to identify the most critical situations to which the system must respond. The following section summarizes the accident analysis that is discussed in more detail in Section 10.4.4.

Note that this work focuses solely on the safety hazards caused by the external environment, since this environment differs greatly between mixed and dedicated lanes. In addition, there will be hazards caused by failures of the automated system itself, such as sudden sensor or communications failure, or mishandling of the automated system by the driver. While such failures will certainly have different impacts on mixed and dedicated lanes, the analysis of them is design-specific, and so must be deferred until there is more explicit system development.

10.4.7.3.2 Crash Causes

The GES accident database was chosen for analysis, since it is based on over 50,000 accidents each year and has significant causal information. One drawback with most of the existing accident analysis is that most of it is from surface streets, especially signalized intersections, and so is not representative of the limited access highways that are the focus for at least early automated deployments. The GES database flags accidents that occur on interstate highways, and so an analysis was performed of these accidents. The analysis of the 1994 GES data (the most recent available) identified the following causes of reported crashes on interstates, which are listed as “critical events.” The reason for the large number of unknowns is that GES does not record critical events for crashes involving more than two vehicles, because of their complexity.

Speed Difference	27.7%
Loss of Control	21.1%
Lane Change/Merge	14.0%
Obstacle In/Near Road	6.1%
Vehicle Defect	2.4%
Other/Unknown	28.5%

These results indicate that the highest payoff in preventing accidents is potentially in maintaining consistent speeds between successive vehicles in each lane to prevent rear-end (speed difference) accidents. Much of the design and analysis work on the automated highway has focused on this area, providing sufficient spacing and coordination to prevent rear-enders. The loss of control accidents are not so clear. There may be many factors, such as reckless driving or slick pavement, that could account for these accidents, and further analysis investigated this. The number of lane change and merge accidents indicate that systems that support lane changes, from blind spot warning to cooperative automated merge, potentially prevent a significant number of accidents. These first three accident causes all have a human error component that will be eliminated with an automated vehicle. The obstacles will not, and so take on more significance than their small percentage at first would suggest. Finally, note that only 2.3% of interstate accidents were caused by a vehicle defect, so that if the AHS were approximately as reliable as current automobiles, and addressed the other accident causes, there is potentially a huge decrease in accidents.

The preceding statistics raise the question of what caused the problem that caused the accident, for example, whether the loss of control was caused by driver error or poor road surface. The following numbers list situations or adverse conditions that might have contributed to the accident. In most cases it is not clear whether they did or not, but this list shows whether the condition was present. Two numbers follow each condition. The first is the percentage of the accidents in which it was the only condition, and the second in which it was present, possibly combined with other conditions (so that it is not clear which one was the major contributor). 33.9% of the accidents occurred under multiple conditions, while 35.8% of them had none.

Light Condition (e.g., night, dusk)	19.0%	42.7%
Speed/Reckless Driving	4.0%	17.3%
Road Surface Condition	2.9%	33.6%
Driver Impaired	2.4%	10.1%
Driver Distracted	1.5%	3.7%
Limited Visibility	0.5%	26.6%

The driver-error conditions will be eliminated by a fully automated system. The environmental conditions, light, road surface and visibility, are a key consideration for both humans and automated systems. The automated systems must be designed to operate at least as well as humans under these conditions.

10.4.7.3.3 General Hazards

There are two shortcomings with any accident data so that it cannot be relied on as the only source of hazard information. One is lack of specificity. For example, "object in roadway" is not described in any more detail than that in the GES database. A response would require knowledge of size, motion, radar reflectivity, source, and so on.

The other shortcoming is the concern that there may be situations that are problematical for an automated system, but that human drivers avoid easily, and hence do not show up in accident statistics. In particular, even if an automated highway system responded perfectly to all of the situations discussed in the previous section, it would not improve safety if it responded poorly to common situations.

The solution to analyzing the full range of hazard situations is to collect data while driving. There are outside studies underway, and the findings will be incorporated as available. As a first cut, the members of the Mixed Traffic team listed situations that they had encountered while driving that would pose a challenge to an automated system, but that the public would expect the AHS to respond to safely. Hence the following list defines a good part of the required response repertoire for the automated vehicle, based on hundreds of thousands of driving miles.

Driver actions

- Hard braking
- Drift into lane
- Swerve into lane
- Tailgater following
- Approaching too fast from behind
- Vehicle backing up
- Lane change into own lane from both sides
- Non-signaled maneuvers
- A vehicle driving slower than the flow of traffic

Malicious driver

- Cutting off a vehicle
- Chasing a vehicle
- Causing a vehicle to involuntarily change its speed or direction of travel
- Hitting a vehicle
- Distracting a driver
- Two racing drivers
- Driver attempting to cause an accident for insurance or robbery

Merging and lane changing

- Merge into traffic from on-ramp

- Traffic merging in from an on-ramp
- Lane change into or out of a congested lane
- Lane change (other vehicle)
- Lane change (own vehicle)
- Lane ends
- Roadway ends
- Lane change into an open spot simultaneously with a vehicle from the other side

Obstacles

- Dropped load
- Animal
- Pedestrian
- Environmental obstacle
- Cones, used to delimit construction areas
- Vehicle, person or animal emerging from a blind spot
- Vehicle-related obstacles
- Debris from an accident
- Parts of tires
- Large truck tires
- Disabled vehicles
- Oil spill
- Flares left in road after accident cleared

Vehicle incidents

- Stalled vehicle in lane
- Stalled vehicle partially in lane (e.g. narrow shoulder)
- Spinout
- Jackknife

Special vehicles

- Passing an oversized vehicle
- Motorcycles

Special situations

- Officer directing traffic
- Highway patrol in pursuit

- Emergency vehicle
- Closed lane
- Construction
- Major road damage (e.g. earthquake)
- Impassable due to weather
- Partially closed lane
- Warning devices
- Road damage, such as potholes

Weather conditions

- Heavy rain
- Falling snow
- Drifted snow
- Fog
- Sleet, hail, etc.
- Standing water
- Black ice
- Thunderstorms (electromagnetic pulse effect)

This list is an implicit list of requirements for safe automated hazard response. It should be noted that there are several items in the list that involve information being conveyed visually to the driver. Examples are officer directing traffic, highway patrol in pursuit, emergency vehicle, closed lane, construction, oversized vehicles, flares, lane end, roadway end, and warning devices. This indicates that in order to address these situations, an automated vehicle must be provided with comparable information in a form that it can interpret. Much of this information is difficult or impossible to get through sensors alone, and so must be sent by the roadway or other vehicles.

10.4.7.3.4 KEY SCENARIOS FOR MIXED TRAFFIC

The team used the accident cause statistics and the list of hazards to focus on the situations that appear most often in crashes. The following scenarios address 56 of the 66 hazard situations and 95% of accidents with known causes. Thus an AHS designed to operate safely in these situations as well as normal driving will alleviate almost all accidents.

The automated vehicle comes up behind a slower, decelerating, hard braking, or stopped manual vehicle. This is the potential rear-end accident. The system must be designed to respond safely if a closely followed vehicle suddenly applies hard braking, over the full range of vehicle braking performance. The manual vehicle is a more stressing scenario since it is less predictable and does not communicate its intentions (except through brake lights).

The automated vehicle changes lanes into manual traffic. While early systems may have a single lane with a single entrance, full mixed traffic will apply to any designated road. The system then must support the automated vehicle in determining the locations and movements of other vehicles in the adjacent lane, and possibly coordinating with them.

A manual vehicle enters the automated vehicle's lane. This is a lane change looked at from the other side. The system needs to react to being cut off by a manual vehicle from an adjacent lane. Such a manual vehicle does not communicate its intentions, except possibly through a turn signal.

An obstacle (including a person or animal) comes fully or partially into the automated vehicle's lane. While automation will potentially eliminate the accidents caused by human error, obstacles will continue to enter the road or fall from vehicles. The next section examines the types, causes and sources of obstacles. It finds that obstacles are seldom stationary, and so the system must be designed to react to obstacles that appear suddenly and/or are moving.

A roadway hazard is in the lane, including weather conditions. Various conditions of the road and atmosphere showed up in the hazards list, and were possible contributing factors to accidents. These include rain, falling snow, drifting snow, fog, icy road, rough road, construction, blocked lane, emergency vehicle, and many others.

10.4.7.3.5 Obstacles

Any automated highway must respond to roadway hazards. Obstacles cannot be entirely eliminated, although dedicated lanes may include provisions to make them less likely. Hazard response may require coordination with other vehicles. The NAHSC obstacle avoidance analysis, reported in the Task C2 final report, showed that there is a benefit in being able to coordinate a lane change to avoid a road hazard.

Obstacles are an important part of the driving environment. They must be well understood to either eliminate them by controlling the roadway, or to avoid them if they occur. Consequently, the team contracted an analysis of the actual police reports that formed the basis of the 1996 GES database currently under development. This is described in more detail in Section 10.4.4. The most common obstacles involved in interstate accidents were found to be as follows:

deer

rock

fixed object

tire debris

metal scrap

tire

wheel

The obstacles were grouped into categories associated with their assumed sources. The results are as follows.

Intruders from the environment (e.g., deer, rocks)	42.3%
Vehicle loads (e.g., wood, ladders)	18.7%
Vehicle components (e.g., tires, mufflers)	17.9%
Highway components (e.g., light poles, Jersey barriers)	4.2%
People (changing tires, pedestrians, workers)	1.2%
Other/unknown	15.8%

The next question is where the obstacles come from, since that impacts the design of mixed traffic AHS vehicles, where they need to look and how fast they must react. Here is what the obstacles were doing when first seen.

entering into traffic lanes	38.1%
lying/standing in traffic lanes	26.6%
falling from vehicle	16.2%
bouncing	11.7%
falling from overhead	0.8%
unknown	5.7%

Note that only 26.6% or slightly more (considering the unknowns) are stationary. This means that the system must be designed to detect and track moving obstacles, and to react quickly.

Also, in designing measures to preclude obstacles, it is necessary to determine the source of these objects. The results below show that both vehicles and the surroundings must be controlled to eliminate obstacles. Furthermore, the vehicles must be able to look in all directions to detect obstacles. Surprisingly, 17% of them came over the median on the interstate, which says that conventional medians are not sufficient to keep out obstacles. Unfortunately, the reports did not include information on whether the median incorporated a barrier.

The source of the obstacle:

Surroundings	42%
Other vehicle	37%
Highway	4%
Unknown	17%

Where the obstacle came from (physical location):

Own lane	41%
Opposite direction	17%
Shoulder	13%
Adjacent lane	6%
Other/unknown	23%

10.4.7.6 IMPLICATIONS FOR AHS DEPLOYMENTS

The hazard analysis identified many situations in which the automated vehicle needed to be cognizant of activities or situations that are normally visually available to the driver, such as construction or highway patrol running a break in traffic. This says that a fully automated operation requires at least some level of cooperation on the part of the roadway operator. This implies a designated road, on which both automated and manual vehicles may operate simultaneously, but which provides the necessary digital information to the automated vehicles. In fact, a promising first step is a protected lane designed to eliminate many of the threatening situations that were identified in the analysis. For example, a single lane with one entrance and one exit would eliminate the lane change and merge situations, while still providing useful access in appropriate situations, such as city center to airport. Barriers may also limit or eliminate many of the obstacles.

10.4.7.7 CONCLUSIONS

The driver cannot be relied upon to act as a monitor if moment-to-moment vehicle control is taken away. That says that any system that supports full-time automation of both lateral and longitudinal movement must also include, either through automation or enforced driver involvement, monitoring, situation awareness, hazard recognition and response. In particular, the system must be designed to react safely to the full range of normal roadway hazards, anomalies and other situations.

There is a long list of hazards and situations that a fully automated mixed traffic AHS must address safely. The major test cases are based on five key scenarios that represent the major causes of almost all accidents currently. A suitable response protocol must be designed for each of these situations.

The list of hazards that the team developed included several that required the vehicle to receive the same information from the vehicles or highway that a driver would receive visually. This implies an obligation on the part of the roadway operator to make such information available in a digital form. That means that fully automated driving requires a certain level of cooperation from the roadway operator, and in particular, that it will at least initially be feasible only on designated roads.

Given that, it is not unreasonable to place restrictions on the vehicles, both manual and automated, that use these specialized roads. It may be that minor restrictions, such as radar-reflective tags on all vehicles, have significant safety benefits at low cost.

So, in general, the four motivations for mixed traffic AHS that were cited with bullets in 10.4.8.1 are long-term goals, and not firm requirements.

Requirements for a mixed traffic AHS

The mixed traffic fully automated highway must meet the following requirements, based on this and previous analysis.

- The fully automated mixed traffic AHS must support prevention of or response to virtually all hazards without manual intervention.
- Any partially automated system for operation in mixed traffic must either have a provision for keeping the driver involved, or strictly control the environment to preclude situations to which it does not react adequately.

- The AHS must react safely in the presence of arbitrary manual vehicles, even if the road is somehow restricted, since the vehicles or restriction mechanisms may fail.
- The AHS must react safely and efficiently in the presence of manual or semi-automated vehicles that meet the roadway restrictions
- Because the fully automated vehicle must react to any contingency, any lane that allows fully automated operation must ensure that the vehicle has the same roadway information available to a manual driver through signage and other visual means (e.g., cones, flares, highway patrol, exit signs, lanes ends signs)
- The automated vehicles must operate in any common weather conditions in which manual vehicles can operate, with at least the same level of safety.
- Based on other analysis of liability issues, the AHS must provide acceptable levels of liability exposure for all parties.

10.4.8 DEDICATED LANES ANALYSIS

Author, Ron Hearne

INTRODUCTION

This section presents the current status on information gained to date on dedicated lanes in C3. Because this is a report of status a more general overview is presented in the General Discussion. Further, two working papers are included in this section in order to capture and document additional new detailed information generated in the C3 dedicated lane activity. Those two papers are:

- "Implications of Road Geometrics on Obstacle Detection Using an On-Board Vehicle Radar System" February 1997," and
- "Study Report on Automated Highway C3 "Obstacle Management Potential External Hazards and Proposed Prevention" May 1997.

  In addition two surveys being prepared are in various stages of completion. One is a survey of transit agencies for insight into their obstacle management policies and procedures, and the other is an obstacle survey form developed to gather information on representative obstacles that automated vehicles in dedicated lanes might have to deal with.

  The section is organized to present the dedicated lane discussion issues first, then the two working papers, followed by the surveys on obstcle management policies and the obstacle survey data form.

It should be noted here that further technical details are required to assess the full impact of the introduction of dedicate lanes in the geometric design of highways. Further technological definition is needed for the following topics:

- Check-in/check-out procedures
- length of merging/demerging lanes
- treatment of dedicated lane interchanges between two freeways
- platoon behavior at closely spaced interchanges.

Further studies are needed to determine the following parameters:
optimum spacing of interchanges for efficient AHS operation of
- platoon operation
- free agent operation
- origin/destination patterns of urban freeway travelers, distribution of trip lenths, entrance exit patterns
- most efficient application of dedicated laness in urban environment i.e. providing by-pass for relatively long trips around congested urban areas.

GENERAL DISCUSSION

Definition of Dedicated Lanes

Dedicated lanes are lanes which are dedicated for the exclusive use of automated highway vehicles. Increased highway safety and greater throughput are the main advantages of dedicated lanes.

Access to dedicated lanes is achieved through existing on ramps with the addition of a transition lane where control is transferred from manual to automated control, or on and off ramps dedicated to AHS equipped vehicles only. The infrastructure could provide the roadway, entry and exit ramps and safety/breakdown areas on which the AHS vehicles operate. Infrastructure may include roadway components to facilitate lateral position on the lanes as well as communication capabilities which may be used to enable vehicle entry or rejection, transition from manual to automated operation, lane changing, and entry and exit from the automated highway. Dedicated lanes may or may not be barrier-separated from manual traffic.

DEDICATED LANES VERSUS MIXED TRAFFIC

In addition to dedicated lanes another operational concept has evolved. That is the mixed lane concept. In mixed lanes both automated vehicles and manually operated vehicles would share the same roadway. However it is thought that fully automated dedicated lanes offer greater safety because actions of automated vehicles are eminently predictable. In contrast, mixed traffic lanes present two significant problems. As we know 90% of accidents are caused by driver error. In mixed traffic driver error is not eliminated and continues to be a problem. Further potential problems lie with the computer's inability to logically predict human intervention during the driving scenarios. In dedicated lanes all vehicles are AHS equipped with compatible computer controlled systems and as a result all vehicles know the capabilities of all other AHS equipped vehicles around them. Unpredictable events due to human intervention are eliminated.

Another advantage of dedicated lanes is high throughput (i.e. lane capacity per hour). To local municipalities with congestion problems the dedicated lanes approach can offer congestion relief while mixed traffic does not. The mixed traffic approach has minimal impact on throughput. The dedicated lanes can handle significantly more traffic in the same right-of-way.

Mixed traffic (partially automated vehicles with manual traffic) is considered an early stage for deployment. Another alternative for an early deployment scenario could consist of partially automated AHS vehicles on existing HOV (high occupancy vehicle) lanes that are converted to AHS dedicated lanes. Conversion of existing HOV lanes to dedicated lanes could require little or no construction of additional infrastructure.

SAFETY IMPLICATIONS FROM HOUSTON METRO EXPERIENCE

Dedicated lanes offer the opportunity to substantially boost safety by reducing human error which is the cause of 9 out of 10 highway traffic accidents today. Dedicated lanes with reliable and intelligent full automation are inherently safer than manual lanes and mixed traffic lanes. In dedicated lanes all vehicles are computer-controlled and the actions of the automated vehicles are predictable.

Just how safe dedicated lanes will actually prove to be has yet to be quantified. To date there are no accident statistics for automated dedicated lanes because there are no dedicated AHS lanes in operation. However some comparisons may be drawn by investigating accident statistics on HOV lanes which are barrier separated, similar to what AHS dedicated lanes may be like. The Houston Metro freeway system in Texas utilizes HOV lanes which are barrier separated. Houston Metro has HOV lanes on the Gulf, Katy, North, Northwest, and Southwest freeways. Police accident statistics from these Houston Metro HOV lanes for the years 1994 and 1995 are summarized below.

1994 HOV Lanes Accident Summary:
FREEWAYS

-cause of driver error	Gulf	Katy	North	NW	SW	TOTAL
rear end	3	6	6	5	4	24
side swipe	1	4	5	-	2	12
hit conc. barrier	-	3	4	1	4	12
hit HOVL gate	-	-	1	-	-	1
subtotal	4	13	16	6	10	49
other						
hit another vehicle*	-	-	1	-	-	1
hit gate arm**	-	-	-	-	1	1
TOTAL	4	13	17	6	11	51

* failed to yield right-of-way
** gate arm came down-hit vehicle

1995 HOV Lane Accident Summary:

	Gulf	Katy	North	NW	SW	TOTAL
rear end	1	3	5	3	2	14
side swipe	-	-	4	-	-	4
hit conc. barrier	-	1	5	2	2	10
flying debris	-	1	1*	-	-	2
bus hit pedestrian	-	1	-	-	-	1
hit wrecker driver	-	-	-	-	1	1
TOTAL	1	6	15	5	5	32

* = debris from bus

In the 1994 accident statistics the police summary attributed 49 out of 51 or 96% to driver error. Of the other two, one was due to mechanical failure of drop arm and one was not clearly identified as to cause of accident.

In the 1995 accident statistics the police summary attributed 31 out of 32 or 97% to driver error. Only one, where a wrecker driver was hit was not specific as to the cause of accident.

For the combined years of 1994 and 1995, the police accident summaries attributed 80 out of 83 accidents to driver error. Of those 83 accidents, 76 accidents, or approximately 91% were attributed to either rear end, sideswipe, or hitting concrete barriers. If we could eliminate those types of human errors it would appear to be theoretically possible to eliminate all but 3 to 9% of all accidents.

From the Houston Metro accident statistics it appears that safety items such as ACC (Adaptive Cruise Control) and AHS lane keeping could be major contributors to eliminate a significant number of these accidents. It also indicates that dedicated lanes could be a very safe deployment option with nominal implementation of AHS safety items. This assumes the driver stays alert and ready to take over in an emergency.

One of the most important safety issues in automated highways is detection of obstacles in the roadway. For dedicated lanes it is equally important but also unique. Dedicated lanes By virtue of being on the far inside of the highway, may be more protected from objects hurled from outside the right-of-way, and from animals and human intruders that gain entry inside the highway right-of-way. Even so, obstacle detection is a real and important aspect of dedicated lane safety. Computer communication between neighboring vehicles allows a warning to be sent to other automated vehicles in the system. (Note: In mixed traffic some of the following vehicles will not receive advance warning.)

Automated detection of obstacles, particularly small obstacles, is recognized as a difficult problem which is still being researched. The current leading technology involves use of radar to detect obstacles. Other technologies being considered include, but are not limited to laser, optical camera detection, and ground mounted sensors. For additional information on detection of objects see the working paper on "Study Report Highway C3 Obstacle Management Potential External Hazards and Proposed Prevention" herein.

THROUGHPUT

The benefits of dedicated lanes are not only increased safety but also greatly increased throughput, especially on long travel trips with few highway entrances and exits. Studies have shown that double the current capacity of vehicles per hour per lane could be achieved with the use of dedicated lanes (4000 vphpl-see section Simulation and

Throughput Findings-Houston Application). Increased throughput along with congestion reduction will become increasingly important.

"Businesses lose $40 billion a year due to congestion. Just to stay even with the growth of congestion, we would need to build 34 percent more highway capacity. Over the next decade, for just 50 cities, that would cost $150 billion. For the same 50 cities implementing an intelligent infrastructure, from virtually scratch, would cost $10 billion and increase capacity by two-thirds." (Former US Secretary of Transportation Pena).

General estimates of throughput increase with AHS dedicated lanes have been made for generic cases. However there is always debate as these are generic and not real case scenarios. The National Automated Highway System Consortium (NAHSC) is conducting a case study with the Houston Metro on the Katy Freeway in Houston. As this is a real case study, the results obtained should be more credible.

As future traffic demand increases the alternatives to provide additional capacity are limited. Either additional freeways must be built or the existing highways need to become more efficient. As the prospect of building new highways becomes increasingly difficult, upgrading capacity of existing highways becomes more relevant. Dedicated lanes can provide the additional capacity needed to cope with the future traffic demands.

Interchanges

Interchange capacity is typically a constraining factor in system throughput, particularly interchanges connecting two intersecting controlled-access highways. There are several alternative general configurations for highway-to-highway interchanges. The general desscription and layout of alernative tratment of interchanges were resented in the C2 report. The first configuration can be used with low traffic volumes on highways such as rural applications. AHS vehicles would exit the dedicated lane through a transition lane, revert to manual control, weave their way though manual traffic, and use existing interchange ramps to make the desired turn. Once on the desired highway route, AHS vehicles would again weave through manual traffic and rejoin the dedicated AHS lanes(s) by going through another set of transition lanes.

The second configuration would also use manual connecting ramps at regional interchanges, but would eliminate the weaving maneuvers. This is achieved by using a flyover from the AHS lane(s) going to the right sides of the manual lanes, reverting to manual control, and then merging with the manual turning traffic and using the common connecting ramps of the regional interchange to reach the desired direction on the crossing highway. Once on the crossing highway, a reverse maneuver would position AHS vehicles to return to automated control and then join the AHS dedicated lane(s).

The third configuration would be to construct a new set of ramps for the exclusive use of AHS traffic, which would directly connect the two crossing highways. This would provide the highest level of service but at the expense of higher construction and ROW acquisition cost. Specific decisions on what type of configurations to be used at intersecting highways will likely be made at the state or local level, in much the same manner as dedicated HOV interchange lanes.

Simulation and Throughput Findings-Houston Application

The SmartCap simulation program, developed by PATH, was applied to the Houston Metro Case Study with westbound and eastbound directions of traffic, three levels of traffic/infrastructure and four concepts spanning levels of cooperation and the associated in-vehicle/infrastructure distribution of intelligence. This resulted in 24 different cases (plus additional variations required to study sensitivity).

The traffic capacity of AHS implementation on Houston Katy freeway is constrained by its infrastructure configuration. With the infrastructure constraints a traffic simulation was performed. A 96/4 percentage vehicle class split was used based on input from Houston Metro. That is 96% passenger vehicles and 4% buses.

Throughout the simulation exercise performed by PATH, a nominal speed of 30 meters/sec (67 miles per hour) was used. Even with the infrastructure configuration constraints initial results of traffic simulations for the Katy Freeway indicate that volumes of 4,000 vphpl (vehicles per hour per lane) can be obtained on a real case study. (Ref. #4) This is double the normal average manual capacity of a highway lane of 2,000 vphpl.

Effect on Arterials

Throughput will be influenced by the capability of the system end points to safely and adequately absorb the high volumes of AHS traffic. If sufficient capacity is not provided at these end points, the resulting overflow would backup on the highway proper and degrade the throughput of the system. It has been suggested that monitoring and control operation may need to extend beyond the domain of the highway to include and integrate traffic monitoring and control with the adjacent local arterial and city street network. This combined monitoring and control activity could be accommodated at a regional Traffic Management Center (TMC).

COST ESTIMATE OF ADDING AHS LANE

The cost of implementing dedicated lanes is borne in three categories. These are: vehicle costs, communications costs and infrastructure costs. As a definitive concept of AHS has not yet been established, conceptual costs estimates for vehicle or communications costs have not been made. Initial work on infrastructure cost estimates conducted in previous C2 activity is summarized here.

Costs for infrastructure improvements have been made on a generic basis. The cost of infrastructure improvements to implement dedicated lanes can be very site specific. But even without a specific site, some conclusions can be reached by assuming generic cases. To this purpose the NAHSC has assumed 3 primary generic cases which are urban, inter-city and rural, and estimated the cost to implement a dedicated lane. For Details see work included in the C2 final report.

In Summary, in the urban scenario, a 25-mile (40 km) corridor was used. This corridor travels though a medium-dense urban environment providing four lanes in each direction, 21 arterial interchanges, and two regional (freeway-to-freeway) interchanges.

For the inter-city environment, a 74-mile (119 km) interstate corridor which links two major urban centers was used. The heavily traveled facility provides three lanes in each direction, 20 arterial interchanges, and two freeway-to-freeway interchanges.

The rural operating environment consists of a 296-mile (476 km) rural interstate highway with 20 interchanges.

Results. In an urban environment, if right-of-way is not available, a dedicated AHS lane for both directions of a roadway may cost up to $50 million per mile, with a significant portion going to interchange modifications. For the inter-city application, the cost is estimated at approximately $7 million per mile. In the rural environment, the cost is almost $3.5 million per mile.

Cost Comparison

In the C3 time frame two estimates were prepared to compare the cost of adding manual lanes to increase capacity versus modifying the highway with AHS dedicated lanes to achieve the same capacity for both directions. The estimates give the costs to increase capacity by two methods. The first is to expand a 4 lane manual highway to a 6 lane manual highway (3 lanes in each direction). The other is to expand the capacity of the existing 4 lane highway by modifying it to two AHS lanes and 2 manual lanes.

Assumptions used in this cost comparison:

- The capacity of an AHS dedicated lane is 4,000 vph (vehicles per hour)
- The capacity of an manual lane is 2,000 vph.
- 100% of any additional right-of-way must be acquired.
- The basis of the infrastructure configuration is the same as used in the cost section of the final C2 Report.

Capacity of highway:

- 4 lane existing manual highway- 8,000 vph
- 6 lane manual highway - 12,000 vph.
- 2 lane AHS/2 lane manual highway - 12,000 vph

Both configurations increase the capacity of the existing highway from 8,000 to 12,000 vph.

Results. The cost to build 2 additional manual lanes is approximately $30.1 million per mile. The cost to incorporate AHS dedicated lanes to achieve the same throughput is approximately $29.5 million per mile.

It is believed that the cost of dedicated lanes on long stretches could be even cheaper. Initial modifications to interchanges increase costs significantly in this scenario. However, additional increases in capacity would not require additional interchange modifications and the cost per mile would be significantly lower.
The cost to include 2 AHS dedicated lanes is about the same as constructing additional manual lanes. It also requires less right-of-way to accomplish the equivalent capacity and is therefore less invasive on the environment

Additional consideration. Thus far it has been inferred that dedicated lanes have to be constructed. However some special lanes do exist as HOV lanes which could be converted to AHS lanes at nominal cost. In some areas these lanes are already barrier separated from other traffic. Thus the primary costs to implement AHS on these already existing HOV lanes would be in the area of communications and possibly some civil infrastructure modifications at entrances and exits of HOV lanes.

DEPLOYMENT CONSIDERATIONS

Factors affecting deployment sequencing are check-in requirements and construction costs of new AHS lanes and check-in facilities. The check-in issue has raised several questions regarding entry into the system, gates, electronic readers, and queuing space required for check-in. At one time it was envisioned that a vehicle might have to stop in order to perform the check- in functions. Due to recent technology developments it now appears that check-in can be accomplished on the fly, at least to speeds of 55 mph. This indicates that long queues would probably not be generated and more importantly that significant changes to existing configuration would not be needed.

There are different possibilities for deployment of dedicated lanes. In general dedicated lane deployment could be accomplished by any of the following:

- Convert existing HOV lane to AHS lanes.
- Take away an existing lane and convert to an AHS lane.
- Build a new lane and convert the inside lane to an AHS lane.
- Build separate AHS lanes for AHS truck traffic within existing right-of-way.
- Build AHS lanes for AHS commercial vehicle operations (CVO) on completely separate right-of-way.

The above deployment options give various paths to deploying dedicated lanes. It is likely that initial deployment of dedicated lanes may take place by conversion of existing HOV lanes to dedicated lanes. Several points can be made in favor of considering the HOV lanes as the AHS lanes of tomorrow. They were built and funded for congestion/emissions reduction, the same goals as AHS. In places where they are under utilized, AHS will help fill them, relieving congestion for all. In places where HOV operates at capacity, we will be increasing the capacity. In places where HOV lanes haven't been built yet, they could serve a dual purpose by being designed to accommodate AHS. In many urban centers where congestion is the worst in the nation, it is extremely expensive and politically unfavoraable to widen freeways, or construct on new alignments. Fixed guideway transit system is likewise expensive to construct on new alignments but sometimes is a feasible alternative. AHS offers another alternative which is more likely to pay for itself because the paradigm of vehicle owners and the highway is maintained.

Assuming that there are enough equipped AHS vehicles to justify the dedication of lanes, the actual deployment will in reality depend on the needs and the financing capability of the local municipality.

ELECTRONIC SYSTEMS

By design, dedicated lanes impart a profound impact on electronic systems associated with AHS vehicles and infrastructure alike. Dedicated lanes create an environment where vehicle movements are accomplished in a predictable manner. This predictability enables a lenient requirement on electronic systems which leads to lenient design constraints. Exclusion of manual traffic, and obstacles to some degree, from the dedicated lane environment keeps electronic systems simple.

Production and maintenance of AHS equipment are the other two major areas which are influenced by the dedicated lanes. From the production and maintenance perspective, vehicle and infrastructure systems have to be looked at separately. Vehicle systems consist of sensors, actuators, processors, and communication systems. Infrastructure systems consist of roadway related systems (examples given under infrastructure), communication systems and Transportation Management Centers (TMC).

Sensors and Actuators

Due to lenient design constraints, vehicle systems will be easier to produce and maintenance will be less cumbersome as compared to vehicles designed to operate in mixed traffic. Fewer sensors, probably with less fidelity, will be able to perform adequately. The same is applicable to actuators.

Processors

Fewer sensors and actuators implies fewer processors, probably with lower performance requirements, to manage the processing load. Lower complexity of the processing system will make it cheaper and easier to maintain.

Communication System

Communication systems would seem not to be impacted much in the case of dedicated lanes. In fact, systems would be more complicated in cases such as platooning. Platooning calls for intra-platoon, as well as inter-platoon communication systems, which makes it complex in nature. Production, calibration and maintenance will be a time consuming exercise.

Infrastructure

Even though the use of dedicated lanes creates an easy design environment for vehicles, it creates additional requirements for infrastructure design. The infrastructure needs to provide support in several areas which are not called for in a mixed traffic situation.

Roadway-Related Systems. Roadway-related systems may consist of lateral guidance support (magnetic nails, magnetic tape, radar reflective striping, better paint striping etc.), dynamic signage (changeable message signs) etc.

Communication Systems. Communications systems may consists of two links. The first communication link is between the vehicle and infrastructure through the use of road side traffic beacons. Second communication link is from traffic beacons to Transportation Management Centers (TMC).

Transportation Management Centers. Transportation Management Centers (TMC) are an essential part of the automated highway infrastructure. Their role will be much more active in case of dedicated lanes. TMC will provide support for tight control and monitoring over the traffic in order to improve throughput and safety.

Even though there might be some commonality for the need of infrastructure systems in dedicated lanes and in mixed traffic environment, dedicated lane environment imposes an extensive demand especially in the area of traffic information accumulation and dissemination. This extensive demand makes the infrastructure system more complex. The additional complexity results in a complex production and maintenance process.

CONCLUSION

The dedicated lane configuration has many advantages, mainly in terms of increased safety and increased throughput. Dedicated lanes are seen as safer and more efficient in throughput than manual or mixed lanes. Still, dedicated lanes are only one of the configurations being considered for future use and it is possible that any of the configurations being considered may be used at various times or at various locations throughout the nation. Each local municipality or MPO (Metropolitan Planning Organization) will likely specify which configuration best meets its local needs and funding program. In doing so local planners will need to take into consideration all of the various issues touched discussed herein.

References

1. National Automated Highway Systems Consortium Milestone 2 Report, Task C2: Downselect System Configurations and Workshop #3, Appendix G, Federal Highway Administration, 1997.

2. National Automated Highway Systems Consortium, Milestone 2 Report, Task C2: Downselect System Configurations and Workshop #3, Appendix H, Federal Highway Administration, 1997.
3. National Automated Highway Systems Consortium Milestone 2 Report, Task C2: Downselect System Configurations and Workshop #3, Section 4.3, Federal Highway Administration, 1997.
4. National Automated Highway System Consortium, Houston Metro Case Study, Phase 1 Katy Freeway Draft Final Report April 15, 1997

AUTOMATED HIGHWAY
SUBTASK C3-B4 OBSTACLE MANAGEMENT
POTENTIAL EXTERNAL HAZARDS AND PROPOSED PREVENTION

1. Introduction

This report deals with one aspect of AHS obstacle management, specifically obstacle exclusion. By obstacle exclusion it is meant those preventative measures that can be taken in order to minimize the possibility of objects, potentially hazardous obstacles to AHS vehicles, from entering the AHS system from outside. The preventative measures discussed are potential modifications to the existing highway infrastructure. For those highway modifications proposed herein, cost estimates were made and included in this report.

Objects which can be generated from outside the right-of-way and become potential hazards are considered herein as follows:

- Rocks with 6" and larger dimension.
- Timber/logs of 6" x 6'' x 1-0" and larger.
- Metal cans with or without contents
- Animal and human intruders
- Other objects reported by highway maintenance

In this study six different generic highway locations are considered:

- Overcrossings (OC)
- Undercrossings (UC)
- Interchanges
- Adjacent frontage roads
- Entry and exit ramps
- Deer and animal crossings

These locations were selected based on probability of where hazardous objects are most likely to enter the system. The hazardous objects could be due to either people intentionally throwing objects on to the highway, or people or animals intruding into the right-of-way.

The highway modifications proposed in this report were done in consideration of obstacle exclusion for dedicated lanes. However, similar modifications are also applicable to mixed traffic lanes.

Objects which are generated from within the AHS right-of-way are not discussed in this report.

2. Assumptions and Definitions

- **Potential hazards**- Objects located on the traveled lanes constitute hazards to automated vehicles. The objects considered herein, such as those listed above, are objects that are typically encountered by highway maintenance crews. These objects are considered in this report. Other objects which become dangerous hazards such as a homemade tripod type of nail, which when thrown always lands with a point up and can be pushed through a 1'' chain link mesh, are considered deliberate sabotage and are not considered in this report due to the low probability and significant increase in preventative effort and cost.

- **Vandalism-** Only acts of nominal vandalism are considered in this report. Conspiratorial aggressive acts, by more than a single individual are considered sabotage and are beyond the scope of this report.

- **Chain Link** - The chain link fence used in this investigation for locations at overcrossings, interchanges and undercrossings consists of metal wire mesh. At these locations mesh with 1" openings is recommended. For other locations such as deer crossings and adjacent frontage roads, the mesh openings could be 2.5". These sizes of metal mesh are considered fine enough to prevent larger size objects from getting into the automated lanes. Therefore, a solid enclosure (with transparent panels) is not considered necessary. For aesthetic reasons, however, a transparent (Plexiglas) enclosure and wood or colored plastic slats in portions of the chain link fences may be considered as an alternate.

- **Automated and/or Mixed-Traffic Lanes-** For the main automated highway, 4 lanes and 8 lanes and/or mixed-traffic lanes are the various cases considered (i.e. 2 and 4 lanes in each direction, respectively). for the 4- lane case, a width of 28'(2-12' lanes and 2' clearance each side) is assumed for each direction. For the 8 lane case, a width of 68' (4'-12' lanes and 10' clearance each side) is assumed for each direction. For the on and off ramps, only 1 and 2 lanes are considered.

3. Descriptions of Proposed Preventive Measures

Three methods to be considered herein to prevent the larger obstacles and animals or people from getting onto the automated vehicle lanes are:

Method 1: Chain link fencing,
Method 2: Chain link enclosures
Method 3: Sensors with alarm devices

Method 1 - Chain Link Fencing

The chain link fencing will serve to prevent the entry of animals and people on to the automated highway lanes. It will also block off the larger obstacles being thrown into the automated lanes by the pedestrians and motorists. As shown in Sketches 1 and 2, a height of 8'- 3" for the fences is generally used. The fence posts may be mounted on the pavement or on the top of the concrete barrier. If it is mounted on the top of the barrier the total height of the fence is increased to about 10'- 6". The heights of 8'-3" or 10'-6" is considered adequate for the purpose proposed.

Chain link fencing can be applied to the following locations:

At Overcrossings - Sketch 6 shows a schematic of a roadway crossing over the automated highway and the proposed arrangement of the chain link fences as described in Method 1. The chain link fencing should be extended at least 40' beyond the automated lanes or to the ends of the overcrossing structure.

At Interchanges - The requirements shown in Sketch 6 for the automated highway at overcrossings are also applicable to the locations at interchanges.

At open Highways - Sketch 9 shows a schematic of a linear segment of the automated highway and the proposed arrangement of the chain link fencing as described in Method 1. The chain link fencing is proposed to extend in each direction 40' beyond both ends of the area susceptible to the deer crossing. In areas of significant deer and cattle a large culvert underneath the highway connecting both sides could be provided. The chain link fencing is in addition to the culvert.

Adjacent to Frontage Roads- The requirements shown in Sketch 9 for automated highway; on open highway is also applicable to frontage roads. The chain link fence is also assumed to extend 40' beyond the beginning and the end of the frontage road. The fence is to block off the objects being thrown onto the automated highway by the pedestrians or motorists from the frontage road.

At Undercrossings - Sketch 8 shows a schematic of the automated highway at an undercrossing and the proposed arrangement of the chain link fences as described above. The fences should be extended at least 40' beyond the width of the undercrossing pavement. The fences are to block off the objects being thrown onto the automated lanes by the motorists from the undercrossing below.

Advantages

- Economical - The chain link fence as shown in Sketches 1 and 2 is a standard metal fixture and a popular type of fence commonly used on California highways. It is easy to install on existing concrete structures. Furthermore, this type of fence has been used at some overcrossings.
- Minimum impact on the traffic during installation - For overcrossing roadways with sidewalk or shoulder, the installation of the fence will not disrupt the vehicular traffic.
- Minimum impact on the aesthetic appearance - The wire mesh for the fence is unobtrusive and has openings of either 1" or 2.5". The steel posts are 2.5" in diameter and spaced at 8". It has been used in many overcrossings in California. Therefore it is believed that it should be acceptable for use in interchanges and in other locations of the open highways.

Disadvantages

- Not 100% effective - The fence can not stop a determined individual who is skillful in throwing heavy objects or has a wire cutter.

Method 2 - Chain link Enclosure

This type of chain link enclosure is an alternative method to Method 1 for some locations and completely encloses and protects the highway traffic lanes. A minimum clear height of 16.5' from the pavement is required as shown in Sketches 3 and 4. The fencing above the highway lanes is supported on 8" diameter posts mounted on footings or special barriers. An alternative scheme is shown in sketch 5. In this scheme the wire mesh is also spanning across the traffic lanes and is supported by longitudinal frames.

Chain link enclosure can be used for enclosing a long segment of road. But motorists and passengers might feel like being in a tunnel and some might even become claustrophobic when being enclosed on such a long stretch. Furthermore, the cost may be well over several million dollars per mile.

Chain link enclosures can be applied to the following locations:

At Overcrossings- Sketch 7 shows the proposed arrangement of the chain link enclosure as described above. This scheme can be used as an alternative to that shown in Sketch 6. The chain link enclosures should be at least 50' beyond both sides of the overcrossing structure.

At Interchanges - The requirements shown in Sketch 7 for the automated highway at overcrossings are also applicable at interchange locations.

Advantages and Disadvantages of chain link enclosure are as follows:

Advantages

- More effective - The chain link enclosure can block off all obstacles larger than 1" in size.
- Minimum impact on the aesthetic appearance - The chain link enclosure will extend a relatively short distance of approximately 50' on both sides of the overcrossing, ramp or connector structures. For short distances here, the thin wire mesh of the fence will not create an adverse tunnel effect on the motorists. It is believed that it should be also acceptable for use at interchange ramps.

Disadvantages

- Some impact on the traffic during installation - The installation of the posts in the median and the overhead members may interfere with the traffic during installation.
- More costly - Specially designed structures and foundations are required for the chain link enclosure, particularly for the roadway with 4 lanes automated and/or mixed-traffic lanes in each direction.
- This type of enclosure could be difficult to keep free of snow in snow county. The snow could enter the enclosure in the form of small flakes. However it would be more difficult to remove the snow after consolidation or compaction.
- The enclosure itself could accumulate debris on top of the structure and could become both an eyesore and a problem for maintenance crews to remove accumulated debris.
- For long longitudinal segments of highways which are enclosed, it is likely that some people might feel like being in a tunnel and some might become claustrophobic.

Method 3 - Sensors at the Entrance of On and Off Ramps

In order to discourage animal and human intruders from entering the automated highway from the on and off ramps, sensors with horns or other devices may be installed at the entrance of on and off ramps. These sensors can be activated by the intruders, but will not be activated by the automated vehicles. Other types of warning devices such as flashing lights, supersonic blast or other more advanced instruments may be used.

Sketch 10 shows a schematic of an automated highway ramp and the proposed arrangement of posts mounted with an assembly of sensors and horns. The required numbers of posts will depend on the effective range of the sensors. It is assumed herein that 4 assemblies would be required.

Advantages and Disadvantages

Advantages

- Minimum impact on the traffic during installation- The posts for the horns and sensors will be located at the outside edges of the shoulder. Therefore, the installation of the posts will have minimum or no impact on the traffic, depending on the width of the shoulder/side clearances.

- Minimum impact on the aesthetic appearance - A few posts at the outside edge of the shoulders will not create a significant impact on aesthetic requirements.

Disadvantages

- Not 100 % effective- The horns may not be effective for stopping human intruders from entering the automated highway even though the horns continuously blast at them.

- More costly - The initial installation and subsequent continuous maintenance costs may be expensive, particularly if the advanced instruments are required.

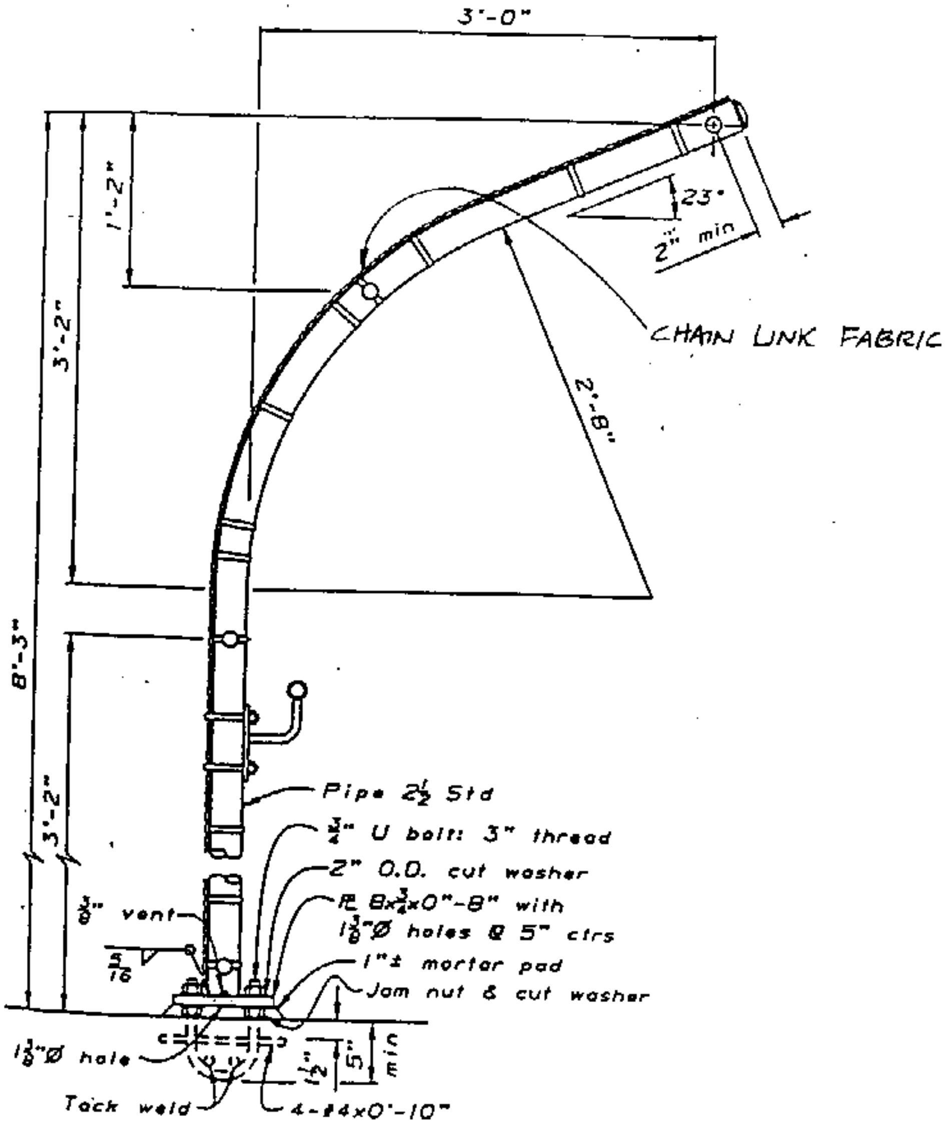
4. Cost Estimates

Table 1 summarizes all proposed applications and shows estimated costs for each method at different locations. The unit costs used in the estimates for Methods 1 and 2 are based on information obtained from the "Contract Cost Data, 1994" by Caltrans with some applicable adjustments. For Method 3 the estimated cost for the sensor and alarm device system at one location ranges from $20,000 to $50,000, depending on the type of system to be used. A more detailed investigation is required to select the most effective system in order to fine tune the cost estimate for this method.

It can be seen that the required cost for Method 1, the chain link fencing, is about 20 times less than that for Method 2, the chain link enclosure. This cost also does not take into account the fact that chain link fencing may exist at some overcrossings structures. Therefore, Method 1 is a more economical approach at many locations for external hazard prevention. However, it does not provide the same degree of protection as Method 2, but Method 2 has more maintenance problems than Method 1.

AUTOMATED HIGHWAY
C3 OBSTACLE MANAGEMENT
POTENTIAL EXTERNAL HAZARDS & PROPOSED PREVENTION
TABLE 1 - SUMMARY

Locations	No. of Automated/ Mixed-Traffic Lanes	Proposed Prevention Methods	Estimated Cost Each Location	Details	Remarks
1. Overcrossing -	4 Lanes	Chain link fence on both sides of the overcrossing. (Method 1)	$3,400	Sketches 1, 2 & 6	
	8 Lanes	Chain link fence on both sides of the overcrossing. (Method 1)	$5,000	Sketches 1, 2 & 6	
	4 Lanes	Chain link enclosure over the automated/mixed-traffic lanes on both sides of the overcrossing. (Method 2)	$68,000	Sketches 2, 3, 5 & 7	
	8 Lanes	Chain link enclosure over the automated/mixed-traffic lanes on both sides of the overcrossing. (Method 2)	$141,100	Sketches 2, 4, 5 & 7	
2. Interchange -	4 Lanes	Chain link fence on both sides of the ramps or connectors. (Method 1)	$5,000	Sketches 1, 2 & 6	
	8 Lanes	Chain link fence on both sides of the ramps or connectors. (Method 1)	$7,500	Sketches 1, 2 & 6	
	4 Lanes	Chain link enclosure over the automated/mixed-traffic lanes on both sides of the ramps or connectors. (Method 2)	$68,000	Sketches 2, 3, 5 & 7	
	8 Lanes	Chain link enclosure over the automated/mixed-traffic lanes on both sides of the ramps or connectors. (Method 2)	$141,100	Sketches 2, 4, 5 & 7	
3. Open Highway - At Deer Crossings	4 or 8 Lanes	Chain link fence on one side of the highway. (Method 1)	$14,700	Sketches 1, 2 & 9	Cost is based on 1200' and double for fence on both sides of the highway
4. Adjacent to - Frontage Roads	4 or 8 Lanes	Chain link fence on one side of the highway. (Method 1)	$13,200	Sketches 1, 2 & 9	Cost is based on 1080' and double for fence on both sides of the highway
5. Undercrossing -	4 or 8 Lanes	Chain link fence on both sides of the highway. (Method 1)	$3,000	Sketches 1, 2 & 8	Consider a 2-lane road under the automated highway
6. Entry and Exit Ramps	1 or 2 Lanes	Sensors with alarm devices that can be activated only by animal or human intruders at the entrance of the ramp. (Method 3)	$20,000 to $50,000	Sketch 10	



TYPICAL POST DETAIL

CHAIN LINK FENCE

Automated Highway Studies

Obstacle Management (C3)

External Hazards & Proposed Prevention

Sketch No. 1

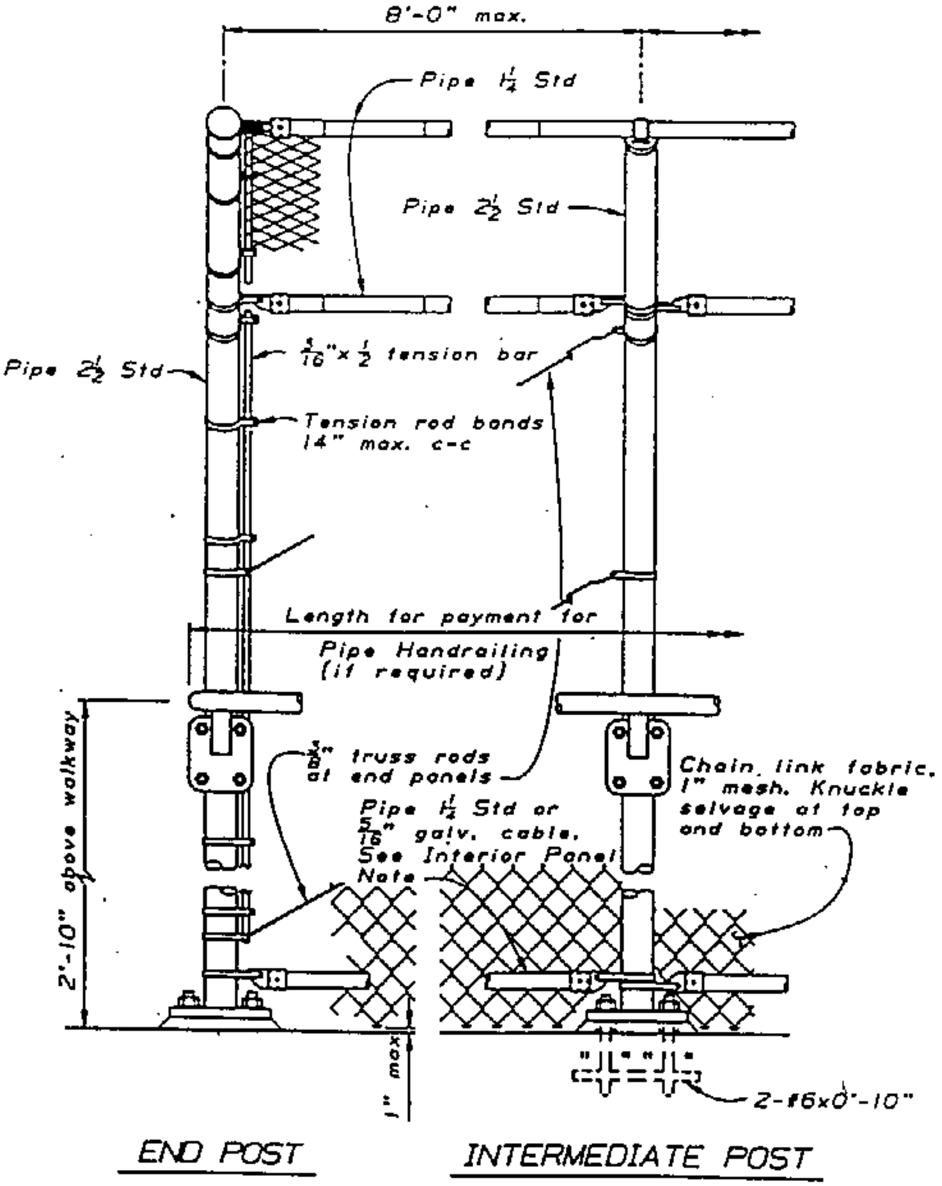
Sheet 8 of

By K. LAM

Approved

Date

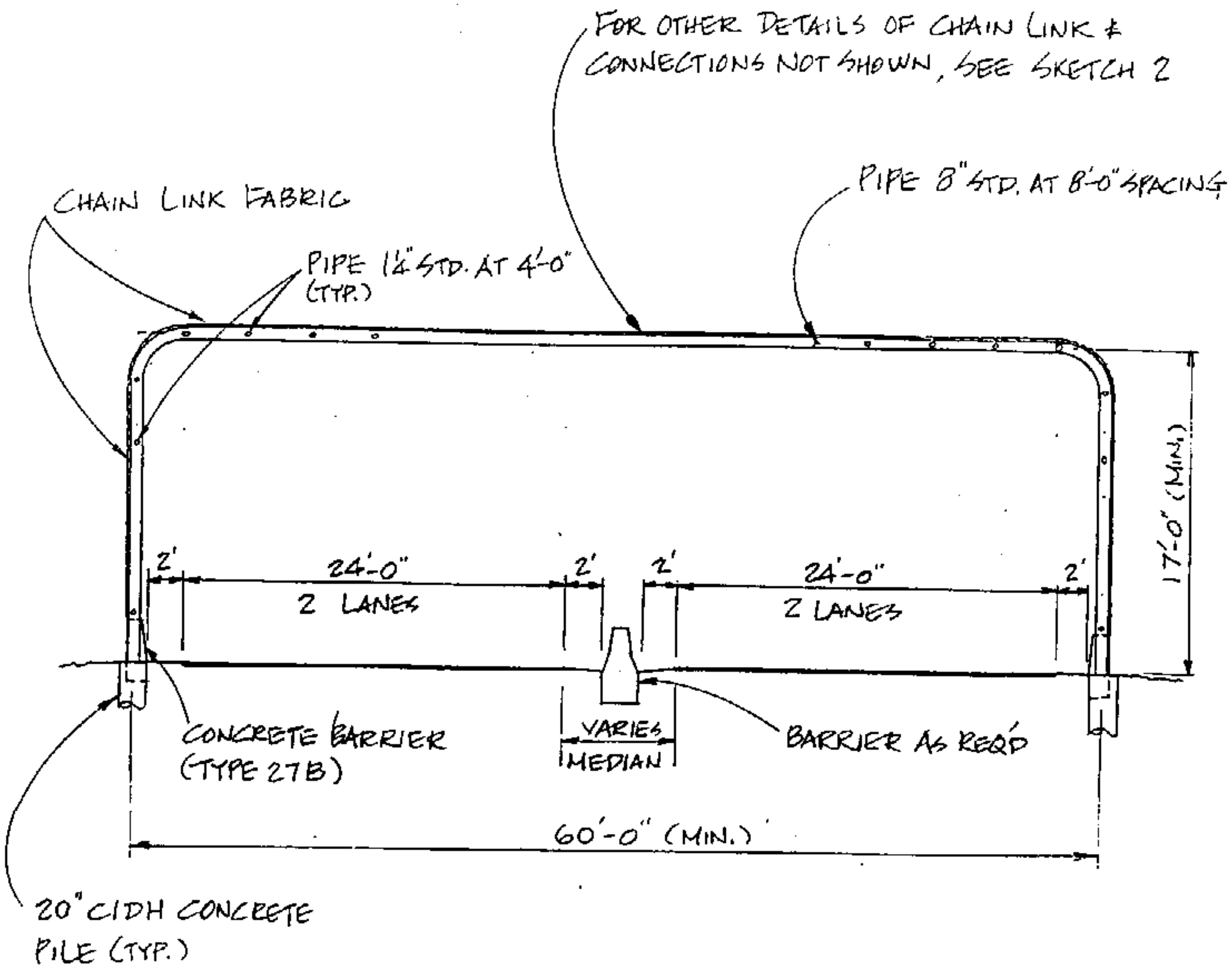
Rev.



TYPICAL POST ELEVATION

CHAIN LINK FENCE DETAILS

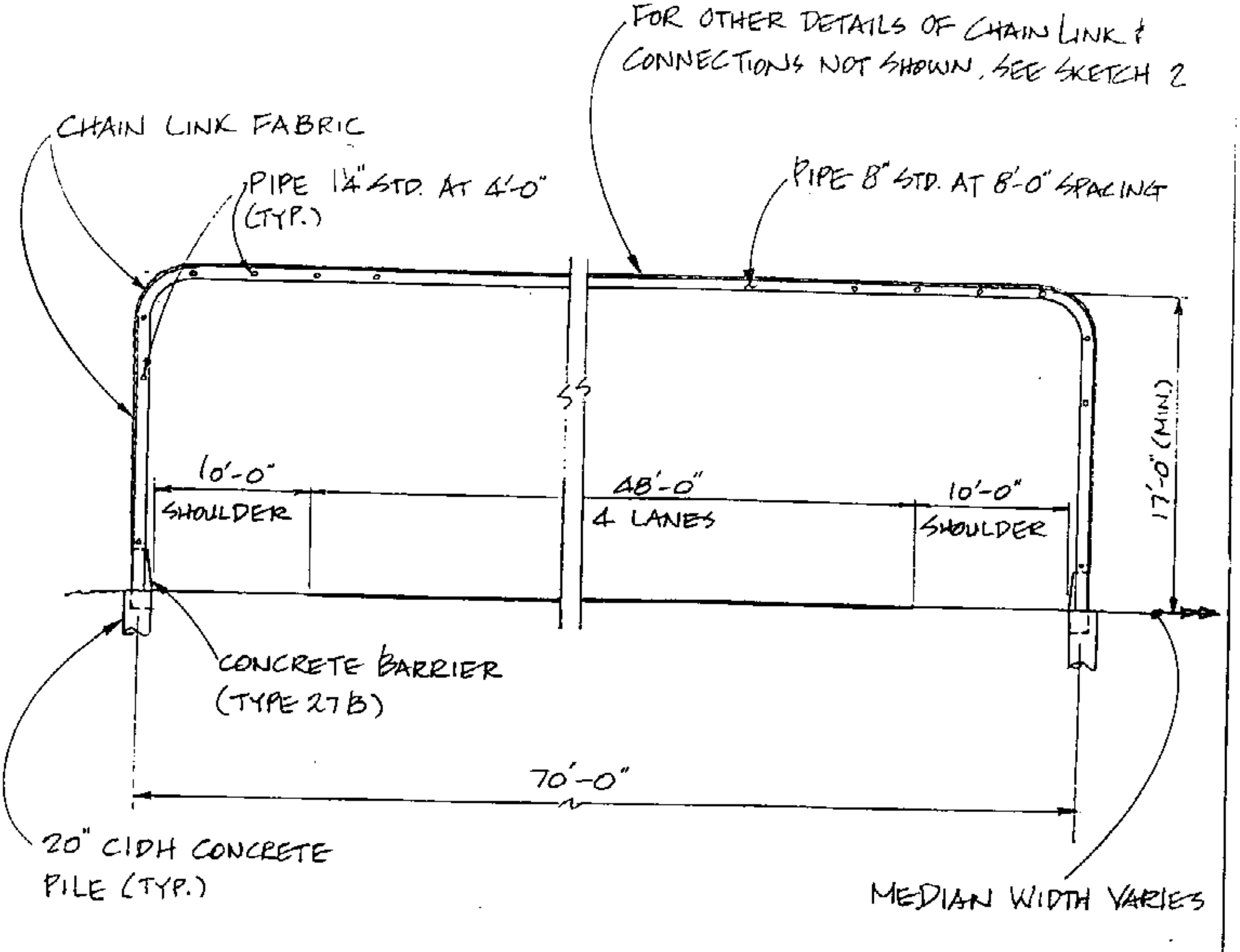
BECHTEL	**Automated Highway Studies** Obstacle Management (C3) External Hazards & Proposed Prevention	Sketch No. 2 Sheet 9 of	By K. LAM Approved Date Rev.



CHAIN LINK ENCLOSURE

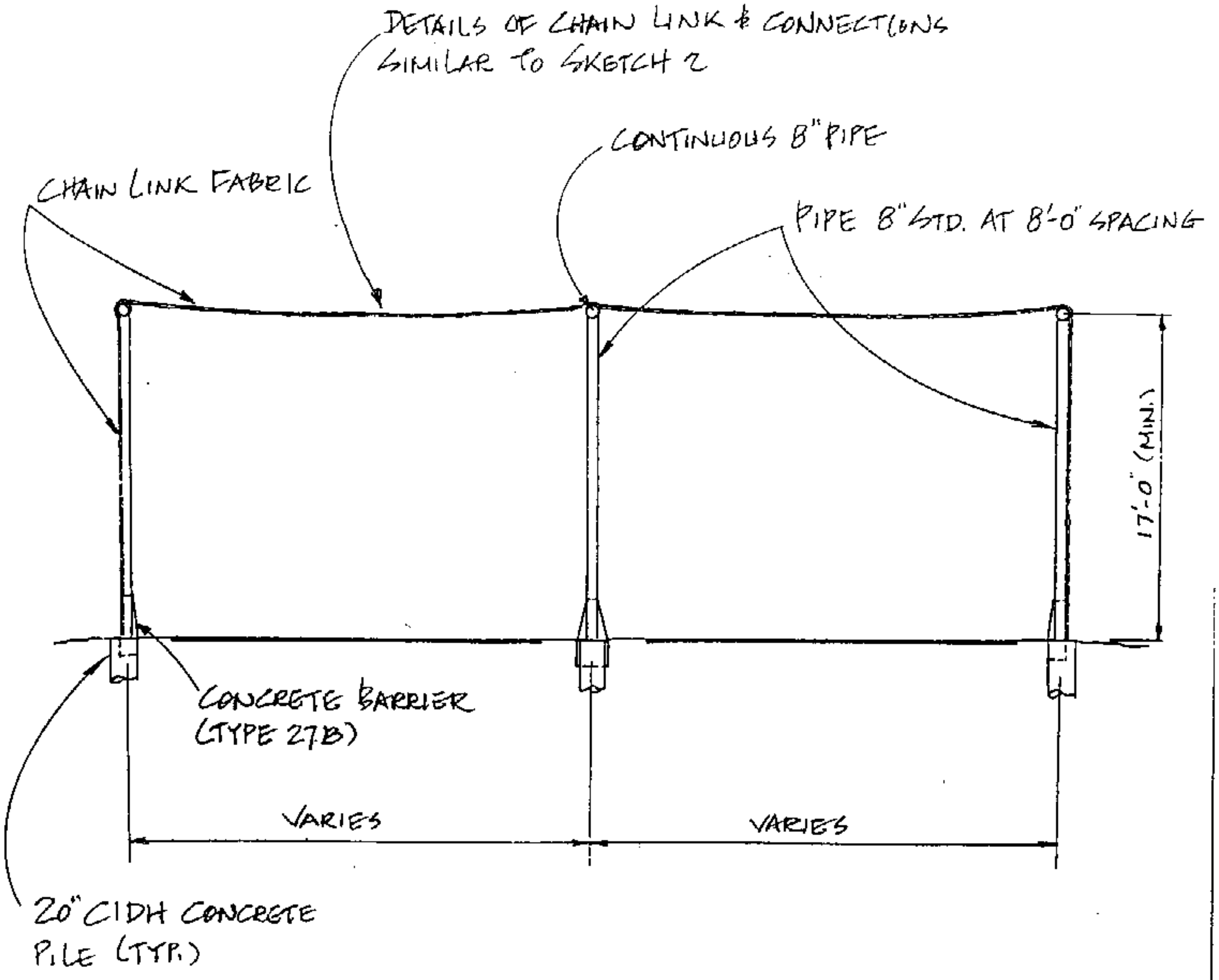
(FOR 4 LANES, BOTH DIRECTIONS)

Automated Highway Studies	Sketch No. 3	By K. LAM
Obstacle Management (C3)		Approved
External Hazards & Proposed Prevention	Sheet 10 of	Date Rev.



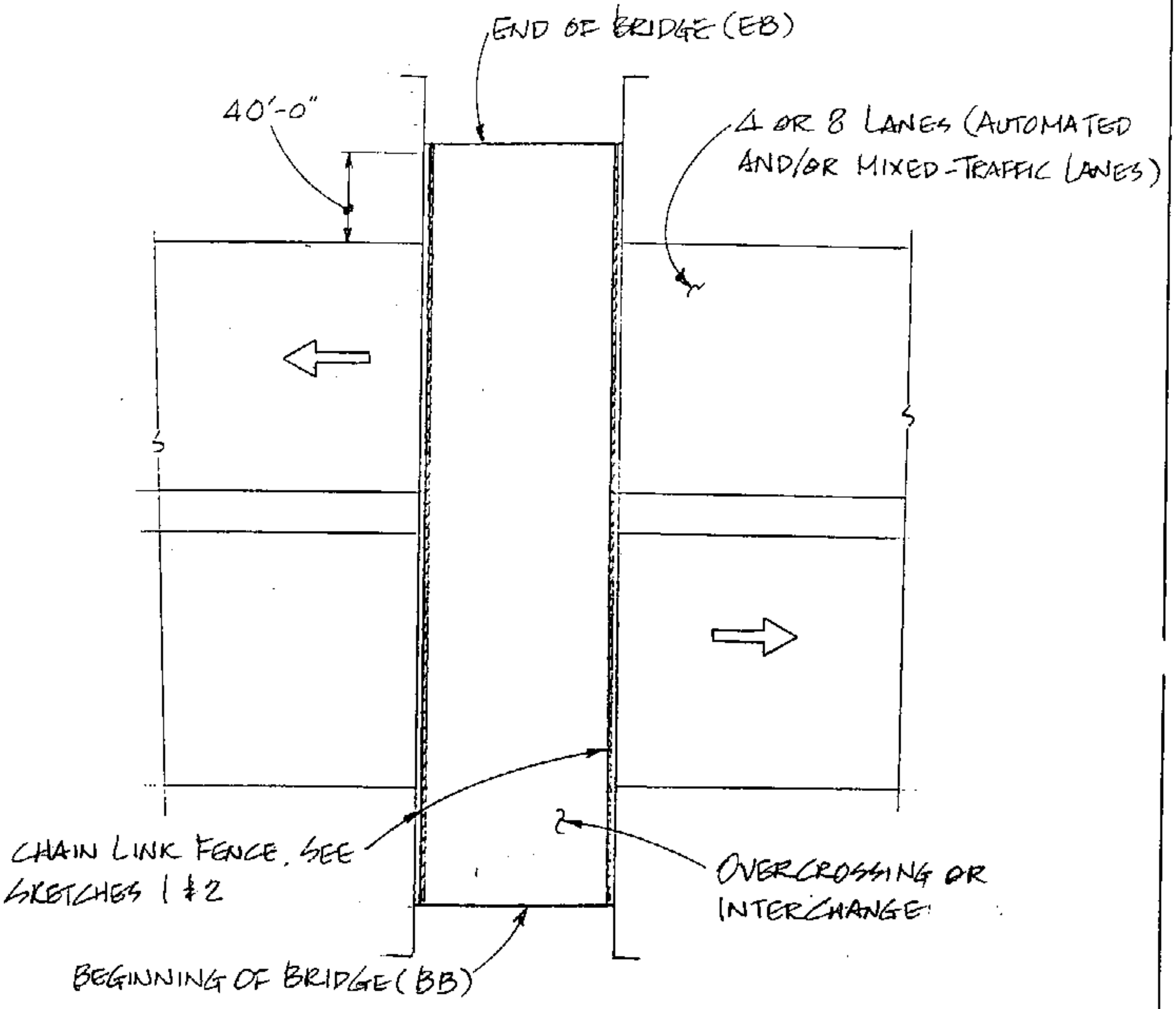
CHAIN LINK ENCLOSURE
(FOR 4 LANES, EACH DIRECTION)

BECHTEL	**Automated Highway Studies** Obstacle Management (C3) External Hazards & Proposed Prevention	Sketch No. 4 Sheet 11 of	By K. LAM Approved Date Rev.



ALTERNATE CHAIN LINK ENCLOSURE
(BOTH DIRECTIONS)

Automated Highway Studies	Sketch No. 5	By K. LAM
Obstacle Management (C3)		Approved
External Hazards & Proposed Prevention	Sheet 12 of	Date Rev.



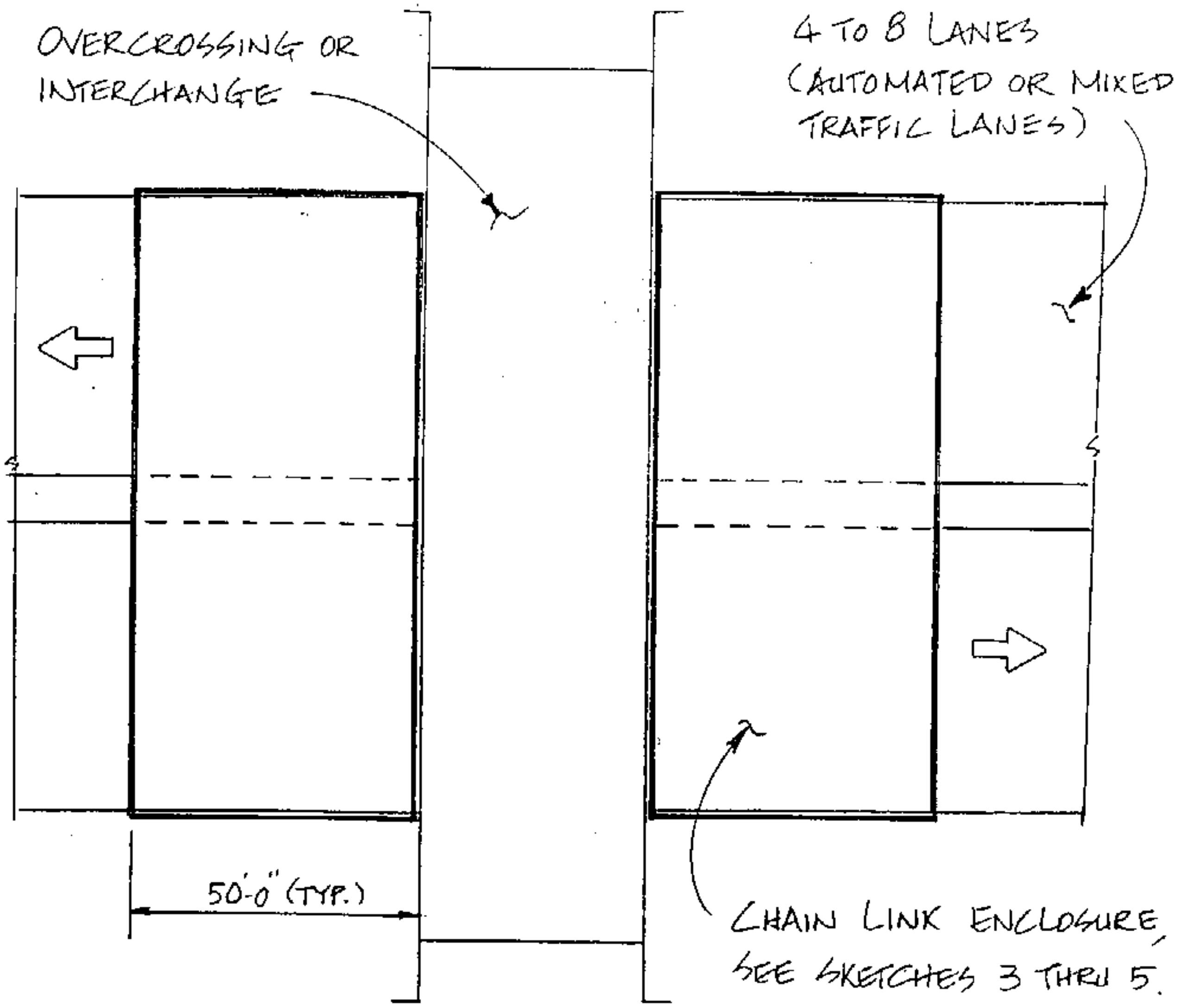
CHAIN LINK FENCE ARRANGEMENT

AT OVERCROSSING OR INTERCHANGE

Automated Highway Studies
Obstacle Management (C3)
External Hazards & Proposed Prevention

Sketch No. 6
Sheet 13 of

By K. LAM
Approved
Date
Rev.



CHAIN LINK ENCLOSURE ARRANGEMENT

AT OVERCROSSING OR INTERCHANGE

Automated Highway Studies
Obstacle Management (C3)
External Hazards & Proposed Prevention

Sketch No. 7

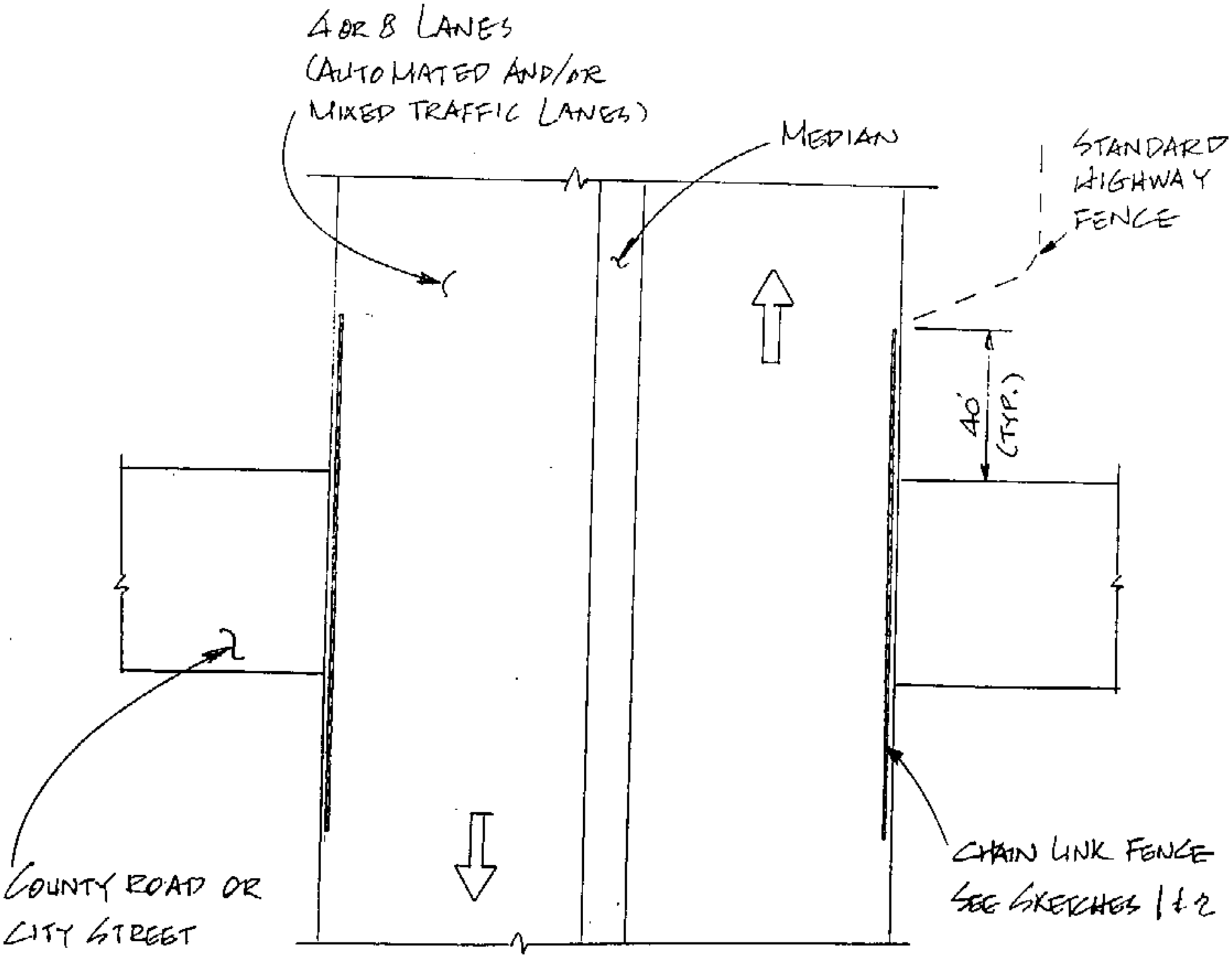
Sheet 14 of

By K. LAM

Approved

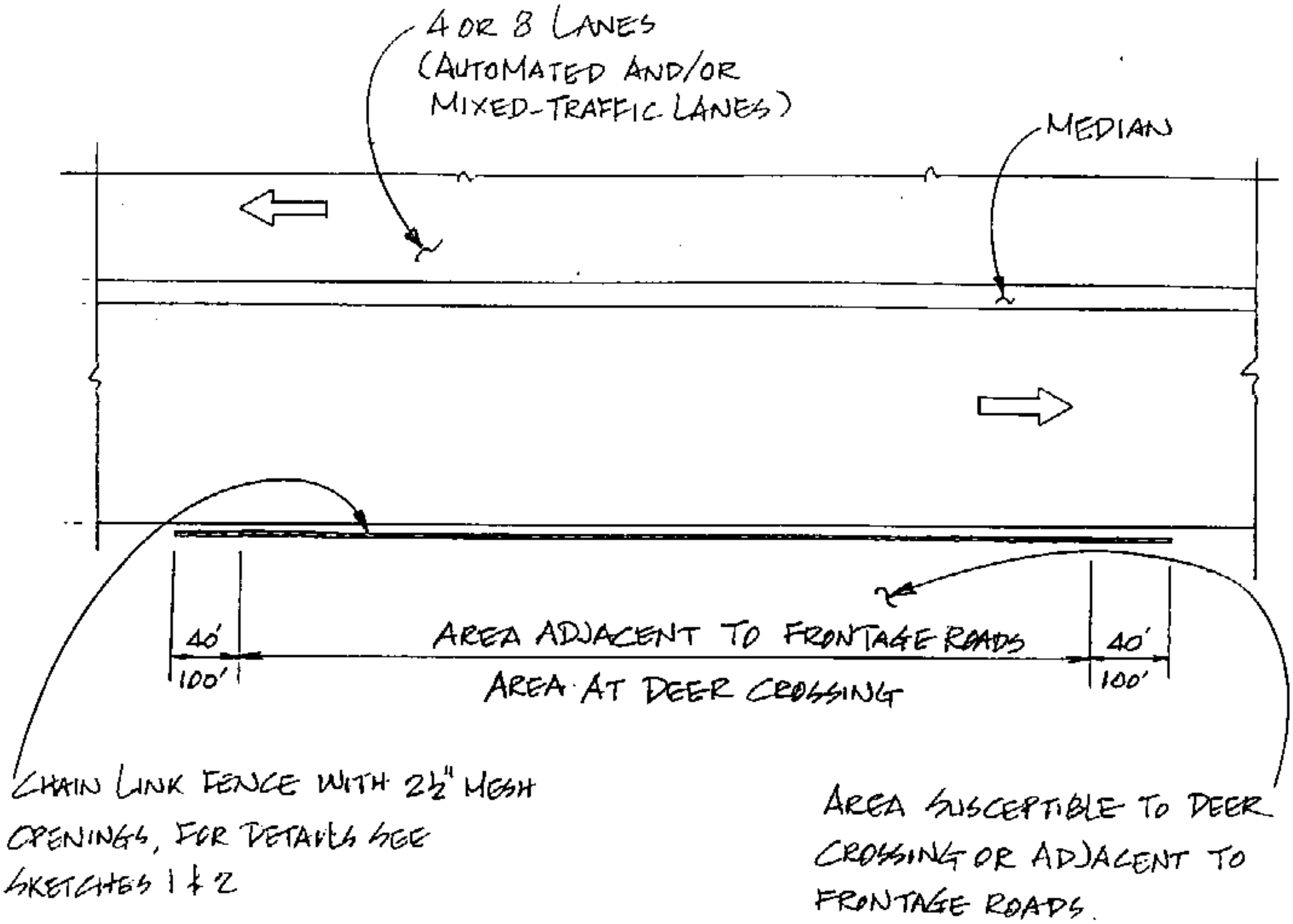
Date

Rev.



CHAIN LINK FENCE ARRANGEMENT
AT UNDERCROSSING

Automated Highway Studies Obstacle Management (C3) External Hazards & Proposed Prevention	Sketch No. 8 Sheet 15 of	By K. LAM Approved Date Rev.



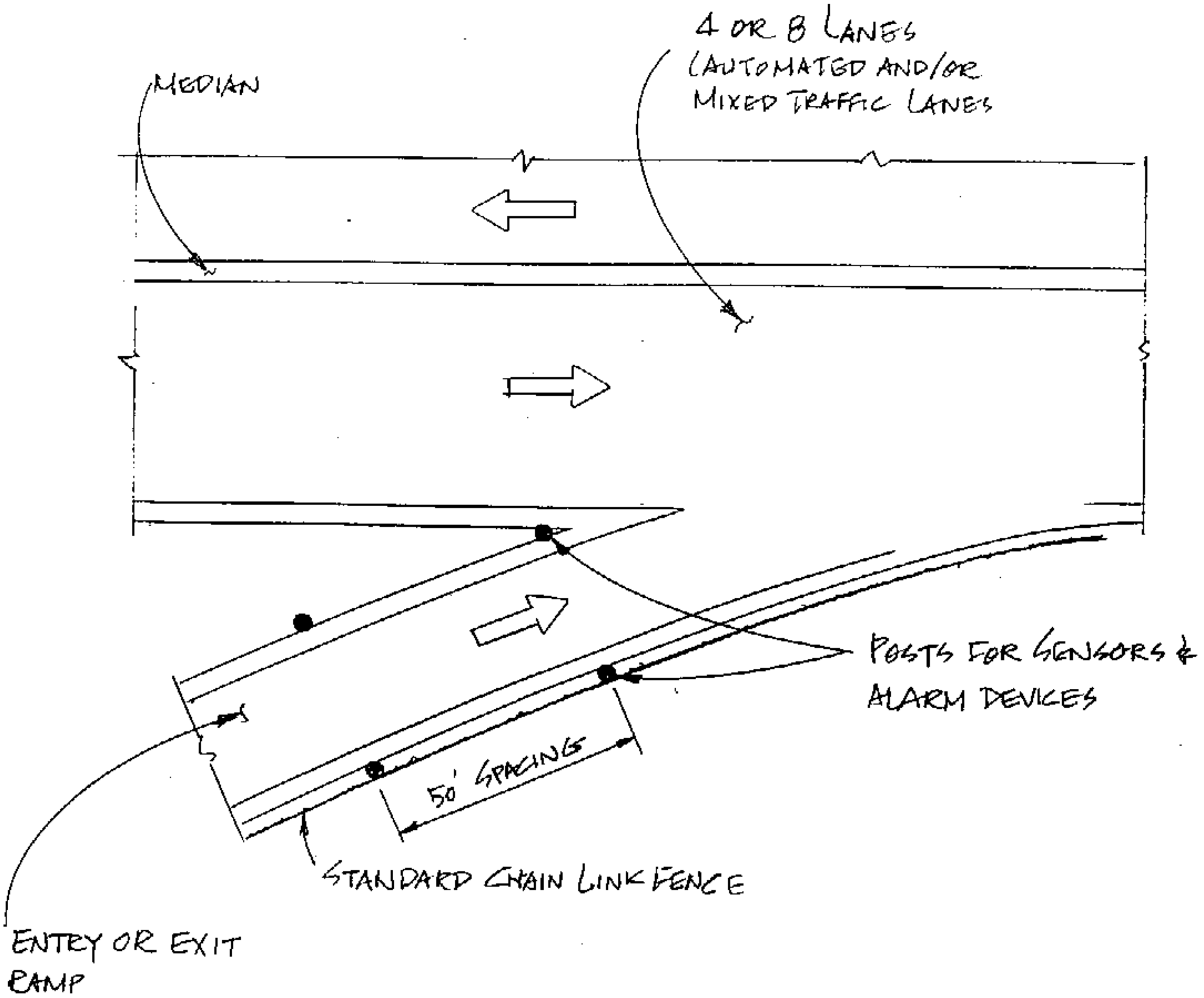
CHAIN LINK FENCE ARRANGEMENT

AT DEER CROSSING OR ADJACENT TO FRONTAGE ROADS

Automated Highway Studies
Obstacle Management (C3)
External Hazards & Proposed Prevention

Sketch No. 9
Sheet 16 of

By K. LAM
Approved
Date
Rev.



SENSOR ARRANGEMENT
AT ENTRY OR EXIT RAMP

	Automated Highway Studies	Sketch No. 10	By K. LAM
	Obstacle Management (C3)		Approved
	External Hazards & Proposed Prevention	Sheet 17 of	Date Rev.

WORKING PAPER

IMPLICATIONS OF ROAD GEOMETRICS

ON OBSTACLE DETECTION

USING AN ON-BOARD VEHICLE RADAR SYSTEM

Bechtel Corporation
Technology and Consulting
50 Beale Street
San Francisco, CA 94105

February 1997

Table of Contents

Introduction

As the vision of highways evolve from manual to automated control, many changes will be required in the design criteria. Currently highways are designed according to human capabilities and limitations. Future highways will also be designed for electronic capabilities and limitations. In this paper we will look at requirements for highway geometrics based on automated control and whether the existing highway geometrics are compatible with the automated control limitations. The designer must determine the size and arrangement for a safe, efficient, and cost effective function of the highway facility.

The primary concern in the design of the geometric layout of the Automated Highway System (AHS) is the collision avoidance and timely detection of objects in the dedicated vehicle travel lanes.

It is essential to have the basic road geometry, in particular the dedicated AHS vehicle travel lanes, laid-out in a safe configuration, based on the design speed. The choice of the design speed is influenced by the functional class, type and volume of traffic, whether the area is urban or rural, and the general conditions of the terrain.

For the automated vehicle to perform satisfactorily the road geometry information and data of any objects in the vehicle path must be provided to the vehicle control system. In this study we are looking at an on-board Radar Sensor based control system for collecting and processing of data. This paper considers an existing highway without any other supplemental or control system.

When the road alignment is on a horizontal curve, the on-board vehicle radar sensor based control system must find and then determine the location of the on-road obstacles and objects. As shown in other studies, under certain geometric road conditions, the radar sensor may cause a potential false alarm or provide false information causing the vehicle control system to malfunction.

The sensor must determine whether the object is located:

- in the AHS dedicated lane
- in the neighboring, parallel, same direction lane of the multilane road
- in the neighboring, parallel, opposite direction traffic lane
- off-road on either on the right or the left side of the dedicated lane

The safety hazard alarm becomes a real alarm only if the object is actually located in the AHS dedicated lane, while all other signals must be rejected by the automatic control system as false alarms. In addition, an object that is in the travel lane, but in an upcoming curve, may be seen by the On-board Vehicle Radar Sensor based control system while the vehicle is still traveling on the tangent and the information discounted by the system as being outside of the travel lane unless there is a supplemental system to alert to the change in alignment.

Assumptions

It is assumed that the On-board Vehicle Radar Sensor based control system is capable of continuous operation and detection of on-road obstacles and objects under all weather conditions.

The system is a stand alone system without other support systems in infrastructure.

The system is programmed to be capable of operation in either the AHS dedicated lanes or in mixed traffic lanes.

The system is based on operation of the radar as a Frequency Modulated Continuous Wave (FMCW) system and a fixed direction radar with several cell units.

There are three levels of highway operation:
Main line, at the design speed of 70 mph
Interchange ramps (I/C) at design speeds of 50 to 55 mph
Interchange loop ramps at design speeds of 30 mph

Radar Sensor Concept

For the purposes of this study we will use the On-board Vehicle Radar Sensor based control system, described in the Robotics Institute, Carnegie Mellon University (CMU) study (1) of radar system for outdoor navigation, which has the following attributes:

- Frequency Modulated Continuous Wave (FMCW) system
- A fixed direction radar
- Maximum range between 300 and 1,000 feet
- Can operate under adverse weather conditions (rain, snow)
- Can operate at night and when visibility is poor (fog)
- Longitudinal resolution is between 3 and 40 inches, depending on distance to object

The GANESHA system, in experiments at CMU, has demonstrated its ability to autonomously drive a vehicle. The system has tracked static features such as a rail, a wall and an array of parked cars, searched for a parking gap, and then parallel parked the vehicle.

The current research at CMU closely follows the design of the radar sensor developed at the Technical University Munich (TUM), because the automotive radar developed by TUM offers the best fit with this task, in terms of capabilities and technological simplicity.

The automotive radar developed by TUM has a Horizontal Field of View (HFoV) of 12 ^{0}, an operating range of 20 to 100m, and range resolution of 0.75m. The 12 ^{0} HFoV is divided into four angular resolution cells of 3 ^{0} each, more cells can be added to increase the HFoV to 16 ^{0}. This radar also returns directional information through wave front reconstruction with multiple receivers. The current design of the radar sensor at CMU has a 12 ^{0} HFoV. The CMU study assumes a lane width of 4 meters. With this assumption, the radar sensor provides; one lane coverage at a range of 19 meters; three lanes at a range of 57 meters; and five lanes at a range of 95 meters. A single 3 ^{0} HFoV cell covers the entire 4 meter lane width at a range of 76 meters. Using the standard lane width of 12 ft (3.7 m) the distances can be recalculated as needed.

Road Geometry

The road geometry information regarding the highway and any objects in the vehicle's path in the driving lane must be provided to the vehicle control system. In this case we are looking at an on-board Vehicle Radar Sensor based control system for collecting and processing of data. As shown in other studies, under certain geometric road conditions, the Radar Sensor may cause a potential false alarm or provide false information causing the vehicle control system to malfunction. The geometric situations where these potential false alarms could appear in the on-board Radar Sensor based control system, are on roads with small radius curved alignment; multilane, divided roads; undivided multilane highways, and roads that are bordered by stationary objects, such as guard rails, poles, cut slopes or trees and vegetation.

Whether the road alignment is straight or laid out on a horizontal curve, the On-board Radar Sensor based control system must detect all potentially hazardous on-road obstacles and objects. After detecting or finding them, the system must then determine the location of the obstacles or objects. It also must determine whether the object is located in the AHS dedicated lane or; in the neighboring, parallel, same direction lane of the multilane road; in the oncoming neighboring, parallel, traffic lane; off-road on either on the right or the left side of the dedicated lane and evaluate their potential hazard. The safety hazard alarm becomes a real alarm only if the object is actually located in the AHS dedicated lane, all other signals must be rejected as false alarms. This process is more complicated when the vehicle is approaching or leaving a curve, especially a small radius curve.

The design speed for a highway (2) (3) depends on alignment, and sight distance. The choice of the design speed is influenced primarily by the functional class, type and volume of traffic, whether the area is urban or rural, and the conditions of the surrounding terrain. Design speeds typically range from 20 to 70 mph, as shown in Tables 1 and 2, with the freeway interchange ramps (I/C) using design speeds of 50 to 55 mph.

		CONDITIONS	Design Speed (mph)
LIMITED ACCESS TYPES			
	Freeways and expressways in mountainous terrain		50-70
	Freeways in urban areas		60-70
	Freeways and expressways in rural areas		70-80
	Expressways in urban areas		50-70
UNLIMITED ACCESS TYPES			
	Rural		
		Flat terrain	60-70
		Rolling terrain	50-60
		Mountainous terrain	40-50(1)
	Urban		
		Arterial streets	40-60
		Arterial streets with extensive development	30-40
(1) FHWA design exception is required for speeds of less than 50mph.			

Table 1. Relations of Conditions to Design Speed.
Source: Table 101.2, of "Highway Design Manual of Instructions. California Department of Transportation," Sacramento, California, Fourth Edition, 1992

The minimum curve radius based on the design speed (2) for rural highways and high-speed urban streets is shown in Table 2.

Design Speed (mph)	e	f	Total (e+f)	Minimum Radius (ft)
20	0.04	0.17	0.21	127
30	0.04	0.16	0.20	302
40	0.04	0.15	0.19	573
50	0.06	0.14	0.20	849
60	0.06	0.12	0.18	1348
70	0.08	0.10	0.18	1910

Table 2. Minimum curve radius based on the design speed (2) for rural highways and high-speed urban streets.
Based on Table III-6. of "A Policy on Geometric Design of Highways and Streets. American Association of State Highway and Transportation Officials," Washington, 1984

The degree of curvature or the radius of the curve is established by a variety of design criteria parameters. The major design parameter being the minimum stopping sight distance at the chosen design speed (2), as shown in Table 3. At low design speeds, curves with small radii are acceptable for the standard design of the highway, but when the AHS additional constraints are imposed, such as the narrow angle of the HFoV of the radar sensor and the straight ahead alignment of the radar sensor, curves with larger radii must be used. Thus many existing small highway curves may become inadequate for AHS operation.

Design Speed	Assumed Speed for Condition	Brake Reaction		Coeff. of Friction	Braking Distance On Level	Stopping Sight Distance	
(mph)	(mph)	Time (sec)	Distance (ft)	f	(ft)	Computed((a)) (ft)	Rounded for Design (ft)
20	20-20	2.5	73.3-73.3	0.40	33.3-33.3	106.7-106.7	125-125
25	24-25	2.5	88.0-91.7	0.38	50.5-54.8	138.5-146.5	150-150
30	28-30	2.5	102.7-110.0	0.35	74.7-85.7	177.3-195.7	200-200
35	32-35	2.5	117.3-128.3	0.34	100.4-120.1	217.7-248.4	225-250
40	36-40	2.5	132.0-146.7	0.32	135.0-166.7	267.0-313.3	275-325
45	40-45	2.5	146.7-165.0	0,31	172.0-217.7	318.7-382.7	325-400
50	44-50	2.5	161.3-183.3	0.30	215.1-277.8	376.4-461.1	400-475
55	48-55	2.5	176.0-201.7	0.30	256.0-336.1	432.0-537.8	450-550
60	52-60	2.5	190.7-220.0	0.29	310.8-413.8	501.5-633.8	525-650
65	55-65	2.5	201.7-238.3	0.29	347.7-485.6	549.4-742.0	550-725
70	58-70	2.5	212.7-256.7	0.28	400.5-583.3	613.1-840.0	625-850

((a))Different values for the same speed result from using unequal coefficients of friction.

Table 3. Stopping sight distance (wet pavements).
Source: "A Policy on Geometric Design of Highways and Streets. American Association of State Highway and Transportation Officials," Washington, 1984

The minimum acceptable curve radius for the design of the AHS dedicated lanes must provide the on-board Radar Sensor based control system a field of view of the entire driving lane of the vehicle, as shown on sketch "A" and also warn of upcoming hazards, whether the vehicle is on a tangent before entering the curve, on the curve itself, or still on the curve but entering the tangent. Some type of forecast data input, of upcoming geometry or curvature of the highway, from infrastructure installations will be necessary. In addition, an object that is in the travel lane in an upcoming curve, may be seen by the On-board Vehicle Radar Sensor based control system while still traveling on the tangent and the information discarded as being outside of the lane unless a supplemental system alerts of the change in alignment.

The figures shown on sketch "A" provide a graphical representation of an AHS vehicle entering a horizontal curve to the right. It is a simple curve, without spiral. The radii shown are the minimums for the given design speed, based on Table 2. Two sets of conclusions can be derived from these figures:

- if the curve has a very small radius, the objects on the inside edge of the lane will not be detected by the radar, even if the HFoV is increased to 16 ^{0}
- as the radius is increased, the design speed as well as the stopping distance both increase, with the result that the vehicle will not be able to stop within the detectable distance of the object.

Object Detection and Avoidance

The objects that must be detected, located and identified by an on-board Vehicle Radar Sensor based control system may be relatively small in size. Some hazardous objects may be on the order of six to eight inches high, such as a concrete block or brick. Items of this size will damage the vehicle or severely affect the vehicle handling, when struck at high speed. The object size could also be very large, such as a stalled vehicle, disabled motorcycle, or a large animal, in these cases a collision may be extremely hazardous.

The radar sensor may have difficulty determining if the object is in the driving lane, when the vehicle is on a horizontal curve. If the vehicle is on a straight stretch of road it does not see the curve ahead, it only sees in the vehicle's current direction of travel. Therefore if the object is outside the radar sensor's HFoV edge line it will not detect objects in its own lane in the upcoming curve with a straight ahead alignment of the sensors. In addition, an object that is in the travel lane in an upcoming curve, may be seen by the On-board Vehicle Radar Sensor based control system while still traveling on the tangent and the information discarded as being outside of the lane unless a supplemental system alerts of the change in alignment. Supplemental systems must be provided to predict an upcoming curve or other changes in the geometrics in order to transfer data on upcoming geometry from the infrastructure to the vehicle control system. Such methods could include magnetic markers, radar reflective striping, radio beacons or other ways, yet to be determined.

Integration of Radar Sensor Design Concept and Road Geometry Systems

The minimum curve radius, acceptable for use in the AHS, must provide the radar sensor with a field of view that covers the entire driving lane of the vehicle. If the object is outside of the radar sensor HFoV edge line, then as seen on sketch "A" the 12^0 HFoV and even the 16^0 HFoV will not detect objects on small radius curves in-time for the vehicle to react and stop to avoid the object, if the geometrics are based on speed alone.

An object on the outside edge of the driving lane will not be detected by a 16^0 HFoV, if the radius of the curve is smaller than 849 feet, in-time for the vehicle traveling at 50 mph to stop and avoid the object. The 16^0 HFoV will provide detection on the inside edge of the driving lane on curves, if the curve radii are greater than 300 feet.

One of the solutions is to limit the speed on curves to a value that will match the sensor object detection distance to within the stopping distance. The other is to provide a wider HFoV of the radar sensor. There may be other technical and mechanical solutions in the future, such as movable or directional radar coupled with the steering.

Results and Conclusions

Main line and Rural roads

The detection of objects in the driving lanes on the mainline highways and rural roads is feasible with the on-board Vehicle Radar Sensor based control system if radii of curves are large. As long as the Radar Sensor HFoV allows full coverage of the driving lane within the braking distance and the system is able to determine the location of objects, even on a curved alignment.

Interchanges

- Ramp

  The ramp design must accommodate the minimum radius curves that are based on the design speed of 50 mph. For the ramps the radii may be as small as 849 ft, this will allow detection of objects in the driving lanes within the braking distance, using an HFoV increased to 16 ^{0}.

- Loop

  The loop design must accommodate minimum radius curves that are based on the design speed of 30 mph. For the loops, the design radii may be 302 ft. This radius will not allow detection of objects on the inside edge of the driving lane, even using an HFoV of 16 ^{0}.

- Problems with existing I/C

  The existing I/C have been designed based on the standard highway criteria. These criteria allow the use of minimum radius curves (302 ft) that are based on the design speed of 30 mph. This radius will not allow detection of objects on the inside edge of the driving lane, even using an HFoV of 16 ^{0}.

Concerns

There is a concern of the driver overriding the automatic control system in only the speed category of the automated control system, meanwhile if the sensors remain set for a lower design speed, the ability of the vehicle to avoid the object may be jeopardized. On rural roads, on relatively straight alignments, there is a tendency by the driver to exceed the posted and the design speed limits. The driver must not be allowed to override the automated controls to increase his vehicles speed under any circumstances.

The implications to date of this study is that although the on-board Vehicle Radar Sensor based control system will work on the main line highways and on the straight or gentle alignment of rural roads, there will be a problem for object detection in the driving lane on the small radius curves.

The detection of objects with the on-board Vehicle Radar Sensor based control system will need to be supplemented by to alert it of changing geometrics in the interchanges ahead. This is particularly necessary on the small radius loops inside the existing Interchanges. As the vehicle enters the I/C it need to be switched to the manual driver control, there has to be some supplemental systems to provide this operation transition.

On rural roads, when small radius curves become a factor in detection of objects in the driving lane, there has to be some supplemental systems to alert of changing geometrics ahead. If the vehicle goes around the horizontal curve in excess of design speed it could overrun the stopping distances before the object is detected and not avoid the object. Posting a lower speed limit may not be an adequate safeguard and the liability may remain, even if the driver manually exceeded the posted speed limit. (Who will be liable if the vehicle hits the object while under the automatic detection, but manually exceeding the speed limit?)

Recommendations for follow-on studies

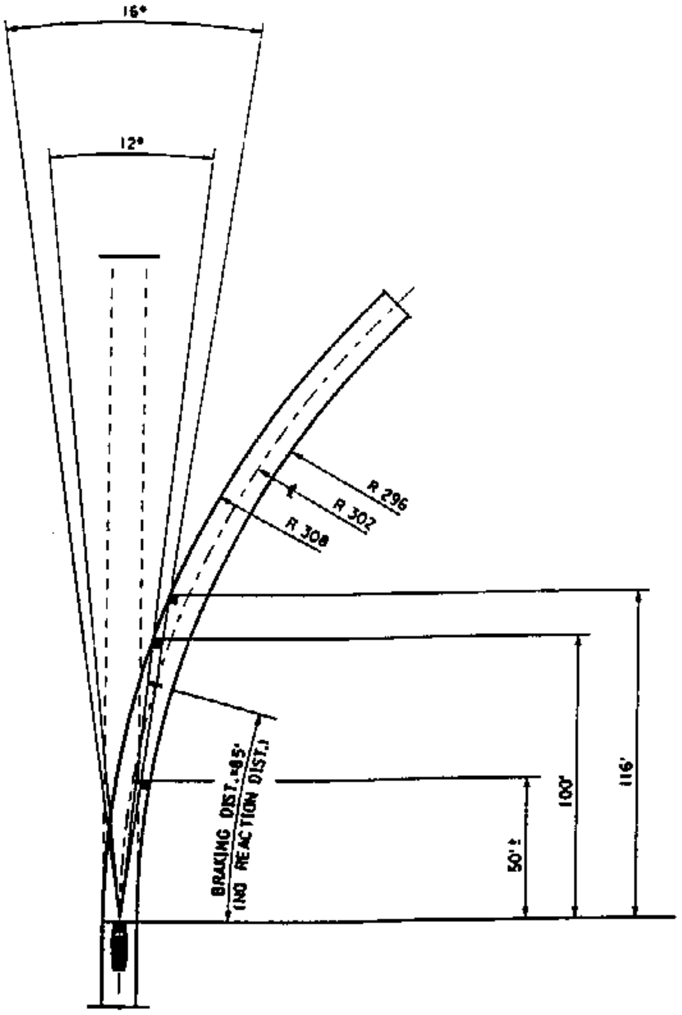
Cost - benefit study of using a radar sensor with a wider HFoV vs. small radius curves.

Cost - benefit study or consideration of a moveable/directional radar connected to the steering mechanism and guided by a supplemental system.

Installation of exterior data sources to provide information to the vehicle control system to control speed automatically and consider the upcoming road geometry. Similar to the magnets embedded in the center of the lane.

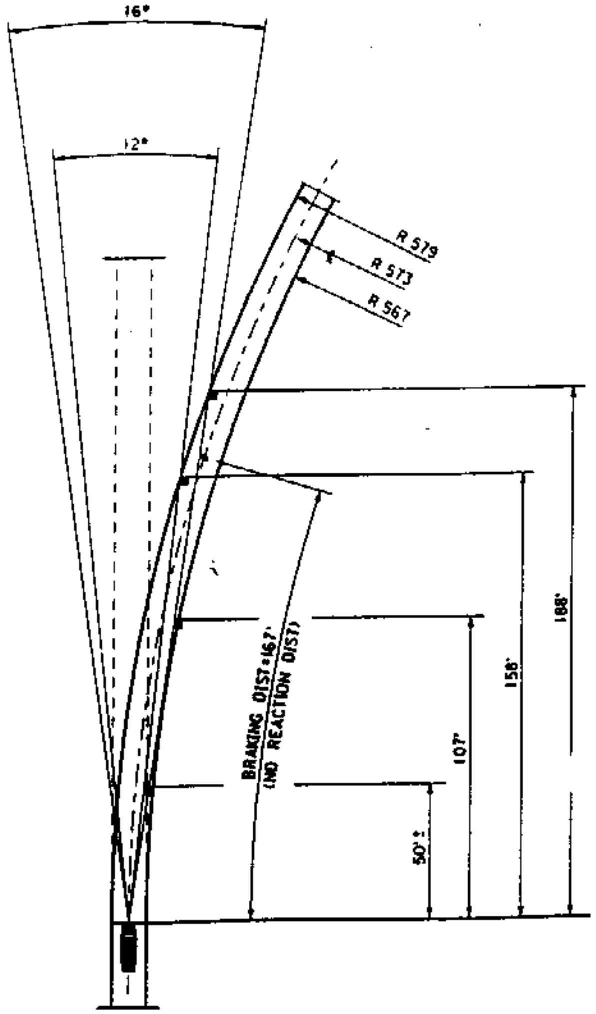
Evaluation of Global Positioning Systems (GPS) as it locates approaching curves, defines and identifies their curvature.

Evaluation of methods to retrofit existing highways, in order to transfer data on upcoming geometry from the infrastructure to the vehicle control system and control vehicle speed. Such methods could include magnetic markers, radar reflective striping, radio beacons or other ways, yet to be determined.



MIN RADIUS
@ 30 MPH

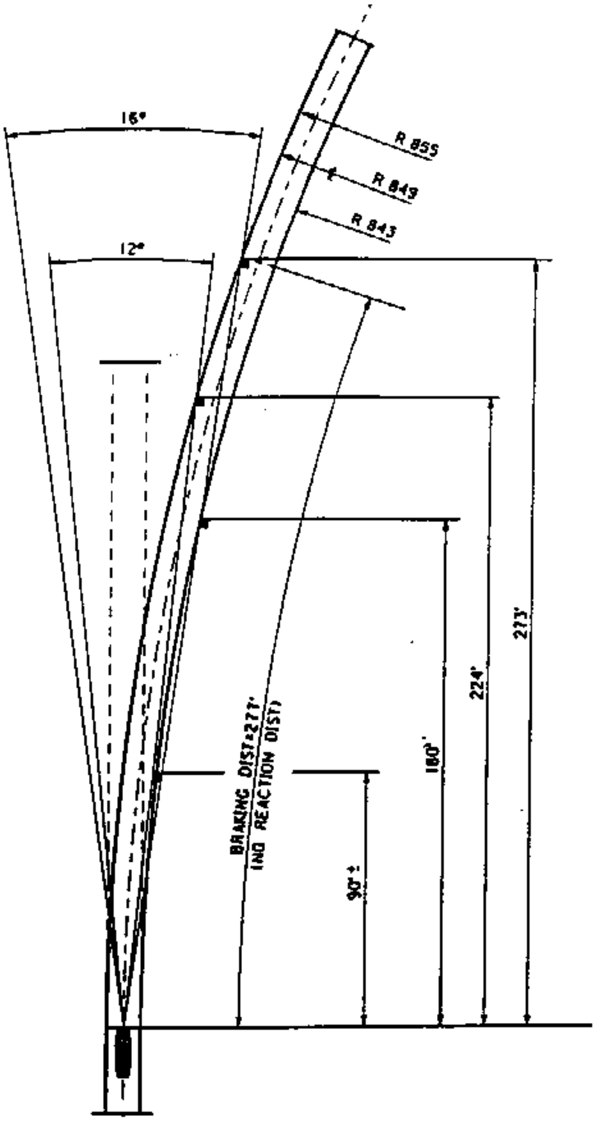
FIGURE 1



MIN RADIUS
@ 40 MPH

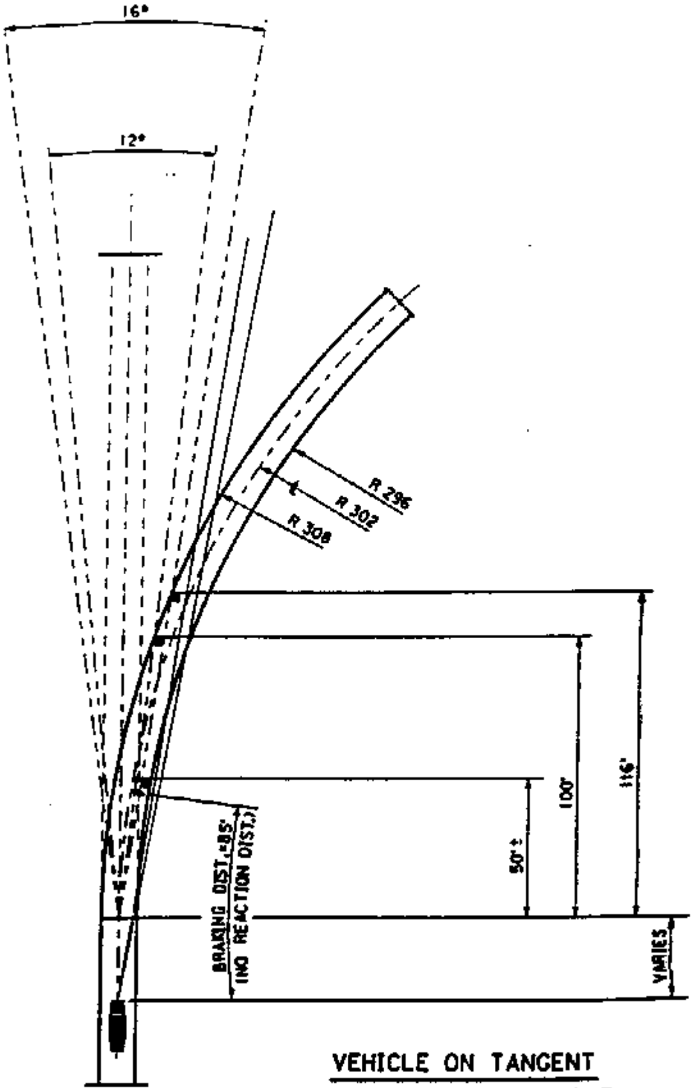
FIGURE 2

SKETCH "A"
SHEET 1 OF 2



MIN RADIUS
@ 50 MPH

FIGURE 3



VEHICLE ON TANGENT
BEFORE REACHING CURVE

FIGURE 4

LEGEND:

■ OBJECT TO BE DETECTED

TRAVEL LANE

OBJECT DETECTION
ON SMALL RADIUS CURVES

SKETCH "A"

SHEET 2 OF 2

References

1. Langer, D. *Proposal for an Integrated MMW Radar System for Outdoor Navigation.* Pittsburgh, Pennsylvania: The Robotics Institute, Carnegie Mellon University, March 1996.

2. *A Policy on Geometric Design of Highways and Streets.* American Association of State Highway and Transportation Officials, Washington, D. C. (1984).

3. *Highway Design Manual of Instructions.* California Department of Transportation, Sacramento, California, Fourth Edition, (1992)

Obstacle Prevention

One of the factors presenting danger to the operation of the AHS equipped vehicles in dedicated lanes is an object laying in the vehicle path. The concept of an exclusive lane is similar to train tracks or transit tracks that exist and most likely face similar situations. The question arises of how to prevent obstacles from coming into the dedicated lanes from outside the environment. Various transportation agencies were contacted to acquire an understanding of existing management practices and policies. A letter was sent to fourteen agencies asking for assistance in obtaining information on their practices. The letter and a list of agencies is attached.

Dear Sirs:

We are writing this letter to request your assistance regarding your experience in obstacle management for access controlled, grade separated and segregated right-of-way. Our concerns include both obstacle prevention from both external and internal sources as well as obstacle detection. Our Research and Development Group at Bechtel is part of the National Automated Highway System Consortium (NAHSC along with eight other core participants. These include Caltrans (California Department of Transportation), Carnegie Mellon University, Delco Electronics Corp., General Motors Corp., Hughes Aircraft Co., Lockheed Martin, Parsons Brinkerhoff, Inc., and the University of California -Partnership for Advanced Transit and Highways (PATH). The nine-member NAHSC is in partnership with the U.S. Department of Transportation (U.S. DOT).

The goal of the Consortium, is to develop fully automated vehicle operation in dedicated lanes under full computer control in which the driver becomes a passenger in their own specially equipped AHS vehicle.

When the driver is disengaged from driving, we face one of our biggest challenges. That is the prevention and detection of dangerous objects and obstacles in the path of the automated vehicles. Our system would be like yours in that it will have access controlled and dedicated right-of-way for automated vehicles.

Based on the successes and the difficulties you have experienced in detecting, controlling and removing obstacles, we would like to ask for your advice on:

1. Prevention of objects or obstacles from entering your right-of-way.
2. Prevention of animals or humans from entering your system, becoming obstacles in the vehicles path.
3 Prevention of objects or obstacles from dropping off your equipment or transit vehicles onto the track or lane area.
4. Removal of objects and obstacles.
5. Types and of objects or obstacles that you have encountered on the right-of-way
6. Frequency of object incidents

7. Time elapsed between object detection and removal.
9. Measures taken to reduce objects' incidents.
8. Safety hazards to train operations
10. Any additional factual and/or anecdotal information you can provide.

We would request that you provide your readily available information for this time frame, and format that best suits your data base.

On behalf of our Bechtel R&D Group, I would like to thank you in advance for any information or advice you are able to provide us at this time.

If you have questions about our project or our request for information, please call me at (415) 768-2604, fax me at (415) 768-2743, or e-mail at rhearne@bechtel.com.

Respectfully yours,

Ronald J. Hearne, P.E.

The letter was sent to the following fourteen agencies and addressed to the persons responsible for operations :

Mr. Michael T. Barnes
SEPTA Operations
1234 Market St. 9th Floor
Philadelphia, Pa. 19107-3780

Mr. G. Robert Butt
Chief Mechanical Officer
Metro North Community Railroad
420 Lexington Ave., 11 Floor
New York, NY 10017

Mr. James Candlish, Jr.
Director of Maintenance
MBTA-Boston Transit
500 Arbor Way
Jamaica Plains, MA 02130

Mr. Charles "Sam" Carnaggio
MTA Director of Operations
Mass Transit Administration
William Donald Schaefer Tower
6 St. Paul Street
Baltimore, MD 21202

Mr. Jeff Demarre,
Supervisor
Satellite Transit System
Port of Seattle- Seattle/Tacoma Airport
P.O. Box 68727
Seattle WA 98168

Mr. Jim Dunn
Chief Engineer
Maintenance Department
BART
800 Madison St.
Oakland, CA 94607

Ms. Ruth Green, Manager
Ad Tranz

Mr. John Hamill
Miami Airport

P.O. Box 11300
Las Vegas, NV 89111

Mr. Jerry Harris
Market Research
Greater Orlando Aviation Authority
One Airport Boulevard
Orlando, FL 32827-4399

Mr. Lawrence Rauter, President
NY City Transit
370 Jay St.
Brooklyn, NY 11201

Ms. Carolyn Wylder
Executive Vice President
Operations and Development
MARTA
2424 Piedmont Road, N.E.
Atlanta, GA 30324

Aviation Maintenance Department
P.O. Box 592075
Miami, FF 33159

Mr. Rajkumar Rambhajan
Managing Director
ATS (Automated Transport
Services)
P.O. Box 66511
Chicago, IL 60666-0511

Mr. Robert F Schive
Metro Chief Transportation Officer
Chicago Metro
547 West Jackson
Chicago, IL 60661

Mr. Chris Gambola
North Cargo Road Bldg. #522
AMF OHARE
P.O. Box 66511
Chicago, IL 60666-0511

Five responses were received out of the fourteen letters sent out. These were from:

- New York City Transit
- O'Hare Airport Transit System, Inc.
- Metropolitan Atlanta Rapid Transit Authority MARTA
- Southern Pennsylvania Transportation Authority (SEPTA)
- Metrolink of Los Angeles

In summary, none of the responding agencies had an official policy or procedure on Obstacle Management. Obstacle prevention was either non-existent or evolved from routine maintenance work. Typically obstacle detection is done manually, visually by the train operators or the people performing the maintenance walk throughs. Obstacle removal was done routinely by maintenance personnel or train operators in the extreme cases.

The general philosophy of the agencies is reflected in a quote from Metrolink. "**Most** objects do not impede or damage the engine due to the mass of the engine and the train. Objects such as animals do not harm the train and the same can be said of pedestrians.

The train operators are instructed to stop for pedestrians whereas they are instructed not to stop for animals or items such as shopping carts."

Some agencies do provide right-of-way fencing, which was typically 6 foot in height, in an effort to discourage animals or pedestrians from accessing the right-of-way. In sensitive areas some agencies used 10 foot fencing. Measures taken to reduce objects incidents include installation of trespassing and other warning signs; none of the responding agencies used active measures or sensors.

Obstacle Survey

In the course of research on obstacle prevention and management it became apparent that there was no ready source of information on specific types and frequency of obstacles that might be encountered. In the absence of existing data it was decided to gather and develop our own information. A survey form was put together with the idea of potentially distributing the form to Caltrans maintenance workers and data would be collected over a period of time (i.e. one month). Due to NAHSC restructuring this effort was discontinued at this time and these survey forms were not distributed. However to document the effort that was expended and record the form for future use, this form is included here. A copy of that form is as follows:

DISTRICT	COUNTY	ROUTE	P.M.

DATE________________
DAY OF WK________________
TIME________________
NAME________________
SUPRV. INITIALS____________

LOCATION OF OBJECT

DIRECTION OF TRAVEL ________________
LANE NUMBER ________________
SHOULDER ________________
Distance to nearest overcrossing ____________

OBJECT

MATERIAL (check one)
- Masonry or stone........................ ☐
- Metal........................ ☐
- Wood, Plastic, Rubber........................ ☐
- Paper, Cardboard, Foam Plastic........................ ☐
- Fabric (Mattress)........................ ☐
- Animal........................ ☐
- Oil........................ ☐
- Other (specify)........................ ☐

SIZE (check one)
- Small (Less than 1ft x 1 ft)........................ ☐
- Medium (1ft to 3 ft)........................ ☐
- Large (Greater than 3 ft)........................ ☐
- Weight (mass)........................ ☐

SHAPE (check one)
- Rectangular........................ ☐
- Round or cylindrical........................ ☐
- Other (specify)________________ ☐

ADDDITIONAL PHYSICAL DESCRIPTION________________________

IMPACT ON TRAFFIC
Did Object cause an accident ?........................ ☐ yes ☐ no
Did Object cause delays ?........................ ☐ yes ☐ no
If yes; how long was delay?
- 5 to 20 minutes........................ ☐
- 20 minutes to 1 hour........................ ☐
- over 1 hour........................ ☐
- don't know........................ ☐

10.4.9 Preliminary Emissions and Fuel Consumption Evaluation of Automated Highway Systems

Matthew Barth
College of Engineering
Center for Environmental Research and Technology
University of California
Riverside, CA 92521
barth@engr.ucr.edu

Abstract

A preliminary evaluation has been carried out in estimating the emissions and energy use (i.e., fuel consumption) associated with an AHS using advanced simulation modeling tools. A detailed AHS microsimulation has been combined with a comprehensive modal emissions model to predict emissions and energy use for a modeled highway. The resulting AHS emissions and fuel consumption are compared to non-automated traffic at different levels of congestion, as well as idealized traffic flow. The results of this preliminary evaluation have shown that an AHS has slightly lower average fuel consumption than a non-automated highway operating at free-flow, and much lower average fuel consumption than a non-automated highway operating under congested conditions, because of its smoother traffic flow. Further, an AHS operating at 60 mph has substantially lower emissions per vehicle-mile traveled than non-automated traffic at the same average speed, again because of its smoother traffic flow. Vehicles that platoon in an AHS can expect an additional 5 - 15% fuel savings and emission reduction due to the aerodynamic drafting effect, which is dependent on the intra-platoon vehicle spacings.

1 Introduction

Automated Highway Systems (AHS) have the potential to substantially improve the safety and efficiency of highway travel. In addition, there are several potential benefits for the environment. Vehicle fuel consumption and emissions will be reduced due to smoother traffic flow (i.e., fewer accelerations/decelerations) and less congestion, resulting in shorter trip times. Further, if vehicles operate at very close spacings (i.e., platooning), the aerodynamic drag on the vehicles will be lower and fuel consumption and emissions will further be reduced.

In order to estimate the potential emissions and fuel consumption benefits of an AHS, preliminary experimentation has been carried out using advanced simulation tools. A detailed AHS microsimulation was combined with a comprehensive modal emissions model to predict emissions and energy use for a modeled highway. This highway was modeled after the Katy Corridor (Interstate Highway 10) of the Houston metropolitan region. For this case study, a single lane freeway with three merge junctions was examined. The resulting AHS emissions and fuel consumption are then compared to the cases of: 1) non-automated traffic at different levels of congestion; and 2) idealized traffic flow.

In Section 2, background information is given on the AHS microsimulation, the comprehensive modal emissions model, and the freeway congested cycles used for the non-automated traffic comparison. In Section 3, the methodology is briefly described, followed by the results given in Section 4. Conclusions and future work are described in Section 5.

2 Background

2.1 AHS Microsimulation

The AHS microsimulation was implemented using the SmartAHS framework developed at PATH [Deshpande, 1997a]. SmartAHS provides the infrastructure elements for simulating vehicle-highway systems. It contains simulation models for highway layout, traffic sources and sinks, vehicle models at different fidelity levels, actuator models, physical level controller models, sensor models, and communication models.

SmartAHS is provided as a collection of libraries written in the SHIFT programming language [Deshpande et al., 1997b]. SHIFT is a programming language for describing dynamic networks of hybrid automata. Such systems consist of components which can be created, interconnected and destroyed as the system evolves. Components exhibit hybrid behavior, consisting of continuous-time phases separated by discrete-event transitions. Components may evolve independently, or they may interact through their inputs, outputs, and exported events. The interaction network itself may evolve.

For this case study, the highway layout was built using the SmartAHS highway models and simple kinematic vehicle models were used. For these simple kinematic vehicle models, the controller provides acceleration and brake inputs to the vehicles. A single lane freeway was examined with three merge junctions, modeled after the Katy Corridor (Interstate Highway 10) of the Houston metropolitan region. For further details on the actual microsimulation setup, please refer to [Antoniotti et al., 1997].

2.2 Comprehensive Modal Emissions Modeling Project

The current emission-factor models developed for large regional areas (i.e., EPA's MOBILE and CARB's EMFAC models) are inappropriate for application to detailed vehicle microsimulation models. Much better suited are *modal* emissions models, i.e., models that predict emissions (and fuel consumption) as a function of vehicle operating mode (i.e., idle, steady-state cruise, various levels of acceleration/deceleration, etc.). Researchers at the University of California, Riverside College of Engineering-Center for Environmental Research and Technology are currently developing a comprehensive modal emissions model for light-duty vehicles under the sponsorship of the National Cooperative Highway Research Program (NCHRP Project 25-11). The overall objective of this project is to develop and verify a modal-emissions model that accurately reflects impacts of speed, engine-load, and start conditions on emissions under a comprehensive variety of driving characteristics and vehicle technologies. The model is comprehensive in the sense that it will be able to predict emissions for a wide variety of Light Duty Vehicles (LDVs) in various states of condition (e.g., properly functioning, deteriorated, malfunctioning).

In this project, approximately 300 in-use vehicles are being randomly recruited and tested on a single roll 48" dynamometer over three different driving cycles: 1) the FTP (Federal Test Procedure); 2) the high-speed US06 cycle [EPA, 1995]; and 3) a specially designed modal emission cycle (MEC01, described in [Barth et al., 1997]). For each of these cycles, second-by-second engine-out and tailpipe carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx), and hydrocarbon (HC) emissions data are being collected. Based on these measured emissions data, a modal emissions model is being developed to estimate vehicle emissions under several operating modes.

Details on the comprehensive modal emissions model are given elsewhere (see, e.g., [Barth et al., 1996; Barth et al., 1997; An et al., 1997]), only a brief description is given here. The model employs a physical, power-demand modal modeling approach based on a parameterized analytical representation of emissions production. In such a physical model, the entire emissions process is broken down into different components that correspond to physical phenomena associated with vehicle operation and emissions production. Each component is then modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, and emission technology. The majority of these parameters are stated as specifications by the vehicle manufacturers, and are readily available (e.g., vehicle mass, engine size, aerodynamic drag coefficient, etc.). Other key parameters relating to vehicle operation and emissions production are deduced from the comprehensive testing program. The model handles operating conditions of cold start, stoichiometric driving, power enrichment, and enleanment conditions. The later three conditions represent hot-stabilized operation.

It is important to note that for this preliminary AHS emissions and energy consumption case study, only a single LDV type is modeled (specifically, a 1996 Buick LeSabre). In future AHS emission analyses, better characterization of the vehicle fleet will be performed.

2.3 Freeway Congestion Cycles

In order to compare AHS emissions and fuel consumption to non-automated traffic, we make use of the US EPA's latest facility-specific congestion cycles. Under contract to the US EPA, Sierra Research [Sierra Research, 1997] has created several facility-specific congestion cycles based on matching speed-acceleration frequency distributions for a wide range of roadway types and congestion levels. These cycles have been developed based on a large amount of "chase car" and instrumented vehicle data collected in the cities of Spokane, Baltimore, Atlanta, and Los Angeles. The congestion level was recorded as different "Levels-Of-Service" (LOS) values based on the LOS measures developed by the Transportation Research Board (TRB, see [TRB, 1994]). FHWA currently employs these LOS measures for congestion. For freeways (i.e., non-interrupted flow), LOS is a function of both average vehicle speed and traffic flow rate. Primarily due to inter-vehicle interaction at higher levels of congestion (corresponding to LOS values of B, C, D, E, and F), vehicles will have substantially different velocity profiles under different LOS conditions. Under LOS A, vehicles will typically travel near the highway's free flow speed, with little acceleration/deceleration perturbations. As LOS conditions get progressively worse (i.e., LOS B, C, D, E, and F), vehicles will encounter lower average speeds with a greater number of acceleration/deceleration events.

Six driving cycles have been developed for freeway driving, ranging from high-speed driving (LOS A+, where vehicles have little or no interaction with other vehicles) to driving in near gridlock conditions (LOS F-). These cycles range from 4 to 12 minutes in length and were constructed to optimally match the observed speed-acceleration and specific power frequency distributions of the on-road vehicle data [Sierra Research, 1997]. These cycles are shown in Figure 1.

3 Methodology

The modal emission model calibrated to 1996 Buick LeSabre has been applied in several different fashions for this AHS analysis:

Application to Non-Automated Traffic

The six cycles described in Section 2.3 were used as input to the modal emission model to determine integrated emissions of CO, HC, NOx, and fuel consumption (all given in grams/mile). For all cases, it was assumed that all of the vehicles are in hot-stabilized operating condition (i.e., no cold start).

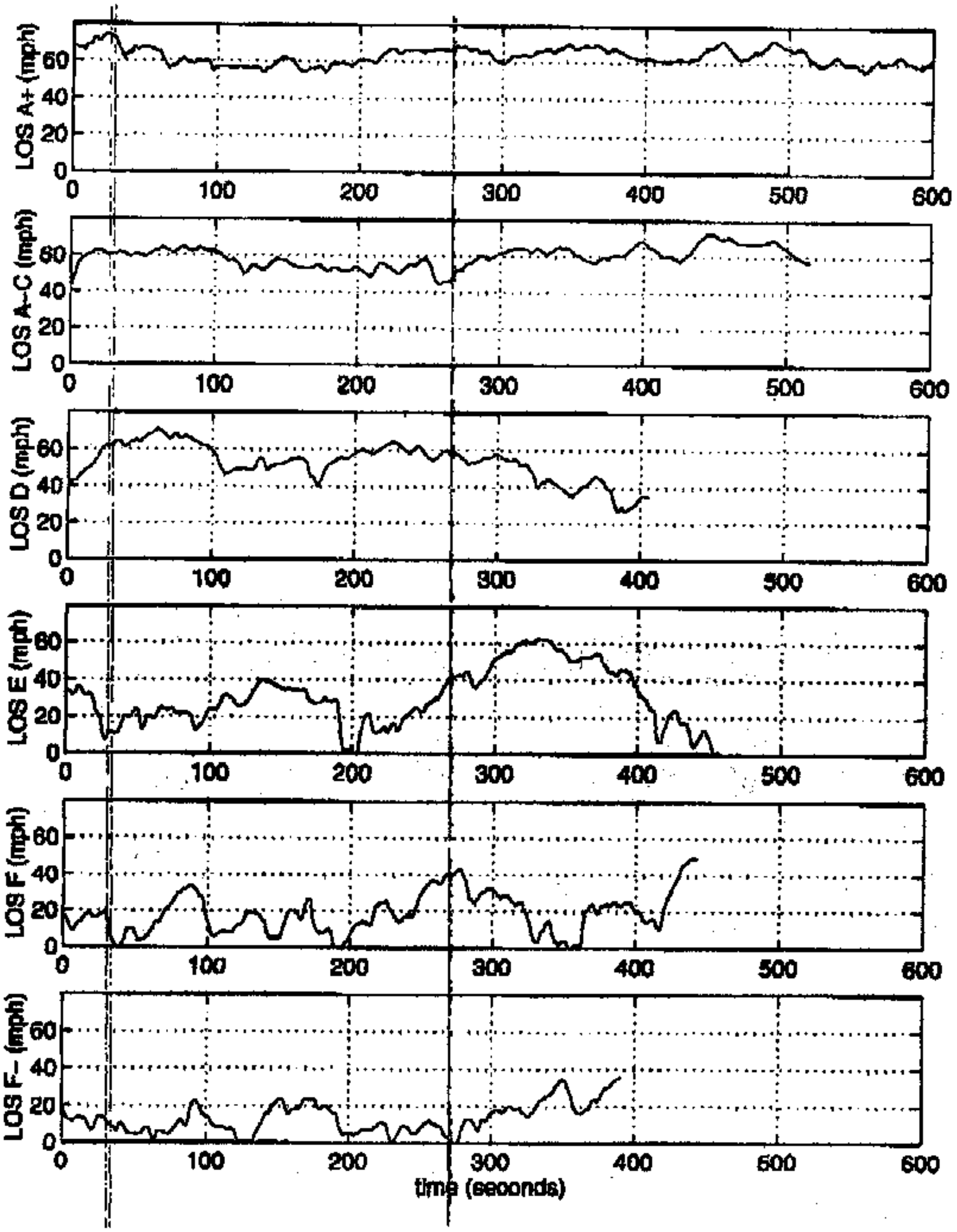


Figure 1. Freeway congestion cycles.

Application to Ideal Constant-Speed Traffic

Using the modal emissions model, emissions and fuel consumption were also predicted for ideal, constant-speed traffic flow. Several constant-speed "cycles" were created at 10, 20, 30, 40, 50, 60, and 70 mph. As before, integrated emissions of CO, HC, NOx, and fuel consumption were determined in grams per mile.

Application to the AHS microsimulation

The AHS microsimulation was run under different conditions of travel demand for the single lane Katy freeway as specified in [Antoniotti et al., 1997]. After the simulation was initiated, each run was allowed to "stabilize" for several simulation-minutes so that the average traffic speed was reasonably constant. At that point, the trajectories of every vehicle in the microsimulation were acquired (second-by-second velocity and acceleration). The modal emission model was then applied to these acquired trajectories and average fleet emissions and fuel consumption (in grams/mile) were calculated.

Simulation runs were performed for two cases:

1) an AHS *cooperative* scenario (described in [Antoniotti et al., 1997]) where vehicles coordinate their activities with each other, even when they are not within each other's sensor ranges. In this scenario, vehicles act as free agents, cooperating together for smooth merging and traffic flow. For this case, vehicles followed each other autonomously with a specified desired time headway of 1 second.

2) an AHS *platoon* scenario, where vehicles coordinate their activities as before, but also can group themselves into platoons for greater capacity. The intra-platoon spacings were set to 5 meters.

In order to account for the aerodynamic drag benefit when platooning, the modal emissions model assumed a near-constant spacing of 5 meters, and appropriately reduced the load (and subsequently emissions and fuel consumption) for the reported percentage of vehicles platooning at any point in time.

4 Results

In Figure 2, fuel consumption per unit distance (given in grams per mile) per vehicle is shown as a function of average vehicle speed for the previously described scenarios of non-automated traffic, ideal constant-speed traffic, and AHS microsimulation. The solid line represents the non-automated traffic scenario, where the data points represent the average fuel consumption for the different congestion cycles described in Section 2.3. The dashed line represents the ideal constant-speed scenario (i.e., traffic without any acceleration/deceleration events) and represents the lower limit of emissions for the vehicle at different constant speeds. Results for the two AHS scenarios (cooperative and cooperative-platooned) are shown to lie between the ideal minimum and the non-automated traffic under light congestion. The platoon-based AHS has lower fuel consumption due to aerodynamic drag reduction when vehicles operate at close spacings.

In Figures 3, 4, and 5, HC, CO, and NOx emissions (given in grams/mile) are shown in a similar fashion. In these figures, the non-automated plots take on the typical parabolic shape of an emissions speed correction factor curve. This parabolic shape (high on both ends, low in the middle) comes about due to two factors. At low speeds, a vehicle has relatively low grams/second emission rate, however because it spends more time on the roadway for a given unit distance, it emits for a longer period of time (i.e., its grams/mile rate is higher). At high speeds, much greater loads are placed on the engine, drastically increasing the grams/second emission rate. The vehicle spends less time on the roadway for the given unit distance, but the increased grams/second rate overwhelms that factor. Emissions (in grams/mile) are typically lowest at medium speeds (i.e., 30 to 50 mph). Because fuel-consumption is not as sensitive to higher speeds as emissions, it only has a moderate increase at the high-end.

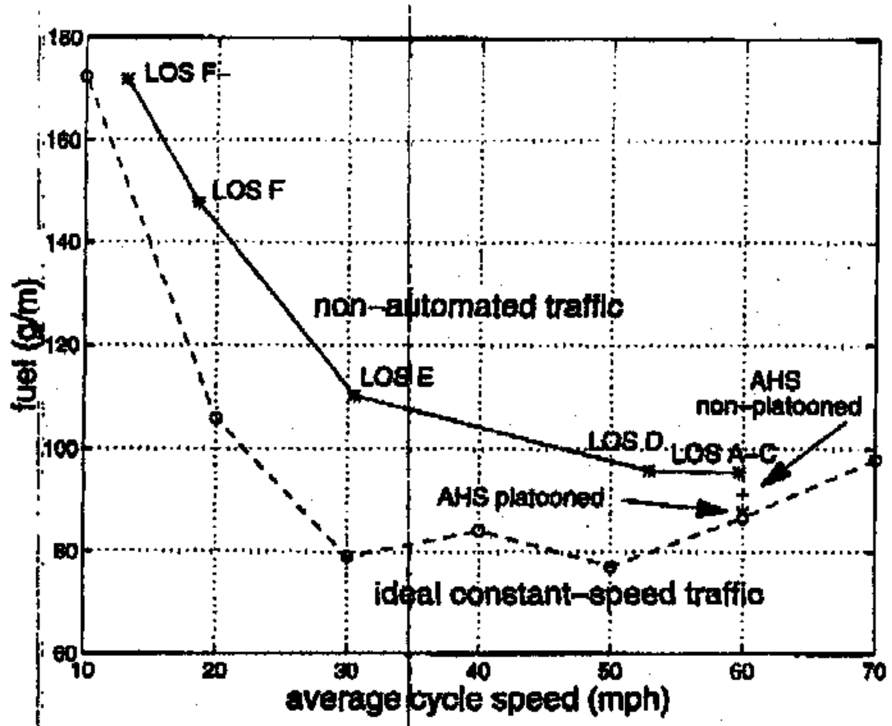


Figure 2. Fuel consumption versus average cycle speed.

It is interesting to note that the average vehicle HC and CO emissions for the LOS A-C case take a sharp turn upwards due to the emissions sensitivity to higher speeds. At the LOS A-C level, vehicles travel at high speeds with a limited amount of congestion-related acceleration/deceleration transients. Preliminary analysis has shown that the primary reason for higher HC and CO emission rates at higher speeds is due to very short enrichment events that occur when a vehicle only slightly accelerates at high speeds. For example, the modeled 1996 Buick LeSabre goes into enrichment only for 2 seconds for the LOS A-C cycle (total length is 516 seconds; vehicle goes enriched 0.3% of the time). As congestion increases, the average speed decreases, with greater acceleration/deceleration transients (see Figure 1). However, the load placed on the engine is not as great as it is at high speeds, even though the vehicle undergoes greater acceleration events.

Given the travel demand level for the Katy Freeway corridor case study, congestion will remain at the LOS F- level if no improvements are made. In Figures 6 - 9, we compare the fuel consumption and emissions for this LOS F- condition against other scenarios. If additional non-automated lanes are added to this corridor, congestion may return to the LOS A level, but the average HC and NOx emissions will remain approximately the same (average CO emissions may increase). The fuel consumption will be reduced to approximately 55% of the baseline non-automated case (a saving of 45%).

If automation in introduced into the traffic system, traffic will flow more smoothly, reducing fuel consumption by 47% (compared to LOS F-), HC emissions by 19%, CO emissions by 33% (compared to LOS A), and NOx by 5%. If vehicles are capable of platooning, the fuel consumption is reduced by 49%, HC emissions by 23%, CO emissions by 36% (compared to LOS A), and NOx emissions by 10%. For comparison, the idealized constant-speed traffic case is also shown.

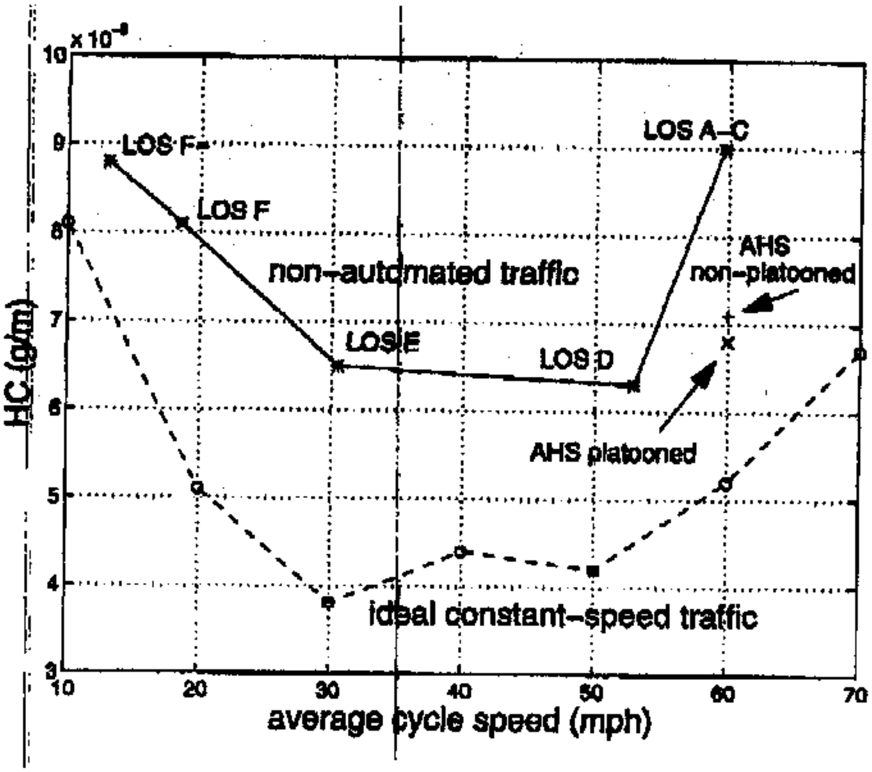


Figure 3. Average vehicle hydrocarbon emissions versus average cycle speed.

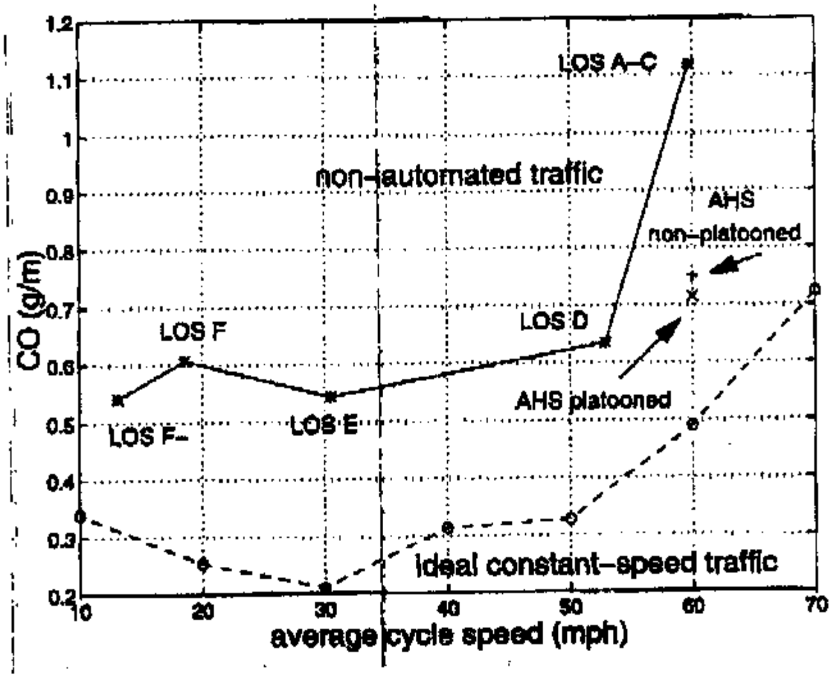


Figure 4. Average vehicle carbon monoxide emissions versus average cycle speed.

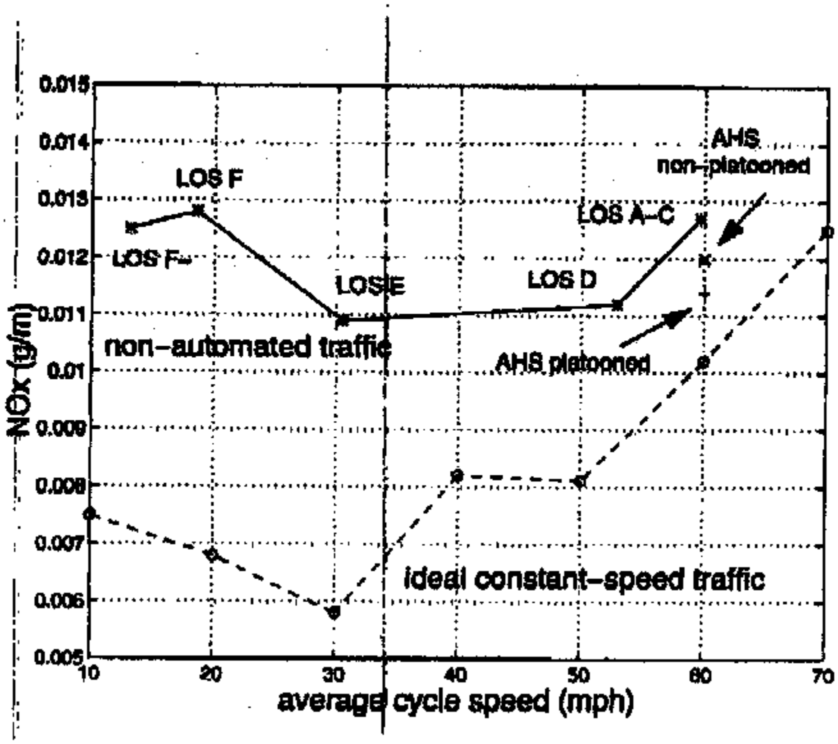


Figure 5. Average vehicle oxides of nitrogen emissions versus average cycle speed.

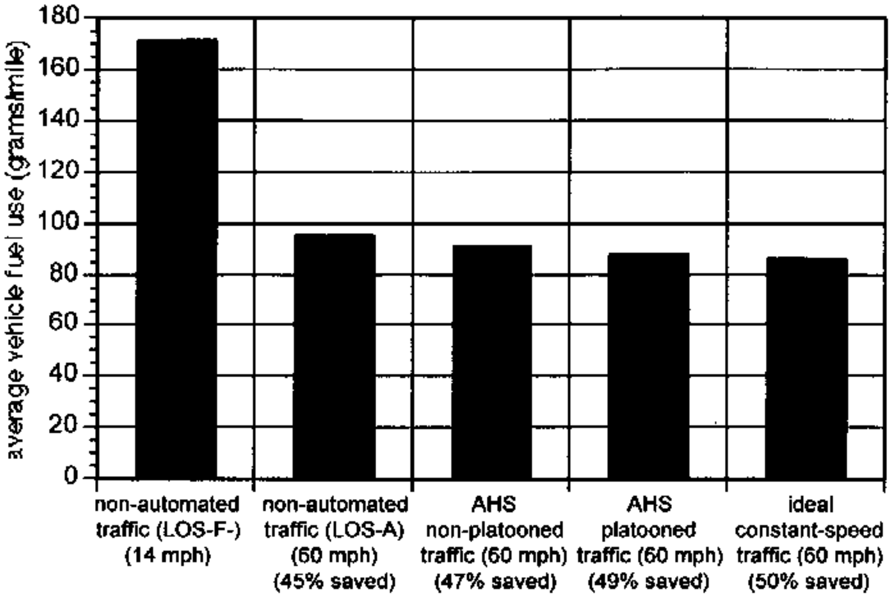


Figure 6. Fuel consumption comparison among various scenarios.

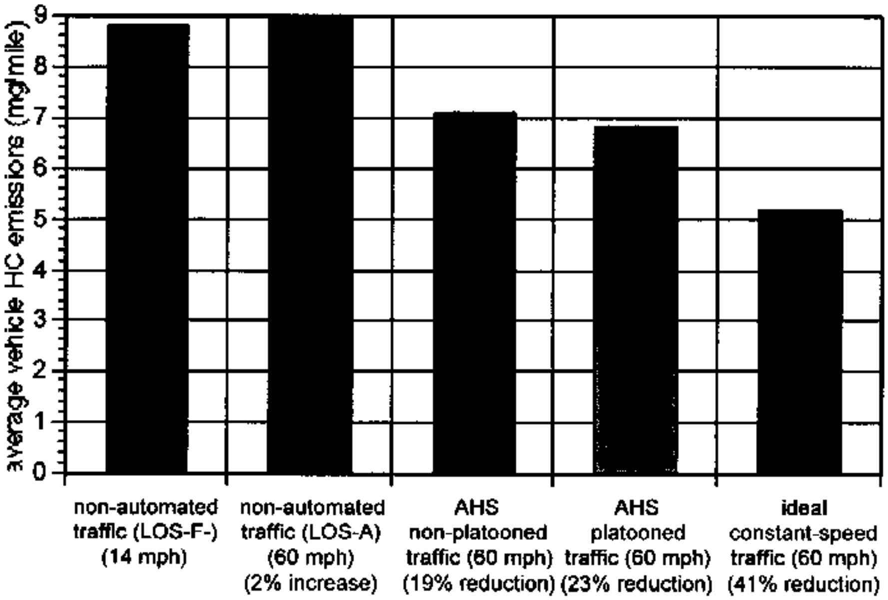


Figure 7. Hydrocarbon emissions comparison among various scenarios.

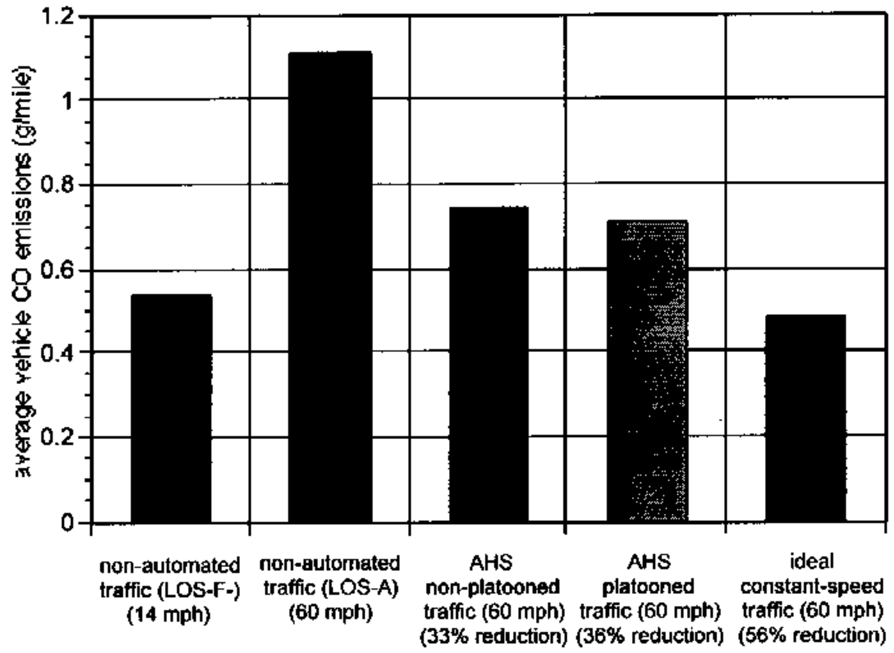


Figure 8. Carbon monoxide emissions comparison among various scenarios.

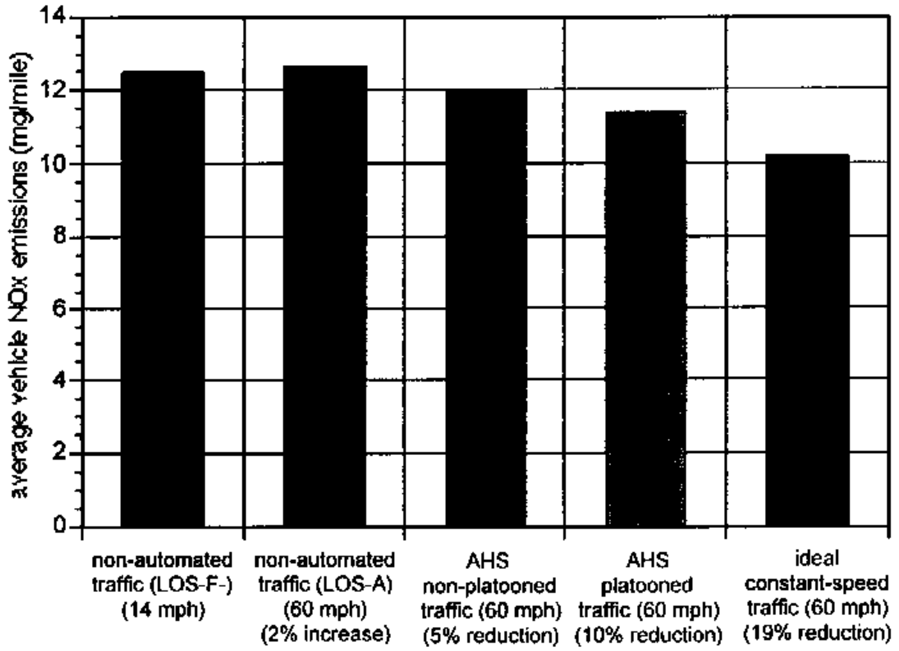


Figure 9. NOx emissions comparison among various scenarios.

It is important to note that these comparisons were made using only a single modeled vehicle. The results of other vehicles may vary greatly depending on numerous factors such as its emissions control strategy, age of the vehicle, emission certification level, etc.

5 Conclusions and Future Work

Based on this preliminary set of comparisons using a single modeled vehicle, we can make the following general conclusions:

- An AHS has slightly lower average fuel consumption than a non-automated highway operating at free-flow, and much lower average fuel consumption than a non-automated highway operating under congested conditions, because of its smoother traffic flow.
- An AHS operating at 60 mph has substantially lower emissions per vehicle-mile traveled than non-automated traffic at the same average speed, because of its smoother traffic flow.
- Vehicles that platoon in an AHS can expect an additional 5 - 15% fuel savings and emission reduction due to the aerodynamic drafting effect, which is dependent on the intra-platoon vehicle spacings.

When the comprehensive modal emission model described in Section 2.2 is complete, it will be possible to perform the same comparisons using many different types of vehicles, including "composite" vehicles that represent specific vehicle/technology categories or even an average fleet. Also, the platooning analysis can be further refined, using variable vehicle spacings as part of the overall AHS strategy.

Another area of research to explore is to change the operating parameters of the AHS to minimize energy consumption and emissions, while still maintaining a high degree of safety and capacity.

6 References

An, F., M. Barth, M. Ross, and J. Norbeck. 1997. "The development of a comprehensive modal emissions model: operating under hot-stabilized conditions", to appear, *Transportation Research Record* No. 1587, Transportation Research Board, National Academy of Science, October 1997.

Antoniotti, M., et al., "Microsimulation Analysis of Multiple Merge Junctions under Different ITS/AHS Policies", to appear, *IEEE Conference on Intelligent Transportation Systems*, Boston, MA, November 1997.

Barth, M., et al., "Modal Emissions Modeling: A Physical Approach", *Transportation Research Record* No. 1520, pp. 81-88, Transportation Research Board, National Academy of Science, August 1996.

Barth, M., T. Younglove, T. Wenzel, G. Scora, F. An, M. Ross, and J. Norbeck. "Analysis of modal emissions from a diverse in-use vehicle fleet", to appear, *Transportation Research Record* No. 1587, Transportation Research Board, National Academy of Science, October 1997.

Deshpande, A. *AHS Components in SHIFT.* California PATH Research Report, 1997a. http://www.path.berkeley.edu/smart-ahs

Deshpande, A. et al., *SHIFT Programming Language and Run-Time System for Dynamic Networks of Hybrid Automata*, California PATH Research Report, UCB-ITS-PRR-97-7, 1997b. http://www.path.berkeley.edu/shift

Sierra Research, "Development of Speed Correction Cycles", US EPA Document Number M6.SPD.001, June, 1997.

TRB, *Highway Capacity Manual - Special Report 209*, Transportation Research Board, National Academy of Science, 1994.

US EPA, "Support Document to the Proposed Regulations for Revisions to the Federal Test Procedure", US EPA technical report, Office of Air and Radiation, 1995.

10.4.10 THIS SECTION INTENTIONALLY LEFT BLANK

10.4.11 AHS Rear-end Crash Mitigation Benefits

Authors, R. Sengupta, D. Godbole

10.4.11.1 Introduction

One important way of evaluating the safety benefits of an automated highway is to estimate the number of crashes that might occur on an automated highway per year of operation. Such an estimate may be quantified in financial terms by multiplying it by the cost per crash. For example, we know from [3] that there were 1.66 million rear-end crashes in the year 1994 that cost a total of 35.4 billion dollars. We also know from [9] that these 1.66 million rear-end crashes corresponds to $2,347,295,000,000$ vehicle miles travelled. We hypothesize a baseline highway with a corresponding operating environment (weather, obstacles, etc.) and demand level (vehicle miles travelled per year of operation, average vehicles per hour, average trip length, etc.) Statistics such as those cited may be used to estimate the number of crashes expected to occur on the baseline highway per year of operation. Alternatively, if the baseline is some actual highway then the number of crashes per year of operation could be obtained from the corresponding crash statistics. We are interested in estimating the expected number of crashes per year of operation if the baseline highway were to be replaced by an automated highway servicing the baseline demand in the baseline operating environment. The subsequent development shows how the probability of a collision in the hard braking emergency scenario may be used to obtain such an estimate.

We restrict our crash mitigation estimation to rear-end crashes occurring on limited access freeways in LVD scenarios. A LVD event is usually a response to another event. Moreover, LVD can be a string phenomenon, i.e., a vehicle in a string decelerates because the one in front of it decelerates. We assume that any string of LVD's is caused by

1. an obstacle appearing on the highway and the first vehicle approaching the obstacle decelerating in response to it, or
2. a vehicle failing (no fuel, tire-blowout, etc.) on the highway and the first vehicle approaching the failed vehicle decelerating in response to it, or
3. an inattentive or careless drivers on the highway braking harder than usual in response to normal highway conditions, or causing cut-in disturbances during lane changes,
4. string instabilities, wherein comfortable braking in response to normal traffic is amplified by following vehicles to cause LVD's as the disturbance propagates through the vehicle string.

Obstacles, vehicle failures, inattentive drivers, and string instabilities are hazards. Note that one occurrence of a hazard may cause occurrence of more than one LVD.

10.4.11.2 Modeling

Assume the existence of a baseline highway and a baseline year for it. Let H_b denote the set of LVD causing hazards that occurred in the baseline highway in the baseline year. H_b may be partitioned as $H_b = H_b^c \uplus H_b^{nc}$, where H_b^c and H_b^{nc} are the sets of LVD causing hazards that did and did not cause rear-end crashes. The set H_b^c for the baseline highway may be known by collecting and analyzing accident data for the baseline highway. The set H_b^{nc}, possibly considerably more numerous, is very difficult to know. It represents the LVD occurrences in which drivers successfully evaded crashes by timely and intelligent action.

It is expected that the number of crashes on an automated highway will be directly proportional to the number of LVD causing hazards that occur. Since the baseline and automated highways are to be compared under the same environmental conditions and demand levels, the following assumptions are made. It is assumed that the set of LVD causing obstacle occurrences is the same for baseline and automated highways. It is also assumed that the number of LVD causing vehicle failure occurrences is the same on the baseline and automated highways. This assumption is reasonable for failures such as tire blowouts, no fuel etc., that are shared by manual and automated vehicles, given identical demand levels. For the time being we ignore crashes caused by failures unique to automated vehicles. We will comment on this again at the end of the appendix. Let $H_{of} \subseteq H_b$ denote the set of LVD causing obstacle or failure hazard occurrences on the baseline and automated highways.

The other two LVD causing hazards on the baseline highway are driver inattention and string instabilities. The former set of hazard occurrences are assumed to be absent on the automated highway for obvious reasons. With regard to the latter, we assume that the stable operation of automated vehicle strings is an AHS design requirement. For the technological feasibility of designing vehicle following systems that attenuate longitudinal disturbances as they propagate through a vehicle string (i.e., string stability) refer to [1]. For these reasons, it is assumed that LVD's caused by string instabilities are negligible on the automated highway. Thus H_{of} represents the set of LVD causing hazard occurrences on the automated highway. Accordingly, the expected number of automated highway crashes n_a is given by

$$n_a = \sum_{h \in H_{of}} p_a(REC \| h),$$

where $p_a(REC\|h)$ is the probability that there is a rear-end crash on the automated highway given the hazard occurrence h. It is assumed a hazard occurrence h is associated with a sequence $\langle v_{mk}^h, r_{mk}^h, \dot{r}_{mk}^h, d_{mk}^h, d_{mk}^{h,max} \tau_{mk}^h \rangle_{k=1}^{k=n_b^h}$, where the respective terms are the speed, range, range-rate, deceleration, deceleration capability, and reaction delay of the $k-$th follower of the obstacle or failed vehicle. n_b^h is the number of LVD's caused by the hazard occurrence h.

Let $H_{of} = H_{of}^c \uplus H_{of}^{nc}$, where H_{of}^c and H_{of}^{nc} are the set of hazards in H_{of} that respectively did and did not cause crashes on the baseline highway. We assume for all $h \in H_{of}^{nc}$ that $p_a(REC\|h) = 0$. This assumption imposes a challenging set of design requirements on the AHS which may be understood in the following manner. For each $h \in H_{of}^{nc}$ the vehicle and roadway capabilities are such that for each LVD caused by the hazard occurrence h, there exists a set of crash avoiding vehicle trajectories that may be realized by braking or lane changing. Furthermore, the driver is able to find and execute one such feasible crash avoiding trajectory. Since the automated vehicle reacts much faster, has better speed regulation, never follows at closer than the set headway, and never goes faster than the set speed, it may be argued that if there exists a crash avoiding feasible trajectory for the manual vehicle, there exists one for the automated vehicle. This argument is similar to that used in [2, 3] for estimating the crash mitigation properties of adaptive cruise control and longitudinal crash warning systems. Benefit assessment relies on a thought experiment that replaces the manual vehicle in every LVD occurrence by an automated vehicle, and assumes (amongst other assumptions) that at the time the LVD starts

- if the manual vehicle was at a speed less than the set automated speed, then the automated vehicle would also be at the same speed, and

- if the manual vehicle was at a range greater than the set automated headway, the automated vehicle would also be at the same range.

Further research and design is required to ensure that partially or fully automated vehicles conform to these behavioral assumptions. Moreover, to justify $p_a(REC\|h) = 0$ for fully automated vehicles, one must also assume that just as the driver was able to find and execute a feasible crash avoiding trajectory, the automated vehicle controllers will also be able to do the same. This is one of the fundamental, and as yet partially solved problems of automated vehicle control design. For reasearch on automated situation assessment required for safety refer [6, 7]. For reasearch on automated emergency lane change maneuvers refer [4, 5].

It should be note that an immediate consequence of the assumption $p_a(REC\|h) = 0$ for all $h \in H_{of}^{nc}$ is that the expected number of crashes for the automated highway will not be greater than the number of crashes on the baseline highway. The next section establishes an upper bound on the magnitude of improvement.

10.4.11.3 Analysis

We begin with the statement

$$n_a = \sum_{h \in H_{of}} p_a(REC\|h).$$

$p_a(REC\|h) = 0$ for all $h \in H_{of}^{nc}$ implies

$$n_a = \sum_{h \in H_{of}^{c}} p_a(REC\|h).$$

Let l_k^h denote the $k-$th LVD associated with the hazard occurrence h. Then

$$n_a = \sum_{h \in H_{of}^{c}} \sum_{k=1}^{k=n_a^h} p_a(REC\|l_k^h),$$

where n_a^h is the number of $LVD's$ caused by the hazard occurrence h and $p_a(REC\|l_k^h)$ is the probability that the first rear-end crash occurs in the $k-$th LVD, or between the $(k+1)-$th and $k-$th followers. Recall that h on the baseline highway was associated with a sequence $\langle v_{mk}^h, r_{mk}^h, \dot{r}_{mk}^h, d_{mk}^h, d_{mk}^{h,max}, \tau_{mk}^h \rangle_{k=1}^{k=n_b^h}$. Likewise $p_a(REC\|l_k^h)$ depends on the values $(v_{ak}^h, r_{ak}^h, \dot{r}_{ak}^h, d_{ak}^h, d_{ak}^{h,max}, \tau_{ak}^h)$ for $k = 1 \ldots n_a^h$. Let v_0 be the set speed, r_0 be the space headway at the speed v_0, ρ_{max} be the maximum velocity tracking error under normal traffic conditions, and τ_r be the maximum reaction delay of the automated vehicle. Then

$$p_a(REC\|l_{k-1}^h) = p_a(REC\|v_{ak}^h, r_{ak}^h, \dot{r}_{ak}^h, d_{a(k-1)}^h, d_{ak}^{h,max}, \tau_{ak}^h) \leq p_a(REC\|v_0, r_0, \rho_{max}, d_{a(k-1)}^h, d_{ak}^{h,max}, \tau_r),$$

since the automated vehicle will not exceed the set speed, come closer than the set headway, exceed the maximum range-rate error or the maximum delay. Since the crash probabilities increase monotonically with $d_{a(k-1)}^h$, we know that

$$p_a(REC\|v_0, r_0, \rho_{max}, d_{a(k-1)}^h, d_{ak}^{h,max}, \tau_{max}) \leq p_a(REC\|v_0, r_0, \rho_{max}, d_{a(k-1)}^h = d_{a(k-1)}^{h,max}, d_{ak}^{h,max}, \tau_r),$$

which is the probability of a crash in the hard braking emergency given that the $(k-1)-$th vehicle has a deceleration capability $d_{a(k-1)}^{h,max}$. Therefore

$$n_a \leq \sum_{h \in H_{of}^c} \sum_{k=1}^{k=n_a^h} p_a(REC \| v_0, r_0, \rho_{max}, d_{a(k-1)}^h = d_{a(k-1)}^{h,max}, d_{ak}^{h,max}, \tau_r).$$

We establish an upper bound on n_a^h. Recall that $p_a(REC \| l_k^h)$ is the probability that the first crash occurs between the $(k+1)-$th and $k-$th vehicles. We will find an n such that if the first crash has not occurred at or before the $(n-1)-$th and $n-$th vehicles, then the probability that it will occur after that is negligible. In an LVD vehicle pair, let d_l denote the deceleration of the lead vehicle and d_f the deceleration of the following vehicle required to come to a stop just behind the lead vehicle, if the lead vehicle brakes until it comes to rest at the rate d_l. Then if the time headway τ_{head} is sufficiently large compared to the response time τ_r, and neglecting the small range-rate errors, d_l and d_f may be related by the equation

$$\frac{v_0^2}{2d_l} + v_0 \tau_{head} = \frac{v_0^2}{2d_f} + v_0 \tau_r,$$

which implies

$$d_f = \frac{v_0 d_l}{v_0 + 2d_l(\tau_{head} - \tau_r)}.$$

We assume that in every LVD pair the follower vehicle brakes just as hard as necessary to avoid a crash. i.e., if the lead vehicle brakes at the rate d_l then the follower vehicle will brake at the rate d_f as determined by the above equation. Observe that the derivative of d_f w.r.t. d_l is positive on the interval $[0, \infty)$. Therefore increasing d_l, increases d_f. Consider the sequence of decelerations $(d_{ak}^h)_{k=1}^{n_a^h}$. The positive derivative implies that maximizing d_{a1}^h maximizes d_{a2}^h, which maximizes d_{a3}^h and so on. Thus maximizing d_{a1}^h maximizes the disturbance propagation and the value of n_a^h. From the braking distribution described in [8], we know that the deceleration capabilities of the vehicles lie in the range $[0.4g, 1g]$. Setting $d_{a1}^h = 10m/s^2$ we obtain $d_{a2}^h = 6.8m/s^2, d_{a3}^h = 5.2m/s^2$, and $d_{a4}^h = 4.1m/s^2$, with $v_0 = 30m/s$, $\tau_{head} = 1sec$, and $\tau_r = 0.3sec$. Therefore it is assumed that if the first, second and third vehicles did not hit each other, then the probability that the fourth vehicle will hit the third vehicle is negligible, i.e., $p_a(REC \| l_k^h) = 0$ for $k > 3$. Accordingly,

$$\begin{aligned} n_a &\leq \sum_{(h,k) \in H_{of}^c \times \{1,2,3\}} p_a(REC \| v_0, r_0, \rho_{max}, d_{a(k-1)}^h = d_{a(k-1)}^{h,max}, d_{ak}^{h,max}, \tau_r) \\ &= \sum_{d_l^{max}, d_f^{max}} p_a(REC \| v_0, r_0, \rho_{max}, d_l = d_l^{max}, d_f = d_f^{max}, \tau_r) n_{d_l^{max}, d_f^{max}}, \end{aligned}$$

where $n_{d_l^{max}, d_f^{max}}$ is the number of vehicles with capability (d_l^{max}, d_f^{max}) in the LVD set $H_{of}^c \times \{1,2,3\}$. But $n_{d_l^{max}, d_f^{max}} = 3|H_{of}^c| p_{d_l^{max}, d_f^{max}}$, where $p_{d_l^{max}, d_f^{max}}$ is the probability that a vehicle pair on the highway has deceleration capability (d_l^{max}, d_f^{max}). Denoting $p_a(REC \| v_0, r_0, \rho_{max}, d_l = d_l^{max}, d_f = d_f^{max}, \tau_r)$ by $p_a^{nom}(d_l^{max}, d_f^{max})$ we obtain

$$\begin{aligned} n_a &\leq \sum_{d^{max}} p_a^{nom}(d_l^{max}, d_f^{max}) 3|H_{of}^c| p_{d_l^{max}, d_f^{max}}, \\ &= 3|H_{of}^c| \sum_{d^{max}} p_a^{nom}(d_l^{max}, d_f^{max}) p_{d_l^{max}, d_f^{max}}, \\ &= 3|H_{of}^c| p_a^{nom,hb}, \\ &\leq 3 p_a^{nom,hb} |H^c|, \end{aligned}$$

where $p_a^{nom,hb}$ denotes the crash probability in the hard braking emergency for the nominal values $v_0, r_0, \rho_{max}, \tau_r$, and $|H_c|$ is the number of rear-end crash incidents that occurred on the baseline highway as obtained from accident records.

It is shown in the safety analyses doumented in [8] that for $v_0 = 30m/s, r_0 = 30m$ ($\tau_{head} = 1sec$, pipeline capacity 3600vphpl), $p_a^{nom,hb}$ is 0.054. This says that no more than 16% of the crashes on the baseline highway would have occurred if the baseline highway had been replaced by an automated highway with a separation policy defined by 1 second headway.

We mentioned earlier that an automated highway may experience crashes due to vehicle and highway failures that do not occur on the baseline highway. This analysis tells us that as long as the fault tolerance of the AHS is such that the expected number of the new fault induced crashes does not exceed $0.84|H_c|$, the safety of the AHS, as measured by the expected number of rear-end crashes, will surpass that of the baseline highway.

10.4.11.4 Summary

We have estimated the rear-end crash mitigation benefits of a fully automated highway system that carries individual vehicles on dedicated lanes. This estimate is derived by extending the hard braking safety analyses conducted during task C2. The rear-end crash mitigation benefits are expressed as a percentage of those that might occur on a baseline manual highway.

A rear-end crash involves a front and a rear vehicle. The estimation is restricted to rear-end crashes that are caused by sudden deceleration of the front vehicle. We refer to this as a rear-end crash (REC) that occurs in the LVD (lead vehicle decelerating) scenario. Accident statistics indicate that this is a significant class of rear-end crashes [3].

The estimation is conditioned on a variety of design requirements imposed upon the AHS. We caution that these requirements are non-trivial and only partially researched. However, under these assumptions we have established that the rear-end crash mitigation benefits of a dedicated lane carrying fully automated vehicles are very significant.

References

[1] Swaroop, D., *String Stability of Interconnected Systems - Application to platooning in Automated Highway Systems* PhD dissertation, U.C. Berkeley (1995).

[2] Farber E., *Using the REMACS Model to Compare the Effectiveness of Alternative Rear End Collision Warning Algorithms* Proceedings of the Annual Meeting of IVHS America, Volume 1, 1994, Washington DC.

[3] NHTSA Benefits Working Group, *Preliminary Assessment of Crash Avoidance Systems Benefits* NHTSA Office of Crash Avoidance Research, October 1996, Washington DC.

[4] Hagenmeyer V., Godbole D.N., Sengupta R., *Obstacle avoidance for AHS* Submitted to 97th IEEE Conference on Decision and Control, San Diego, California.

[5] Sundar S., Shiller Z., *Emergency Manœuvres for AHS Vehicles* Systems and Issues in ITS, Warrendale PA, 1995.

[6] Sukthankar S., *Situation Awareness for Tactical Driving* Phd Thesis, January 1997, Carnegie Mellon University, Pittsburgh.

[7] Huang T., Ogasawara O., Russell S., *Symbolic traffic scene analysis using dynamic belief networks* Institute of Transportation Studies, University of California, California PATH, [1993] PATH technical memorandum ; 93-8.

[8] Shladover S.E., *National Automated Highway System Consortium Milestone 2 Report: Task C2 Downselect System Configuration* National Automated Highway System Consortium, February 1997, Detroit.

[9] Martinez R., *Traffic Safety Facts 1994* NHTSA, August 1995, Washington D.C.

10.4.12 Design of Emergency Maneuvers for Automated Highway System: Obstacle Avoidance Problem

Authors, V. Hagenmeyer, D. Godbole, R. Sengupta

10.4.12.1 Introduction

In this appendix, we analyze the problem of obstacle avoidance in an Automated Highway System (AHS). For a given scenario (traffic state, obstacle location, etc.), we synthesize the best possible avoidance maneuver for each vehicle. Our aim is to obtain a distributed strategy so that the obstacle avoidance maneuvers can be executed by vehicle based controllers (with some inter-vehicle communication) as opposed to a roadside controller making decisions and communicating it to the individual vehicles. The models and algorithms used for design are also coded as software that can be used as an obstacle analysis tool. The tool can be used to derive minimum obstacle clearing distances from assumptions on the capabilities of the automated vehicle.

We restrict attention to the design of emergency maneuvers for fully automated vehicles on a dedicated lane. Emergencies arise in an AHS primarily due to faults and system intrusions. The management of AHS malfunctions is extensively discussed in [1] and [2]. The management of system intrusions has received less attention. An important class of system intrusions is represented by obstacles on the AHS roadway and it is desirable that the automated vehicles have obstacle avoidance capabilties. This appendix is concerned with the design of obstacle avoidance maneuvers.

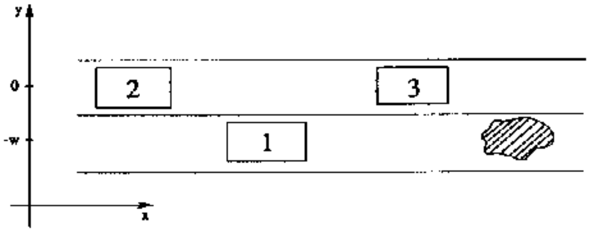


Figure 10.4.12.1: The three vehicles problem for gap selection

The general obstacle avoidance scenario is as shown in figure 10.4.12.1. Vehicle 1 must avoid the obstacle. We refer to it as the principal vehicle. The principal vehicle can try to stop or change lanes. The selected maneuver must be executed in a safe and comfortable manner. If the obstacle is sensed at a large range the vehicle should execute either a *normal stop* or a *normal lane change*. If the obstacle is sensed at short range then safety considerations predominate over comfort and the vehicle should execute either an *emergency stop* or an *emergency lane change*. Thus we assume that there are four maneuvers to choose from. The emergency maneuvers involve braking or steering as hard as possible.

The vehicle should select the appropriate maneuver by estimating the distance required for each maneuver. If a comfortable lane change is possible then it is preferred since it will permit the vehicle to continue its journey. If the distance required for this is too great but comfortable stopping is an option then this is to be preferred over either of the emergency maneuvers. If the comfortable maneuvers are not feasible then the principal vehicle should estimate its minimum stopping distance and the minimum emergency lane change distance and pick the maneuver requiring the smaller longitudinal distance.

If a vehicle can estimate its deceleration capability then the estimation of stopping distance is a simple kinematic problem. We will not concern ourselves here any further with the estimation of stopping distance. For deceleration capability estimation refer [3]. In the rest of this appendix we will address the problem of estimating the distance or time required for normal and emergency lane changes. We shall do this by designing an optimal trajectory for each maneuver as a function of the capabilities of the principal vehicle and the prevailing traffic conditions. We shall also require that the optimal trajectory be safe in the sense that the principal vehicle should not strike neighbouring vehicles during the maneuver or depart the roadway.

It should be noted that if the lane of the principal vehicle has a shoulder adjacent to it, the principal vehicle should change lanes onto the shoulder. This is simpler since one does not have the difficulties of avoiding traffic in the target lane. However, in our approach, changing lanes onto the shoulder is a special case of changing lanes in traffic. Therefore the general scenario represented by figure 10.4.12.1 is addressed first. We refer to the lane of vehicle 1 as the *source lane* and that of vehicles 2 and 3 as the *target lane.* The gap defined by vehicles 2 and 3 is assumed to be the *target gap.* Vehicle 3 is the *front vehicle of the gap* and vehicle 2 is the *rear vehicle of the gap.* The lane change maneuver begins in the source lane and ends with vehicle 1 being inbetween vehicles 2 and 3, and aligned with the centerline of the target lane.

In general, the principal vehicle has more than one target gap to choose from. We refer to this as the *gap selection* problem. The gap selection problem is to be solved by solving a series of trajectory design problems for each gap and then picking the gap associated with the lowest cost trajectory. The rest of the appendix discusses the trajectory design problem for a given gap.

10.4.12.1.1 Trajectory Design Methodology

We use an optimal control approach. For normal lane changes (NLC) we design a trajectory that is efficient in terms of the time required for the lane change. For emergency lane changes (ELC) on the other hand we design a trajectory that is efficient in terms of the longitudinal distance travelled during the lane change. We attempt to minimize the distance travelled towards the obstacle during the lane change.

The vehicles are modeled as point masses. The equations of motion are kinematic. The control inputs are the longitudinal and lateral accelerations. The longitudinal and lateral accelerations are assumed to be elliptically constrained ([4]) in a manner related to the tyre friction ellipse. Thus the optimal trajectory accounts for vehicle capability constraints thereby ensuring that the vehicle will not depart the roadway during the ELC. For NLC, we assume that the longitudinal and lateral forces are constrained by a comfortable rectangle within the ellipse. Thus the control inputs are decoupled and the trajectory design problem is simpler. It is assumed that vehicles must not travel backwards on the highway. We neglect actuator delays and lags in the dynamics though we do account for them in certain other constraints discussed later.

It is desirable that the principal vehicle not collide with the target gap vehicles during the lane change. Vehicle 3 might brake gently while the lane change is in progress in response to normal traffic disturbances or it might brake hard because the obstacle moves into its lane. If the maneuver trajectory is not suitably designed such braking disturbances will result in rear-end or sideswipe crashes. We propose to mitigate such crashes by requiring that the principal vehicle be properly aligned with the target gap before it begins to moveover. Thus for a lane change maneuver we design a *gap alignment trajectory* followed by a *moveover trajectory.* In the special case of the vehicle changing lanes onto a road shoulder, the alignment phase is not required. The moveover trajectory is designed as discussed for the general case.

The precise meaning of proper alignment is as follows. We provide a parameter in the trajectory design process that models a bound on the braking disturbances generated by the front vehicle of the gap. In other words, it is required that if the front vehicle of the gap generates any disturbance trajectory within the bound, the principal vehicle should be capable of responding with a control trajectory that will avoid collision with the front vehicle of the gap. Likewise, we require that for any control trajectory generated by the principal vehicle during the lane change, the rear vehicle of the gap should be capable of generating a control trajectory that will avoid collision with the principal vehicle. In general, these conditions can only be satisfied by deliberately driving the principal and target gap vehicles into a subset of the state space. We refer to this subset as the *safe set*. The terminal state constraint for the gap alignment trajectory is the safe set. Since moveover follows gap alignment, it always commences from an initial state in the safe set.

We provide an analytical derivation of the safe set. The derivation assumes point-mass models of the vehicles. Accelerations are assumed to be controllable subject to certain bounds and a pure time delay. This delay parameter can be used to account for vehicle sensing and actuation delays.

It should be noted that the alignment and moveover trajectories are optimized separately, i.e., first we calculate an optimal gap alignment trajectory and then use its terminal state as an intial state to calculate the moveover trajectory. The concatenation of the two pieces is the final maneuver trajectory. The concatenated trajectory, though hopefully efficient, is not necessarily optimal in the set of all possible concatenated trajectories.

10.4.12.1.2 Literature Review

The obstacle avoidance problem has been studied in the literature. We present a brief review in this section.

Optimal lane change maneuver trajectories are designed in [4] for lane changes onto a shoulder. A bicycle model of the car with independent constraints on lateral and longitudinal acceleration is used to calculate emergency lane change trajectories for obstacle avoiadance. In this appendix we consider the more general problem of designing trajectories for obstacle avoidance in traffic, albeit with a simpler vehicle model.

In [5], a simplified point mass model is used to classify crashes arising due to unsafe, uncoordinated lane changes. The classification is then used to provide insight into the design of collision avoidance and driver warning systems for partially automated driving applications. The work of Schuster [6] analyzes obstacle avoidance on an AHS. The impact of longitudinal braking disturbances on trajectory design is not considered in [6]. For a given set of system parameters, the optimal obstacle avoiadance trajectory is found by simulating different parametrized trajectories. The approach used here is more analytical.

10.4.12.2 Problem Formulation

We model the vehicles kinematically; the indices refer to the vehicles as numbered in figure 10.4.12.1. x and y are position coordinates. The coordinates are inertial; x is the along the lanes, and y is orthogonal to the lanes. The intial conditions are

$$\begin{array}{ccc} x_i(0) = x_{i0}, & \dot{x}_i(0) = \dot{x}_{io}, & i = 1,2,3, \\ & \dot{y}_i(0) = 0, & i = 1,2,3, \\ y_{10} = -w, & y_{20} = 0, & y_{30} = 0. \end{array}$$

The parameter w is the width of a lane. The control inputs are the lateral and longitudinal accelerations represented by $u_{i,lat}$ and $u_{i,long}$ respectively for the i-th vehicle. Since the vehicles in the upper lane will not move laterally, we ignore their lateral dynamics. The dynamical system is linear and time invariant. In state space form it is

$$\dot{x} = \frac{d}{dt}\begin{bmatrix} \Delta x_{31} \\ \Delta \dot{x}_{31} \\ \Delta x_{12} \\ \Delta \dot{x}_{12} \\ \dot{x}_1 \\ y_1 \\ \dot{y}_1 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} x$$

$$+ \begin{bmatrix} 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & -1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u_{1,long} \\ u_{2,long} \\ d \\ u_{1,lat} \end{bmatrix} \qquad (10.4.12.1)$$

Note that the disturbance d models $u_{3,long}$. Since it is required that vehicles not travel backwards, we impose the state constraint

$$\dot{x}_i \geq 0 \ \forall t, i = 1,2,3.$$

The control constraints are as follows. We assume that the forces vehicle 1 is able to effect on the road in x- and y-direction are constrained by the ellipse

$$\frac{u_{1,long}^2}{\alpha_1^2} + \frac{u_{1,lat}^2}{\beta_1^2} \leq 1. \qquad (10.4.12.2)$$

Since vehicles 2 and 3 have no lateral motion the ellipse flattens for these vehicles into the interval

$$-\alpha_i \leq u_{i,long} \leq \alpha_i; \quad i = 2,3. \qquad (10.4.12.3)$$

Note that the above equation also constrains the disturbance input. Since lateral motion does not start before gap alignment is complete, no lateral forces are developed by vehicle 1 during the alignment stage. Accordingly equation 10.4.12.2 is also replaced by its corresponding interval for design of the alignment trajectory.

In contrast to the ELC, for the NLC we assume, that the acceleration constraints are not the tyre ellipse (10.4.12.2). They are described by some comfortable rectangular area within the ellipse. Thus the acceleration constraints are

$$\begin{array}{rcl} a_{i,l} & \leq & u_{i,long} \leq a_{i,u}, \quad i = 1,2,3 \qquad (10.4.12.4) \\ b_{i,l} & \leq & u_{i,lat} \leq b_{i,u}, \quad i = 1,2,3 \qquad (10.4.12.5) \end{array}$$

We assume $b_{i,l} = -b_{i,u}, \; b_{i,u} \geq 0$.

In the following two subsections we discuss the cost functions and the terminal state constraints for the alignment and moveover trajectory design problems.

10.4.12.2.1 The Gap Alignment Problem

For nomal lane change gap alignment we design a minimum time alignment trajectory with the controls subject to rectangular constraints determined by comfortable acceleration limits. The cost function is

$$J = \int_0^{t_{f,a}} 1 \; d\tau. \tag{10.4.12.6}$$

For emergency lane change gap alignment we design a minimum distance alignment trajectory with the controls subject to vehicle capability constraints, i.e., the vehicle is permitted to decelerate or accelerate as hard as possible. The cost function is

$$J = \int_0^{t_{f,a}} \dot{x}_1 \; d\tau. \tag{10.4.12.7}$$

As stated in the introduction the alignment trajectory should terminate with the three vehicles in a state in the safe set. We next present a mathematical definition of the safe set.

10.4.12.2.1.1 The Safe Set

The safe set is a subset of the state space. We have noted earlier that for a pair of vehicles that overlap laterally and are following each other longitudinally, safety means that for any disturbance that the front vehicle is capable of generating, the following vehicle should be capable of generating a control response that will avoid a collision. For the dynamical system described by equation 10.4.12.1, it is shown in [7], that the worst disturbance generated by the vehicle in front is the application of its brakes as hard as possible until it comes to rest, to which the best control response of the following vehicle is to apply its brakes as soon and as hard as possible until it too comes to rest. Therefore the safe set is the set of all states from which on application of maximum braking by the front vehicle, the rear vehicle is able to prevent a collision by also applying maximum braking with a certain reaction delay. We refer to this notion of safety as *hard braking safety*. These observations, proven in [7], provide a set of necessary and sufficient conditions that can be used to define the safe set.

Another way of defining the safe set is given in [8]. This derivation assumes the same braking and acceleration abilities for both vehicles. We believe this is unduly restrictive though considerably simpler. In this appendix we make no such assumption.

Since we are dealing with a three vehicle problem we require that two sets of hard braking safety conditions be satisfied (see figure 10.4.12.2). Vehicle 1 must be safe against braking disturbances generated by vehicle 3 and vehicle 2 must be safe against braking disturbances generated by vehicle 1. If these two sets of conditions are satisfied then for any disturbance generated by vehicle 3, vehicle 1 may avoid collision by using any control of which it is capable, and in turn vehicle 2 will remain capable of a control trajectory that will avoid collision with vehicle 1. We describe the safe set conditions for a generic vehicle pair. The conditions are the same for the second pair.

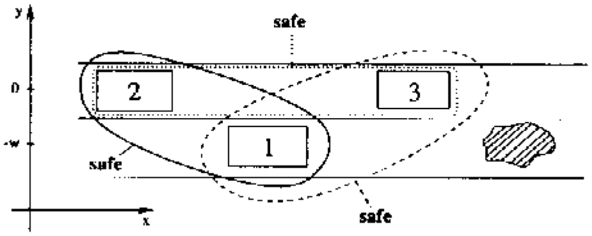


Figure 10.4.12.2: Pairwise safety as the end constraint of the alignment state

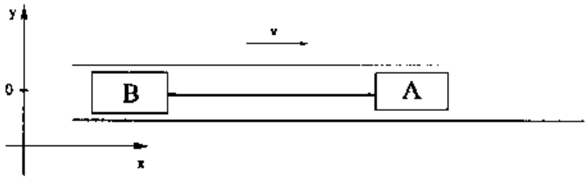


Figure 10.4.12.3: The two vehicles problem for pairwise longitudinal safety

Consider two vehicles that overlap laterally (see figure 10.4.12.3). The front vehicle is designated A and the rear vehicle is designated B. The state is denoted

$$z = (\Delta x, \Delta\dot{x}, \dot{x}_B)^T, \tag{10.4.12.8}$$

where $\Delta x = x_A - x_B$ and $\Delta\dot{x} = \dot{x}_A - \dot{x}_B$. We assume that the acceleration of the vehicles is within the interval $[a_{i,l}, a_{i,u}]$, $i = A, B$. Furthermore, at time $t = 0$ vehicle A starts braking at the rate $a_{A,l}$ and vehicle B reacts to this maneuver with delay $t = \delta$, and brakes at the rate $a_{b,l}$. The stoppin times of the vehicles, assuming that they do not collide, are

$$\begin{aligned} t_A &= -\frac{\dot{x}_A(0)}{a_{A,l}} && (10.4.12.9) \\ t_B &= \delta - \frac{\dot{x}_B(\delta)}{a_{B,l}} = \delta - \frac{\dot{x}_B(0) + \ddot{x}_{B0}\delta}{a_{B,l}}, && (10.4.12.10) \end{aligned}$$

where $\ddot{x}_{B0} = const > 0$ is an allowance for acceleration by vehicle B in the time interval $[0, \delta]$.

The set of safe states is the set of all states for which the trajectory has the property

$$\{z_0 : \Delta x(t; z_0) \geq 0, \; t \in [0, t_B]\}. \tag{10.4.12.11}$$

A state is an element of the safe set if and only if the state satisfies the following inequalities. If $\delta \leq t_A \leq t_B$ or $t_A \leq \delta$ then the state must satisfy

$$\begin{aligned} &\Delta x_0 - \frac{\delta^2\, \ddot{x}_{B0}}{2} + \frac{\delta^2\, \ddot{x}_{B0}^2}{2\, a_{Bl}} - \frac{\dot{x}_{A0}^2}{2\, a_{Al}} - \delta\, \dot{x}_{B0} \\ &+ \frac{\delta\, \ddot{x}_{B0}\, \dot{x}_{B0}}{a_{Bl}} + \frac{\dot{x}_{B0}^2}{2\, a_{Bl}} \geq 0, . \end{aligned}$$

If $\delta \leq t_B \leq t_A$ then the state must satisfy

$$\begin{aligned} &\Delta x_0 + \frac{\delta^2\, (a_{Al} - \ddot{x}_{B0})}{2} + \delta\, (\dot{x}_{A0} - \dot{x}_{B0}) \\ &- \frac{(a_{Al}\, \delta - \delta\, \ddot{x}_{B0} + \dot{x}_{A0} - \dot{x}_{B0})^2}{2\, (a_{Al} - a_{Bl})} > 0. \end{aligned}$$

Finally the state must always satisfy $\Delta x_0 \geq 0$.

For the derivation of these conditions refer [9]. The trajectory condition (equation (10.4.12.11)) is reduced to a condition on the initial state of the trajectory by observing that the trajectory as a whole is non-negative iff its minima are non-negative. For example if the initial state satisfies $\delta \leq t_A \leq t_B$ then the accelerations of the two vehicles are constant on the time intervals $[0, \delta], [\delta, t_A]$, and $[t_A, t_B]$. At the boundaries of the intervals the acceleration is discontinuous. However, the $\Delta x(t)$ trajectory is convex and continuous on each interval and therefore has a unique minimum on each interval. The trajectory is also twice differentiable on the interior of each interval. The equations are derived by requiring that Δx be non-negative on the boundaries of the intervals and in the interior if a minimum exists on the interior.

10.4.12.2.2 The Moveover Problem

For nomal lane change moveover we design a minimum time moveover trajectory with the controls subject to rectangular constraints determined by comfortable acceleration limits. The cost function is

$$J = \int_0^{t_{f,m}} 1 \; d\tau. \tag{10.4.12.12}$$

For emergency lane change moveover we design a minimum distance moveover trajectory with the controls subject to vehicle capability constraints, i.e., the vehicle is permitted to decelerate or accelerate as hard as possible. The cost function is

$$J = \int_0^{t_{f,a}} \dot{x}_1 \; d\tau. \tag{10.4.12.13}$$

The initial state of the moveover trajectory is in the safe set for both normal and emergency lane changes. The final state constraints for a moveover trajectory are

$$y_1(t_{f,m}) = 0, \;\; \dot{y}_1(t_{f,m}) = 0.$$

Therefore the moveover trajectory ends with the principal vehicle aligned with the centerline of the target lane and having zero lateral velocity.

10.4.12.3 Trajectory Design

In this section we describe the lane change trajectories that solve the optimal control problems formulated in the previous section. We begin with the NLC and ELC alignment problems.

10.4.12.3.1 Gap Alignment Design

Since we require that the three vehicles satisfy the hard braking safety constraints prior to the commencement of lateral motion, the lateral dynamics may be ignored in the gap alignment stage. Accordingly we analyze the following reduced order form of equation 10.4.12.1.

$$\dot{x} = \frac{d}{dt}\begin{bmatrix} \Delta x_{31} \\ \Delta \dot{x}_{31} \\ \Delta x_{12} \\ \Delta \dot{x}_{12} \\ \dot{x}_1 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} x +$$

$$\begin{bmatrix} 0 & 0 & 0 \\ -1 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & -1 & 0 \\ 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} u_{1,long} \\ u_{2,long} \\ d \end{bmatrix} \tag{10.4.12.14}$$

The initial state, terminal state, and control constraints are as previously described.

To solve the problem, we use the Pontryagin Principle [10]. The Hamiltonian for the time optimal problem is

$$H(x,p,u) = 1 + p^T(Ax + Bu). \tag{10.4.12.15}$$

From (10.4.12.14) $H(x,p,u)$ is

$$\begin{aligned} H(x,p,u) &= 1 + p_1\Delta\dot{x}_{31} + p_2 d + p_3\Delta\dot{x}_{12} - p_4 u_{2,long} + \\ & \quad (-p_2 + p_4 + p_5)u_{1,long}. \end{aligned} \tag{10.4.12.16}$$

Since the control constraints are rectangular the minimum principle yields

$$u_{1,long}(t) = -sgn(-p_2 + p_4 + p_5)|a_{1,l\vee u}| \tag{10.4.12.17}$$
$$u_{2,long}(t) = -sgn(-p_4)|a_{2,l\vee u}|, \tag{10.4.12.18}$$

which is a bang-bang control. From (10.4.12.14)and (10.4.12.16) we get

$$\dot{p} = \begin{bmatrix} 0 \\ -p_1 \\ 0 \\ -p_3 \\ 0 \end{bmatrix} \tag{10.4.12.19}$$

. whence for an initial costate $p_0 = p(0)$ we get

$$\begin{aligned} p_1(t) &= p_{10}, \\ p_2(t) &= p_{20} - p_{10}t, \\ p_3(t) &= p_{30}, \\ p_4(t) &= p_{40} - p_{30}t, \\ p_5(t) &= p_{50}. \end{aligned}$$

The p-vector (costate) is never identically 0. As p_2, p_4 and p_5 are affine, the corresponding $u_{i,long}$, $i = 1,2$ switch their bang-bang behaviour at most once. If they switch, it is at the moment when p_4 or $-p_2 + p_4 + p_5$ change signs.

We are able to show ([9]) that the optimal control for vehicle 2 is

$$u^{\star}_{2,long} = a_{2l}; \;\; t \geq 0, \tag{10.4.12.20}$$

i.e., it should brake as hard as comfortable for a NLC and as hard as possible for a ELC. We have developed a software package to compute the optimal control for vehicle 1. Since two pairwise safety conditions have to satisfied each with two equations, the package computes four trajectories and picks the lowest cost trajectory from the four as the optimal control.

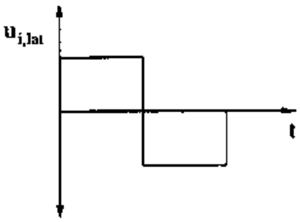


Figure 10.4.12.4: Moveover Lateral Acceleration

10.4.12.3.2 Moveover Design

In this section we describe the trajectory design process for the moveover stage. The dynamics are as described by equation (10.4.12.1), the terminal state constraints, initial state constraints, and control constraints are as previously described.

The Hamiltonian is formed as usual. It is a linear functional. The control constrains are compact and convex. From these two properties we can establish that the Hamiltonian is minimized on the boundary of the ellipse. Consequently, the optimal controls lie on the boundary of the ellipse. To obtain a sinusoidal lane change trajectory we assume that the lateral acceleration is as shown in figure 10.4.12.4.

As the lateral velocity of a vehicle is zero before and after the maneuver, the lateral acceleration a_{lat}, the lane width W and the moveover time $t_{f,m}$ are related by

$$W = \frac{a_{lat}t_{f,m}^2}{4} \qquad (10.4.12.21)$$

If the vehicle applies longitudinal deceleration a_{long} during moveover, the longitudinal distance traveled is given by

$$x = \frac{-1}{2}a_{long}t_{f,m}^2 + v_0 t_{f,m} \qquad (10.4.12.22)$$

where v_0 is the longitudinal speed at the beginning of the moveover. The lateral and longitudinal decelerations are related by the ellipse equation (10.4.12.2). The objective is to determine a_{long} and a_{lat} such that the distance traveled longitudinally in the lane of origin is minimized subject to the constraints.

The minimization problem can be solved analytically by first substituting for $t_{f,m}$ and a_{long} in equation (10.4.12.22) by using the other two relationships. Now, by setting the derivative of x w.r.t. a_{lat} to zero, the following cubic equation is obtained.

$$v_0^2 a_{lat}^3 - v_0^2 b^2 a_{lat} + 4W\alpha^2\beta^2 = 0 \qquad (10.4.12.23)$$

The optimal lateral acceleration is a solution of this equation. The longitudinal deceleration is obtained by substiting this value in the ellipse equation (10.4.12.2).

10.4.12.4 Summary of results

In this appendix, we have analyzed the obstacle avoiadance scenario, for automated vehicle operation on an AHS. We proposed a complete obstacle avoidance strategy. The lane change problem is divided into three steps; gap selection, gap alignment, and moveover. The trajectory synthesis for each step of the lane change is formulated as an optimal control problem. The solution to the optimal control problem provides valuable insight into the lane change design in traffic. In the future, we would like to combine the different maneuver designs into a comprehensive computational tool to evaluate the effectiveness of obstacle avoidance strategies for various scenarios. We also believe that trajectory design is an important step towards the design of feedback control laws for lane changes. Furthermore, these design techniques should be extended to handle partially automated obstacle avoidance systems. Such extension requires that models representing driver detection and response behavior to stopped or slow moving objects be incorporated within the analysis. Some data is available for objects that are stopped or slow moving vehicles. This type of data can be used to seed the required models.

10.4.12.5 Acknowledgment

The authors would like to thank Dr. John Lygeros, Prof. Shankar Sastry and Dr. Steve Shladover for helpful discussions providing insight into this problem.

References

[1] V. Garg, *Fault detection in nonlinear systems : an application to automated highway system.* PhD thesis, Department of Mechanical Engineering, University of California, Berkeley, California, 1995.

[2] J. Lygeros, D. N. Godbole, and M. E. Broucke, "Design of an extended architecture for degraded modes of operation of IVHS," in *ACC* 1995.

[3] C. Liu and H. Peng, "Road friction coefficient estimation for vehicle path prediction." In IAVSD Symposium 1995, Ann Arbor, Michigan.

[4] Z. Shiller and S. Sundar, "Emergency maneuvers for AHS vehicles." Paper # 951893, SAE Future Transportation Technology Conference, Costa Mesa, 1995.

[5] J. L. Bascunana, "Analysis of lane change crash avoidance." Paper # 951895, SAE Future Transportation Technology Conference, Costa Mesa, 1995.

[6] S. K. Schuster, "Obstacle Avoidance Analysis Method and Detailed Results." NAHSC Milestone 2 Report, Appendix K, June 1997.

[7] J. Lygeros, D. N. Godbole, and S. Sastry, "A verified hybrid controller for automated vehicles," in *IEEE CDC*, 1996.

[8] P. Li, L. Alvarez and R. Horowitz, "AVHS Safe control laws for platoon leaders," in *IEEE CDC*, 1996.

[9] V. Hagenmeyer, D. N. Godbole and R. Sengupta, "Obstacle Avoidance for AHS." Tech. Report, California PATH, Univeristy of California, Berkeley, 1997.

[10] J. Macki and A. Strauss, *Introduction to Optimal Control Theory.* Springer-Verlag, 1980.

10.4.13 Multiple Collision Analysis and Inter-Vehicle Spacing

Authors, D. Godbole, J. Lygeros

10.4.13.1 Introduction

During C2, different AHS concepts and separation policies were evaluated in terms of pipeline capacity and hard braking safety. The pipeline capacity analysis used the calculation of minimum safe separation between vehicles as a function of their technological capability. The minimum safe spacing between individual vehicles and platoons was derived based on the specification that if a vehicle applies maximum braking until it comes to halt, the following vehicle or platoon should be able to stop without colliding with it. This specification was justified by the analysis in [1] which showed that hard braking by a vehicle is the worst disturbance it can generate for a string of following vehicles in the same lane. Due to wide variation in braking capability of vehicles and control loop lags in terms of sensing, actuation and communication, the typical inter-vehicle spacings [2] are orders of magnitude larger than the 1-4m desired intra-platoon spacings. Therefore, the hard braking safety criterion can not be used to calculate intra-platoon spacing. Vehicles operating in close spaced platoons need to coordinate their braking effort so as to avoid intra-platoon collisions. One possible control design for intra-platoon operation is presented in [3] which guarantees string stability and no intra-platoon collisions during normal mode of operation. If a malfunction or system intrusion renders cooperation impossible, intra-platoon collisions may be possible.

To investigate the effect of malfunctions and system intrusions, the C2 hard braking safety analysis [4] calculated frequency and severity of the first forward collision between two vehicles due to hard braking by the front vehicle. It was shown that small values of intra-platoon spacing and communication delay result in low severity first forward intra-platoon collision due to a hard braking disturbance, where severity is measured by relative velocity at impact.

The current analysis extends the C2 work by including secondary and subsequent collisions as a result of hard braking disturbance. We also study the effect of such intra-platoon collisions on the minimum safe inter-platoon spacings.

10.4.13.2 Collision Analysis Tool

Vehicle Model

Consider a string of vehicles moving along a single lane highway. Figure 1 shows three such vehicles labeled A, B and C. Assume that vehicles A and B have lengths L_A and L_B and let x_A and x_B denote their positions with respect to a fixed reference on the road. Assume that vehicle B is leading while vehicle C comes last, i.e. $x_B > x_A > x_C > 0$. Vehicles A and B are used to model the interaction between any two consecutive vehicles in the string. Vehicle A is the subject vehicle under consideration and vehicle B models the disturbance. To keep the calculations tractable we use a simple model to describe longitudinal dynamics of vehicle A. In particular, we assume that acceleration of vehicle A can be directly controlled. Let v_A and v_B denote the longitudinal speeds of vehicles A and B respectively.

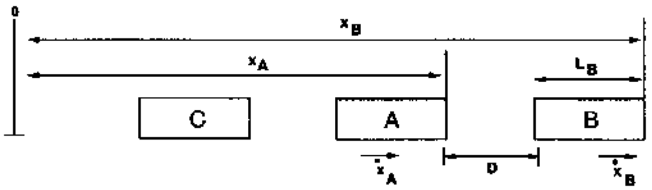


Figure 1: Vehicle Following

Scenario

We model the following scenario. At $t = 0$, vehicle B notices a malfunction or an obstacle and applies maximum braking in response at $t = d_B$. After a delay modeling sensing/communication and actuation, vehicle A also applies maximum braking at $t = d_A$. Thus A and B follow the acceleration trajectories of Figure 2 until the vehicles stop or collide.

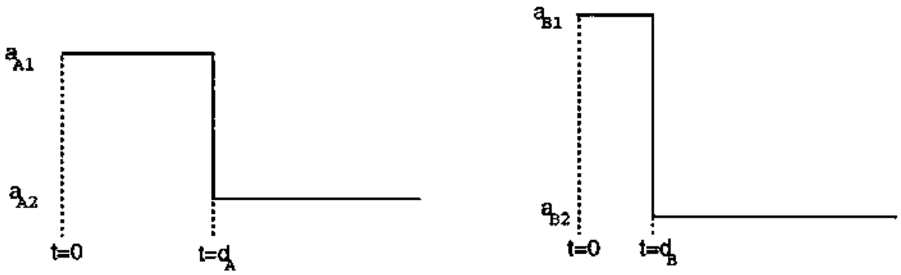


Figure 2: Assumed acceleration trajectories

To prevent the vehicles from going backwards we assume that the acceleration becomes zero as soon as the vehicle stops. As $v_B \geq 0$ and we are interested in investigating the cases where the vehicles collide, we restrict our attention to the interval of time when $v_A > 0$. It is easy to show that under these conditions the spacing, x_{AB}, and relative velocity, v_{AB}, between vehicles A and B is given by:

$$x_{AB}(t) = \frac{a}{2}t^2 + bt + c + x_{AB}(0) \tag{1}$$

$$v_{AB}(t) = at + b \tag{2}$$

The values of a, b, and c depend on the parameters of the problem (deceleration capabilities of A and B, and the communication delay). They are tabulated in Section . If a collision takes place, equation (1) allows us to determine the time T at which it happens while equation (2) gives us the relative velocity at impact.

To analyze cases where multiple collisions occur we would also like to determine the vehicle velocities after the collision. We model collision elasticity by a coefficient of restitution γ. If the collisions are centered, γ relates the longitudinal velocities before and after collision as follows:

$$\gamma = \frac{v_B(T^+) - v_A(T^+)}{v_A(T^-) - v_B(T^-)} \tag{3}$$

$\gamma = 1$ models perfectly elastic collisions whereas $\gamma = 0$ corresponds to inelastic collisions. The second equation relating the speeds before and after collision is given by conservation of linear momentum.

Let m_A and m_B denote the masses of the two vehicles and define $M = m_B/m_A$. Then:

$$v_A(T^-) + Mv_B(T^-) = v_A(T^+) + Mv_B(T^+) \tag{4}$$

The coefficient of restitution value depends on the design of car body and bumpers. Given a particular value of γ, the above set of equations can be solved for $v_A(T^+)$ and $v_B(T^+)$, and the process can be repeated. Note that the equations 3, and 4 take into account force balance on each vehicle assuming that the collision is centered (i.e., collision does not produce any rotational moments).

Note: The choice of trajectories for the accelerations of the two vehicles is motivated by physical considerations (such as actuator and communication delays) relating to the operation of the platoons. In addition the class of trajectories characterized in this way can be shown to contain trajectories which are in some sense optimal. A measure of the severity of the collision is the relative velocity at impact which can be encoded by the cost function:

$$J'(x(0), u, d) = |v_{AB}(T)| \tag{5}$$

Assume that vehicle B does not collide with the vehicle ahead of it and vehicle A is not hit from behind and let the deceleration of vehicle B represent the disturbance d while the deceleration of A model the control u. If we model vehicles A and B as opponents in a two person zero sum game where vehicle A tries to minimize impact velocity and vehicle B tries to maximize it, we can show that [5]:

Lemma 1 *The saddle solution $(u^{*'}, d^{*'})$ for cost function J' is such that:*

1. *at every time, $u^{*'}$ and $d^{*'}$ assume either their minimum or their maximum values (bang-bang solution)*
2. *at the time of impact, $u^{*'}$ and $d^{*'}$ assume their minimum values*
3. *If the vehicles collide with a non zero relative velocity, $u^{*'}$ and $d^{*'}$ involve at most one switching from their maximum to their minimum values. In particular, three kinds of behavior are possible:*
    - *(a) Both optimum trajectories assume only their minimum.*
    - *(b) $d^{*'}$ assumes its maximum first and then its minimum, while $u^{*'}$ assumes only the minimum.*
    - *(c) Both optimum trajectories start by assuming their maximum values and $u^{*'}$ switches to the minimum before $d^{*'}$. A non zero amount of time elapses between the two switchings.*

This calculation can be taken only as an indication of what the optimal trajectories might look like. Within a platoon the information structure can be quite different from the one assumed above (for example vehicles may have information about the acceleration of the vehicle ahead of them and the platoon leader). The situation is further complicated by the possibility of multiple collisions within a platoon. The optimal solutions do not have to be "bang-bang" and if they are, the switching patterns are likely to be very complicated. Similarly, the optimal solutions may be different, if the individual vehicles also receive some preview information such as an emergency warning from vehicles ahead of the preceding vehicle.

Collision Tool Development

The calculations described above were implemented in a computational tool to analyze multiple collisions within a string of vehicles. The tool accepts as input the acceleration levels a_{ij}, $j = 1, 2$, the delays d_i, the masses m_i and the coefficients of restitution γ_i for each vehicle in the string (i denotes the i^{th} follower and $i = 0$ denotes the leader). Then, for a given set of initial velocities $v_i(0)$ and initial spacings $x_{i,i+1}(0)$ the tool calculates all collisions that will occur and the corresponding relative velocities. To accomplish this the tool solves equation (1) for all vehicles, determines the smallest collision time, T, and the vehicles involved, j and $j-1$, calculates the state (position and velocity) of all vehicles right before the collision, $x_i(T^-), v_i(T^-)$ for all i, solves equations (4) and (3) to obtain $v_j(T^+)$ and $v_{j-1}(T^+)$, and repeats the process. The iteration terminates when no more collisions are possible.

10.4.13.2.1 Spacing Equation & Parameter Values

As discussed above the spacing between two vehicles following the deceleration profiles of Figure 2 is given by the equation:

$$x_{AB}(t) = \frac{a}{2}t^2 + bt + c + x_{AB}(0)$$

Let v_A and v_B denote the initial velocities of vehicles A and B and define:

$$T_{A1} = \begin{cases} -1 & \text{if } a_{A1} \geq 0 \\ -\frac{v_A}{a_{A1}} & \text{if } a_{A1} < 0 \end{cases} \qquad T_{A2} = \begin{cases} -1 & \text{if } a_{A2} \geq 0 \\ d_A - \frac{a_{A1}d_A + v_A}{a_{A2}} & \text{if } a_{A2} < 0 \end{cases} \tag{6}$$

$$T_{B1} = \begin{cases} -1 & \text{if } a_{B1} \geq 0 \\ -\frac{v_B}{a_{B1}} & \text{if } a_{B1} < 0 \end{cases} \qquad T_{B2} = \begin{cases} -1 & \text{if } a_{B2} \geq 0 \\ d_B - \frac{a_{B1}d_B + v_B}{a_{B2}} & \text{if } a_{B2} < 0 \end{cases} \tag{7}$$

The values of a, b and c depend on the deceleration trajectory parameters and the time t. They are summarized in the following table:

a	b	c	t
$a_{B1} - a_{A1}$	$v_B - v_A$	0	$C_1 \bigwedge C_3$
$-a_{A1}$	$-v_A$	$\frac{a_{B1}T_{B1}^2}{2} + v_B T_{B1}$	$C_1 \bigwedge C_4$
$a_{B2} - a_{A1}$	$(a_{B1} - a_{B2})d_B + v_B - v_A$	$\frac{(a_{B2}-a_{B1})d_B^2}{2}$	$C_1 \bigwedge C_5$
$-a_{A1}$	$-v_A$	$-\frac{(a_{B1}d_B+v_B)^2}{2a_{B2}} + \frac{a_{B1}d_B^2}{2} + v_B d_B$	$C_1 \bigwedge C_6$
$a_{B1} - a_{A2}$	$(a_{A2} - a_{A1})d_A + v_B - v_A$	$-\frac{(a_{A2}-a_{A1})d_A^2}{2}$	$C_2 \bigwedge C_3$
$-a_{A2}$	$(a_{A2} - a_{A1})d_A - v_A$	$\frac{a_{B1}T_{B1}^2}{2} + v_B T_{B1} - \frac{(a_{A2}-a_{A1})d_A^2}{2}$	$C_2 \bigwedge C_4$
$a_{B2} - a_{A2}$	$(a_{B1} - a_{B2})d_B + (a_{A2} - a_{A1})d_A$ $+v_B - v_A$	$\frac{(a_{B2}-a_{B1})d_B^2}{2} - \frac{(a_{A2}-a_{A1})d_A^2}{2}$	$C_2 \bigwedge C_5$
$-a_{A2}$	$(a_{A2} - a_{A1})d_A - v_A$	$-\frac{(a_{B1}d_B+v_B)^2}{2a_{B2}} + \frac{a_{B1}d_B^2}{2}$ $+v_B d_B - \frac{(a_{A2}-a_{A1})d_A^2}{2}$	$C_2 \bigwedge C_6$

Table 1: Table of Coefficients

Let $\bigwedge$ and $\bigvee$ denote logical "AND" and "OR" respectively. $C_i, i = 1, \ldots, 6$ are predicates on the time, t, defined by:

$$C_1 = t \leq d_A \bigwedge (t \leq T_{A1} \bigvee T_{A1} < 0)$$

$$C_2 = t > d_A \bigwedge t \le T_{A2} \bigwedge T_{A2} \ge 0 \bigwedge (d_A \le T_{A1} \bigvee T_{A1} < 0)$$
$$C_3 = t \le d_B \bigwedge (t \le T_{B1} \bigvee T_{B1} < 0)$$
$$C_4 = t > T_{B1} \bigwedge d_B > T_{B1} \bigwedge T_{B1} \ge 0)$$
$$C_5 = t > d_B \bigwedge t \le T_{B2} \bigwedge T_{B2} \ge 0 \bigwedge (d_B \le T_{B1} \bigvee T_{B1} < 0)$$
$$C_6 = t > T_{B2} \bigwedge (d_B \le T_{B1} \bigvee T_{B1} < 0)$$

Parameter Values The nominal parameter values used in the calculations were: minimum jerk $j_{min} = -25ms^{-3}$, intra-platoon spacing $F = 1m$, vehicle length $L = 5m$, vehicle mass $m = 1500Kg$, coefficient of restitution $\gamma = 1$ (elastic collisions) and default speed $25ms^{-2}$ with nominal platoon size of 5 vehicles. The value of γ depends on the design of car bumpers. In the current population of cars on the road, there is a large variation in bumper design ranging from very elastic to very soft bumpers [10]. But for all bumpers it is true that at low impact velocities, the bumpers behave as perfectly elastic. Therefore, we choose the nominal value of $\gamma = 1$ and study the sensitivity with respect to variations in elasticity.

10.4.13.3 Collisions Due to Emergency Braking

Consider the case of emergency braking by the leader of a platoon. This may occur because of a "brakes on" failure of the leader or because of emergency maneuvers (such as the *Crash Stop* maneuver of [6]) initiated in response to other failures (e.g., steering lock) or to the appearance of uncontrolled obstacles [7, 8]). If only individual vehicles populate the AHS such braking will not result in any collisions, as long as the inter-vehicle spacings are calculated according to the C2 minimum safe spacing design of [2]. Multiple collisions may be possible, however, for multi-vehicle platoons. The reason is the possible mismatch in deceleration capabilities between the followers that may lead to collisions if the string stability requirement of [3] is violated.[1]

To investigate this effect the collision tool can be used. As an emergency braking system for platoons has not been designed yet, a simple control scheme is considered: follower i ($i = 0$ for the leader) keeps a constant acceleration a_0^i until a time d_i when it switches to its minimum acceleration (i.e., maximum braking) level a_{min}^i. (In the following analysis, we have used a_0^i=0.) The time d_i may depend on the processing and actuation delays as well as the communication architecture within a platoon. For hop-by-hop communication a delay of d is added for each follower (i.e., $d_i = i \cdot d$). For broadcast communication, on the other hand, the delay is d for all the followers (i.e., $d_0 = 0$, $d_i = d, i > 0$).

Numerical Experiments

The collision tool can be used to obtain collision statistics for platoons of various sizes. The subsequent figures reflect expected values of the quantities over the probability distribution of Figure 3 representing vehicle braking capabilities. This braking distribution was generated during task C2 safety analysis by collecting data about new car braking rates and degrading the brake performance by 30% in order to account for tire and brake wear, and change in road-friction coefficient. On the other hand another braking capability distribution has been generated and used during C3 analysis.

---

[1] Recall that coordinated platoon braking according to control laws designed in [3] require that followers brake at higher rates than the leader. It was also shown in [3] that the need for such braking amplification does not propagate beyond fourth follower.

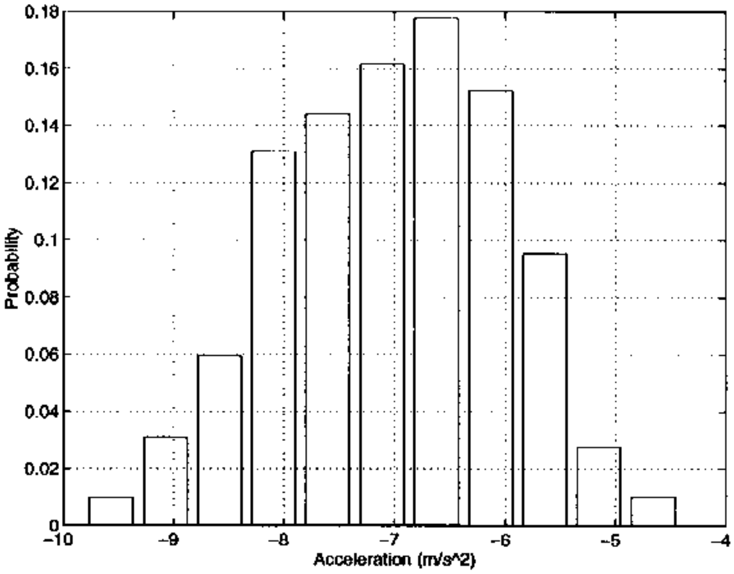


Figure 3: Minimum acceleration probability distribution for passenger vehicles

This distribution, described in appendix 10.4.1 of this report, contains the new car braking rates for a comprehensive list of cars sold in north America. The distribution is not degraded to non-ideal conditions. These two braking distributions represent two ends of the spectrum and thus help us bound the problem. We choose the C2 braking distribution (Figure 3) to represent nominal distribution. We will also study sensitivity of our results to variations in this distribution. The above choice of nominal distributions makes our nominal results compatible with C2 safety and pipeline capacity analysis.

The braking distribution of Figure 3 is divided into 10 bins. For every combination of braking capabilities of all vehicles in a platoon, the collision tool collects data regarding all possible collisions in the platoon due to hard braking by the platoon leader. Collision velocity distribution is generated by appropriately weighting the results for each run by the input probability specified by Figure 3. Unless otherwise stated it will be assumed that the platoon is initially at steady state with $v_i^0 = 25ms^{-1}$, $a_i^0 = 0ms^{-2}$, intra-platoon spacing=1m for all i, that all vehicles have equal mass $m_i = 1500Kg$ and that all collisions are elastic ($\gamma = 1$). The default communication architecture will be hop-by-hop with a delay of $d = 0.05s$. The collisions will be classified according to their relative velocity at impact, which is a measure of their severity [9].

Figure 4 shows the percentage of collisions that on the average fall into classes (starting at $0ms^{-1}$ and each class having a width of $0.3ms^{-1}$). The figure indicates that even though most of the collisions occur at small relative velocities, there is still a significant probability of higher relative velocity collisions. This probability increases with the size of the platoon. Some more statistics extracted in the experiments are given in Figure 5. Note that the average number of collisions per vehicle due to hard braking by the platoon leader increases roughly linearly with the platoon size.

Sensitivity Analysis

More experiments were conducted to investigate the sensitivity of the collision statistics with respect to various design parameters. First we considered sensitivity with respect to the communication architecture and the speed of operation. Figure 6 shows the results for broadcast communication with a 0.05s delay, Figure 7 the results for hop-by-hop communication with 0.02s delay and Figure

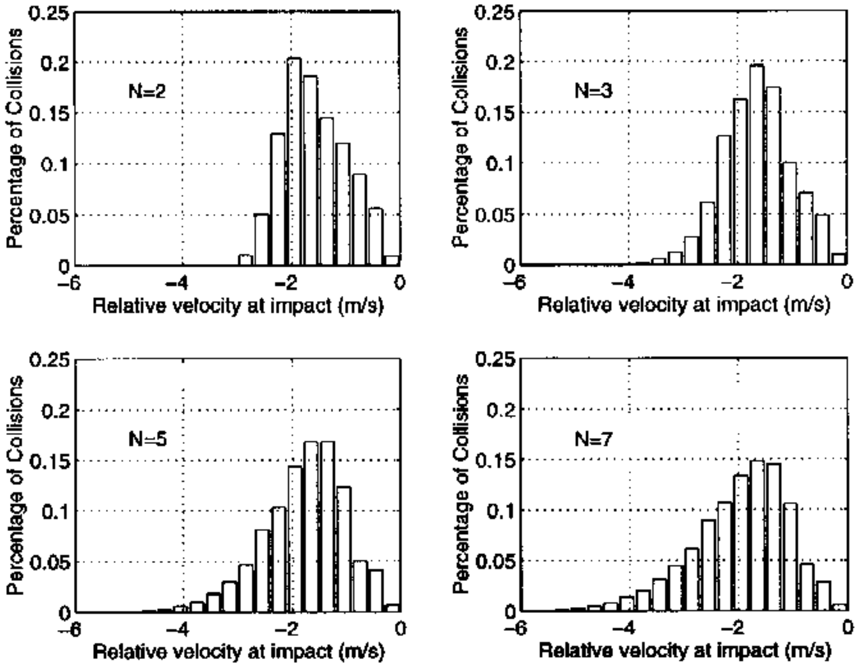


Figure 4: Classification of collisions by relative velocity

8 the results for an initial speed of $v^0 = 30ms^{-1}$. All figures look remarkably similar to Figure 4, indicating that the sensitivity of the statistics with respect to these parameters is low. Then sensitivity with respect to follower spacing was considered. The results for 2m initial intra-platoon spacing are shown in Figure 9. Clearly the statistics are much more sensitive with respect to this parameter.

To make the model more realistic, a coefficient of restitution that depends on the relative velocity of impact was introduced. Motivated by the work of [10] the following formula was used to calculate the coefficient of restitution for a collision with relative velocity δv:

$$\gamma = \begin{cases} 1 + \frac{0.9\,\delta v}{|v_\gamma|} & \text{if } v_\gamma \leq \delta v \leq 0ms^{-1} \\ 0.1 & \text{if } \delta v \leq v_\gamma \end{cases} \tag{8}$$

The above relationship takes into account the fact that collisions at low impact velocity are typically elastic and they start becoming less elastic as the impact velocity increases. The parameter v_γ represents the impact velocity above which all collisions become almost plastic, with $\gamma = 0.1$. The results for the default arrangement and $v_\gamma = -4.5ms^{-1}$ are shown in Figure 10. The statistics seem to be sensitive with respect to this parameter as well.

Finally, to investigate sensitivity with respect to changes in the deceleration distribution, we reduce the width of original braking distribution in half, while keeping the same proportion between the samples.[2] The results, summarized in Figure 11, indicate that the statistics are rather sensitive with respect to this parameter as well.

Some further experiments were conducted to establish trends for the parameters to which the statistics seem to be the most sensitive. The results are summarized in Table 2. Plots illustrating these trends are also shown.

---

[2] Note that this half width distribution is close to the C3 braking braking distribution in terms of its width but has a different shape. we use the half-width distribution as a surrogate for non-degraded braking distribution. In the future, we would like to replce the half-width distribution cases with the ones corresponding to C3 distribution.

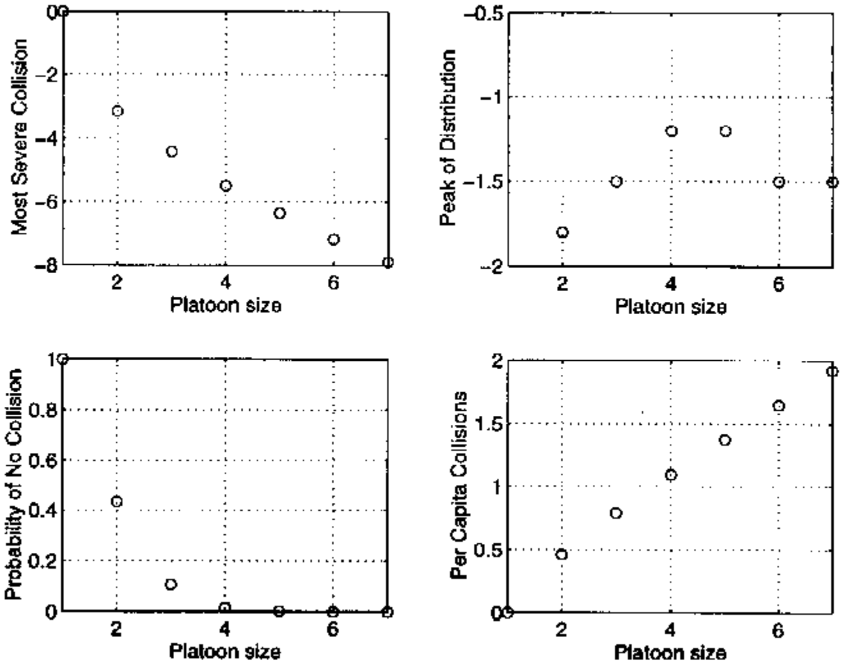


Figure 5: Other Collision Statistics

Note that all the sensitivity results assume nominal platoon size of 5.

Discussion of Results

The numerical experiments indicate that even though collisions take place primarily at low relative velocities, there is still a substantial number of moderate-speed collisions[3]. Moreover the number of collisions and their severity increases as the platoon size increases. The collision statistics are rather insensitive to the communication architecture and the speed of operation. A slight improvement is obtained if the broadcast architecture is used and the communication delays are reduced and if the speed of operation is lower. However the changes are rather small, at least for the parameter ranges considered here.

The statistics seem to be more sensitive with respect to changes in the intra-platoon separation, the elasticity of the collisions and the deceleration distribution. An increase in intra-platoon separation decreases the frequency of the collisions but increases their severity. A decrease in elasticity on the other hand seems to decrease both collision frequency and severity. The same is true about a decrease in the width of the deceleration distribution. It should be noted here that these trends reflect changes *on the average*. Particular runs may exhibit very different behavior; they may be sensitive to the "insensitive" parameters, exhibit reductions where increases are observed on the average, etc.

The results described in this section can be especially useful in technology and policy decisions. For example, our results indicate that eliminating vehicles with low braking capability from the AHS (e.g. by using tighter check-in procedures) should on the average result in an improvement in the severity and number of collisions observed in emergency situations. A similar improvement is

---

[3] The value of $3ms^{-1}$ is quoted in [9] as a threshold for relative velocity at impact for collisions that do not result in significant injuries.

Parameter Variation	No collision Probability	per capita Collisions	worst case Collision speed	$P(\Delta v < -3ms^{-1})$
Vary intra-platoon spacing				
1m	0.0016	1.37	-6.36	0.0385
2m	0.0156	0.76	-8.92	0.2371
3m	0.03	0.63	-10.92	0.4451
Vary coeff. of rest. v_γ				
elastic	0.0016	1.37	-6.36	0.0385
-6.5 m/s	0.0041	2	-5.44	0.0058
-4.5 m/s	0.0042	3.24	-5.09	0.0019
Vary braking distribution				
Original	0.0016	1.37	-6.36	0.0385
Half width	0.0016	1.13	-4.69	0.0037
IP=1m, half width, vary v_γ				
elastic	0.0016	1.13	-4.69	0.0037
-6.5 m/s	0.0039	0.99	-4.15	0.00012
-4.5 m/s	0.0039	1.17	-3.95	0.000025
IP=2m, half width, vary v_γ				
elastic	0.042	0.59	-6.46	0.0692
-6.5m/s	0.042	0.6	-5.45	0.0176
-4.5m/s	0.042	0.74	-5.12	0.007

Table 2: Collision statistics

expected if the collisions are made less elastic[4] (by appropriate bumper design for example) and if the vehicles in a platoon are packed more closely (the number of collisions will increase in this case, but their severity will decrease). Similar use can be made of the trends observed in the remaining parameters.

Finally a technical note. The collision statistics need to be averaged over a relatively large number of collisions to settle down. In cases where a small number of collisions is observed (for example if the platoons are small or the intra-platoon spacing is large) the deceleration distribution has to be sampled more densely for the statistics to be accurate. In cases where many collisions are observed the sampling may be coarser.

10.4.13.4 Relating Collisions and Throughput

The spacing design tool used during C2 maps the braking capabilities of a pair of vehicles along with the control loop delays and initial speed differential into minimum safe spacing necessary to avoid collision during a hard braking emergency. As part of the C2 pipeline analysis [2], it was shown that the minimum safe spacing and hence the pipeline capacity are highly sensitive to (i) the difference in braking capabilities of vehicles, and (ii) relative velocities at the instant of hard braking between

---

[4] It is interesting to note that if the collisions are made less elastic, the bumpers will be damaged in the first collision and hence will behave differently in subsequent collisions. There is also a trade-off between cost and severity of subsequent collision.

consecutive vehicles. Imagine that the vehicles A, B and C of Figure1 represent 3 platoons. If the leader of platoon B applies hard braking, there is a possibility of intra-platoon collisions as observed in the last section. An intra-platoon collision between the last vehicle of platoon B and its preceding vehicle would result in a "sudden" drop in the speed of the last vehicle of platoon B. Thus from the perspective of platoon A, it experiences two kinds of disturbances; (i) hard braking by the preceding platoon, and (ii) "sudden" jumps in relative velocity.

The second kind of disturbance imposes a further restriction on the capacity that can be achieved safely. To ensure that the collisions that occur because of emergency braking affect only the platoon that executes the maneuver, additional inter-platoon spacing is needed. The amount of extra spacing necessary can be calculated by obtaining the relative velocities of the most severe collision experienced by the leader and the last vehicle in the platoon (using the collision tool). These relative velocities can then be used to characterize the relative velocity disturbance in the spacing design tool. The result will be an increase in the inter-platoon spacing, to guarantee that collisions of one platoon do not affect another, and a consequent reduction in pipeline capacity. Our numerical experiments are geared towards estimating the magnitude of this effect on pipeline capacity of platooning.

Numerical Experiments

The spacing design tool used during C2 have been extended to take into account the collision disturbance. The extension is based upon results reported in [11]. As part of future work, the results of the collision analysis tools will be used as an additional input to the extended spacing design tool to obtain the revised values of inter-platoon spacing and pipeline capacity.

10.4.13.5 Concluding Remarks

We presented an extension of the C2 hard braking safety analysis that takes into account multiple collisions in a platoon of closely following vehicles. The results indicate that as the platoon size increases, the frequency and severity of collisions increase. We also identified the most sensitive parameters that affect the safety metrics under hard braking. It is shown that safety decreases by increasing collision elasticity, nominal intra-platoon separation and width of the braking distribution.

In the future, we would like to understand the effects of intra-platoon collisions on minimum safe inter-platoon spacing required to prohibit propagation of collisions in a string of platoons. The spacing design tools have already been modified to take into account the collision disturbance.

References

[1] J. Lygeros, D. N. Godbole, and S. Sastry, "A verified hybrid controller for automated vehicles," in *IEEE Control and Decision Conference*, 1996.

[2] J.B. Michael, D. N. Godbole, J. Lygeros, and R. Sengupta, "Capacity Analysis of Traffic Flow over a Single-Lane Automated Highway System," to appear in *ITS Journal*, 1997.

[3] D. Swaroop, *String Stability of Interconnected systems: an application to platooning in automated highway systems.* PhD thesis, Department of Mechanical Engineering, University of California, Berkeley, California, 1994.

[4] J. Carbaugh, D. N. Godbole, and R. Sengupta, "Safety and Capacity Analysis of Automated and Manual Highway Systems," to appear in *Transportation Research - C*, 1997.

[5] J. Lygeros, "To brake or not to brake? is there a question?," in *IEEE Control and Decision Conference*, 1996.

[6] D. N. Godbole, J. Lygeros, E. Singh, A. Deshpande, and A. Lindsey, "Design and verification of coordination layer protocols for degraded modes of operation of AHS," in *IEEE Control and Decision Conference*, pp. 427–432, 1995.

[7] S. K. Shuster, "Collision avoidance on the AHS," in *ITS America*, 1997.

[8] D. N. Godbole, V. Hagenmeyer, R. Sengupta, and D. Swaroop, "Design of Emergency Maneuvers for Automated Highway System: Obstacle Avoidance Problem," in *IEEE Control and Decision Conference*, 1997.

[9] A. Hitchcock, "Casualties in Accidents Occuring During Split and Merge Maneuvers," California PATH Technical Memorandum 93-9, Institute of Transportation Studies, University of California, Berkeley, 1993.

[10] C.-Y. Chan, "How to model collisions." Private communication, 1996.

[11] J. Lygeros, D. N. Godbole, and S. Sastry, "A Verified Hybrid Controller for Automated Vehicles," California PATH Research Report, UCB-ITS-PRR-97-9, Institute of Transportation Studies, University of California, Berkeley, 1997.

Sensitivity Analysis Plots

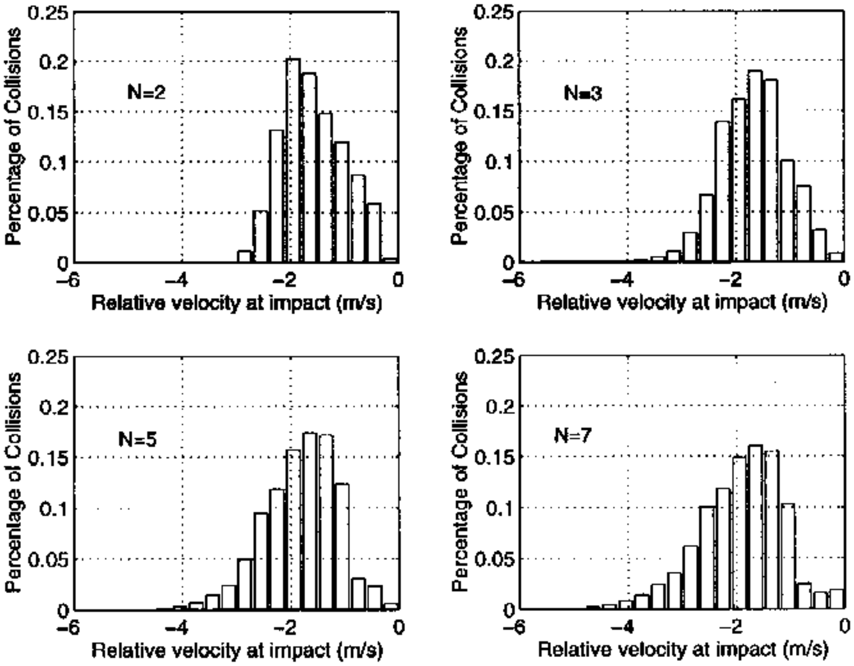


Figure 6: Broadcast, 50ms delay

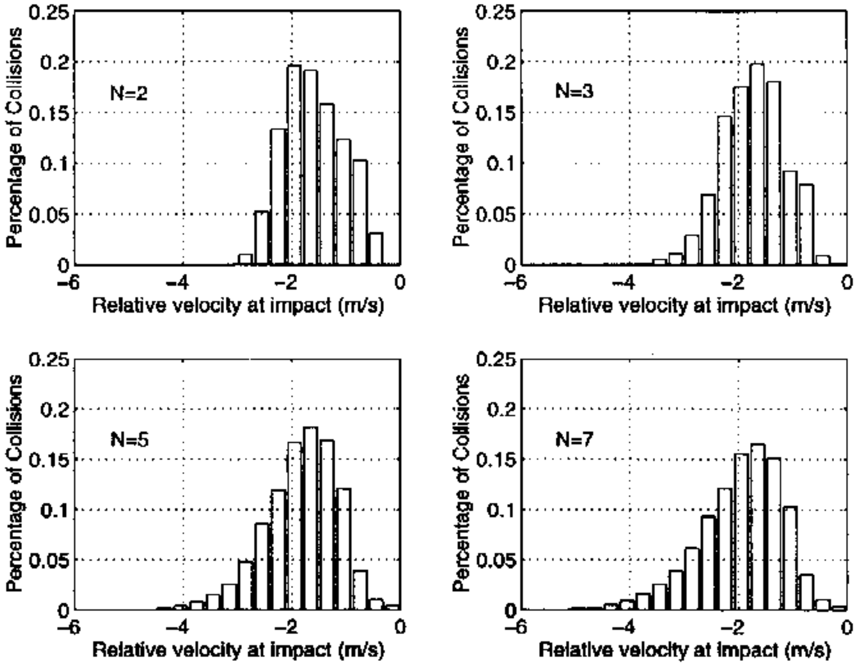


Figure 7: Hop-by-hop, $20ms$ delay

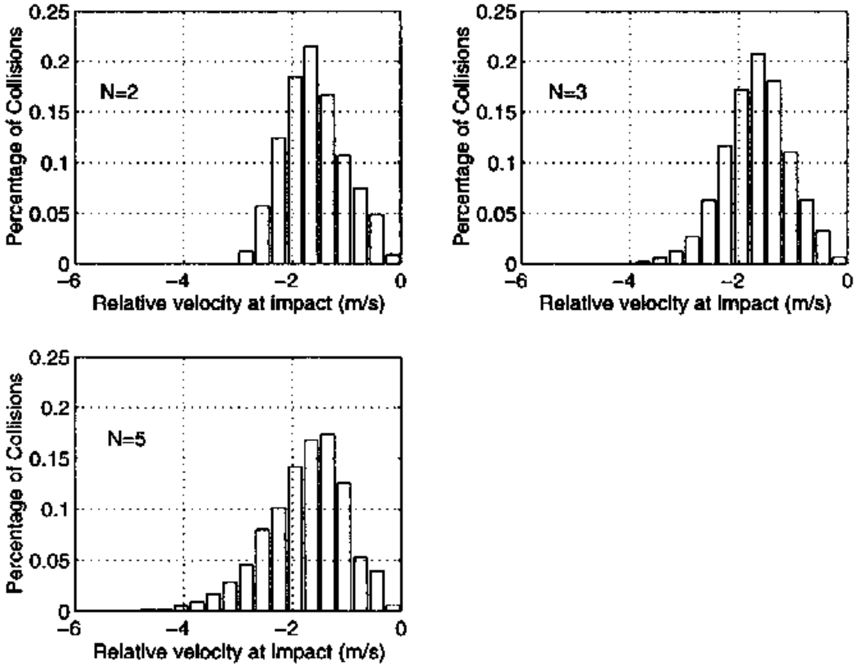


Figure 8: Hop-by-hop, $50ms$ delay, $30ms^{-1}$

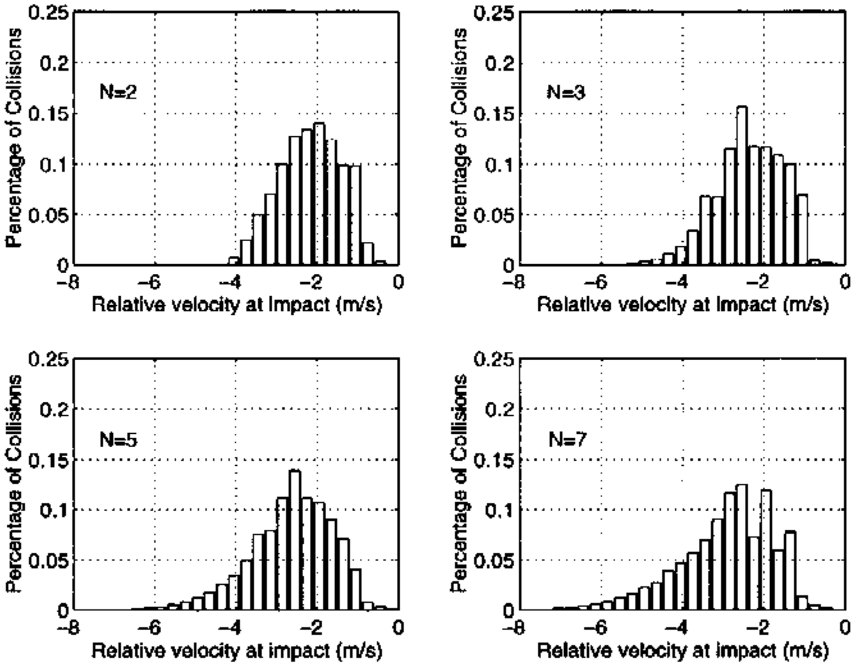


Figure 9: Hop-by-hop, 50ms delay, 2m spacing

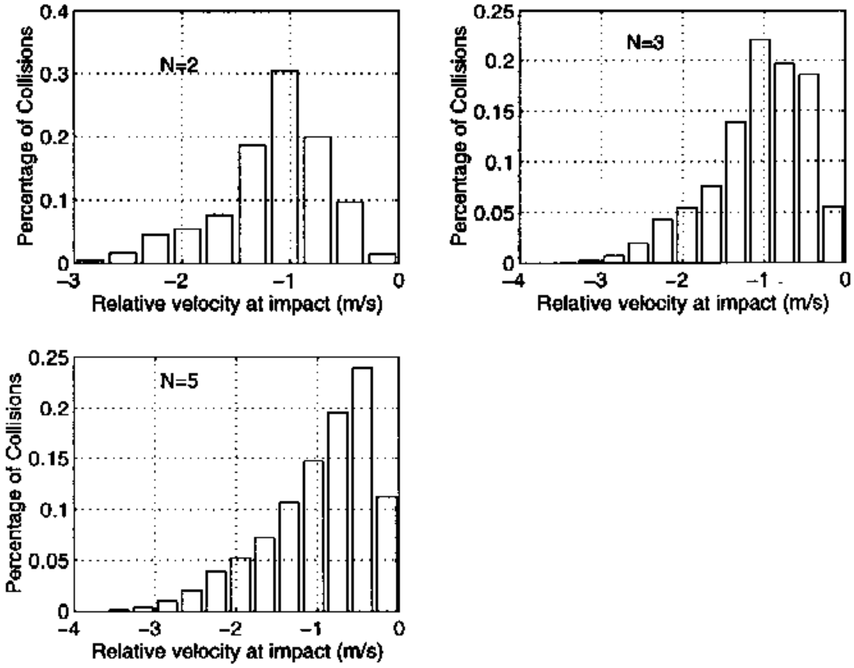


Figure 10: Hop-by-hop, 50ms delay, variable restitution

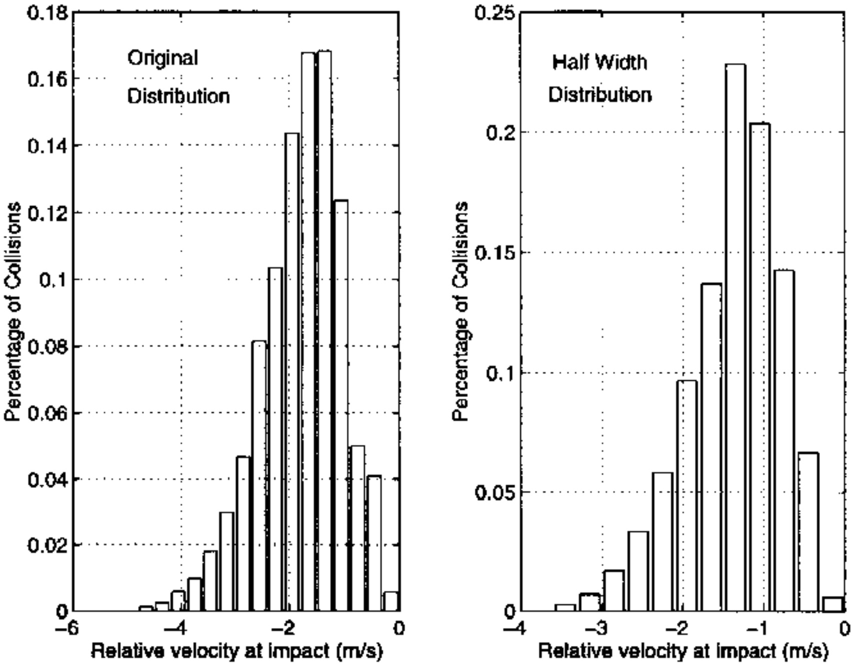


Figure 11: Variation in braking distribution

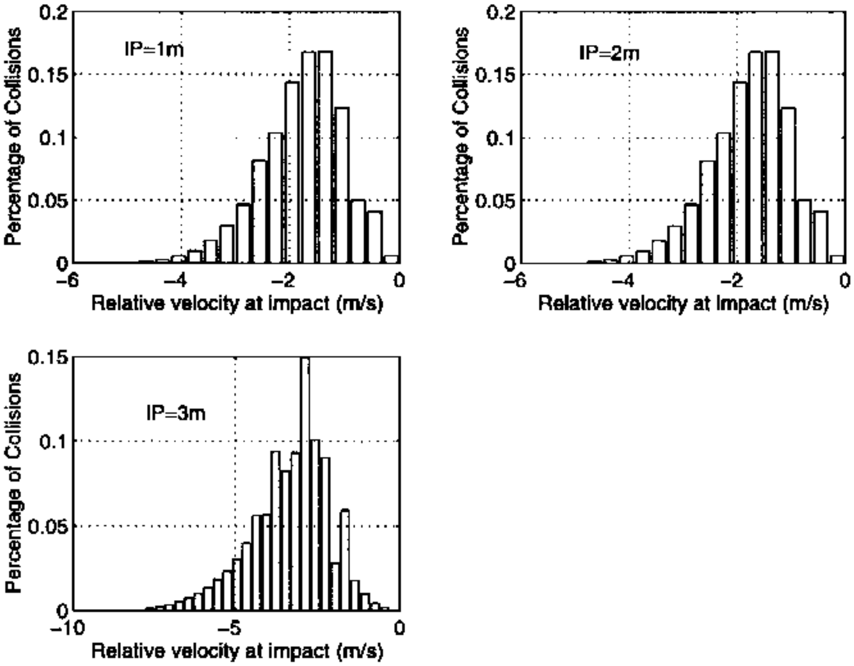


Figure 12: Variation in intra-platoon spacing (IP)

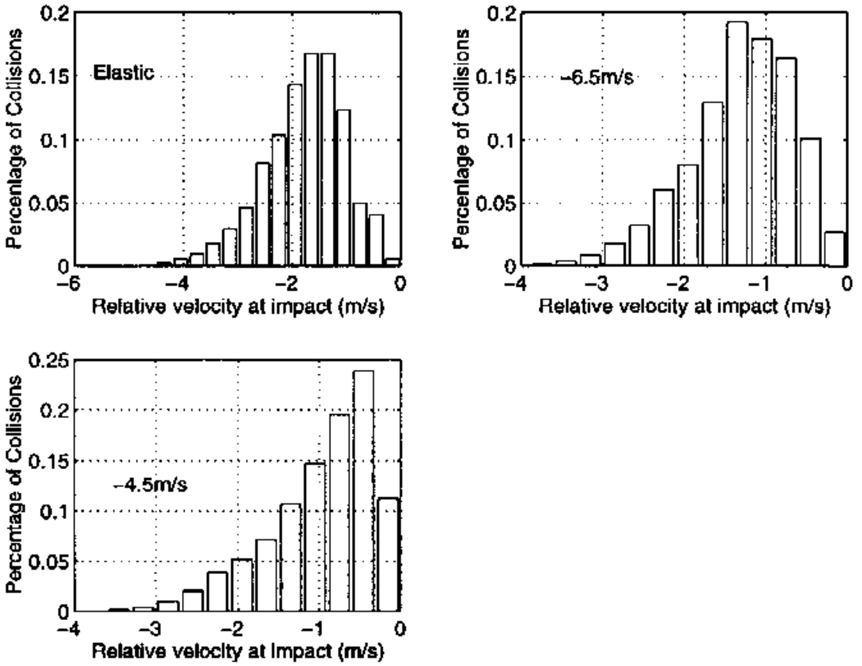


Figure 13: Variation in collision elasticity parameter v_γ

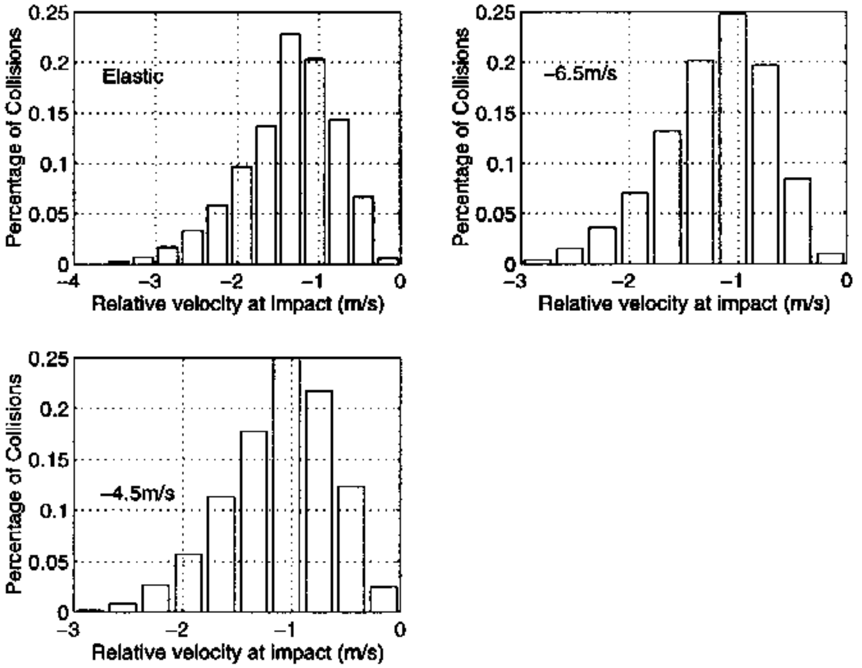


Figure 14: Variation in v_γ with IP=1m, reduced width braking distribution

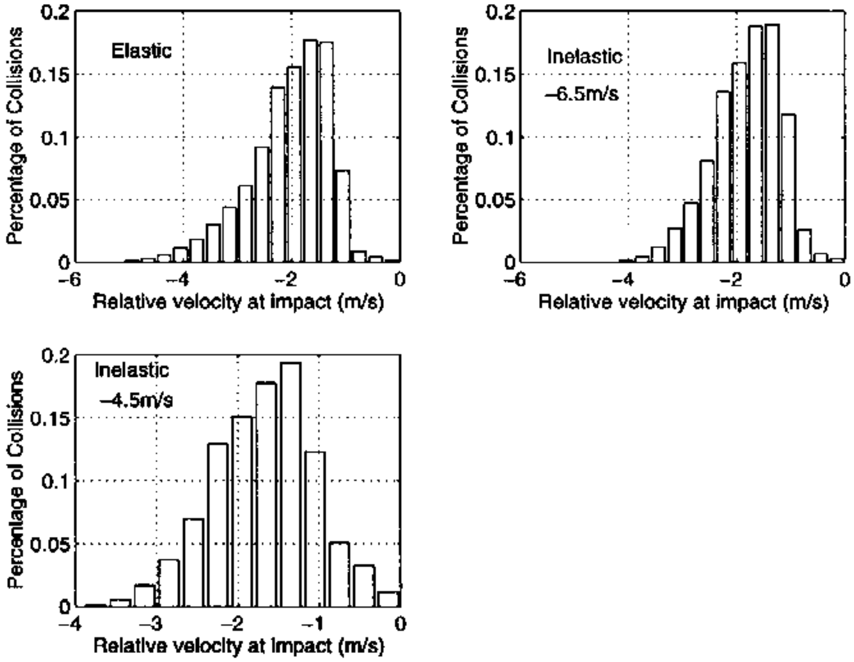


Figure 15: Variation in v_γ with IP=2m, reduced width braking distribution

Appendix 10.4.14 Benefit Evaluation of Crash Avoidance Systems

Authors, D. Godbole, R. Sengupta, N. Kourjanskaia,
J. Misener, J. Michael

We describe a five layer model, tool and task hierarchy (HARTCAS: Hierarchical Assessment and Requirements Tools for Crash Avoidance Systems) for benefit assesment and requirements development of crash avoidance systems. The hierarchy is discussed in general terms and illustrated by analysis of a forward collision warning system. In the context of this example, measures of effectiveness are defined in terms of safety and user acceptance (nuisance alarms, false alarms, etc.). The relationship between the effectiveness of a warning and the probability that the warning is a nuisance is quantified. Three human detection models are described and their use is demonstrated. Several model, tool and experimental data needs are discussed.

10.4.14.1 Introduction

Partial automation systems within the AVCSS area, such as the market packages being developed by C3 team, have the potential to improve driver safety, comfort and mobility. For example a Forward Collision Warning System (FCWS) can enhance the performance of the driver by providing advance warning of a possible rear-end crash. Similarly, an Adaptive Cruise Control (ACC) system can assist the driver to follow the preceding vehicle at a safe distance.

These different automation systems are characterized by the technological capabilities of their control, communication, sensing, actuation, and human-machine interface (HMI) subsystems, and by the benefits they promise in terms of safety, comfort and mobility. A systematic methodology is needed to map the technological capabilities of partial automation systems to its benefits. We have developed such a methodology supported by B5 analysis and simulation tools which can be used for unbiased evaluation of different market packages. The initial version of the methodology was developed for NHTSA and hence is aimed at safety evaluation of Crash Avoidance Systems (CAS) developed by NHTSA's office of crash avoidance. We are in the process of extending this methodology so as to be applicable to a wide variety of market packages including autonomous and cooperative systems.

The HARCAS framework is applicable during all phases of development of the individual market packages within the entire timeline of CAS development and deployment. Evaluation and design of the early concepts will be based upon simple kinematic models of CAS subsystems with the data being provided by small focused experiments or simulator studies. The detailed dynamic analysis using microsimulations is used for obtaining/validating simple kinematic models and guiding the design process. Results of experimental testing of the prototype as well as field operational test data will be used in the later stages to refine and validate the earlier benefit estimate.

10.4.14.1.1 Objectives

We are interested in developing a framework to analyse the Crash Avoidance Systems and using this framework to systematically estimate the safety benefits of CAS and identify the sensing, actuation, control and human machine interface requirements associated with the benefits.

Safety benefits of collision avoidance systems has been a subject of considerable experimental and analytical research [1] which has established conceptual descriptions of various kinds of CAS [2], CAS designs and sub-system performance guidelines [3, 4, 5], crash types targeted by different CAS [2], crash mitigation benefit estimates for different CAS concepts [3, 4, 5], and design and specification guidelines for CAS human-machine interfaces [6]. The research has aimed to characterize the performance of prototype systems [3, 4, 5], the operating environment of CAS sensor sub-systems [7, 8], driver behavior under normal driving conditions [9, 10], and driver interaction with partially automated vehicles [3, 9, 11]. Although a great deal of progress has been made in these areas, much work is still required to better understand the relationships between benefits, user acceptance, CAS subsystem requirements, driver behavior and the driving environment. Further investigation of negative CAS performance measures, such as false alarms and nuisance alarms is required. The impact of driver or automatic control dynamics on system capability and benefits is not well understood. On the other hand much experimental data [7, 9] has become available which if integrated properly into analytical models can help get more useful estimates of CAS benefits and requirements. In this paper, we show how this rich variety of experimental and analytical work can be integrated to conduct benefit analyses that assist the formulation of deployment initiatives, produce requirements that serve as guidelines for effective design, and examine the interaction of several CAS. We also identify some new tools, analyses and experiments required to better utilize the existing tools and data.

In view of the differing granularity of the knowledge accumulated through different lines of experimental and analytical research, we propose that the integration of past analytical and experimental work be accomplished within a five layer hierarchical modeling, tool and task framework for CAS benefit assesment and requirement development. We refer to the structure as the HARTCAS (Hierarchical Assesment and Requirement Tools for Crash Avoidance Systems) framework. As expected, the tasks we associate with each layer determine the models and tools of the layer. The relationship between existing models, tools and HARTCAS is illustrated. The HARTCAS framework is an extension of the benefit assessment methodology described in [1]. The ideas underlying this framework are inspired by two sources, namely, the benefit estimation equations described in chapter 1 of [1], and the performance measure discussion in [12].

In this paper, Section describes the five layer HARTCAS modeling, tool and task framework. Section is an example illustrating HARTCAS as applied to the assessment of the rear-end crash mitigation properties of forward crash warning systems (FCWS) in the LVNM (lead vehicle not moving) [2] scenario, i.e., when the prinicpal vehicle is approaching another vehicle that is not moving. The paper concludes with a summary of its principal observations in section .

10.4.14.2 The HARTCAS Framework

From top to bottom, the five layers of HARTCAS are the benefit assessment layer, system performance and user acceptance layer, kinematic layer, dynamic layer, and experimental layer (refer figure 1). The semantics of the five layers ensure that as the hierarchy is ascended there is a progressive abstraction of detail into fewer parameters. This reduction in model complexity allows the study of parameter variations over wider ranges, thereby analyzing diverse environmental conditions and system capabilities. Thus, higher levels of analyses are broad and coarse. For example, a benefit assessment layer task should be able to compute the number of LVNM rear-end crashes reduced by a FCWS at a given level of market penetration. The lower levels of analyses are narrow and fine. For example, experimental layer tasks should be able to characterize the radar cross-section (RCS) of a vehicle, or the headways maintained by driver and ACC controlled vehicles operating on limited access freeways in high density traffic. Furthermore, the causal relationship between the probability of avoiding a crash with a vehicle in front and its RCS is not immediate. We show how it can be established through analytical work at the dynamic, kinematic and performance layers.

It may be noted that while hierarchical abstraction is helpful in managing the computational complexity of the CAS benefit assessment and requirement development process, it is desirable that each step of abstraction correctly represent the knowledge embodied in the analyses or experimental data being accumulated at lower levels. We classify the problems to be solved at the benefit, performance and kinematic layers by defining a set of crash types. A suitable set is suggested by the target crash problem classification in [2]:

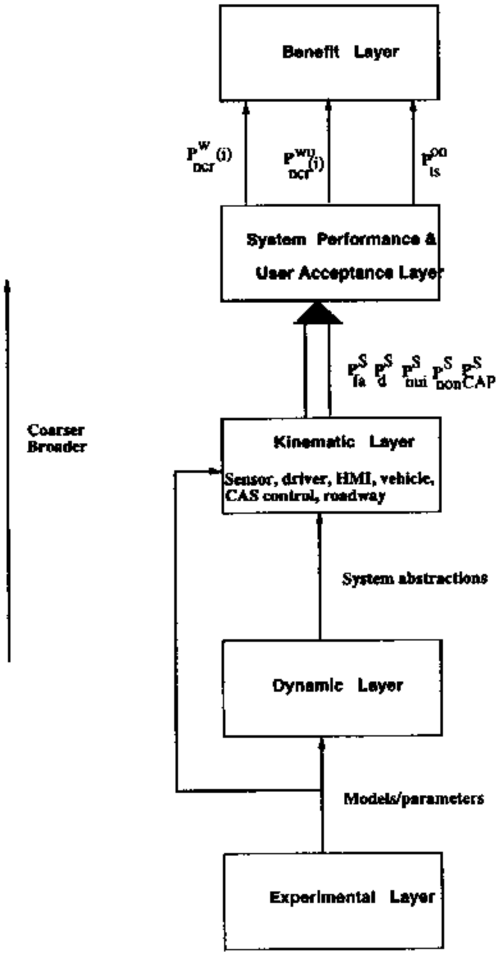


Figure 1: The HARTCAS Modeling Hierarchy

- Rear-end crashes: lead vehicle stationary or not moving (LVS or LVNM) and lead vehicle moved or decelerating (LVM or LVD) are the major subclasses.

- Backing: this category is divided into encroachment backing and crossing path backing
- Lane change/merge (LCM): this type is divided into two subtypes, angle/sideswipe LCM and rear/end LCM.
- Single vehicle road departure (SVRD)
- Intersection crossing path (ICP): this category consists of the subtypes, signalized intersection straight crossing path (SI/SCP), unsignalized intersection straight crossing path (UI/SCP), left turn across path (LTAP).
- Opposite direction (OD)

Observe that analyzing the effectiveness of a particular CAS in mitigating crashes of a type in the set is a large-scale problem and could entail analysis over several sets of weather, road, and traffic conditions. The top three layers of the hierarchy are concerned with such large-scale problems.

We begin by describing the objective of each layer of the HARTCAS hierarchy.

1. **Benefit Layer:** This is the top layer of the HARTCAS hierarchy. It is associated with the computation of benefit assessment equations [1] of the form

$$b(i) = \frac{(p_t^{wo}(i) - p_{ts}^{w}(i))p_{ts}^{on}}{p_t^{wo}(i)}. \tag{1}$$

   where $p_t^{wo}(i)$ is the probability that a crash of type t and of severity level i occurs without deployment of the CAS s, $p_{ts}^{w}(i)$ is the same assuming deployment of the system, p_{ts}^{on} represents the probability that the system is installed in the vehicle and active at the time of occurrence of the type t hazard . One possible classification of severity levels is suggested by the AIS scale [13]. The symbols p_t^{wo} and p_{ts}^{w} without the argument i denote the total crash probability. This equation is used to estimate benefits for a particular CAS s with respect to a particular crash type t. p_{ts}^{on} is the basic measure of user acceptance.It captures the fact that at the time of a potential accident causing hazard, the CAS was installed and active. Moreover the driver was paying appropriate attention to the CAS warnings.
   Within this layer it is useful to view p_{ts}^{w} as

$$p_{ts}^{w}(i) = 1 - p_{ncr}^{w}(i),$$

   where p_{ncr}^{w} is the probability that no crash occurs given that the system is on and active. p_{ncr}^{w} is a measure of CAS performance. Note that p_{ts}^{on} and p_{ncr}^{w} are CAS performance measures that do not relate to specific subsystems. The measures p_{ts}^{on} and $p_{ncr}^{w}(i)$, should be computed by the system performance and user acceptance layer. Let $p_t^{wo}(i) = 1 - p_{ncr}^{wo}(i)$. The measure $p_{ncr}^{wo}(i)$ does not depend on the CAS; it should be computed by the kinematic layer. Examples of benefit layer computations may be found in [1].
   The benefit as defined by equation (1), characterizes the fractional decrease in accidents of a particular severity level. For a particular crash type, this computation should be performed for all severity levels to obtain the overall impact. The total benefit of a particular CAS can then be obtained by looking at the overall impact of the CAS for each of the crash types that is affected by the CAS.

2. **System Performance and User Acceptance Layer:** This layer maps probabilistic performance measures on the CAS sensing, actuation, control and Human-Machine Interface (HMI) sub-systems to the CAS performance and user acceptance measures (p_{ts}^{on} and p_{ncr}^{w}) required at the benefit layer.

   We propose that p_{ncr}^{w} be expressed as a function of two probabilistic performance measures. One specifies the performance of the CAS sensing system and the other the performance of the control, actuation and human machine interface sub-systems. These three subsystems will be decomposed at the kinematic layer. The two measures are:

   - Detection Probability: This is the probability that the CAS sensors detect the threat as intended by the CAS designers. It is identical to the detection probability as defined in the theory of signal detection (TSD). It is denoted by p_d^s and is a property of the CAS sensing sub-system. (Refer to Section for an example)
   - System Capability: This is the probability of avoiding a crash conditioned on the CAS sensors detecting as designed. This probability is primarily determined by the CAS warning or control design, actuation design and human-machine interface design. Designs may allow tolerances for sensing inaccuracies. System capability is denoted by p_{cap}^s. Examples of analyses computing these measures may be found in [3, 5, 14].

   It is expected that p_{ncr}^{w} is directly proportional to p_d^s and p_{cap}^s. Section provides one example of an exact relationship.

   The user acceptance measure p_{ts}^{on} should be related to p_{ncr}^{w} and the following four CAS performance measures. The first two represent requirements on the CAS sensing subsystems, while the third and fourth are requirements on the performance of CAS control, actuation and HMI subsystems. The measures are similar to those in [12] and are:

   - False Positive Probability (FPP): This is the probability that the sensors of the CAS detect threats where there are none. This measure is identical to the sensor false alarm probability as defined by TSD. It is a property of the sensing subsystem within the CAS and is denoted by p_{fa}^s.
   - False Negative Probability (FNP): This is the probability that the CAS sensors fail to detect the threat they are designed to detect. This measure is similar to the sensor missed detection probability defined by TSD. It is a property of the sensing subsystem within the CAS and is denoted by $p_{md}^s = 1 - p_d^s$.
   - Nuisance Alarm Probability (NAP): This is the probability that the CAS executes an action that alarms the driver and the driver considers the action unnecessary, though the CAS sensing systems have performed correctly. It is denoted p_{nui}^s.
   - Perceived Non-Alarm Probability (PNAP): This is the probability that the driver perceives a threat situation and expects an alarm action from the system but does not receive it from the system in time, though the CAS sensors have performed correctly. It is denoted p_{non}^s.

   It is expected that p_{ts}^{on} is directly proportional to p_{ncr}^{w} and inversely proportional to $p_{fa}^s, p_{md}^s, p_{nui}^s$, and p_{non}^s. It is not entirely clear how the measures p_{nui}^s and p_{non}^s should be defined so that they can be related to performance requirements on control, actuation, and HMI subsystems. This is further discussed in section . Section provides one example of an exact relationship.

3. **Kinematic Layer:** This is the first layer at which the performance of a CAS is to be determined by modeling the time varying behavior of sensing, control, actuation, and HMI subsystems, and by analyzing their interaction with each other, the driver, and the interaction of the CAS equipped principal vehicle with a time varying environment. Therefore this layer relates the measures $p^s_{cap}, p^s_{fa}, p^s_{md}, p^s_{nui}, p^s_{non}$ required at the system performance and user acceptance layer and the measure p^{wo}_{ncr} required at the benefit layer, to simple models describing the environmental conditions (roadway, weather, obstacles, proximate vehicles) associated with the crash type under consideration, vehicle and actuator dynamics, driver interaction with the CAS HMI, sensor performance as a function of vehicle and environmental state variables, and driver or automated control of vehicle actuators.

   Most of the models at this level are probabilistic. Driver interaction models are almost always so. The primary motivation for keeping models simple is to be able to analyze the effect of probabilistic variations of multiple model parameters. From our past experience with such analyses [15] we believe that the computational complexity is manageable if one adheres to the following modeling assumptions.

   (a) The state of a vehicle and its neighbors may be described by positions, velocities, and accelerations with upto six degrees of freedom.
   (b) Accelerations, whether generated by drivers or control systems, are required to be piecewise constant functions of time for all vehicles.
   (c) Vehicle motions are described by kinematic equations.
   (d) Actuator behavior is described by saturation limits, pure time delays, and first-order lags.
   (e) Roadway geometry and surface conditions are piecewise constant.
   (f) Atmospheric parameters are piecewise constant.
   (g) Target signatures are invariant over short time intervals.
   (h) Sensor detection and false alarm probabilities are described as functions of the state variables and target signatures.

   The piecewise constant restrictions allow vehicle trajectories to be computed by solving algebraic equations. This facilitates large-scale computation. The system performance analyses performed for rear-end collisions in [1] and the analysis of different forward collision avoidance systems reported in [14] are examples of kinematic layer analyses.

4. **Dynamic Layer:** Tasks associated with this layer validate the models used at the kinematic layer. In particular, the piecewise constant abstractions used at the kinematic layer may have to be developed from analyses at the dynamic layer. Unlike the three previous layers, dynamic and experimental layer tasks do not attempt to analyze large-scale problems such as the safety of one or more CAS as pertaining to a crash type. Rather, the focus should be on analyses that can build the simple vehicle, driver, control, sensing, and HMI performance abstractions required for large-scale analyses at the kinematic layer by analyzing principal and proximate vehicle dynamics. Dynamic layer models and tools should support the analysis of:

   - forces and moments at various points of the vehicle body, and
   - system or driver generated acceleration commands that are piecewise continuous functions of time or state for principal and proximate vehicles.

   Experimental data on dynamics can also be used to build kinematic abstractions.

5. **Experimental Layer:** The tasks associated with this layer are field operational testing of CAS equipped vehicles under normal driving conditions [11, 16], experimental evaluation of prototype CAS and CAS subsystems, data collection on driver behavior with and without the presence of automation, the behavior of proximate vehicles, sensor target signatures [7], visibility, road surface conditions and engagement geometrics. The data obtained from the experiments should be incorporated into analytical models at the dynamic and kinematic layers that can then extrapolate the data to derive the behavior of a CAS equipped vehicle under *near-miss* or *crash inevitable* conditions. These extrapolations, based on actual experimental data, underpin the kinematic models used to derive the large-scale crash mitigation properties of a given CAS operating in a hazard situation associated with a given crash type.

10.4.14.3 The Analysis of LVNM Crashes

In this section, we illustrate the HARTCAS model, tool, and task hierarchy through an analysis of the effectiveness of a Forward Collision Warning System (FCWS) in mitigating rear-end crashes (REC) in the LVNM (Lead Vehicle Not Moving) scenario. Of the six CAS subsystem performance measures (section) generated by the kinematic layer we analyze detection probability, system capability, missed detection probability (false positive), and nuisance alarm probability. Analytical relationships mapping these measures to benefits are established. We formulate a mathematical definition of nuisance alarms and use it to derive an analytical relationship between the nuisance alarm probability and system capability. As expected, they are directly related, i.e., increasing one leads to an increase in the other. It should be noted that these relationships are established in the limited context of this example. Their generalization, to the best of our understanding, is non-trivial.

Since our objective is to demonstrate the broad contours of benefit assessment and requirements development in the context of the HARTCAS hierarchy, we make simplifying assumptions on design, driver behavior, and scenario to limit the analysis detail just enough to establish salient features of the hierarchical approach.

This section is organized into two subsections. The first subsection is an integrated FCWS benefit analysis that begins with a discussion of data associated with the experimental layer and ascends through the hierarchy to compute an estimate at the benefit layer. To reiterate, this analysis makes various assumptions on the performance of FCWS subsystems. The second subsection demonstrates how richer models of the FCWS subsystems can yield more insight into these performance assumptions, establish sensitivity of the performance to degraded environmental conditions, and help subsystem designers derive design requirements for different environmental conditions.

The LVNM scenario used in this example is shown in figure 2. The principal vehicle approaches another vehicle that is stopped in the same lane. No other vehicles or objects are present in the scenario and it is assumed that the lane is straight. The stopped vehicle does not move for the duration of the scenario. The principal vehicle travels at constant speed until the stopped vehicle is detected. Thereafter we expect that after some delay the driver will react by braking. Since the probability of a crash is ultimately dependent on when the driver starts braking we shall model the reaction time. The detection time is not modelled explicitly. It is only assumed that it preceeds the reaction time. The reaction time instant is the time at which the driver hits the brake. The principal vehicle may or may not be equipped with a FCWS. If the principal vehicle is FCWS equipped the driver may react before or after the warning. In either case, it is assumed that the driver reacts by braking as hard as necessary to avoid a REC. If a crash is unavoidable then the driver brakes as hard as possible under the prevailing vehicle and roadway conditions. In all cases it is assumed that the driver does not attempt crash avoidance by lane changing. Since no detection time is modelled, in the subsequent development we use the terms detection time and reaction time interchangeably to refer to the same time instant, i.e., the instant at which the driver hits the brake. Similarly we use the terms detection range and reaction range interchangeably to refer to the same range, i.e., the range at which the driver hits the brakes.

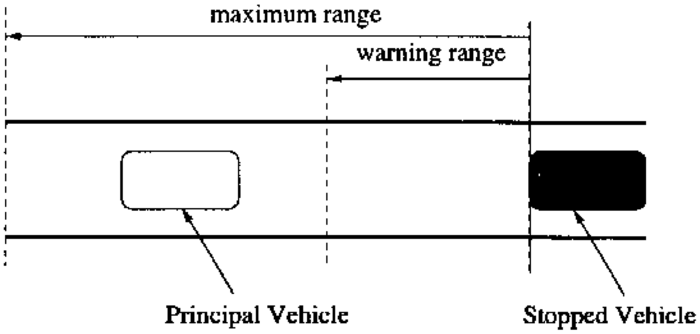


Figure 2: The LVNM Scenario

A FCWS operating in the LVNM scenario aims to provide a warning at a range sufficient for the driver to react and bring the vehicle to a stop. Therefore, the FCWS has a sensing subsystem, an alarm or HMI subsystem, and a warning subsystem that accepts inputs from the sensing subsystem, performs computation, and triggers the alarm subsystem as necessary (figure 3). The alarm may be haptic, kinesthetic or auditory as discussed in [3]. The alarms are assumed to be obstrusive e.g., high jerk deceleration if kinesthetic. This has the advantage of alerting the inattentive driver in a hazardous situation, and the disadvantage of being a possible nuisance to the attentive driver. This concept of an alarm is similar to the collision imminent warning [17, 3, 14].

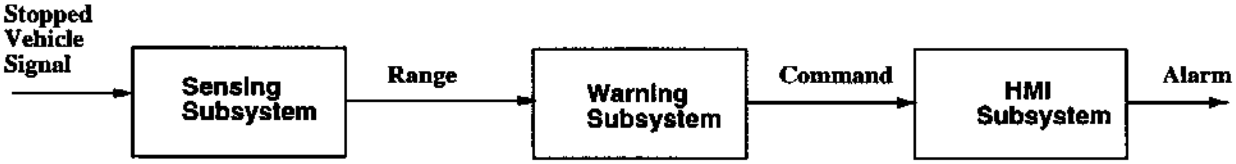


Figure 3: FCWS Subsystems

10.4.14.3.1 Integrated LVNM Analysis

Our analysis proceeds upwards through the HARTCAS hierarchy. We begin our discussion at the experimental layer.

The ability to avoid a crash in the LVNM scenario depends on the relationship between the range at which the driver reacts to the stopped vehicle and the vehicle stopping distance or deceleration capability. Deceleration capability models are preferable to stopping distance models because they can be used for computation at various speeds. Moreover since there can be considerable variations in both parameters the data set should be rich enough to justify a probabilistic structure on the variation. If the reaction range is greater than the stopping distance there is no crash.

We construct a probability distribution of vehicle deceleration capability as described in

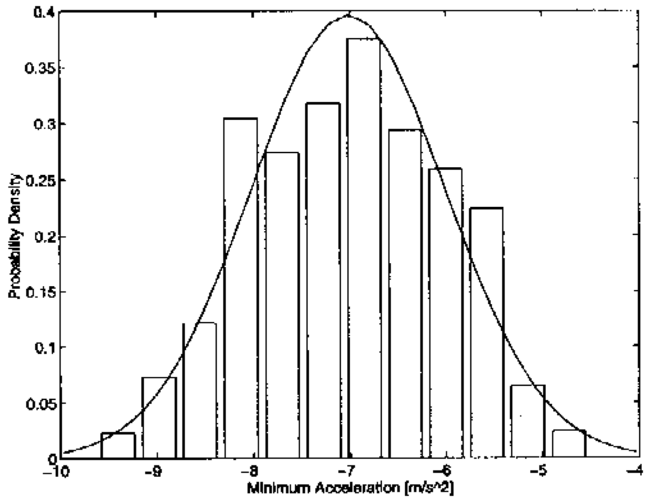


Figure 4: Estimated Distribution of Braking Capabilities for Vehicles

[15]. Maximum deceleration capabilities of the vehicle population are modeled by using data on the maximum deceleration on dry pavement of new light duty passenger vehicles as compiled in [18]. The proportion of each type of vehicle on the highway is derived from the North American production figures in [19], modified by the recognition that deceleration capability of a vehicle is highly sensitive to the tire and roadway surface condition. In order to account for wear, precipitation, and pavement degradations we apply an assumed 30% derating factor to the vehicle's maximum deceleration. This yields the histogram shown in figure 4. Note that the low values correspond well with the wet pavement deceleration data in [18]. A truncated Gaussian distribution is fitted to this data as shown in the figure. The Gaussian is clipped at -10 and -4 m/s^2, has a mean of -7.01 m/s^2, and a standard deviation of 1.01 m/s^2

We are interested in data that describes the behavior of unalerted drivers and drivers alerted by a warning. To the best of our knowledge no experimental data is available on the ranges at which drivers detect or react to stopped vehicles. In section , we discuss some models that derive detection range from environmental and stopped vehicle visibility characteristics. However, we prefer to use these models for sensitivity studies.

In this section we use reaction time data to derive detection range data. For drivers alerted by a warning we use a surprise reaction time distribution from [20]. Our use of the data is similar to [14]. This reaction time was collected as drivers crested a hill and encountered an obstacle on the road. No warning was provided at the top of the hill, and the hillcrest was the first opportunity for sighting the stopped vehicle. However, one may assume that the drivers were alert since they knew they were participating in an experiment. Therefore the driver reaction time to a warning is a random variable denoted by T_d^w that is normally distributed with mean $1.1 sec$ and variance 0.305.

For unalerted drivers we use data from [21]. A distribution of unalerted driver reaction times for highway driving was obtained by fitting a lognormal distribution to reaction time data collected by Sivak as described in [21]. The data was collected by measuring reaction times of unalerted drivers to the brake lights of a vehicle in front at speeds up to about 20 m/s. Though reaction times to stopped vehicles are arguably different from reaction time to brake lights, we use this data for its inattention component. The lognormal distribution is fixed with median $\lambda = 1.07$ s, mean $\mu = 1.21$ s, standard deviation $\sigma = 0.63$ s, and dispersion parameter $\zeta = 0.49$. The distribution

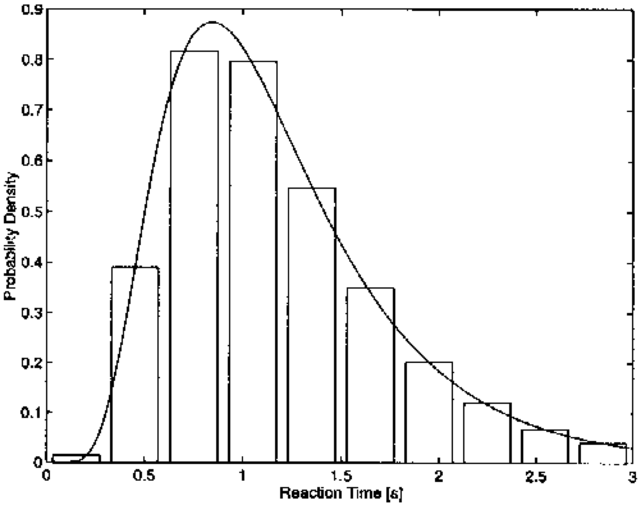


Figure 5: Reaction Time of a Typical Unalerted Driver

is shown in Figure 5. These three sets of data together with the associated probability distributions constitute the experimental layer work used in this example.

No specific dynamic layer analyses are conducted in our example. Instead, assumptions on the environmental and principal vehicle dynamics are discussed while presenting the kinematic models. We show kinematic abstractions modeling the interaction of the driver with the HMI subsystem of the FCWS, the stopped vehicle detection behavior of the driver both with and without the presence of the FCWS, the actuator commands generated by the driver, and the motion of the vehicle in response to the driver commands.

Let R_d be the random range at which the driver detects the stopped vehicle and r denote the time varying range of the principal vehicle w.r.t. the stopped vehicle. For $r > r_d$, where r_d denotes some realization of the random variable R_d, it is assumed that the principal vehicle travels at constant speed. For $r \leq r_d$ it is assumed that the principal vehicle decelerates at constant rate d until it comes to a stop, i.e., the stopping distance of the vehicle after detection is given by

$$\frac{v^2}{2d}$$

If a crash is unavoidable we assume $d = d^{max}$. If there exist deceleration rates d for which a crash can be avoided, i.e.,

$$\frac{v^2}{2d} < r_d,$$

then it is assumed that the average deceleration of the vehicle is some such d. Therefore the deceleration of the principal vehicle is a piecewise constant function of range as shown in figure 6. In the figure the detection range is $90m$.

In a dynamic layer analysis, one could examine the assumption that if there exists a crash avoiding average deceleration after the stopped vehicle is detected then the driver will find it. Since a driver reacts according to the looming effect of the stopped vehicle, the deceleration of the principal vehicle increases as the range decreases. It is of interest to verify that this time varying deceleration averages out as assumed in the kinematic abstraction.

We pick a simple kinematic abstraction for the FCWS warning subsystem. It is assumed

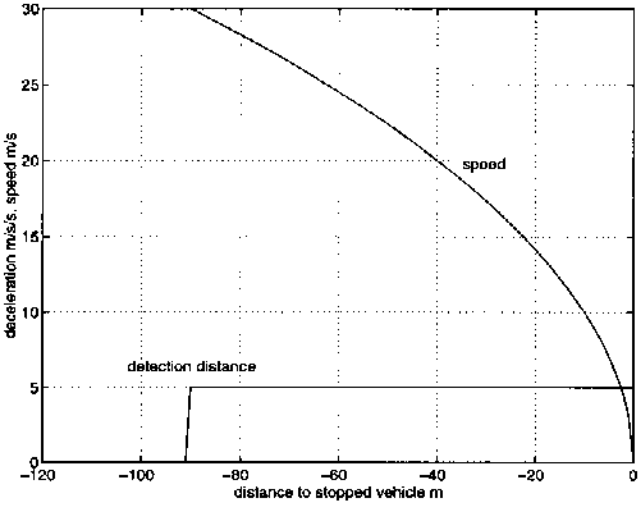


Figure 6: Deceleration and Speed of the Principal Vehicle

that the warning range is related to the speed of the vehicle by

$$r^s = \frac{v^{s2}}{2d^s} + t_d^s v^s,$$

where t_d^s is the nominal reaction time of the driver to the warning, d^s is the nominal deceleration of the vehicle after the driver begins braking, r^s is the warning range, and v^s is the speed of the vehicle at the warning range. This equation is similar to the warning function in [14]. The design assumes that the vehicle maintains constant speed during the driver reaction delay. Therefore, a warning design is a surface in the velocity range space defined by the equation

$$w(r^s, v^s) = 0, \qquad w(r^s, v^s) = r^s - \frac{v^{s2}}{2d^s} + t_d^s v^s,$$

where it is assumed that the FCWS provides an obstrusive warning to the driver whenever this surface is crossed. Figure 7 shows such a surface for $d^s = 0.4g, t_d^s = 1.8s$ a maximum speed of $40m/s(90mph)$, and a corresponding sensor range of $260m$. Such a sensor range is high though it seems unavoidable if the reaction time data is to be believed. Under these assumptions the set of all possible warning designs is characterized by the set of possible pairs (d^s, t^{ds}). The figure shows another warning surface (dotted line) for $d^s = 0.3g$ and $t_d^s = 1.6s$. Since for any v^s the equation $w = 0$ can be solved for a unique r^s, we sometimes use $w(v^s)$ to denote the corresponding warning range. The probability of an alarm in an LVNM scenario is the probability of crossing the surface.

For a FCWS equipped vehicle the range at which the driver detects the stopped vehicle may be greater or less than the warning range. If $R_d > w(v)$ then $R_d = R_d^{wo}$, where R_d^{wo} denotes the detection range of the driver unaided by a warning system. Thus we assume that there is no risk compensation by the driver. In this case R_d^{wo} is related to the reaction time of the unalerted driver (T_d^{wo}) by

$$R_d^{wo} = r_0 - vT_d^{wo}, \tag{2}$$

where r_0 is assumed to be the range at which the stopped vehicle is detectable, i.e., it is assumed that at ranges greater than r_0 the vehicle is not detectable. If $R_d < w(v)$ then $R_d = R_d^w$, where R_d^w

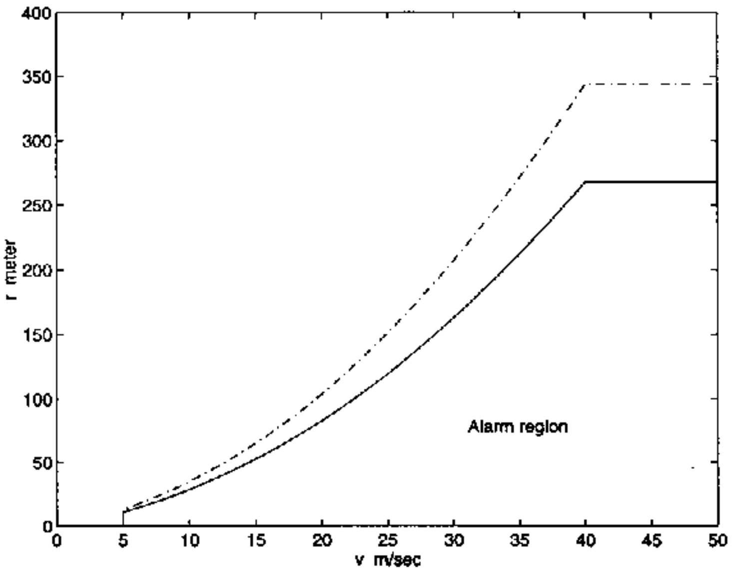


Figure 7: Two Warning Design Surfaces

denotes the detection range of the driver alerted by the warning. In this case R_d^w is related to the reaction time of the alerted driver (T_d^w) by

$$R_d^w = w(v) - vT_d^w. \tag{3}$$

The stopped vehicle has no kinematics or dynamics. It is a static target in a static background with fixed return characteristics, i.e., static cross-section, reflectance, contrast for human vision, static RCS for millimeter wave radar, etc. The performance of the FCWS sensors with respect to the stopped vehicle target is specified by the measure $p_d^s(r_d^s, v)$, which is the probability that the sensors detect the stopped vehicle at a range greater than r_d^s when the principal vehicle is assumed to travel at velocity v before detection. As usual, the missed detection probability is

$$p_{md}^s(r_d^s, v) = 1 - p_d^s(r_d^s, v).$$

In particular, the missed detection probability at the warning surface is $p_{md}^s(w(v), v)$.

It is of interest to note that driver reaction time to warnings can increase with reduced visibility (subsection). Likewise, the maximum deceleration developed by a car can degrade due to wear, precipitation or pavement quality. Therefore, sophisticated warning designs may adjust the warning surface dynamically based on weather, coefficient of friction estimation, or driver condition monitors. The simple warning design used here ignores such possibilities though analysis based on this simple model can estimate the potential value added by these extensions. Brake actuation delays are neglected though they are relatively easy to include in the warning design. Since brake systems are not part of FCWS design we exclude their performance specifications from our models. It is assumed that if the driver is braking then the driver is alert and the warning will not sound if the driver is braking while crossing the warning surface. This helps reduce nuisance alarms.

The purpose of the kinematic abstractions is to quantify the CAS subsystem performance measures that are used at the system performance and user acceptance layer. In this example, we analyze the system capability p_{cap}^s and the nuisance alarm probability p_{nui}^s. In the subsequent analysis we restrict attention to total crash probabilities.

For an FCWS we expect that p^s_{cap} should be a measure of the effectiveness of the warning in mitigating a crash. Accordingly, at a given speed v it is defined to be the probability of avoiding a crash given that the driver did not detect the stopped vehicle prior to the warning. Mathematically,

$$\begin{aligned} p^s_{cap}(v) &= p^w(no\ crash|R^{wo}_d < w(v)), \\ &= p^w(\frac{v^2}{2D^{max}} < R^w_d < w(v)|R^{wo}_d < w(v)), \end{aligned} \tag{4}$$

where D^{max} is the random variable representing the deceleration capability of the principal vehicle. We have used numerical integration routines to integrate the joint distribution of the random variables R^w_d and D^{max}. The probability distributions on R^{wo}_d and R^w_d can be computed by using equations 2 and 3, and the two reaction time distributions. It is desirable that p^s_{cap} be as high as possible. Note that p^s_{cap}, as defined, is independent of the FCWS sensor performance. It is the effectiveness of the system given that the sensors successfully detect the stopped vehicle before the warning range as intended by the FCWS sensor design.

The nuisance alarm measure (p^s_{nui}) is intended to quantify the probability that the system warns the driver that a collision is imminent with the stationary vehicle and the driver disagrees, i.e., the driver thinks that the warning is premature. Mathematically,

$$\begin{aligned} p^s_{nui}(v) &= p^w(no\ crash|R^{wo}_d < w(v), D = d^{com}), \\ &= p^w(\frac{v^2}{2d^{com}} < R^w_d < w(v)|R^{wo}_d < w(v)), \end{aligned} \tag{5}$$

where d^{com} is a comfortable deceleration limit. It is assumed that the stationary vehicle is really present, i.e., a nuisance alarm is not a false positive or sensor false alarm. In relating nuisance alarms to a comfortable deceleration limit, we are assuming that if the vehicle can be brought to a non-emergency stop, the driver would consider such an alarm unnecesssary. While this definition has the advantage that it is parametrized by d^{com}, it is not satisfactory in several respects. For example, the inattentive driver may still be glad that the alarm drew her attention to the stopped vehicle. Moreover, the characterization of comfort is simplistic. Jerks or low frequency disturbances are not considered.

On the basis of these mathematical definitions we can now quantify the relationship between the probability that an alarm is effective and the probability that it is a nuisance. Figure 8 shows such a relationship. For a given warning design w, at every speed v, one obtains unique values of $p^s_{nui}(v)$ and $p^s_{cap}(v)$. Therefore the curve is obtained by varying over the space of warning designs. The speed is held constant at $30ms^{-1}$ and the warning range is varied from $115m$ to $170m$. The comfortable deceleration limit used in this nuisance alarm computation is $0.4g$. This curve appears good from a design standpoint. However, it is desirable that its underlying assumptions be researched with more rigor.

The next level of the hierarchy is the system performance and user acceptance layer. At this layer we establish the relationships between the FCWS subsystem measures computed at the kinematic layer and the higher level effectiveness measures, namely, the probability that the system is on and active in the LVNM scenario (p^{on}), the probability of avoiding a crash with the FCWS (p^w_{ncr}), and the probability of avoiding a crash without the FCWS (p^{wo}_{ncr}).

The probability of a crash with the system is given by

$$\begin{aligned} 1 - p^w_{ncr}(v) &= p^{wo}(crash|R^{wo}_d > w(v))p(R^{wo}_d > w(v)) \\ &\quad + p^w(crash|R^{wo}_d < w(v))p(R^{wo}_d < w(v)), \end{aligned} \tag{6}$$

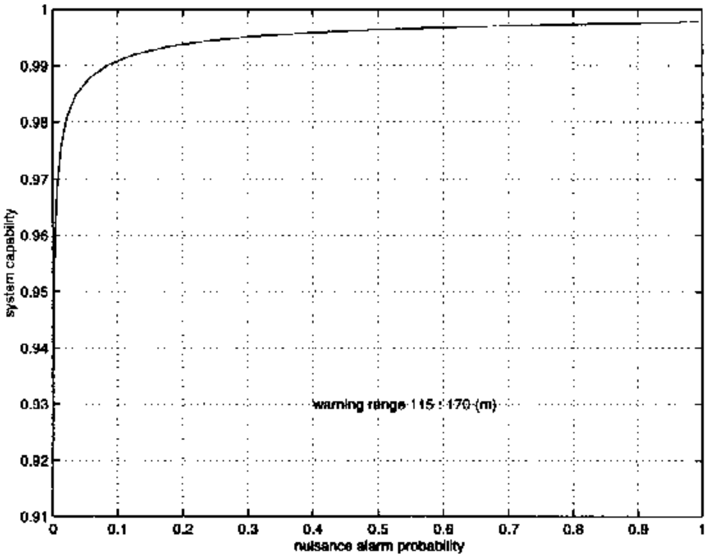


Figure 8: The Nuisance Alarm and System Capability Trade-off

$$\begin{aligned} p^w(crash|R_d^{wo} < w(v)) &= p^w(crash|R_d^s > w(v), R_d^{wo} < w(v))p_d^s(v) \\ &\quad + p^w(crash|R_d^s < w(v), R_d^{wo} < w(v))p_{md}^s(v), \end{aligned} \tag{7}$$

where R_d^s is the random range at which the FCWS sensors detect the stopped vehicle, and $p(R_d^{wo} > w(v))$ and $p(R_d^{wo} < w(v))$ are obtained from the unalerted driver distribution by using equation 2 and

$$p^{wo}((crash|R_d^{wo} > w(v)) = p^{wo}(\frac{v^2}{2D^{max}} > R_d^{wo}|R_d^{wo} > w(v)).$$

Next we assume that $p^w(crash|R_d^s < w(v), R_d^{wo} < w(v)) \simeq p^{wo}(crash|R_d^s < R_d^{wo} < w(v))$. The exact expression is complex. Actually the lefthand side is generally slightly less than the righthand side, but since this results in a lower bound on the benefit estimate we proceed with this approximation. This approximation together with $p^w(crash|R_d^s > w(v), R_d^{wo} < w(v)) = 1 - p_{cap}^s(v)$ implies

$$p^w(crash|R_d^{wo} < w(v)) = p^{wo}(crash|R_d^{wo} < w(v))p_{md}^s(v) + (1 - p_{cap}^s(v))p_d^s(v), \tag{8}$$

$$\text{and } p^{wo}(crash|R_d^{wo} < w(v)) = p^{wo}(\frac{v^2}{2D^{max}} > R_d^{wo}|R_d^{wo} < w(v)). \tag{9}$$

Therefore using equations 6, 8, 9 and the probability distributions on alerted driver reaction times, unalerted driver reaction times, and deceleration capability we can compute p_{ncr}^w or p_{cr}^w. Figure 9 plots the probability of a crash with the system (p_{cr}^w) as the warning distance is varied at a fixed speed of $30ms^{-1}$. As expected the crash probability decreases as the warning range is increased. The topmost curve (the driver capability curve) is the probability of a crash for unassisted drivers given that they have not detected the stopped vehicle prior to the warning range. The second curve is the system capability curve. Observe that at a given warning range the overall probability of a crash is even smaller than the system capability. This is because it is assumed that the driver acts in parallel to the system, i.e., for a FCWS equipped vehicle crash two failures are required. Firstly the driver has to fail to detect prior to the warning range, and then the driver has to fail to detect again in response to the warning.

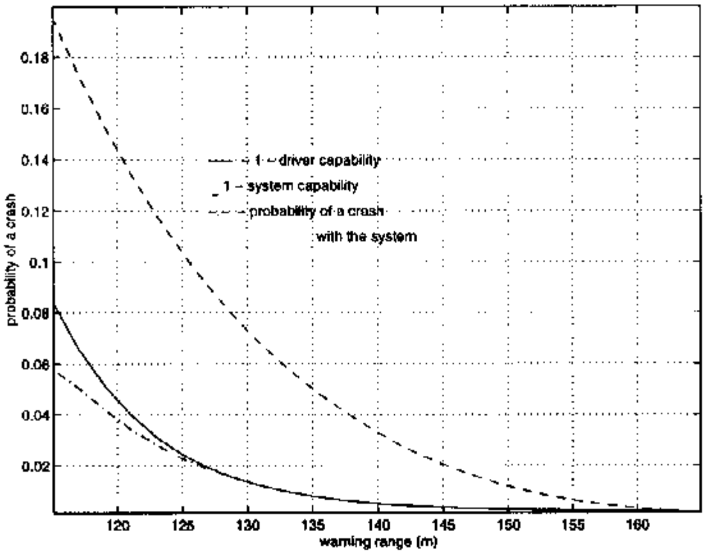


Figure 9: The Probability of a Crash with the System

The probability of avoiding a crash without the system (p^{wo}_{ncr}) is computed by

$$p^{wo}_{ncr} \;=\; p^{wo}\left(\frac{v^2}{2D^{max}} < R^{wo}_d\right) \tag{10}$$

This probability can be computed using the unalerted lognormal reaction time distribution and equation 2. One needs to assume a value for the distance (r_0) at which the reaction time clock starts. We have no good basis for this number. In this example we use $145m$ since this is close to the maximum warning ranges we consider for the computation of benefits. Note that p^{wo}_{cr} is invariant to warning distance.

The final benefit layer computations are as follows. The benefit equation is

$$b \;=\; \frac{(p^{wo}_{cr} - p^{w}_{cr})p^{on}}{p^{wo}_{cr}}. \tag{11}$$

Figure 10 plots benefit as a function of p^{w}_{cr} for $p^{on} = 1$. The numerator of the benefit equation is given by

$$p^{wo}_{cr}(R^{wo}_d < w(v))p^{d}_{md}(v) - (1 - p^{s}_{cap}(v))p^{d}_{md}(v),$$

where $p^{d}_{md}(v) = p^{wo}(R^{wo}_d < w(v))$, i.e., this is the probability that the unassisted driver fails to detect the stopped vehicle before the warning range. In view of our reservations about the largest possible reaction distance (r_0) of the unassisted driver, we plot the numerator of the benefit equation. Since the denominator is constant its only effect would be to alter the scale of the curve. The shape would remain the same. Observe that the benefit is a bell shaped function of the warning distance. This can be understood as follows. At very small warning distances both the probability of a crash with the system and the probability of a crash without the system is one and the benefit is zero. On the other hand, at very large warning distances both $1 - p^{s}_{cap}$ and $p^{wo}_{cr}(R^{wo}_d < w(v))$ are very small. Therefore the difference is very small and the benefit is nearly zero. Somewhere in the middle the benefit is maximized. Further investigation is required to ascertain if such bell shaped curves are obtained in general. Such bell shaped curves are also mentioned in [22].

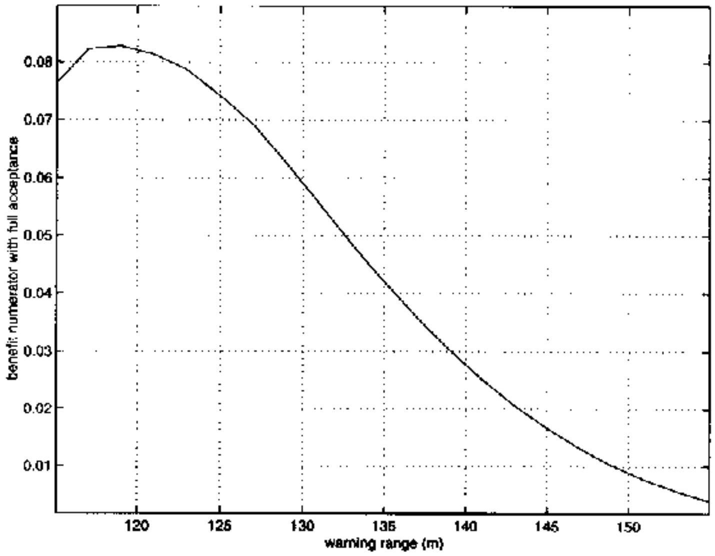


Figure 10: Benefits and Warning Design with Full User Accetance

As the rate of nuisance alarms increase we expect the rate of system utilization to decrease. Studies with aircraft operation [23] show that as the nuisance alarm rate increases cockpit personnel pay less attention to the alarm. It may be conjectured that drivers will show similar patterns. The relationships between p^{on} and p_a^f, p_{nui}^s are not well understood and merit further research. For lack of better data, and to demonstrate a point, we hypothesize that

$$p^{on} = 1 - p_{nui}^s. \tag{12}$$

Figure 11 plots benefit (with varying user acceptance) as a function of the warning range and figure ?? shows the two benefit curves together. As expected the benefit levels are lower for the case of varying user acceptance. As the warning range increases the nuisance alarm probability tends to one, and by equation 12 p^{on} tends to zero. Thus the benefit tends to zero.

10.4.14.3.2 FCWS Requirements Analyses

This section focusses on the sensing subsystem of the FCWS. We examine the sensitivity of sensor performance to design and environmental parameters in much the same way in which we examined the sensitivity of system capability to warning design in the previous subsection.

We provide an example application of an empirical human detection probability model, and we extend tenets of laser and millimeter wave (mmw) radar system ranging to illustrate the utility of these models toward quantifying performance. The applications highlight the importance of understanding and modeling target, background and weather characteristics in determining the detectability of proximate vehicles. For now, we illustrate how analyzing human and sensing parameters can be applied to highlight input sensitivities and particular data needs to help focus subsequent analytical and experimental efforts.

Our examples focus on the effects of atmospheric conditions. Thus, we assume the driver to be alerted and attentive (i.e., any attention deficit is assumed to be either overcome, perhaps by a collision warning). This restriction need not be applied to further studies, conducted within the

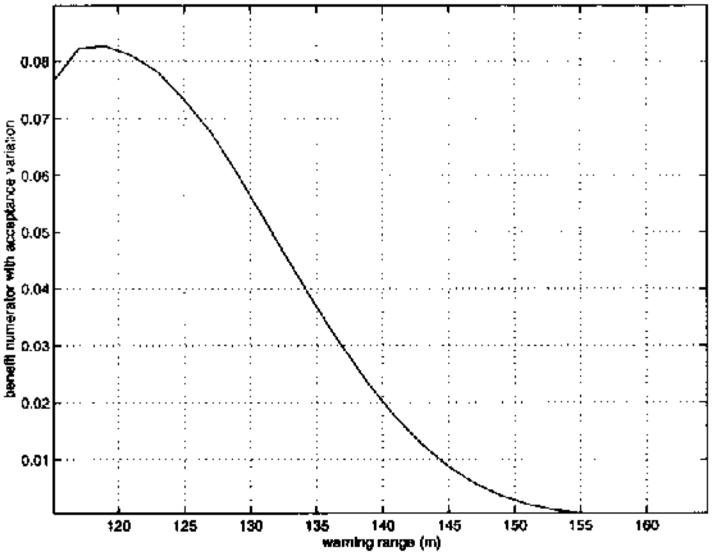


Figure 11: Benefits and Warning Design for Varying User Acceptance

performance or dynamics layers of the HARTCAS hierarchy described in Section 2; these studies can be conducted at the appropriate level of scenario-specific detail, then fed into the higher level benefits calculation (equation 1). In this manner, factors for vigilance, attentiveness, driver reaction time and even any unique driver-assist effects on vehicle dynamics are explicitly incorporated into the calculation of CAS benefits.

10.4.14.3.2.1 LVNM Example: Sensing Problem Formulation

The LVNM forward collision warning sensing system should yield the basic outputs of distance to the obstacle r_d and detection and response time t_{od}, which would in turn be translated to the net available stopping or maneuver distance d via

$$d = r_d - t_{od} v, \tag{13}$$

where v is the average vehicle speed during the target acquisition.

However, d is also a function of many detection-specific parameters which must be made explicit. These parameters generally describe a variety of obstacle detection sensing systems, including human detection. Detection function can generally be written as:

$$P_d = a_e r_d f_{sensor}(p_a^f, p_{md}, SCR, p_n, a_o, \frac{p_o(x)}{p_b(x)}) \tag{14}$$

where a_e is the atmospheric extinction, and the sensor processing function f_{sensor} is written in terms of a combination of obstacle-descriptive parameters (area a_o, range x, target signature distribution $p_o(x)$), background-descriptive parameters (background signature spatial distribution $p_b(x)$), and sensor and sensor processing parameters (sensor noise distribution p_n, false alarm probability p_a^f, missed detection probability p_{md}, signal to clutter threshold design point SCR).

The f_{sensor} parameter is almost infinitely adjustable. Each particular sensing system possesses unique detection decision criteria which comprise the factors within f_{sensor}. For example,

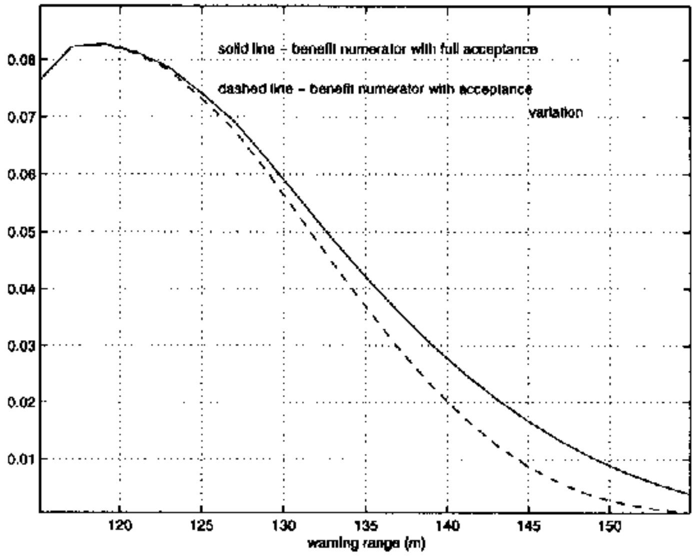


Figure 12: Benefits vs. Warning with Full and Varying User Acceptance

a CAS radar designer will likely specify what is termed a Neyman-Pearson or likelihood ratio receiver [24], where p_a^f and p_{md} are stochastic distributions. The compromise or design point between these distributions can be specified by first determining the likelihood ratio SCR/p_n [24]. When we consider that $p_a^f = f(SCR/pn)$ and then f is highly dependent on the specific radar processing design. In addition, a priori knowledge of the rage of target and background signature characteristics is necessary in determining SCR.

A vision enhancement system designer will typically approach f_{sensor} using different terms but in an essentially equivalent manner. The Neyman-Pearson receiver of the CAS radar designer is in the vision case simply an application of TSD decision-making, and p_a^f is related to p_d for each unique target/background/vision/processing device combination via a curve known as the receiver operating characteristic (ROC). The ROC is an empirical measure to specify or test to either p_a^f or p_d. The detection criterion is the value of the decision variable, which is a likelihood ratio. A variety of ROC curves have been derived for human vision for specific backgrounds and targets [25].

10.4.14.3.2.2 Analysis of the Detection Performance of Drivers

We illustrate the LVNM detection problem with the first of three successively higher fidelity models to represent human vision: the Bailey-Rand (BR) Contrast Model.

Bailey-Rand Contrast Model: Background, Assumptions and Similar Models. The BR model predicts $p_d(x)$ for static, circular targets in the absence of background clutter [25]. It is constructed via the Blackwell-McCready data set, and is therefore empirically formulated with data from single glimpses of $1/3s$ duration. By way of example, we apply the BR model to "get us in the ballpark" in determining p_d and also to understand sensitivities to input parameters. We leverage its empirical basis and prior DoD application [25], and we also utilize its incorporation of first-order effects of luminance contrast, plus the representation of atmospheric phenomenology.

The BR model differs from the Visibility Index and Visibility Index/Fog (VI/FOG) models [8] in that the BR model more rigorously defines meteorological parameters affecting detectability

(SGR, V). The VI/FOG models, however, take glare from artificial illumination into consideration, including street lights and rear lamps. An improvement to the psychophysics embedded within the VI/FOG models is represented by the PCDETECT model, which takes into account driver age and glare. All three competing models (BR, VI/FOG, PCDETECT) are based on data from the classical Blackwell experiments, which relate differences in visual contrast over a wide range of illumination conditions [26, 27]. In these experiments, targets are circular, the background is uniform, and the target-to-background discriminant is luminance (i.e., gray scale) contrast. These assumptions exist within the other models, but the BR model makes explicit acknowledgment of this. We believe that the common use of Blackwell's data allows models to yield similar "gets us in the ballpark" results.

We prefer the BR model in our example iteration because it can be compactly expressed in three equations (equations 16, 18,19), and it is acknowledged outside the transportation safety community [27]. We believe that VI/FOG and PCDETECT are equally valid for this first iteration, but we also believe that the human visual system must be more rigorously modeled in subsequent iterations to get us out of this estimation stage.

In abstracting the LVNM target for the BR model, we recognize that although the LVNM target is static, it is certainly not circular, nor is the surround clutter-free; moreover, we recognize that considerably more spatial, spectral and temporal description is necessary to capture the early vision process. For this first iteration, however, we acknowledge that the circular target assumption is simplifying, but again, it "gets us in the ballpark". In addition, the clutter-free background is not the case with most roadways; however, it can be envisioned to be true in certain constrained-area surrounds. (The highway scene, sans other vehicles, certainly has less local clutter than many natural backgrounds.) Once more, this assumption "gets us in the ballpark".

We also note that there is no explicit driver search model in the BR formulation; rather, each $1/3s$ BR glimpse is assumed to be independent. Various investigators have debated the independent glimpse assumption for the battlefield surveillance task [25, 28], but aside from investigating overt head dwell and gaze abduction behavior at intersections, there are very few field experiments on which to build driver visual search models [29, 30]. We expect that the design of a FWS will be such that the driver will direct the alerted search to the lane directly ahead; however, this is not necessarily the search pattern for most normal driving.

The BR detection model prescribes:

$$P_d = 0.5 \pm 0.5\{1 - exp\{-4.2(\frac{C_R}{C_T} - 1)^2\}\}^{0.5}, \tag{15}$$

$$+ \quad when \;\; \frac{C_R}{C_T} \geq 1, \tag{16}$$

$$- \quad when \;\; \frac{C_R}{C_T} \leq 1, \tag{17}$$

where

$$C_T = 10^{-2}10^{\frac{1}{\log(3440(D/r_d)+0.5)}}, \tag{18}$$

and

$$C_R = \frac{C_0}{1 + SGR\{exp(3.912r_d/V) - 1\}}. \tag{19}$$

In equations 16,18, and 19, the human detection threshold C_T is equivalent to the generic sensor SCR threshold defined earlier; C_R is the apparent contrast and is expressed as a function of C_o, the physical target contrast with the local surround; SGR is the sky-to-ground luminance ratio; V is the visibility, or the maximum range to a target with $C_R = 1$, where C_R is diminished no more than 2 %; $D$is the diameter of the equivalent area target circle; and r_d is the detection range. The D/x term in the expression for C_T is an angular resolution term; it may be expressed in terms of line pairs/target, cycles/mrad or some other appropriate measure of spatial frequency.

Applying the BR Model to the LVNM Case: We substitute the following parameter values:

- In determining $C_T : D = 2.26m$ ($4m^2$ target, representing a nominal geometric cross-section of the rear end of a light duty passenger vehicle)
- In determining C_R :

  $$C_o \;=\; \frac{L_0 - L_b}{L_b} = \frac{R_0 - R_b}{R_b} = \frac{0.5 - 0.15}{0.15} = 2.3, \qquad (20)$$

  [31, 32], where L_0 and L_b are target and background luminance, respectively. Given the same insolation and no internal target shadowing, they equate to first order to R_0 and R_b, the target and background reflectances. Substituting readily available values for R_0 (gray paint [31]) and R_b (asphalt [32]) yields a value for C_0.
- $SGR = 1.4$, a typical value for clear skies and desert conditions[32]. Values for desert floor reflectivity are near those for asphalt reflectivity [31], and the environment is nearly clutter-free, similar to unobscured road surfaces. Variations due to SGR are typically due to different sky conditions (e.g., clear vs. diffuse) and terrestrial surface reflectivities (e.g., snow vs. desert vs. forest canopy). The range of SGR values is 0.2 (clear sky, snow surface), to 25 (diffuse sky, forest canopy surface).

Using the BR input values for the ranges considered $x = 90m$ to $160m$, $C_T(90m) = 0.033$, and $C_R/C_T > 1$. For a singular $1/3s$ glimpse, $p_d = 1.0$ at a typical $V = 10,000m$ [33]. This confirms intuition: a visually unimpaired and alerted human performs well in an unobscured direct line-of-sight detection task over relatively short ranges.

While there are many variables which influence detectability (e.g., target size, contrast ratios) it is interesting to focus this example on one: V, the ratio of detection distance to visibility, because V corresponds to the atmospheric extinction due to environmental obscurants as fog and rain (along with SGR), and p_d is sensitive to it. Hence, it allows us to assess the effects of weather obscuration. Figure 13 shows that according to the BR model inputs, human detection performance was indeed shown to be highly sensitive to variations in V at a fixed range $x = 90m$. It can be concluded that p_d will diminish rapidly under extremely obscured or inclement conditions – and that some obscurant penetrating system such as millimeter wave or laser radar is needed as a supplement under these conditions.

The magnitude of weather obscuration to effect variations in p_d can also be derived from the BR results. From figure 13, $p_d = 1$ near $V = 110m$. The rain rate required to elicit this value of V can be determined by substituting empirical rain rate-extinction relationships into the Beer-Lambert or Koschmeider's Law:

$$T(\lambda) \;=\; \exp^{-ar_d}, \qquad (21)$$

where $T(\lambda)$ is the transmittance and a is the precipitation volume extinction coefficient (km_1). The empirical expression to determine a under moderate/widespread rain conditions is:

$$a \;=\; 0.36r^{0.63}, \qquad (22)$$

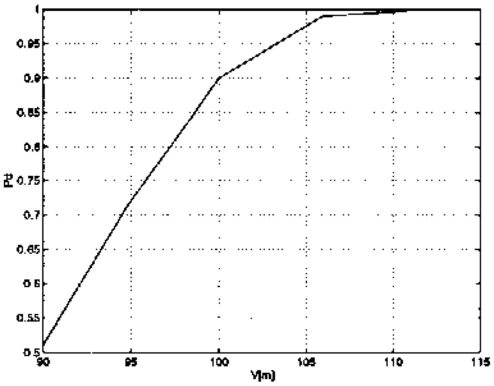


Figure 13: BR-Derived Detection Probabilities as a Function of Visibility

where r is the rain rate expressed in mm/h [33].

With $T(\lambda) = 0.98, r = 2.9mm/h$. Interestingly, with $p_d = 0.51$ (corresponding to $V = 90m$), $r = 2.1mm/h$. Both these rain rates fall within the definition for the common condition of moderate/widespread rain [33, 34]. Hence, for the analyzed LVNM case, p_d's can fall off dramatically with small variations in even moderately inclement weather.

This result points to the potentially frequent need for human vision augmentation in a CAS. Moreover, the augmenting device should be some type of a rain-penetrating sensing system. The results also begin to clarify the value of the human detection probability component in a CAS benefits assessment. It follows that better human vision models, which exist and can be adapted within the benefits assessment framework, would yield higher confidence answers to questions on CAS efficacy, benefits and requirements.

10.4.14.3.2.3 Analysis of the Detection Performance of Radar

We present laser and mmw radar range equations to illustrate parallels to the human detection in inclement weather. However, the analogy is not complete; these potential CAS sensing systems can have very specific (and proprietary) designs to include all elements in the f_{sensor} function of equation 14, in addition to other explicit design elements such as transmitter power P_t and antenna area A_e, and a variety of loss factors. Nonetheless, it is useful to examine the relationships to determine design sensitivities vis-a-vis the human detection system that these CAS sensors presumably supplement or enhance.

Laser Range Equation: From [24],

$$r_d = (\frac{\pi P_t A_e \rho}{32 S_{min}})^{0.5}, \tag{23}$$

where r is the in-band surface reflectivity and S_{min} is the minimum detectable target. The form of equation 23 assumes the worst case, i.e., no corner cube retroreflectors present, that the laser radar return is Lambertian (or diffuse). It also assumes that the incident beam is both smaller than and orthogonal to the target surface. Note that the range scales with the square root of controllable design factors, namely P_t, A_e and S_{min}.

Radar Range Equation: Also from [24],

$$r_d = (\frac{P_t G A_e \sigma}{4\pi^2 S_{min}})^{0.25}, \tag{24}$$

where G is the system gain and σ is the $RCS(m^2)$. The form of equation 24 assumes that G and A_e are independent of radar frequncy. Note that in this equation range scales with the fourth root of controllable design factors, namely P_t, G, A_e and S_{min}.

System Performance: Both laser and mmw systems are generally designed to have p_d's approaching 1, especially at the limited (approximately 100 m) ranges of the example CAS application. Because of this, and because we are not presenting a specific sensor design, instead of determining p_d outright, we instead pose the question that given the range of rain rates used in the human detection example (2.1 to 2.9 mm/hr), what design parameters must be adjusted to overcome the atmospheric extinction brought on by rain? In essence, we wish to examine elements of the laser and radar range equation that will compensate for any rain extinction.

For a near infrared (NIR) laser radar system, the first cut atmospheric extinction assumption is that it is equivalent to visual band extinction [33]. This assumption can be later modified by application of a standard band model or line-by-line atmospheric transmission code (e.g., MODTRAN or FASCODE). Using this assumption, for now, we see from equation 21 that $a = .70km^{-1}$ for $r = 2.9mm/h$ and $a = .58km^{-1}$ for $r = 2.1mm/h$. Using a for the heavier rain rate, equation 22 gives us a 50% reduction in t (or equivalently, a_e). From equation 23, this gives a requirement for the combination of controllable parameters – Pt, A_e and S_{min} to be increased by 25%. This should not be too difficult to accomplish in designing a NIR sensing system, and obviously impossible to change with the earlier human sensing system.

Applying a similar analysis to a mmw radar system, we observe from [33] that we can rewrite equation 22 in the functional form

$$a = cr^b, \tag{25}$$

where c and b can be empirically determined. For a 94 GHz radar, $c = 0.345$ and $b = 0.634$ [33], yielding a 51% reduction in τ or A_e for $r = 2.9mm/h$ - a similar value in atmospheric extinction to that for the laser radar; for a 35 GHz radar, , $c = 0.063$ and $b = 0.945$ [33], yielding a 7% reduction in τ or A_e - showing that atmospheric extinction is quite small at this frequency. Hence, at 94 GHz, the combination of controllable parameters - this time, P_t, G, A_e and S_{min} - needs to be increased by about 6%. This improvement is even easier than the NIR design requirement. At 35 GHz, however, there is virtually no design change needed - the radar is indeed rain-penetrating as is.

This example is a simple illustration of the detection performance calculation for two generic types of CAS sensing systems. Performance benefits are roughly determined, along with input design sensitivities. Substituting CAS sensor values and especially the system-specific f_{sensor} value – into these equations, along with a notion of geometries (fields of view, scanning fields of regard, etc.), will allow the evaluator to go one step beyond this example: toward determining requirements due to inclement weather and roadway topographies.

10.4.14.4 Summary

We have suggested a hierarchical framework (HARTCAS) for the organization of analytical anc experimental work on the benefit assessment and requirements development for crash avoidance systems. We have illustrated the interpretation and use of the hierarchy by providing an illustrative analysis, and by discussing how some of the exisiting analytical and experimental work could be usefully integrated in the HARTCAS framework to support future analyses, that are both deeper and broader.

The CAS analysis problem is multi-faceted and large-scale. The driving environment is highly diverse and uncertain, drivers are highly variable, and the range of applicable technologies is wide. Considerable real world data is becoming available on certain aspects of the environment, though possibilities for the collection of experimental data on other aspects is constrained by technological and institutional difficulties. Therefore, CAS analyses are to be conducted by collecting data to the greatest possible extent on normal operating conditions, and using such data to build models that analyze the rare abnormal conditions. A paradigm is required to structure the collection and use of such knowledge. The HARTCAS methodology is a possibility. We believe that developing and populating such a hierarchical framework is worthy of further research and development. Use of HARTCAS methodlogy for benefit estimation is also helpful to identify holes in the analysis hierarchy leading to well-definined statements of needed analyses.

The integration of CAS subsystem performance into overall CAS effectiveness estimates is discussed in general and addressed within the context of mitigating rear-end crashes in the LVNM scenario (Section). In this example, we have used Bayesian probabilistic methods to incorporate sensor detection probabilites, human detection probabilities and nuisance alarms in the assessment of benfits. We have also given some indication of the degradation of human detection performance in the LVNM scenario with increasing rain. Some analyses on the sensitivity of benefits to warning design and subsystem performance measures are provided. One can see from the example, that the computation and analysis of system performance measures is complex even for a simple scenario. Better experimental data on user acceptance and the performance of the driver with and without the system, are required to deal with these complexities. These directions are worthy of further research.

The HARTCAS hierarchy integrates the kinematic modeling (e.g., spacing design, hard braking safety analysis) and simulation (e.g., SmartAHS) tools developed by B5 researchers in a unified benefit assessment framework. Experimental data and detailed SmartAHS dynamic simulations are used to build simple kinemtic models for different subsystems (e.g., sensors, actuators, HMI, etc.) whose parameters cover a wide range of environmental and traffic conditions. Performance of individual subsystems, evaluated using kinematic analysis tools, is aggreagted to derive system level benefits such as reduction in number of rear-end crashes. The SmartAHS simulations also provide information about the frequency of hazards and the effect of automation systems on system throughput. The HARTCAS method can also be used to derive technological requirements to satisfy given system specification.

In the next phase of C3 analysis, this framework will be extended and applied to different market packages. The work involves definition of MOE's, application scenarios for tool use, identification of experimental data needs, and development of models and tools. The B5 group has already started developing and coding in SmartAHS, models for driver behavior, and longitudinal control and assistance system. The first step in the evaluation process should be a detailed analysis of different ACC systems (e.g., ACC with different levels of braking authority, ACC with FCWS, etc.) As the ACC systems will be deployed before any other market package, the above ACC analysis will develop a baseline for benefits and requirements. The second phase will involve analysis of systems with further capability, such as automatic collision avoidance, cooperation between vehicles and roadside, etc.

References

[1] "Preliminary assesment of crash avoidance systems benefits." NHTSA Benefits Working Group, October 1996.

[2] "Synthesis report: Examination of target vehicular crashes and potential ITS countermeasures." Research Report, U.S. Department of Transportation, DOT-VNTSA-NHTSA-95-4, prepared by VOLPE National Transportation Center, June 1995.

[3] "Forward-looking collision warning system performance guidelines." Research report prepared by Frontier Engineering for NHTSA Office of Crash Avoidance Research, December 1996.

[4] C. Eberhard, P. Moffa, S. Young, and R. Allen, "Development of performance specifications for collision avoidance systems for lane changing, merging, and backing." NTIS Report number DOT HS 808 430, September 1995.

[5] "Run-Off road collision avoidance using ITS countermeasure." Research report prepared by the Robotics Institute, Carnegie Mellon University for NHTSA Office of Crash Avoidance Research, 1995.

[6] "Human factors guidelines for crash avoidance devices." Prepared by COMSIS Corporation and CTA Inc. for NHTSA Project number DTNH22-91-C-07004.

[7] "RCS characteristics of common roadway objects catalog." Environmental Research Institute of Michigan, prepared for U.S. Department of Transportation, 1996.

[8] L. Tijerina and E. Al., "Examination of reduced visibility crashes and potential IVHS countermeasures." U.S.Department of Transportation. DOT HS 808 201, January 1995.

[9] P. Fancher, Z. Bareket, J. Sayer, G. Johnson, R. Ervin, and M. Mefford, "Fostering development, evaluation, and deployment of forward crash avoidance systems (FOCAS)." Annual Research Report ARR-5-15-95, NHTSA Contract Number DTNH22-94-Y-47016, UMTRI Report No. 95-31, Ann Arbor, Michigan, May 1995.

[10] R. W. Allen, R. E. Magdaleno, C. Serafin, S. Eckert, and T. Sieja, "Driver car following behavior under test and open road driving conditions." SAE Paper Number 970170, Presented at SAE International Congress and Exposition, Detroit, 1997.

[11] P. Fancher, R. Ervin, J. Sayer, M. Hagan, S. Bogard, Z. Bareket, M. Mefford, and J. Haugen, "Intelligent cruise control field operational test." UMTRI Research Report 97-11, NHTSA Contract Number DTNH22-94-Y-47016, March 1997.

[12] A. Burgett, "DOT's approach to ITS safety evaluation," in *Safety Evaluation Workshop, ITS America Safety and Human Factors Commitee*, May 1995.

[13] "The abbrevated injury scale: 1980 revision." AAAM (American Association for Automotive Medicine: Committee on Injury Scaling, Morton Grove, IL, 1980.

[14] E. Farber, "Using the REAMACS model to compare the effectiveness of alternate rear end collision warning algorithms," in *IVHS America*, pp. 400–407, 1994.

[15] J. Carbaugh, D. Godbole, and R. Sengupta, "Hard braking safety analysis for automated highway systems." in National Automated Highway Systems Consortium: Milestone 2 Report.

[16] P. S. Fancher, J. R. Sayer, and Z. Bareket, "A comparison of manual versus automatic control of headway as a function of driver characteristics," in *World Congress on Intelligent Transportation Systems*, 1996.

[17] P. Fancher and Z. Bareket, "Evaluating headway control using range versus range-rate relationships," *Vehicle System Dynamics*, vol. 23, pp. 575–596, 1994.

[18] A. Kanaris, P. Ioannou, and F.-S. Ho, "Spacing and capacity evaluations for different AHS concepts." Appendix A: Vehicular Data References Compiled from Consumer Reports and Road and Track, PATH Research Report, 1996.

[19] "U.S. domestic and imported car sales." Crain Communications, Automotive News (Q1, 1996), 1995.

[20] P. Olson, D. Cleveland, P. Fancher, L. Kostyniuk, and L. Schneider, "Parameters affecting stopping sight distance." National Cooperative Highway Research Program Report 270, TRB, June 1984.

[21] G. T. Taoka, "Brake reaction times of unalerted drivers," *ITE Journal*, vol. 59, no. 3, pp. 19–21, 1989.

[22] A.D.Horowitz and T.A.Dingus, "Warning signal design: A key human factors issue in an in-vehicle front-to-rear-end collision warning system," *Proceeding of the Human Factors Society 36th Annual Meeting*, vol. 2, pp. 1011–1013, 1992.

[23] E. L. Wiener and D. C. Nagel, *Human factors in aviation*. San Diego : Academic Press, 1988.

[24] M. Skolnik, *Introduction to Radar Systems*. Mc-Graw Hill Book Company, New York, 1980.

[25] J. Doll and D. Schmieder, "Observer false alarm effects on detection in clutter," *Optical Engineering*, vol. 32, no. 7, pp. 1675–1684, 1993.

[26] H. Blackwell and D. McCready, "Foveal detection thresholds for various durations of target presentations." Proceedings of NAS-NCR Vision Committee, 1952.

[27] R. Gerhart and E. Al., "Target acquisition methodology for visual and infrared imaging sensors," *Optical Engineering*, vol. 35, no. 10, pp. 3026–3036, 1996.

[28] S. Grossman and E. Al, "Target acquisition and false alarms in clutter," *Optical Engineering*, vol. 34, no. 8, pp. 2487–2494, 1995.

[29] T. Heckmann and E. Al., "Visual search of drivers at intersections - a field study." General Motors Publications, R&D-8417, Sep. 1995.

[30] P. R. Mouron and T. H. Rockwell, "Mapping eye-movement patterns to the visual scene in driving: An exploratory stray," *Human Factors*, vol. 12, no. 1, pp. 81–87, 1970.

[31] G. Wyszecki and W. Stiles, *Color Science: Concepts and Methods, Quantitative Data and Formulae*. John-Wiley and Sons, New York, 1982.

[32] W. Wolfe and G. J. Zissis, "The infrared handbook." Environmental Research Institute of Michigan, Ann Arbor, MI, 1995.

[33] "Quantitative description of obscuration factors for electro-optical and millimeter wave systems." DOD-HDBK-178(ER), Washington D.C., U.S. Department of Defence, July 1986.

[34] "Research, development, test and evaluation of material for extreme climatic conditions." U.S. Army Regulation No. 70-38, Aug. 1979.

C3 Interim Report

10.5 Case Studies

Includes:
10.5.1 NAHSC Case Study - Request for Information
10.5.2 Houston Metro - NAHSC Case Study
10.5.3 Rural Automated Highway Systems Case Study

NAHSC

10.5.1 REQUEST FOR INFORMATION

Author, Matt Hanson

PURPOSE OF THIS REQUEST

This request for information (RFI) is being sent to (agencies previously expressing interest in NAHSC case studies including) state and local departments of transportation, metropolitan planning organizations, and transit authorities to solicit expressions of interest in participating in Automated Highway System (AHS) case studies. In addition, an advertisement is being placed in the Commerce Business Daily. These studies will be conducted in cooperation with the National Automated Highway System Consortium (NAHSC).

The NAHSC expects to initiate at least three new AHS case studies this fiscal year. Contract awards are expected in the Spring of 1997. Case studies are expected to be multiple-phase and multiple-year contracts and will parallel the AHS concept development process.

The NAHSC is moving towards a flexible concept that defines an AHS that provides for incremental adoption of automation features, can support specific local options, and has the capacity to accommodate freight, transit, and personal vehicles.

RESPONSES REQUESTED FROM INTERESTED JURISDICTIONS

Jurisdictions interested in participating in AHS case studies should respond to this RFI by March 21, 1997, and furnish the information requested which includes:

- Name(s) of a contact person from your organization with address, phone number, and e-mail address,
- A general description of the region,
- Written response to the questions under the Selection Criteria section, and
- Any other information the jurisdiction believes may be pertinent to AHS case studies.

This RFI may not contain all the information necessary to answer the questions; therefore, the NAHSC has assigned personnel to work with interested parties and to answer their questions concerning automated highway systems and this RFI.

Responses should be directed to:

Dennis Casey (Contract Contact)
Lockheed Martin
PO Box 179 MS DC4350
Denver, CO 80201

or

Lockheed-Martin Doc 5
12257 State Highway 121
Littleton, CO 80127

303-977-8959 (voice)
303-971-4093 (fax)
Casey@ssv.den.mmc.com

Technical questions should be directed to:

Matt Hanson (Technical Contact)
Caltrans, New Technology & Research
PO Box 942873 MS 83
Sacramento, CA 94273-0001

or

1227 O Street, Fifth floor
Sacramento, CA 95814

916-654-8171 (voice)
916-657-4580 (fax)
mhanson@trmx3.dot.ca.gov

NATIONAL AUTOMATED HIGHWAY SYSTEM CONSORTIUM

The NAHSC is a collaboration of automotive, aerospace, automotive electronics, andinfrastructure development firms, a state department of transportation, and two of America's leading universities, along with a broad range of associate stakeholders to help ensure development of a national consensus on the AHS system design. The NAHSC was formed by the U. S. Department of Transportation to conduct systems design feasibility, systems definition and prototyping of a safe, reliable, and cost-effective AHS. The AHS must be capable of substantially improving safety, throughput, and air quality along high-demand travel corridors. The NAHSC is a partnership between the Federal Government and the other participants. The AHS program, mandated by the 1991 ISTEA legislation, is an integral part of the national Intelligent Transportation Systems (ITS) program.

The participants in the NAHSC envision automated highways as high performance surface transportation systems that integrate advanced vehicle and highway communication, sensing, and control technologies in a seamless, cohesive fashion. AHS is seen as the next major advance in surface transportation.

NAHSC MISSION

The Mission of the National Automated Highway System Consortium is to specify, develop and demonstrate a prototype AHS. The specification will provide for an incremental deployment that can be tailored to meet regional and local transportation needs. The NAHSC will seek opportunities for early introduction of vehicle and highway automation technologies to achieve benefits for all surface transportation users. The NAHSC will incorporate public and private stakeholder views to ensure that an AHS is economically, technically and socially viable. The NAHSC's approach to this work includes incorporation of inputs from various decision-making organizations.

WHAT IS AN AUTOMATED HIGHWAY SYSTEM?

An automated highway system is the integration of vehicle and highway automation technologies designed to significantly improve traffic safety, highway efficiency, travel time, comfort, convenience and reduce energy consumption and emissions. As part of the Intelligent Transportation System, AHS builds on developments in the rest of ITS, especially in the elements of Advanced Vehicle Control and Safety Systems (AVCSS).

AHS is still in the very early stages of development, dealing with general concepts - not actual designs. The general concepts are based upon six key attributes:

- What is the proper distribution of intelligence and communication between the vehicle and the highway? Where and how are the decisions made and how are they communicated?
- What are reasonable scenarios for AHS deployment sequences? What are reasonable assumptions for the timing of AHS deployment?
- Should the AHS consist of lanes dedicated exclusively to automated vehicles, lanes containing a mix of automated and manual vehicles, or should it include both dedicated and mixed traffic lanes?
- Should vehicles be grouped in "platoons" of vehicles or should vehicles remain autonomous?
- To what extent should the AHS be designed for obstacle exclusion versus a design based on obstacle detection and avoidance?
- What are the roles of the driver in an automated mode? What provisions should be made for driver override or intervention?

It is understood that there is no single right answer for AHS. The best configuration will depend on particular regional characteristics including: transportation system priorities, existing facilities, funding constraints, timeframe, etc. The NAHSC is moving towards a flexible concept that defines an AHS that supports incremental adoption of automation features, can accommodate specific local options, and has the capacity to accommodate freight, transit, and personal vehicles.

PURPOSE OF CASE STUDIES

The purpose of case studies is primarily to evaluate the technical, economic, and institutional impacts an AHS will have on regional transportation systems including traffic congestion, safety, air quality and energy conservation. In addition, local case studies will serve as "realistic" studies of local AHS deployment and explore the validity and implications of deploying AHS under site specific constraints. AHS is being studied and developed as one tool that a region can use to solve local transportation problems.

The NAHSC is using case studies as part of its AHS design and development process. Case studies are regarded as planning activities designed to look at possible AHS configurations within a specified region using actual and forecast data to determine:

- What AHS will look like in both a physical and institutional context
- What effect implementation will have on the rest of the system
- What logical steps might be followed to achieve AHS deployment
- What the rough order of magnitude benefits and costs are
- How AHS compares to other possible transportation alternatives

The regional agency is the expert on the local transportation network and NAHSC has an understanding of AHS. Together, using regional planning and evaluation tools along with NAHSC-developed analytical and simulation tools, it should be possible to define an AHS that is deployable and complements the regional transportation system.

CASE STUDY OBJECTIVES

Case study objectives include the following:

- Input into AHS functional and physical architecture development and evaluation.
- Evaluation of system performance resulting from implementation of AHS.
- Examination of major technical and institutional issues (dedicating lanes, vehicle spacing, driver-vehicle interface, operations, planning, etc.)
- Safety relevant to AHS in the given scenario (Urban, CVO, Transit, etc.)
- Creation of a deployment sequence(s) from the present system to the regional AHS

For a more complete and specific listing of NAHSC concept development goals and objectives see Appendix A.

CASE STUDY PROCESS

The Case Study process is expected to be multiple-phase and is intended to address the prevalent issues that arise during AHS architecture development. As the AHS architecture is more fully defined, the case study can be focused to look at specific issues, especially those that concern regional planning and operating agencies. For example, phase one will be used to select a suitable site, assemble existing data, and address general system level planning requirements. Phases two and three will look more closely at how AHS affects the region and describe AHS in sufficient detail so that it can potentially be incorporated into the existing transportation plans and be compared to other transportation alternatives.

SITE SELECTION

Site selection within a region will be based on availability of data and on discussions with and advice from the regional agency(s) involved. As part of the selection process a preliminary assessment to determine the potential for AHS deployment may be performed.

ASSEMBLE DATA

Assemble the data identified below in Appendix B, which includes highway geometrics, traffic incident and safety statistics, and current and projected traffic volumes. It is assumed that most information exists in current state or regional databases in electronic format and that no substantial raw data collection will be necessary.

ASSESSMENT

The assessment consists of two parts:

1) Use the set of NAHSC tools, models, and evaluation methods, as well as the data assembled above, assess proposed AHS and AHS subsystems. This includes issues such as vehicle spacing, merging distances, vehicle check-in and check-out protocols, and other AHS-specific design alternatives;

2) Use regional planning methods to analyze and evaluate local and regional impacts of AHS. This includes how the proposed AHS will affect adjacent arterials, energy , liability,
consumption, emissions, intermodality, existing institutional arrangements, etc.

Phase I - FY 97

Examine general concerns regarding AHS using interviews, workshops, market studies, and other high level evaluation methods to determine what it will take to include AHS in the regional transportation plans and begin to identify the key region-specific institutional and technical concerns.

Phase II - FY 98

Develop the necessary information and begin evaluating AHS as if it were an alternative in an MIS using the region's planning tools and models.

Phase III - FY 99

Continue the process begun in Phase II and complete the evaluation of AHS as one of the region's potential transportation alternatives.

REPORT RESULTS

Both written reports and oral presentation(s) will be included as part of the scope of work for each case study.

FUNDING

The consortium has a FY 97 budget of $25K to $70K for each case study. The budget is allocated for assembling data, running regional planning tools and/or conducting interviews, workshops, or other studies where needed. It is expected that the regional agency will cost-share with funds and/or labor.

SELECTION CRITERIA FOR CASE STUDY SITES

Candidate case study selection will be based on an NAHSC evaluation of answers to the following groups of questions. The answers will be scored and weighted on a scale of 1 to 10: a weighting factor (WF) of 10 is the most important and a WF of 1 is the least important relative to NAHSC goals. Answers to the questions should be brief.

Site suitability for AHS (WF = 4)
What are the problems you are currently having with your transportation system?

What types of transportation problems are you anticipating in 10 years? 20 years?

What are your current transportation priorities (in descending order)? (i.e., Improving operation of existing facilities, maintenance of existing facilities, construction of new facilities, etc.)

Do you have any specific site(s) in mind for potential case studies? If so, please give a brief description of the site(s) and it's potential for an AHS application. (Sites that are currently undergoing or have recently undergone an MIS or similar planning exercise are potentially ideal sites.)

Availability of reasonably current and projected geometric, traffic volume, safety and other data (WF = 7)
What data is available for the sites(s) under consideration as a potential case study? We are looking for:

- Highway Geometrics
- Safety, Incident, Obstacle data
- Traffic Volumes (both current and projected)
- Regional Transportation, ITS Deployment, or Showcase Plans

- List of transportation-related organizations (and their roles) which "own", operate, maintain or otherwise influence capital investment or operating policies in the region.

[For a more complete listing of the data needs see Appendix B]

Willingness to consider new technology as transportation alternatives (WF = 6).
What are your plans for integrating ITS Services into your present system?

Willingness to be actively involved in a case study (WF = 6).8
Would a member(s) of your staff be available to participate and assist the NAHSC in fine-tuning alternative AHS design concepts?

Are there regional analytical tools or methods available which could be used to estimate the effects and the benefits of AHS at the study site? If so, briefly list the types of tools or methods available and used in the region.

Are there other state, regional, local agencies that might be willing to participate with you in a case study?

What would you like to see come out of an AHS Case Study in your area?

Are there specific AHS features or scenarios that you would like to cover in the study? i.e., dedicated lanes, mixed traffic, commercial vehicle operations, transit, etc..

Willingness to cost share (WF = 9).6
Assuming that there is between $25K to $70K of federal funds to put into the first phase of a Case Study, how much are you willing to cost share? In what manner?
Funds?
Labor?
Other?

OTHER SELECTION CRITERIA

Site adds balance to the geographic representation of all case study sites (WF = 2) (e.g., the NAHSC would like to see an even distribution of case studies across the nation),

Site adds balance to study emphasis (WF = 5) (e.g., all classes of vehicles, transit, truck, urban, intercity, dedicated AHS lanes, mixed automated and manual lanes).

APPENDIX A - NAHSC Concept Development Objectives

Below are the objectives for some NAHSC tasks related to case studies. These objectives have been attached to give the reader a broader sense of the concept development work currently underway.

Architecture Development and Evaluation

Develop the AHS operations concept, functional architecture and physical architecture for the "mature" AHS:

1) Integrate the results of the critical issues teams and produce/update the baseline AHS architecture.
2) Identify/prioritize which issues need to be addressed for architecture development.
3) Integrate the results of the Evaluation tasks to provide a feasible architecture.

System Performance Evaluation

1. Throughput - pipeline values with derating for merging, demerging and lane changing
2. Throughput achievable in "real world" application scenarios
3. Travel times from AHS entry to AHS exit points in "real world" application scenarios (mean values, variances and perhaps distributions)
4. Total travel times for linked origin/destination pairs in "real world" application scenarios (mean values, variances and perhaps distributions)
5. Effects of AHS operations on local traffic at access and egress points, with adjustments to local traffic operations - changes in traffic volumes, speeds and delays
6. Energy consumption and emissions effects of AHS operations (local to AHS freeway, and at access and egress points)
7. Region-wide AHS impacts on traffic flows, trip making, delays, energy and emissions
8. Effects of incidents on AHS operations (time to respond and recover, impacts on traffic flow, travel times, queuing, energy and emissions)
9. Degradations in AHS operating speeds, throughput, travel times based on adverse environmental conditions, incidents, and AHS malfunctions

Technical and Institutional Issues Analysis

1. Determine characteristics and necessary steps for inclusion of AHS into regional transportation plans.
2. Identify potential obstacles and constraints to regional AHS development.
3. Identify strategies to mitigate above obstacles and constrains.

APPENDIX A - Cont.

Cost Benefit - Analysis

1. Phase I - Generate rough order of magnitude costs
2. Phase II and III - Develop cost and benefit data suitable for an MIS like analysis

Deployment Development

1. Provide the deployment basis for parallel and subsequent consortium technical work.
    a. Includes creating a baseline deployment plan document.
2. Identify constraints or requirements on system architecture due to deployment
    a. Identify requirements necessary for implementation.
    b. Assess deployment feasibility of dedicated lanes.
    c. Identify any constraints or requirements on distribution of intelligence.
3. Provide confidence that the Consortium's AHS architecture is deployable.
    a. Develop and refine Macro-Deployment Paths (i.e. National Deployment Strategy).
    b. Develop example Micro-Deployment Paths from case studies, and show that local deployability is robust.
4. Have coordination and buy-in from the stakeholders.
5. Identify and help Consortium better align with "spin-off" opportunities.
6. Examine deployment Societal and Institutional issues.

APPENDIX B - CASE STUDY DATA REQUIREMENTS

Several tools have been developed to analyze specific elements of an AHS:
- SmartAHS - AHS microsimulation tool,
- SmartCap - Mesoscale AHS capacity and flow determining tool,
- Smart Merge - Used to determine required merge lengths,
- Safety evaluation tools, and
- Cost-benefit assessment tool.

Below is the list of the data needed to populate NAHSC Tools:

Physical/geometric characteristics for mainline portion of roadway network with AHS application using a node and link structure:
- link length
- number of lanes
- lane width
- median width
- inside and outside shoulder width
- right-of-way width
- curvature, grade, and degree of banking (low priority)

Physical/geometric characteristics of entry and exit facilities' portion of roadway network using node and link structure:
- link length
- number of lanes
- lane width

Transportation system data by time-of-day (AM peak, PM peak, off-peak) and for present day as well as for any future projected volumes (e.g. 20-year forecast horizon):
- link traffic volumes on all applicable roadway segments, such as mainline, entry & exit points, and freeway interchanges (or expressway interchanges, etc.)
- Distribution of entry/exit traffic, i.e. distribution of traffic at each entry point among all exit points.

Incident-related data:
- number of incidents
- data per incident: number of vehicles involved, cause, severity, response time, duration, and number of lanes blocked, weather conditions

HOUSTON METRO-NAHSC CASE STUDY
PHASE I-KATY CORRIDOR

FINAL REPORT

October 27, 1997

1. INTRODUCTION AND BACKGROUND

In 1996, the Houston Metropolitan Transit Authority (METRO), an associate member of the NAHSC, entered into a collaborative effort with the NAHSC to study the potential for AHS implementation on one of the Houston metropolitan area's High Occupancy Vehicle (HOV) lanes. METRO selected the HOV facility on Interstate 10 (I-10), also known as the Katy Freeway, as this corridor is currently part of a Major Investment Study to select an alternative for this corridor in order to address growing travel demands.

The Katy corridor is a representative urban corridor which connects the CBD at the corridor's eastern end with major employment generators along the length of the corridor. The freeway corridor, located between two heavily traveled north-south routes, carries significant amount of traffic in both eastbound and westbound directions, that is, there are considerable amounts of peak period directional traffic. There has been strong local public concern about the congestion on this part of the Katy Freeway. The HOV lane, a single reversible lane located in the median of the freeway, is approximately 19.3 kilometers (12 miles) long and operates seven days a week from 5 AM until NOON in the eastbound direction (inbound toward the Houston CBD) and from 2 PM until 9 PM in the westbound direction (outbound from the Houston CBD). Secondly, METRO has a strong interest in the whole area of ITS and in particular, AHS. Thus, the institutional support is widespread. Thirdly, and linked with the institutional support, is the availability of the needed data.

The analysis performed during Phase I consisted of the following primary elements and are presented in Sections 3 through 5:

- System Performance
- Societal & Institutional Perspective

2. TYPES OF DATA AND INFORMATION

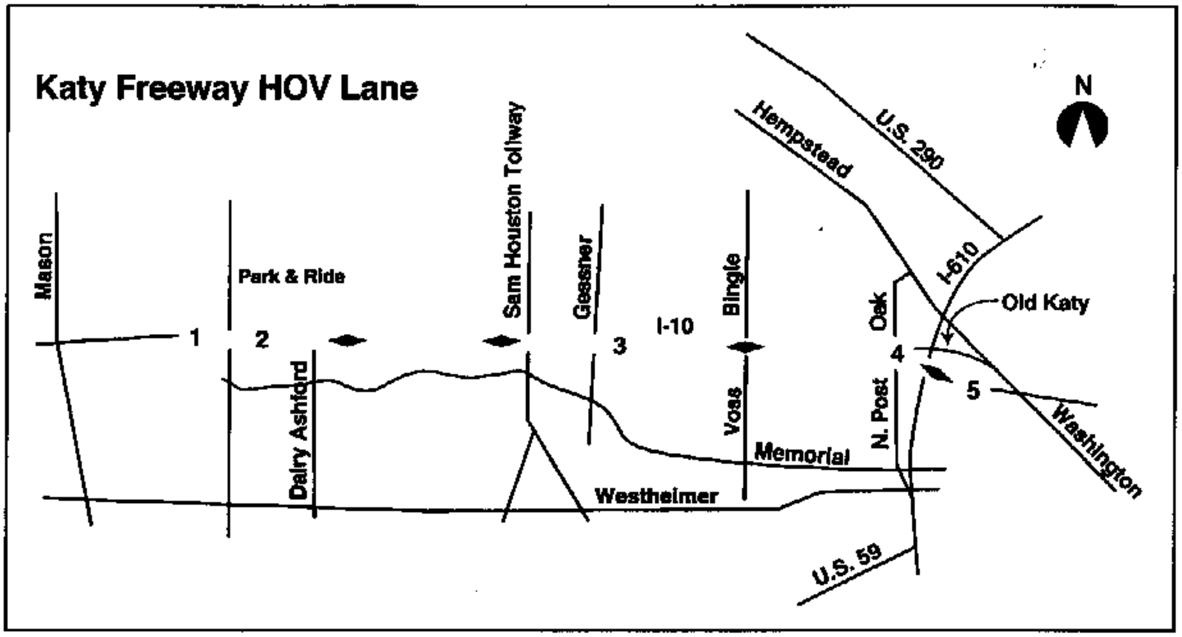
The information obtained for the Katy Freeway scenarios are of the following two primary types: geometric/physical characteristics and travel demand data.

2.1 Geometric/Physical Characteristics

Figure 1 presents a graphical depiction of the Katy Freeway scenario. Five locations, within circles, are highlighted as follows:

1 = Western Terminus
2 = Flyover access/egress point for Park & Ride facility
3 = Slip ramps providing access to the HOV facility from non-HOV lanes heading eastbound, and exit from HOV lane to non-HOV lane heading westbound
4 = HOV exit near Eastern Terminus
5 = Eastern Terminus

FIGURE 1: DIAGRAM OF KATY CORRIDOR WITH ACCESS/EGRESS POINTS



2.1.1 Existing Configuration

The Katy Freeway HOV lane is a one-way reversible flow lane, separated from the mainline, or non-automated traffic, by concrete barriers. The average width is 6 meters (19.5 feet), with one 4.3-meter (14-foot) travel lane and a .84-meter (2.75-foot) shoulder on each side. There are, however, several locations in which the travel lane width is 3.7 meters (12 feet). The entry and exit facilities are limited on the HOV lane, with there being only 5 along the corridor. These facilities alternate their directions in the morning and afternoon operating periods and remain closed during non-operating hours. Table 1 shows the locations and types of the entry/exit locations. Each location corresponds to the five highlighted areas on Figure 1.

The operation is designed to facilitate the different travel needs in the morning and afternoon. Between 5 AM and NOON it is used for the eastbound traffic heading inbound to the CBD. A 2+ occupancy policy is enforced, except during the peak of the AM peak period, between 6:45 AM and 8 AM, which requires a 3+ vehicle occupancy for entry. During the 2 PM to 9 PM time period, the corridor accommodates westbound traffic with a 2+ vehicle occupancy policy, except during the peak of the afternoon peak period, between 5 PM and 6 PM, in which a 3+ policy is applied. Based on data from the HOV facility, the vehicle class split on the HOV facility is approximately 4% buses and 96% light-duty passenger vehicles (LDPV).

TABLE 1: CONFIGURATION OF EXIT/ENTRY

Location/Function	Configuration	Direction	AM	PM
(1) State Highway 6/ Western Terminus	Direct connection with mainline lanes	One-way	Entry	Exit
(2) Addicks/Park and Ride	At grade T-ramp to the Park and Ride lot	Two-way	Entry/ Exit	Entry/ Exit
(3) Gessner/Slip Ramps	Slipramp with direct connection with mainline lanes	One-Way	Entry	Exit
(4) Off-ramp/North Post Oak	At grade flyover to the surface street	One-Way	Exit	Entry
(5) I-610/East Terminus	Direct connection with mainline lanes	One-Way	Exit	Entry

The two-way nature at the Addicks/Park and Ride location refers to the fact that vehicles may exit off the roadway to get to the Park and Ride facility as well as enter the roadway from the Park and Ride facility.

2.1.2 AHS Application

The AHS application scenarios on the Katy Freeway HOV lane has been developed into three alternative scenarios: low demand, mid demand and high demand. These three alternatives correspond to development of an AHS system that correlates with the growth in market penetration of automated vehicles. The three scenarios have differences in their physical characteristics, capacities and matching market demands for AHS implementation. A major justification for developing these scenarios, is that the capacity of the AHS facility is limited by the capacity of mainline freeway lanes and the ability of the adjacent street system to feed and absorb the AHS traffic. Thus, improvement on the mainlines is considered an important component for each of the scenarios, especially the potential widening of mainline lanes in the vicinity of AHS access and egress points.

Scenario 1 (Low Demand):

- No major implementation on the existing HOV lane: one-lane, one-way operation.
- Provide feeder lane at western and eastern terminus. Feeder lane is a special auxiliary lane on the mainlines that serve to allow sufficient distance for automated vehicles weaving through manual lanes to enter the AHS lane or exiting automated vehicles enough distance to merge into mainline:
  At western terminus: 4.8 kilometer (3 mile) feeder lane from west terminus to west of Mason Road.
  At eastern terminus: 1.6 kilometer (1 mile) feeder lane east of terminus.

- Entry/exit and transition lane:
  Extend transition lane to a length of 335 meters (1100 feet) at Park & Ride T-ramp and at Post Oak access/egress point.
  Move slipramps (at Gessner) eastward and provide an additional 1.6 kilometers (1 mile) of merge lane for eastbound and 1.6 kilometers (1 mile) de-merge lane for westbound flow, with corresponding freeway widening.

Scenario 2 (Mid Demand):

- Two way operations with one lane for each direction.
- Provide feeder lane at western and eastern terminus over longer distance as compared to near-term scenario:
  At western terminus: 9.7 kilometer (6 mile) feeder lane extending west from terminus.
  At eastern terminus: 6.4 kilometer (4 mile) feeder lane extending east from terminus.
- Entry/exit and transition lanes
  At Park & Ride T-ramps: extend transition lane length to 671 meters (2200 feet) in each direction:
  At slipramps: replace slipramps with Park & Ride T-ramp facilities. Transition lane is 610 meters (2000 feet) long for each direction of traffic.
  At Post Oak access/egress point: build another flyover to separate the use for entry and exit with transition treatment.

Scenario 3 (High Demand):

- Two way operations with one lane for each direction.
- Provide 2-lane feeder lanes including transition at both of the termini:
  Western terminus: 2 lanes, 6.4 kilometer (4 mile) feeder lanes extending west from terminus.
  Eastern terminus: 2 lanes, 6.4 kilometer (4 mile) feeder lanes extending east from terminus.
- Replace transition lane facilities at Park & Ride and T-ramps built in mid-term with direct connectors (Y or wishbone design). These direct connectors allow flows between automated lane and mainlines, automated lane and frontage service roads. At Addicks Park & Ride (original), the direct connectors also link Park & Ride lot.

2.2 Travel Demand

The diverse urban economic and transportation activities along the corridor make the Katy Freeway significant in the region. Facing increasing demand over recent years, the current Katy Freeway is operating at its designed capacity. During the peak periods of the day, certain portions of the freeway operate at an average speed lower than 8.9 m/s (20 mph). Thus, its ability to accommodate further demand is constrained. Even for the HOV lane which is still able to accommodate speeds of around 22 m/s (50 mph), the demand increases correspondingly with the total demand in the corridor. The access points to the HOV lane are already near their designed capacity. According to METRO's projection, by the year 2010, the demand in a 3+ mode is going to exceed the HOV lane operation capacity. By year 2020, the overall freeway/HOV lane demand is expected to double.

2.2.1 Baseline Level

METRO's existing operating capacity is 2000 vphpl for mainline and 1500 vphpl for HOV lane. Based on 1995 traffic flow data for the freeway, during a portion of the peak period (6 AM-7 AM), some segments of the mainline (non-HOV) operate over the designed capacity, with an average speed of 12 m/s (27 mph). In still other locations, congestion is worse with an average speed of at most 8.9 m/s (20 mph). For westbound traffic in the afternoon peak periods, traffic is slightly better than that during the morning. During the peak of the afternoon peak period, 5 PM-6 PM, the same segments operating beyond capacity during the AM peak are still operating beyond capacity. Nevertheless, HOV lane system performance is better than the mainline, in comparison.

2.2.2 AHS Levels

The traffic capacity for AHS implementation on Houston Katy Freeway is constrained by the design of its infrastructure. Consequently, divergent AHS infrastructure implementation serves different market demand and provides different capacities. An example of the data provided and estimated is provided below in Table 2. In the eastbound direction, the point of greatest demand occurs at the Gessner Access point. In the low demand scenario, this location is a slip ramp very similar to the current HOV configuration. For both the mid and high demand scenarios, the slip ramp configuration is modified to a Park-and-Ride configuration. At the low demand, mid demand, and high demand scenarios, the demand levels are 1750 vehicles per hour per lane (vphpl), 3000 vphpl, and 3900 vphpl respectively. METRO's projected AHS traffic flow for the eastbound direction during a portion of the peak period, 6 AM - 7 AM, and its distribution along the HOV lane is shown in Table 2, that is, the origin-destination trip table which provides the distribution of all entering AHS traffic among all subsequent exiting AHS traffic.

TABLE 2: HOV FACILITY ORIGIN-DESTINATION TABLES
(6 AM - 7 AM/Eastbound)

LOW DEMAND ALTERNATIVE

	PARK & RIDE OFF-RAMP	POST OAK EXIT	EASTERN TERMINUS	ENTRANCE TOTAL
WESTERN TERMINUS	50	271	679	**1000**
PARK & RIDE ON-RAMP		143	357	**500**
SLIP RAMP		86	214	**300**
EXIT TOTAL	**50**	**500**	**1250**	**1800**

MID DEMAND ALTERNATIVE

	PARK & RIDE OFF-RAMP	POST OAK EXIT	EASTERN TERMINUS	ENTRANCE TOTAL
WESTERN TERMINUS	100	633	1267	**2000**
PARK & RIDE ON-RAMP		200	400	**600**
SLIP RAMP		167	333	**500**
EXIT TOTAL	**100**	**1000**	**2000**	**3100**

HIGH DEMAND ALTERNATIVE

	PARK & RIDE OFF-RAMP	POST OAK EXIT	EASTERN TERMINUS	ENTRANCE TOTAL
WESTERN TERMINUS	100	487	1413	**2000**
PARK & RIDE ON-RAMP		256	744	**1000**
SLIP RAMP		256	744	**1000**
EXIT TOTAL	**100**	**1000**	**2900**	**4000**

3. SYSTEM PERFORMANCE

The system performance element of the analysis consisted of five components that will be described within this section. They are referred to as the top level analysis, localized merge and queuing analysis, corridor-wide merge simulation, corridor-wide capacity analysis, and emissions and fuel consumption evaluation.

Throughout the system performance analysis, four distribution of intelligence attributes (DOIA) were used. They are independent autonomous, low cooperative, high cooperative, and cooperative platoons. In the independent autonomous case, the vehicle does not communicate with other vehicles, rather it applies its vehicle-borne sensing to perform maneuvers. The low cooperative attribute involves communication of emergency messages only from one vehicle to vehicles behind it. The high cooperative distribution of intelligence attribute includes the low cooperative and maneuver coordination messages from one vehicle to vehicles behind it at regular time intervals. The cooperative platoon attribute consists of the high cooperative level of intelligence from a vehicle to members of the same platoon and low cooperative level of intelligence from a vehicle to other platoon leaders following this vehicle. Cooperative platoons do differ from high cooperative in the degree of vehicle state information and, because of this difference, in the ability to perform stable close vehicle following.

3.1 Top Level Analysis

The primary objective of the top level analysis was to analyze the relationships between AHS distribution of intelligence attributes and alternative demand levels for the three AHS scenarios. In other words, in terms of either the pipeline capacity or the inter-vehicle spacings, how do the four DOIAs perform relative to the levels of demand projected for the corridor for the three scenarios? A significant input to determining either the pipeline capacity or inter-vehicle spacings is the braking rate distribution for the vehicle class(es) under examination. Modifications to the braking rate distribution would affect the answer to this question concerning DOIAs. Another objective was to determine what impact, if any, entry limitations based on braking rate capability would have on the performance of the four DOIAs relative to the levels of demand projected for the corridor.

3.1.1 Methodology

The general methodology used to perform this analysis consisted of

- finding the point along the corridor of greatest demand levels for the three scenarios
- determining the corresponding pipeline capacities (this includes applying a derating factor to account for merging)
- estimating the spacing required to handle the maximum demand levels
- comparing these spacings with the minimum safe-spacings for the four DOIAs
- adjusting the braking rate distribution to measure the impact on DOIA system performance

3.1.2 Assumptions and Input

Throughout the analysis, a nominal speed of 30 meters/sec (67 miles per hour) was used. Based on input provided by Houston Metro, a 96/4 percentage vehicle class split exists along the Katy Corridor relative to light-duty passenger vehicles (LDPV) and buses, respectively. With two such vehicle classes, there are thus four possible vehicle-following pairings, that is, LDPV following another LDPV, a LDPV following a bus, a bus following a LDPV, and a bus following a bus. The maximum demand level along the corridor is located immediately downstream of the Gessner Access in which the three demand levels corresponding to the three scenarios (low demand, mid demand, and high demand) are 1750 vehicles per hour (vph), 3000 vph, and 3900 vph, respectively. In the derivation of the pipeline capacity listed in the methodology (Section 3.1.1), the demand levels were adjusted upward to accommodate merge turbulence that would occur upon vehicle entry from, for example, the mainline lanes. The adjustment upward in the demand level is equal in magnitude to the merge derating factor, which is the percentage that is applied to the pipeline capacity to represent its potential reduction due to merging and lane changing. In this analysis, the calculation is in the reverse order and thus the merge derating factor is applied to the demand levels to increase its value to derive the pipeline capacity. The magnitudes of the merge derating factors used this analysis depend on the DOIA and are consistent with subsequent analysis in Section 3.2. Though the values provided in Table 3 are given as point estimates, they are only approximations and are used as such in determining the performance of each of the four DOIAs .

TABLE 3: MERGE DERATING FACTORS

Distribution of Intelligence Attribute	Merge Derating Factor Percentages
Autonomous	25
Low Cooperative	10
High Cooperative	10
Platooning	20

3.1.3 Results and Conclusions

Table 4 provides the estimates for the spacing requirements to handle the maximum demand for the three scenarios.

TABLE 4: SPACING REQUIREMENTS FOR DOIAs (METERS)

Distribution of Intelligence Attribute	Level of Demand		
	Low	Medium	High
Autonomous	46.3	27.0	20.8
Low Cooperative	55.5	32.4	24.9
High Cooperative	55.5	32.4	24.9
Platooning*	49.4	28.8	22.2

*The values for platooning for each level of demand are intended to represent an approximate value for inter-vehicle spacing and would then take into account both inter-platoon as well as intra-platoon spacings.

The next step is to compare these spacing requirements with the minimum safe-spacings that can be achieved for each of the four DOIAs. These inter-vehicle safe-spacings are provided in Table 5 for both the cases of uniform and non-uniform spacings. The difference between these two types of spacings involves the level of information about the braking rate capability for each vehicle in a pair of vehicles. Uniform spacings do not vary with respect to vehicle braking rate capability, whereas, non-uniform spacings are dynamic and assume that a vehicle knows its own braking rate capability and, depending on the amount of communication between vehicles, may or may not know the braking rate capability of the preceding vehicle. Based on this information, the inter-vehicle spacing is determined. In general, non-uniform spacings are less than uniform spacings. Such minimum safe spacing depends on the braking capabilities of the two vehicles, the type of information available for vehicle control, sensing delays, and operating speed. Full details for the estimation of these minimum safe spacings may be found in (1). It is important to note the following parameter values used in the derivation of these minimum inter-vehicle safe spacings:

- Light-duty passenger vehicle length = 5 meters
- Bus length = 12 meters
- Platoons are of homogeneous vehicle class, i.e. buses only or LDPV-only
- Nominal LDPV platoon size = 10 vehicles
- Nominal bus platoon size = 3 buses
- Intra-platoon vehicle separation for a LDPV platoon = 2 meters
- Intra-platoon vehicle separation for a bus platoon = 4 meters

The inter-vehicle safe-spacings derived were those for each of the four DOIAs coupled with each of the four possible vehicle-vehicle pairings (See Section 3.1.2). The spacings listed in Table 5 are weighted averages for each DOIA given the current vehicle class percentage split of 96/4 for LDPV/Bus for the corridor and the four possible vehicle-vehicle pairings. It is assumed that this percentage split will not change.

TABLE 5: AVERAGE INTER-VEHICLE SAFE SPACINGS FOR THE DISTRIBUTION OF INTELLIGENCE ATTRIBUTES (METERS)

Distribution of Intelligence Attribute	**Uniform Spacings**	**Non-uniform Spacings**
Autonomous	28.7	27.7
Low Cooperative	26.4	22.4
High Cooperative	24.0	*
Platooning	10.8	10.8

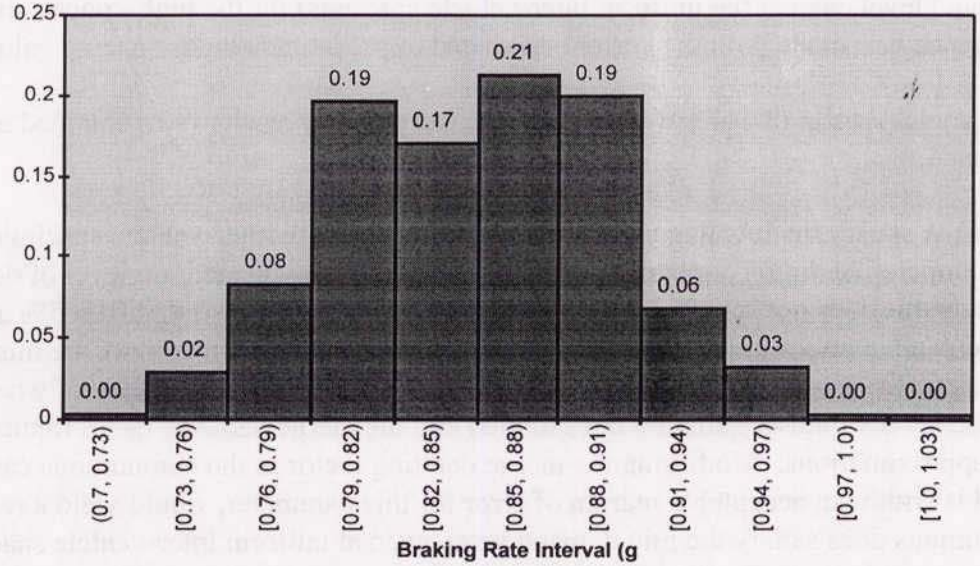
*It was determined based on previous work (1) that the non-uniform spacing value for the high cooperative distribution of intelligence attribute is bounded above by both the uniform spacing value for high-cooperative (24.0 m) as well as the smaller value associated with the non-uniform spacing for the low cooperative case (22.4 m). Knowing these upper bound relationships, it was not necessary to explicitly calculate the spacing value for the non-uniform spacing of the high cooperative DOIA because the strongest possible conclusion (high cooperative DOIA satisfies the high demand level even at the uniform inter-vehicle spacings) for the high-cooperative distribution of intelligence was made with the current estimated upper bounds on its spacing values.

Based on a comparison of Table 4 with Table 5 the following results were obtained and conclusions may be made:

- All DOIA satisfy the low demand level even using uniform inter-vehicle spacings
- Low cooperative, high cooperative, and platooning satisfy the medium level of demand
- Autonomous does not satisfy mid demand level, however, it is within about 5% and $2^1/_2$% of this demand level for uniform and non-uniform spacings, respectively. (Care must be taken here, since the results for the autonomous DOIA are close to the boundary of where the mid demand level would be satisfied/not satisfied and the merge derating factor inputs in Table 3 are only approximations. Modifying the merge derating factor in the autonomous case by only 5%, which is within an acceptable margin of error for this parameter, would yield a result that autonomous does satisfy the mid demand level, even at uniform inter-vehicle spacings.)
- Low cooperative satisfies the high demand level for non-uniform spacings, not for uniform spacings
- High cooperative and platooning satisfy the high demand level, even at the uniform inter-vehicle spacings
- There is at least one distribution of intelligence attribute that satisfies each given level of demand.

For the uniform inter-vehicle spacings case in which the autonomous DOIA did not satisfy the mid demand level, one alternative remedy to this situation is to examine more closely the braking rate distribution. Figure 2 depicts the frequency distribution as a histogram for dry pavement braking rates for light-duty vehicles (cars and trucks). The distribution used in the calculation of inter-vehicle safe spacings was [0.76, 1.025] in units of g's. This distribution truncates 3.2% off the full braking rate distribution, i.e. the 3.2% of the poorest performing light-duty vehicles in terms of their braking rate capability. This histogram is based on data from Consumer Reports for vehicles produced and sold in the 1994-1995 time frame and accounts for approximately 90% of such vehicles. The braking rate for buses was based on available data obtained from recent tests performed at the NHTSA Vehicle Test Center on heavy vehicles (trucks and buses). The available data is considerably more sparse than for light-duty vehicles, and so a full distribution is not available. The minimum and maximum braking rates for buses were 0.484g and 0.636g. An analysis was performed to determine what the lower end threshold would have to be for the braking rate distribution in order to have the autonomous DOIA satisfy the mid demand level. Such a threshold was determined to be 0.79g. Thus, if the braking rate distribution were [0.79, 1.025], i.e. truncating an additional 8.2% off the low end of the braking rate distribution for light-duty vehicles while making no change in braking rate capability for buses results in all DOIA satisfying the mid demand level, even for uniform inter-vehicle spacings using the merge derating factors in Table 3. This would require the exclusion from the AHS lane of the 11.4% of the vehicle population with the lowest braking capability.

FIGURE 2: RELATIVE FREQUENCY DISTRIBUTION OF DRY PAVEMENT BRAKING RATES



3.2 Localized Merge and Queuing Simulation and Analysis

The primary objective of the localized merge and queuing analysis was to analyze merging and queuing requirements for alternative AHS distribution of intelligence attributes relative to alternative demand levels for the three AHS scenarios. The term "localized" stems from the fact that this analysis examined the merging and queuing requirements at the point along the corridor of greatest demand (Gessner Access), consistent with the top level analysis. A corridor-wide consideration was conducted using the modeling framework tool SmartAHS. In this case, more of the interaction effects among consecutive access points along the corridor were examined. This work is discussed in Section 3.3.

3.2.1 Methodology

The general methodology used for this component of the analysis was an aggregate vehicle simulation modeling tool which provides as its principal output measures of effectiveness queuing-related statistics (average wait time and queue spill-back space) and merging-related statistics (length of space needed to merge into an AHS lane from an on-ramp). Details are provided in (2).

3.2.2 Assumptions and Inputs

The assumptions and inputs used for this analysis consisted of the inter-vehicle safe spacings for both the uniform and non-uniform cases (Section 3.1.3, Table 5), at a nominal speed of 30 meters/sec at the point along the corridor of greatest demand providing 1750 vph, 3000 vph, and 3900 vph for the low demand, mid demand, and high demand AHS scenarios. The analysis was again based on the 96/4 percentage vehicle class split along the Katy Corridor relative to light-duty passenger vehicles (LDPV) and buses, respectively. It has also been assumed that there would be no mainline, that is, on the automated lane, slowdown in the autonomous cases.

The three cases of greatest demand have the following ramp and mainline volumes and are henceforth referred to as Case I, Case II, and Case III:

- Case I: ramp volume = 300, mainline volume = 1450
- Case II: ramp volume = 500, mainline volume = 2500
- Case III: ramp volume = 1000, mainline volume = 2900

For the autonomous case, both non-stop and stopped vehicle check-in systems were simulated for Case I, whereas, only the stopped vehicle check-in was simulated for Cases II and III. This was done to have the simulations more accurately reflect the physical configuration of the actual corridor for each Case, since for Case I a slip ramp is used for access, whereas, for Cases II and III, vehicles access the AHS via a Park & Ride lot. An additional explanation is provided below in this section. In the non-stop system, vehicles are checked in while in motion, whereas in the stopped system vehicles must come to a stop to be checked in. In either case, the check-in process is assumed to follow a three second cycle, meaning that vehicles can depart from the check-in system no more frequently than once per 3 seconds. If vehicles arrive over a shorter interval, they must be held back in queue to await their turn. In the non-stop system, vehicles are slowed down slightly to wait, whereas in the stopped case vehicles must eventually come to a rest. The check-in processes behaves the same as a ramp metering system with a 3 second cycle time.

Three platooning concepts were evaluated. In the first concept, vehicles are allowed to enter the highway as platoons, and must allow a full inter-platoon spacing in front and in back relative to vehicles already on the automated roadway. In the second concept, vehicles are allowed to "tag-on" to mainline automated vehicles. This means that when vehicles are released from the entry ramp, they are allowed to enter immediately following mainline platoons, separated by the intra-platoon distance. However, in this concept, vehicles are released one at a time, with a minimum inter-platoon spacing between ramp vehicles. In the third concept, vehicles enter the highway individually, and must allow for a full inter-platoon spacing both in front and behind, relative to either ramp vehicles or mainline vehicles.

For Case I, which provides a direct connection from the freeway mainline (via a slip ramp), two configurations are considered for vehicles entering under the platooning and cooperative concepts. In either case, vehicles must be precisely positioned to match available gaps on the mainline by the time they leave the ramp. In one configuration, this is accomplished by slowing vehicles from 30 m/s to 27 m/s over a section of the ramp. The length of this section is determined by the amount of time the vehicle must be delayed in order to coincide with the gap. In the second configuration, all vehicles are brought to a stop and then released at a time that allows them to enter into available gaps. For Cases II and III, vehicles enter from a stopped position in a Park & Ride lot. Because there is little or no advantage to checking in vehicles while in motion, only the second configuration is used.

For Case I, the ramp length is calculated as the sum of a deceleration distance, queuing distance, acceleration distance, and merging distance. For Cases II and III, only the queuing distance, acceleration distance, and merging distance are counted (no deceleration). For the first configuration, the queuing distance was set at a "3 sigma" limit and reflects the distance needed for queuing. This means that more than 99% of the vehicles would be properly positioned for entry at the end of the segment if slowed to just 27 m/s over the entire segment. When delays exceed the 3 sigma limit, then a small number of vehicles would have to be slowed below 27 m/s. For the second configuration the queuing distance was only set at a 2 sigma limit, as the consequence of exceeding the available space is less significant (queue spills into the Park & Ride lot).

3.2.3 Results and Observations

The results are presented in Tables 6 through 8 corresponding to the point along the corridor of highest demand for the three AHS scenarios. The results are presented in terms of the various distances required to complete the access process, including deceleration, queuing, acceleration, and merging.

The entries in Tables 6-8 in the "Deceleration" and "Acceleration" columns were estimated for worst case conditions, i.e., a bus having to decelerate and accelerate. Even though only 4% of the vehicle fleet is composed of buses, they must be accommodated. A constant deceleration and acceleration rate for buses of 0.46 meters (1.5 feet) per second per second was used to estimate the distances required. All entries in the "Merging" column include a distance of 150 meters that represents the approximate distance required to change lanes from the merge lane to the mainline AHS. This value is based on experimental results for lane changes indicating 3 to 5 seconds would be necessary for such a maneuver. The upper bound of 5 seconds was used for vehicles traveling at 30 meters/second to yield the 150 meter estimate.

Two separate analyses were performed for the cooperative and platooning cases. Results of these analyses are labeled in Tables 6-8 as "Full stop for check-in; 5m/s while in queue" and "Slow down to 27m/s" that are explained in Section 3.2.2. For the "Slow down to 27m/s" configuration, a single estimate was made for Case I which includes deceleration, queuing, and acceleration and is indicated in the "Queuing" column. The fact that for this case the distances required for deceleration, queuing, and acceleration are aggregated and listed in the "Queuing" column is indicated by
"-------->" and "<--------".

Table 6: DISTANCE MEASURES (M) REQUIRED FOR CASE I

Distribution of Intelligence Attribute	Deceleration	Queuing	Acceleration	Merging	Total
Autonomous (Uniform):					
non-stop with 3 second metering	0	180	0	480	660
stop for check-in with 3 second metering	969	30	969	480	2448
non-stop and no metering	0	180	0	550	730
Autonomous (Non-uniform):					
non-stop with 3 second metering	0	180	0	420	600
stop for check-in with 3 second metering	969	30	969	420	2388
non-stop and no metering	0	180	0	480	660
Full stop for check-in; 5m/s while in queue:					
Low Cooperative (Uniform)	969	30	1008	150	2157
Low Cooperative (Non-uniform)	969	30	1008	150	2157
High Cooperative	969	30	1008	150	2157
Platooning					
platoon and no tag	969	30	1008	150	2157
free agent with tag	969	30	1008	150	2157
free agent	969	30	1008	150	2157
Slow down only to 27m/s:					
Low Cooperative (Uniform)	-------->	486	<--------	150	636
Low Cooperative (Non-uniform)	-------->	385	<--------	150	535
High Cooperative	-------->	425	<--------	150	575
Platooning					
platoon and no tag	-------->	596	<--------	150	746
free agent with tag	-------->	142	<--------	150	292
free agent	-------->	803	<--------	150	953

Table 7: DISTANCE MEASURES (M) REQUIRED FOR CASE II

Distribution of Intelligence Attribute	**Deceleration**	**Queuing**	**Acceleration**	**Merging**	**Total**
Autonomous (Uniform):					
stop for check-in with 3 second metering	0	45	969	2650	3664
Autonomous (Non-uniform):					
stop for check-in with 3 second metering	0	45	1008	2150	3203
Full stop for check-in; 5m/s while in queue:					
Low Cooperative (Uniform)	0	45	1008	150	1203
Low Cooperative (Non-uniform)	0	30	1008	150	1188
High Cooperative	0	45	1008	150	1203
Platooning					
platoon and no tag	0	45	1008	150	1203
free agent with tag	0	30	1008	150	1188
free agent	0	45	1008	150	1203

Table 8: DISTANCE MEASURES (M) REQUIRED FOR CASE III

Distribution of Intelligence Attribute	**Deceleration**	**Queuing**	**Acceleration**	**Merging**	**Total**
Autonomous (Uniform):					
stop for check-in with 3 second metering	0	90	969	*	*
Autonomous (Non-uniform):					
stop for check-in with 3 second metering	0	90	969	*	*
Full stop for check-in; 5m/s while in queue:					
Low Cooperative (Uniform)	0	1800	1008	150	2958
Low Cooperative (Non-uniform)	0	75	1008	150	1233
High Cooperative	0	150	1008	150	1308
Platooning					
platoon and no tag	0	165	1008	150	1323
free agent with tag	0	30	1008	150	1188
free agent	0	3120	1008	150	4278

* =Demand is greater than pipeline capacity, steady-state conditions never achieved, i.e. infeasible conditions

The following observations may be made from an examination of these results.

- For each of the three autonomous cases at the low demand level, i.e. Case I, ("non-stop with 3 second metering", "stop for check-in with 3 second metering", and "non-stop and no metering"), the use of non-uniform inter-vehicle spacings performs better than uniform inter-vehicle spacings in terms of total distance required, as expected. For the autonomous case of "stop for check-in with 3 second metering" at the mid demand level, similar results hold. For the low demand level, total distances required for non-uniform spacings are approximately 10% less than for uniform spacing counterparts. For the mid demand level, total distance required for non-uniform spacings are approximately 80-90% of their uniform spacing counterpart. For the highest demand level, infeasible conditions exist for both uniform and non-uniform cases and thus autonomous is not a feasible solution for the greatest traffic volume.

- For the "Full stop for check-in; 5m/s while in queue" case, all cooperative cases yield identical total distance requirements for the low demand level. At the mid demand level, all cooperative cases yield similar results that are approximately 55% of the total distance required at the low demand level. This occurs even though the demand level increases from low to mid, however the physical configuration changes from that of a slip ramp to a Park & Ride lot and the check-in process changes accordingly. It is at the high demand level, however, at which the total distance required for low cooperative for uniform inter-vehicle spacings grows significantly resulting in the other two cooperative cases (low cooperative non-uniform and high cooperative) being approximately 40-45% of low cooperative-uniform.

- For the "Full stop for check-in; 5m/s while in queue" case, all platooning cases yield identical total distance requirements for the low demand level. At the mid demand level, all platooning cases yield similar results that are approximately 55% of the total distance required at the low demand level. It is at the high demand level, however, at which the total distance required for the free agent case grows significantly resulting in the other two platooning cases (platoon and no tag and free agent with tag) being approximately 30% of the free agent case.

- For the "Slow down only to 27m/s" case (Table 6: low demand level only), the low cooperative/non-uniform and high cooperative cases result in smaller total distances required than for low cooperative-uniform. For the low demand level, low cooperative/non-uniform and high cooperative are approximately 85-90% of the low cooperative-uniform distance required.

- For the "Slow down only to 27m/s" case (Table 6: low demand level only), the platoon/no tag and free agent/tag cases result in smaller total distances required than for the free agent case. For the low demand level, the platoon/no tag and free agent/tag are approximately 30-80% of the distance required for the free agent case.

- For autonomous, metering improves results, i.e. reduces merge lane length requirement, yet autonomous is infeasible at the high demand level (Case III).

- For each of three demand levels, the platooning case of free agent with tag requires the smallest total distance compared to all other DOIA cases. For the "Full stop for check-in; 5m/s while in queue" case, the distance required actually decreases as the demand level increases. This occurs since the physical configuration changes from that of a slip ramp to a Park & Ride lot and the check-in process changes accordingly, resulting in no distance needed for deceleration in the mid and high demand levels.

- The second best DOIA case in terms of total distance required relative to the platooning case of free agent/tag is approximately twice as large, identical, and approximately equal to the free agent/tag case in the low, mid, and high demand levels respectively.

- The "Slow down only to 27m/s" case (Table 6: low demand level only) yields smaller total distances for each DOIA case (cooperative and platooning) relative to the "Full stop for check-in; 5m/s while in queue" case, respectively.

It is important to note that at any of the three levels of demand, there exists a distribution of intelligence attribute and associated check-in procedure to yield a total distance required of 1.2 kilometers. In fact, at the low demand level, such a total distance required is approximately 0.3 kilometer.

3.3 Corridor-wide Merge Simulation (See Appendix A)

In this case study, we examined a single lane freeway with three merge junctions. The highway was approximately modeled after the HOV portion of the Katy Corridor (Interstate Highway 10) of the Houston metropolitan region. The main modification was to reduce the distance between Entry 2 and Entry 3. (Because only the merge locations were being examined, the elimination of this portion would not effect the results.)

We studied two travel demand characteristics: low intensity and high intensity. These were taken from projections made by the Houston Metropolitan Transit Authority. We used the origin-destination travel demand derived from this data.

Different traffic automation strategies have been proposed by the NAHSC. Typically, they are classified according to their distribution of intelligence attributes. Here, "intelligence" refers to the techniques used to govern the flow of traffic. At one end of the spectrum, all automation intelligence is concentrated within individual vehicles---leading to the autonomous scenario. In the autonomous case, vehicles incorporate enhanced sensing, computation and actuation technologies to improve vehicle control functions such as lane keeping, headway keeping and velocity tracking. At the next level, individual vehicles cooperate by communicating selected state information to each other---leading to the cooperative scenario. The communication may be directly from vehicle to vehicle or it may be mediated by the transportation infrastructure. Finally, vehicles may form tightly coordinated, closely spaced groups by communicating more detailed state information at a greater frequency---leading to the platooning scenario.

Looking solely at the mainline capacity under these different policies, it may be expected that the cooperative case performs better than the autonomous case and that the platooning case performs better than the cooperative case. But mainline traffic analysis is not sufficient in the presence of entry ramps with merging traffic. Merging traffic perturbs the flow of mainline traffic due to micro-level phenomena such as yielding and merging. Yielding typically leads to a build up of density just before the merge junction and merging leads to a build up of density just after the merge junction. In the case of platooning, one must consider platoon formation before and after the merge.

In addition to the disturbance to mainline traffic at a single merge junction, it is necessary to study the interference caused by multiple merge junctions and exit ramps. Exit ramps disturb the mainline traffic density profile by opening gaps. These gaps could potentially be used for merging unless they get smoothed out by the headway following laws on the mainline. The increase in density just after the merge junction dissipates over a certain distance. In case the next merge junction is placed before that distance, there may be significant interference to traffic flow between the two junctions. Several important questions needed to be answered in a comparative analysis of the different automation approaches for a given highway layout:

1. What level of traffic is supported without significant queue build up?
2. What probability distribution of the distance is required for a vehicle to merge successfully?
3. For a given merge ramp length, what percentage of vehicles cannot complete the merge successfully?
4. What are the steady state density and speed profiles along the mainline.

We used the Smart-AHS microsimulation approach which has been designed to answer such questions in a wide range of highway layout and travel demand scenarios. Smart-AHS provides the infrastructure elements for simulating vehicle-highway systems. It contains simulation models for highway layout, traffic sources and sinks, vehicle models at different fidelity levels, actuator models, physical level controller models, sensor models and communication models.

Smart-AHS is provided as a collection of libraries written in the SHIFT programming language. SHIFT is a programming language for describing dynamic networks of hybrid state transition machines. Such systems consist of components which can be created, interconnected and destroyed as the system evolves. Components exhibit hybrid behavior, consisting of continuous-time phases separated by discrete-event transitions. Components may evolve independently, or they may interact through their inputs, outputs and exported events. The interaction network itself may evolve.

We applied the Smart-AHS approach to the Interstate Highway 10 Katy Corridor of Houston Metro region with autonomous AHS operation. In subsequent work, we have analyzed cooperative merging and platoon merging using the same simulation framework. We note that the merge simulation setup is flexible and reusable. Both parameter values as well as control logic can be easily modified to obtain families of merge simulators. We used kinematic vehicle models in which the controller provides acceleration and brake inputs to the vehicles. Our main work consisted of developing the controllers for mainline and merging vehicles. The objective of control consisted of a combination of several factors listed below in their priority order:

1. Avoiding collisions

2. Ensuring that merging vehicles are able to merge
3. Maintaining the desired time headway between vehicles
4. Maintaining the nominal speed for the lane (28 m/s was used as the nominal speed for the mainline)

We ran the simulation with two levels of travel demand, the low intensity case and the high intensity case, and with two values for the desired headway, one second and three seconds. Some of the salient results of the study are summarized below:

- The average distance to begin merge was least in Entry 1 and highest in Entry 3.
- In the one second time headway case the maximum distance to complete merge was 200 m in the low intensity case and 220 m in the high intensity case.
- In all cases the number of drop outs was zero.
- In all cases the number of accidents for Entry 1 and Entry 2 was zero. Entry 3 exhibits accidents, particularly in the case of one second headway.
- Low intensity level of travel demand can be supported with no queue build up.
- High intensity level of travel demand cannot be supported without queue build up, indicating that ramp metering or some other strategy that lowers demand is essential. At Entry 1, in 15 minutes of simulation, 400 vehicles were admitted instead of 500. At Entries 2 and 3, in 15 minutes of simulation, 200 vehicles were admitted instead of 250. This indicates that the travel demand is not sustainable.

3.4 Corridor-wide Capacity Analysis (See Appendix B)

The activity based theory of traffic flow is applied to evaluate highway capacity for four different concepts employing automated vehicles in the HOV lane of the Houston Katy Freeway. With these concepts, three increasing patterns of traffic demand are considered. SmartCap, a meso-scale software tool developed in the California PATH program as part of the NAHSC Tools effort, was used to simulate the highway behavior.

The four AHS concepts include three "independent" vehicle concepts, where each vehicle is assumed to operate in a car-following mode, gauging its position and velocity from the vehicle in front. The first concept, Independent Vehicle with Range and Range Rate Information (IVRR), assumes no intervehicle communication; the second concept, Independent Vehicle with Range and Range Rate and Warning Information (IVRRW), assumes communication only in cases of emergency, i.e., a sudden stop; the third concept, Independent Vehicle with Range and Range Rate and Acceleration Information (IVRRA), assumes that the acceleration from the vehicle in front is known. The final concept, Platoon Organization (PO), assumes range, range rate and acceleration information in closely spaced, coordinated longitudinal groupings of up to 10 vehicles.

The resulting simulations indicate that the Platoon Organization concept provides smaller entry queues while sustaining a service time comparable or better to that provided by the Independent Vehicle concepts. This reduction on the size of the entry queues implies, in turn, a smaller required on-ramps to service the queues and a reduced impact in the collateral urban network. The reduction of the entry queues can be explained by the extra free highway space that is created after joins activities are executed.

For the Platoon Organization concept it was found that the factor that most limits additional reductions in service time is the size of the transition lanes in the off-ramps. Arbitrarily incrementing the platoon size does not provide any additional advantage and produces severe reductions on the velocity of the sections that precede an exit that must be taken by a high proportion of the through traffic.

3.5 Emissions and Fuel Consumption Evaluation (See Appendix C)

An estimate of the emissions and energy use (i.e., fuel consumption) associated with an Automated Highway System has been made using advanced simulation modeling tools. A highway was modeled after the Katy Corridor (Interstate Highway 10) of the Houston metropolitan region. For this case study, a single lane HOV facility with three merge junctions was examined. Vehicles traveling on this highway were modeled after the 1996 Buick LeSabre.

The emissions and fuel consumption of the AHS vehicles have been compared to the case of non-automated traffic under different levels of congestion. The comparative emissions/fuel consumption results for the AHS and non-automated traffic are illustrated in four graphs.

In Figure 1, fuel consumption per unit distance (given in grams per mile) per vehicle is shown as a function of average vehicle speed for different levels of congestion. The solid line represents the non-automated traffic under different "Levels-of-Service" (LOS), corresponding to different congestion levels. The lower dashed line corresponds to the idealized constant-speed traffic (i.e., traffic without any acceleration/deceleration events) and represents the lower limit of emissions for the vehicle at different constant speeds. Results for the two AHS scenarios (cooperative and cooperative-platooned) are shown to lie between the ideal minimum and the non-automated traffic under light congestion. In the first scenario, vehicles in the AHS act as free agents, cooperating together for smooth merging and traffic flow, but not in platoons. In scenario 2, the vehicles in the AHS can also group themselves in platoons for greater capacity. The platoon-based AHS has lower fuel consumption due to aerodynamic drag reduction when vehicles operate at close spacings.

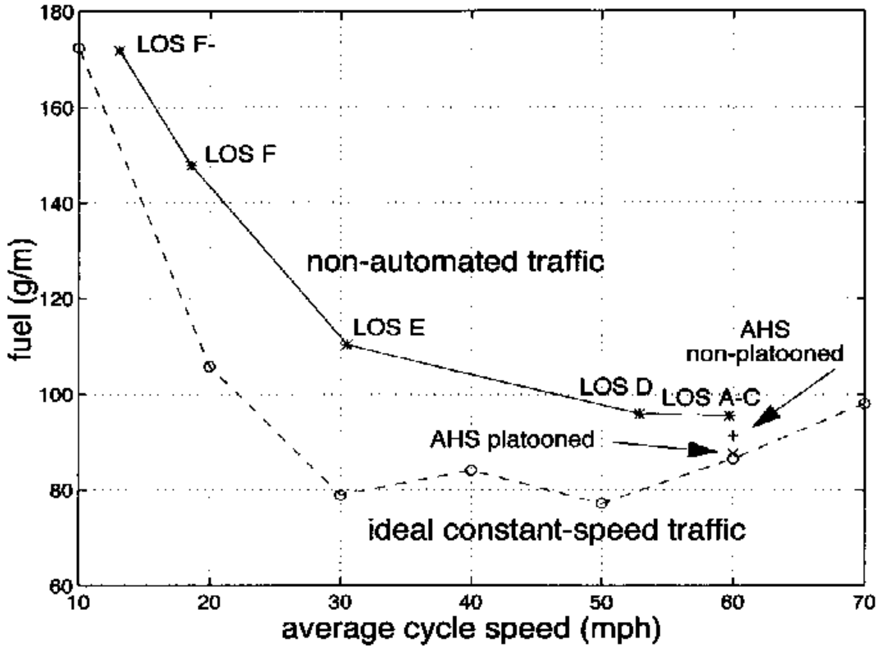


Figure 1. Fuel consumption versus average cycle speed

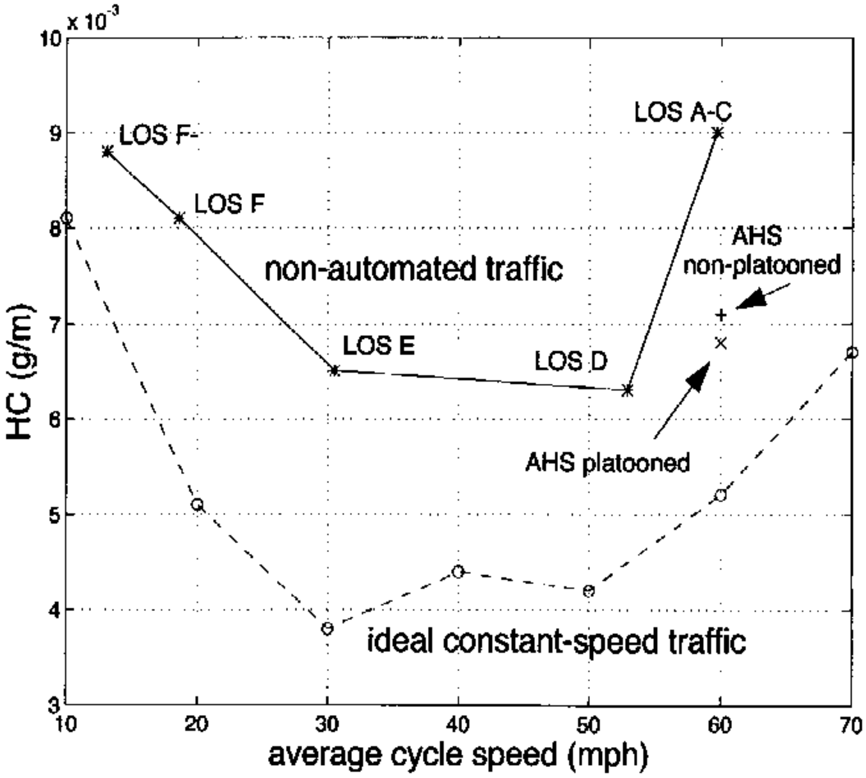


Figure 2. Average vehicle hydrocarbon emissions versus average cycle speed

In Figure 2, hydrocarbon (HC) emissions (given in grams/mile) are shown in a similar fashion. It is interesting to note that the average vehicle HC emissions for the LOS A-C case take a turn upwards due to the emissions sensitivity to higher speeds. The AHS scenarios again fall between the non-automated traffic and idealized constant-speed traffic, but represent a significant improvement relative to the non-automated traffic.

Given the travel demand level for the Katy Freeway corridor case study, congestion will remain at the LOS F- level if no improvements are made. In Figures 3 and 4, we compare the fuel consumption and HC emissions for this LOS F- condition against other scenarios. If additional non-automated lanes are added to this corridor, congestion may return to the LOS A level, but the HC emissions will remain approximately the same. The fuel consumption will be reduced to approximately 55% of the baseline non-automated case (a saving of 45%). If automation is introduced into the traffic system, traffic will flow more smoothly, reducing fuel consumption by 47% (compared to LOS F-), and HC emissions by 19%. If vehicles are capable of platooning, the fuel consumption is reduced by 49%, and HC emissions by 23% relative to the LOS F- base case. For comparison, the idealized constant-speed traffic case is also shown.

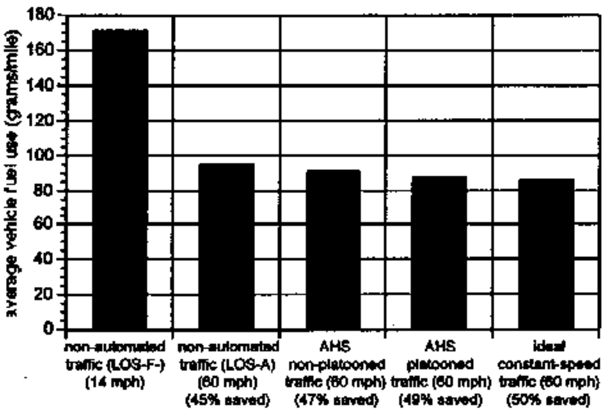


Figure 6. Fuel Consumption Comparison Among Various Scenarios.

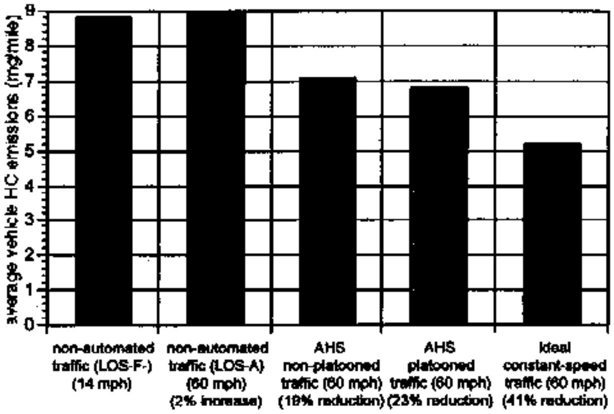


Figure 7. Hydrocarbon emissions comparison Among Various Scenarios.

4. SOCIETAL AND INSTITUTIONAL PERSPECTIVE

As called out in the statement of work, the societal and institutional (S&I) factors of AHS deployment were to be evaluated with respect to the METRO area. A meeting was held in conjunction with the ITS America Annual Meeting in April, 1996, which provided the opportunity to dialogue with Houston-area officials to provide perspectives on the S&I issues of AHS deployment with METRO. An extensive list of questions concerning planning, land use, public participation, policy, maintenance and operation, funding, and transit was presented to METRO. Many of these questions were the topic of discussion and were answered satisfactorily that day. Some of the questions, specifically transit-related issues, were not answered completely and will carry over to Phase II for further investigation.

4.1 A HISTORY OF METRO

Houston has a history of growth and development, and the transportation system is no different. In the late 1970's, growth due to the oil boom increased the number of vehicles dramatically. Houston was not prepared - old buses didn't run well, roads were congested. During the 1978 election, voters approved the creation of METRO and a local 1¢ sales tax increase to support the construction and operation of a comprehensive regional transit system. (The increase in sales tax provided $240 million for METRO in 1996 alone.) Unfortunately, the Texas Department of Transportation (TxDOT) did not have the congressional support necessary to obtain state funds for the new highways desperately needed to keep up with growth.

In 1983, Houston residents were presented with the option to vote on financing of a 30 kilometer (18.5 mile) Rail Rapid Transit project in their area. The referendum failed in the June 1983 election. The message was clear - Houston will not end up with a traditional rail transit system. After the referendum defeat, Metro needed to focus on building its bus system. Agency credibility was a major public issue in 1983. There had been no regional plan for transit in 1983, just the proposed 18 mile line, which voters perceived as too little for too much.

With the success of the contraflow lane on the North freeway as the model, plans developed for a total of three HOV lanes on radial freeways. The plan was also driven by the desire to hold onto federal funding. Within two days of the referendum's defeat, $50 million in federal transit funding commitment had been reappropriated to Los Angeles and Atlanta. In its desire to hold onto the remaining $100 million in federal transit dollars, Houston had nine months to come up with plans to use those funds for other transit purposes. This led eventually to 60 miles of new HOV lanes.

With a change in state politics, one-third of state transportation money began to flow to Houston ($600 million per year). The Greater Houston Partnership decided to have a policy making body (Mayor, County Judge, Chair of Metro board, Chief technical individuals, others), plus technical representatives, to present a collective effort. This was an ad hoc group (not formal) but it had credibility and created the regional mobility plan This group ("the super group") still continued to meet even after things got underway to assure everyone was informed and things proceeded in the planned direction. The MPO staff joined the technical people within the group, and the MPO board membership overlapped this policy council membership. The MPO role is primarily a programming organization. The MPO looked for the funds to "get it done", established priorities, sequenced activities, and played a key implementation role.

A chronological history of METRO is located in Appendix B of this document.

4.2 WHAT ABOUT USE OF THE HOV LANES?

HOV ridership formation is sensitive to the availability of HOV lanes. METRO began to introduce carpools at 4-person level on the Katy freeway. It was not successful (about 150 vehicles in peak hour used it, on a facility with a lane capacity of 1600 vehicles). Then carpools went from the 4-person to the 3-person requirement, and only had about 50 additional vehicles. Carpools had to be inspected for safety, and there was a driver test required in the years 1986-87. Also, in the late 1980s and early 1990s, gas prices remained low. However, after six months, the occupancy requirement was lowered to 2 per vehicle, and within two days the use jumped dramatically (an additional 1000 vehicles). (During this period, the number of vanpools declined.)

4.3 WHO RIDES HOUSTON METRO NOW?

Metro operates local urban bus routes, with express routes built into the system. The express bus operates at least 6 miles with no stops. Also, a park and ride commuter system operates, with a guaranteed seat for each passenger, primarily to/from downtown. The reverse commute is subsidized ($1 instead of $4 fare).

Metro carries about 1/4M people per day. 90% is local, and most of those riders are transit-dependent. 30% of downtown workers ride transit. About 25,000 riders use the park-and-ride. There are 80,000 trips on HOV lanes, of which about 25% are on the buses.

4.4 WHAT ITS APPLICATIONS ARE CURRENTLY IN PLACE?

A traffic surveillance system, the new centralized TRANSTAR traffic management center, and linked computerized signal systems are among the ITS improvements already in place. The Galleria area is the only area with computer controlled signals now, but planned for rapid expansion.

4.5 PUBLIC PERCEPTION OF NEW TECHNOLOGIES

The Houston public is fairly accepting of new technologies. However, they must be cost effective and demonstrated feasible. AHS should not be marketed as a "technology," but for the attributes - safety, comfort, fuel mileage, etc. METRO suggests a set of increments that lead to an AHS.

4.6 INTEREST GROUPS / PUBLIC CONCERNS

Land developers in Houston have a transportation agenda. The beltway was created by a developer-influenced planning group in the 1980's. The major long range plans for Houston always assumed enough land to build on. There are Municipal Utility Districts in the area. A developer can form such a group and turn an unincorporated area into a patchwork of such developer-created entities.

The companies that are growing tend to be out on the beltway. Their thinking and planning is not just regional, but global. They attend to a window of time of tolerable commute times (30 minutes to an hour). Houston is starting to see residential development closer to downtown.

There is some grass roots, anti-development activity, but pure environmental groups are not very effective in Houston. Some groups oppose a new freeway because it is taking people past them. Anti-freeway people say wider freeways reduce property values and increase noise for the benefit of those further out. They tend to fight elevated freeways. If roadways are elevated or widened, environmental groups complain, but not for a lot of the other traditional reasons, such as cutting down trees to build roads to develop land.

4.7 THE FUTURE OF AHS IN HOUSTON

If AHS isn't a way to do it cheaper, it will not have public acceptance. If AHS lets people travel faster in HOV-type corridors, it may serve only limited populations. It would seem technology will have to be applied more generally. What can AHS do for the low income or inner city population? AHS would sell to the suburbs--people who could afford it.

4.8 AHS AND THE PLANNING PROCESS

The planning process itself is not the problem with the AHS. The problem is that it is not tangible enough now to get it into future plans. It is not yet a viable alternative. There would need to be an on-the-ground feasibility demonstration. The agencies would need to support and promote it and present it to the MPO. TxDOT and Metro are the agencies that generate the projects sent to the MPO for inclusion in the regional planning documents. They are not sure what they should be doing to anticipate this technology in their plans. For example, "What would we do differently if we anticipated AHS in 15 years? Would we hold off from adding freeway lanes now? What different investments would we make?"

The projects that are NOW in planning will start construction in nine years -- and be built over a number of years until 2020. Design and construction-wise you are looking at a 5-10 year horizon. But since the 20 year plan is financially constrained, someone will have to give something up to include a new item that costs something, such as AHS. For an alternative to get into the plan, it will need to pay for itself. METRO suggests that AHS could be tolled lanes, even for HOVs.

4.9 TRANSIT ISSUES

As mentioned earlier, the S&I assessment lacked detail in the area of transit-specific (or METRO-specific) issues. Some of the questions remaining to be explored in Phase II are, for example: What are important benefits for automated vehicles in transit operation? (i.e. reliability, safety, cost, flexible operations, etc.) What immediate application opportunities in the transit system do you see for vehicle control automation? Is there a particular system improvement that you would like to accomplish in the next 10 or 15 years? Do you see the need for transit-only lanes in certain areas? What propulsion system will likely be used by your system in the 21st century? What is METRO's capital budget over the next 5 years, and how is that divided between equipment and facilities?

By identifying and addressing the answers to these questions, it will help to bring us closer to implementing an AHS in Houston.

5. INFRASTRUCTURE MODIFICATIONS

Basis of alternatives

1) Three separate alternatives are being prepared - a low level alternative, a mid level alternative, and a high level alternative. For each alternative, the improvements identified are the specific improvements necessary to implement AHS, beginning with the existing facility as the base. There is no consideration given to interim or staged improvements.

2) Improvements not specific to AHS implementation will not included as that is "work that would have been done anyway."

Flyover Structures

Flyover structures are required for the high-level alternative at both the Gessner and Addicks locations. These connector structures will be specified as either low speed or high speed. Assumed design parameters include:

Design Parameter	Low Speed Connection	High Speed Connection
Design Speed	13 m/s (30 mph)	25-27 m/s (55-60 mph)
Radius of Curvature	91 meters (300 feet)	350 meters (1,150 feet)
Maximum Grade	6%	6%
Minimum Vertical Clearance	5.0 meters (16.5 feet)	5.0 meters (16.5 feet)

A typical cross section of a one-lane flyover structure is shown in Figure 1. Some of the significant parameters of this structure include:

1) Total outside width of structure = 8.4 meters (27.5 feet).
2) Number and width of traveled lanes = one lane, 3.7 meters (12 feet) wide.
3) Shoulder width = 1.2 meters (4 feet) left, 2.4 meters (8 feet) right.
4) Barrier = Concrete barrier on both sides.
5) Maximum span = 46 meters (150 feet)
6) Structure depth = 2.0 meters (6.5 feet)

AHS Through Lanes

Low level alternative.

No change from the existing highway section is required. The existing reversible HOV lane will become a reversible AHS lane.

Mid level and High level alternatives.

The existing reversible HOV lane will be replaced by one AHS lane in each direction. The through lanes will be separated by a breakdown lane which will allow the minimum 5.9 meters (19.5 feet) required for two buses to pass.

Western Terminus

Low level alternative.

Provide eastbound and westbound feeder lanes 4.8 km (3.0 miles) in length. Provide check-in and check-out facilities, and accommodation for vehicle rejection.

Mid level alternative.

Remove median shoulder and reconstruct to accommodate eastbound and westbound feeder lanes 9.6 km (6.0 miles) in length. Provide check-in and check-out facilities and accommodation for vehicle rejection.

High level alternative.

Remove median shoulder and reconstruct to accommodate eastbound and westbound feeder lanes 9.6 km (6.0 miles) in length. Provide check-in and check-out facilities and accommodation for vehicle rejection.

Addicks

Low level and Mid level alternative.

Provide 670 meter (2,200 foot) long entrance and exit transition lanes adjacent to the AHS through lanes. This will require the mainline freeway to be shifted to the outside. AHS improvements to this park and ride lot include provision for check-in, check-out facilities, and vehicle rejection.

High level alternative.

The existing viaduct in the median of the freeway and the perpendicular T-ramp structure coming in from the Addicks Park & Ride must be demolished. AHS improvements to this park and ride lot include provision for check-in, check-out facilities, and vehicle rejection. Construct high speed flyovers between the Park & Ride and the AHS lanes as follows:

1) Southbound Park and Ride to Eastbound AHS
2) Southbound Park and Ride to Westbound AHS
3) Eastbound AHS to Northbound Park and Ride
4) Westbound AHS to Northbound Park and Ride

Provide 670 meter (2,200 foot) long entrance and exit transition lanes adjacent to the AHS through lanes. This will require the mainline lanes to be shifted to the outside.

Construct three additional low speed flyover structures to provide for the following movements:

1) Westbound frontage road to Westbound AHS
2) Eastbound frontage road to Eastbound AHS
3) Eastbound AHS to Eastbound frontage road

Additional transition lanes will be constructed to allow for these three movements.

Gessner

Low level alternative.

Access to the AHS through lanes will still be via slip ramps, although they will be relocated to the east. Transition lanes of 1.6 km (1.0 mile) length will be provided in each direction. This will require the mainline freeway to be shifted to the outside. A new Park & Ride facility will be constructed north of the freeway. This is not AHS specific. However, AHS improvements to this park and ride lot include provision for check-in, check-out facilities, and vehicle rejection

Mid level alternative.

A new Park & Ride facility will be constructed north of the freeway. While not AHS specific, AHS improvements to this Park & Ride include provision for check-in, check-out facilities, and vehicle rejection. Provide 670 meter (2,200 foot) entrance and exit transition lanes adjacent to the AHS through lanes. This will require the mainline lanes to be shifted to the outside.

High level alternative.

A new Park & Ride facility will be constructed north of the freeway. This is not AHS specific. However, AHS improvements to this park and ride lot include provision for check-in, check-out facilities, and vehicle rejection. Construct high speed flyovers between the Park & Ride and the AHS lanes as follows:

1) Southbound Park and Ride to Eastbound AHS
2) Southbound Park and Ride to Westbound AHS
3) Eastbound AHS to Northbound Park and Ride
4) Westbound AHS to Northbound P&R

Construct three additional low speed flyover structures to provide for the following movements:

1) Westbound frontage road to Westbound AHS
2) Eastbound frontage road to Eastbound AHS
3) Eastbound AHS to Eastbound frontage road

Additional transition lanes will be constructed to allow for these three movements.

North Post Oak

Low level alternative.

Provide one reversible lane 670 meters (2,200 feet) in length to facilitate the westbound entry in the afternoon and eastbound exit in the morning. Convert the existing HOV enforcement area to an AHS check-in, check-out facility.

Mid level and high level alternative.

Provide one reversible lane 670 meters (2,200 feet) in length to facilitate the westbound entry in the afternoon and eastbound exit in the morning. Convert the existing HOV enforcement area to an AHS check-in, check-out facility.
The existing flyover structure may need to be widened.

Eastern Terminus

Low level alternative.

Restripe roadway to accommodate one westbound feeder lane 1.6 km (1.0 mile) in length. Provide check-in and check-out facilities.

Mid level alternative.

Restripe roadway to accommodate one eastbound feeder lane 6.4 km (4.0 miles) in length. Provide check-in and check-out facilities and accommodation for vehicle rejection.

High level alternative.

Restripe roadway to accommodate two eastbound and two westbound feeder lanes 6.4 km (4.0 miles) in length. Provide check-in and check-out facilities and accommodation for vehicle rejection.

6. CONCLUSION

The results presented in this document show that implementation of an Automated Highway System is highly feasible in the Houston area. With the cooperation of METRO, we have been able to show that the low-, mid-, and even the high-level demand figures can be satisfied by some form of automation on their freeways. We have learned that from a societal and institutional perspective Houston could be very receptive to automation technologies. We have shown that some form of automation can be achieved with even minimal infrastructure improvements, or even better results may be achieved with slightly more elaborate infrastructure improvements, still showing a net benefit by greatly increasing throughput.

The NAHSC is very grateful to METRO for enthusiastically participating in this case study. By utilizing the results contained herein, and acknowledging many lessons learned from this inaugural case study, we can look forward to dramatic achievements from subsequent studies with METRO.

7. REFERENCES

1. National Automated Highway Systems Consortium, *Milestone 2 Report, Task C2: Downselect System Configurations and Workshop #3, Appendix G,* Federal Highway Administration, 1997.

2. National Automated Highway Systems Consortium, *Milestone 2 Report, Task C2: Downselect System Configurations and Workshop #3, Appendix H,* Federal Highway Administration, 1997.

APPENDIX A

MICROSIMULATION ANALYSIS OF MULTIPLE MERGE JUNCTIONS UNDER AUTONOMOUS AHS OPERATION

Abstract

In this paper we present a simulation study of autonomous automated vehicle operation on the Houston Katy Corridor. The simulation study was built on top of the SHIFT/SMART-AHS system. We developed the control algorithm for autonomous automated vehicles driving on a highway with multiple merge junctions. The algorithm is distributed and it controls both merging and yielding operations of vehicles in the merge lane and main lane respectively. Using this control system we evaluated the impact on safety and congestion on the Katy Corridor under different travel demand conditions and technology assumptions. The immediate conclusion we reached is that only the low level demands hypothesized by the Houston Metro Transportation Authority are feasible for autonomous automated vehicles.

INTRODUCTION

Traffic congestion and passenger safety are growing problems in several urban corridors. Construction of more lanes on congested highways or use of emerging technologies for more automated traffic control are two approaches which can be used to alleviate these problems. The first approach, constructing more lanes or highways, is rapidly becoming untenable because of lack of right of ways, complexity of highway design and layout, cost and environmental considerations. Hence several metropolitan transportation agencies are turning towards higher levels of automation technologies to address these problems.

Different traffic automation strategies have been proposed (1). Typically they are classified according to their distribution of intelligence attributes. Here, ``intelligence" refers to the techniques used to govern the flow of traffic. At one end of the spectrum, all automation intelligence is concentrated within individual vehicles---leading to the *autonomous* scenario. In the autonomous case, vehicles incorporate enhanced sensing, computation and actuation technologies to improve vehicle control functions such as lane keeping, headway keeping and velocity tracking. At the next level, individual vehicles cooperate by communicating selected state information to each other---leading to the *cooperative* scenario. The communication may be directly from vehicle to vehicle or it may be mediated by the transportation infrastructure. Finally, vehicles may form tightly coordinated, closely spaced groups by communicating more detailed state information at a greater frequency---leading to the *platooning* scenario.

Looking solely at the mainline capacity under these different policies, it may be expected that the cooperative case performs better than the autonomous case and that the platooning case performs better than the cooperative case. But mainline traffic analysis is not sufficient in the presence of entry ramps with merging traffic. Merging traffic perturbs the flow of mainline traffic due to micro-level phenomena such as yielding and merging. Yielding typically leads to a build up of density just before the merge junction and merging leads to a build up of density just after the merge junction. In the case of platooning, one must consider platoon formation before and after the merge.

In addition to the disturbance to mainline traffic at a single merge junction, it is necessary to study the interference caused by multiple merge junctions and exit ramps. Exit ramps disturb the mainline traffic density profile by opening gaps. These gaps could potentially be used for merging unless they get smoothed out by the headway following laws on the mainline. The increase in density just after the merge junction dissipates over a certain distance. In case the next merge junction is placed before that distance, there may be significant interference to traffic flow between the two junctions.

Several important questions need to be answered in a comparative analysis of the different automation approaches for a given highway layout:

- Level of traffic supported without significant queue build up.
- Probability distribution of the distance required for a vehicle to merge successfully.
- For a given merge ramp length, the percentage of vehicles that cannot complete the merge successfully.
- The steady state density and speed profiles along the mainline.

In this paper, we use the Smart-AHS (4) microsimulation approach which has been designed to answer such questions in a wide range of highway layout and travel demand scenarios. Smart-AHS provides the infrastructure elements for simulating vehicle-highway systems. It contains simulation models for highway layout, traffic sources and sinks, vehicle models at different fidelity levels, actuator models, physical level controller models, sensor models and communication models.

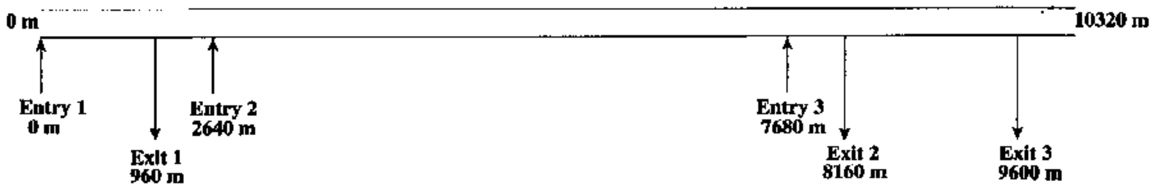
Smart-AHS is provided as a collection of libraries written in the SHIFT (5) programming language. SHIFT is a programming language for describing dynamic networks of hybrid automata. Such systems consist of components which can be created, interconnected and destroyed as the system evolves. Components exhibit hybrid behavior, consisting of continuous-time phases separated by discrete-event transitions. Components may evolve independently, or they may interact through their inputs, outputs and exported events. The interaction network itself may evolve.

We present the results of applying the Smart-AHS approach to the Interstate Highway 10 Katy Corridor of Houston Metro region with autonomous AHS operation. In subsequent work, we have analyzed cooperative merging and platoon merging using the same simulation framework. We note that the merge simulation setup is flexible and reusable. Both parameter values as well as control logic can be easily modified to obtain families of merge simulators.

CASE STUDY DESCRIPTION

In this case study we examine a single lane freeway with three merge junctions. The highway is approximately modeled after the HOV portion of the Katy Corridor (Interstate

Highway 10) of the Houston metropolitan region. The main modification was to reduce the distance between Entry 2 and Entry 3. Figure 1 shows the overall layout of the highway being studied.



We studied two travel demand characteristics: low intensity and high intensity. These were taken from projections made by the Houston Metropolitan Transit Authority (2). We used the origin-destination travel demand (6) derived from this data. The low intensity travel demand is shown in Table 1. The high intensity travel demand is shown in Table 2.

Table 1: Low Intensity Travel Demand

	Entry 1	Entry 2	Entry 3
Average Flow	1000/hr	500/hr	300/hr
Inter-arrival Time Distribution	Uniform [3.1,4.1]	Uniform [6.7,7.7]	Uniform [11.5,12.5]
Exit Distributions	Exit 1 5% Exit 2 27.1% Exit 3 67.9%	Exit 1 0% Exit 2 28.6% Exit 3 71.4%	Exit 1 0% Exit 2 29% Exit 3 71%
Initial Speed	11 m/s	22m/s	22m/s

Table 2: High Intensity Travel Demand

	Entry 1	Entry 2	Entry 3
Average Flow	2000/hr	1000/hr	1000/hr
Inter-arrival Time Distribution	Uniform [1.3,2.3]	Uniform [3.1,4.1]	Uniform [3.1,4.1]
Exit Distributions	Exit 1 5% Exit 2 24% Exit 3 71%	Exit 1 0% Exit 2 25.6% Exit 3 74.4%	Exit 1 0% Exit 2 25.6% Exit 3 74.4%
Initial Speed	11 m/s	22m/s	22m/s

We ensured that new vehicles would not enter the highway in an unsafe configuration in case of congestion. For this, we required that the new vehicle had sufficient space in front of it in order to stop without collision in case the vehicle in front of it applies maximum braking deceleration.

We used kinematic vehicle models in which the controller provides acceleration and brake inputs to the vehicles. Our main work consisted of developing the controllers for mainline and merging vehicles.

Controller Description

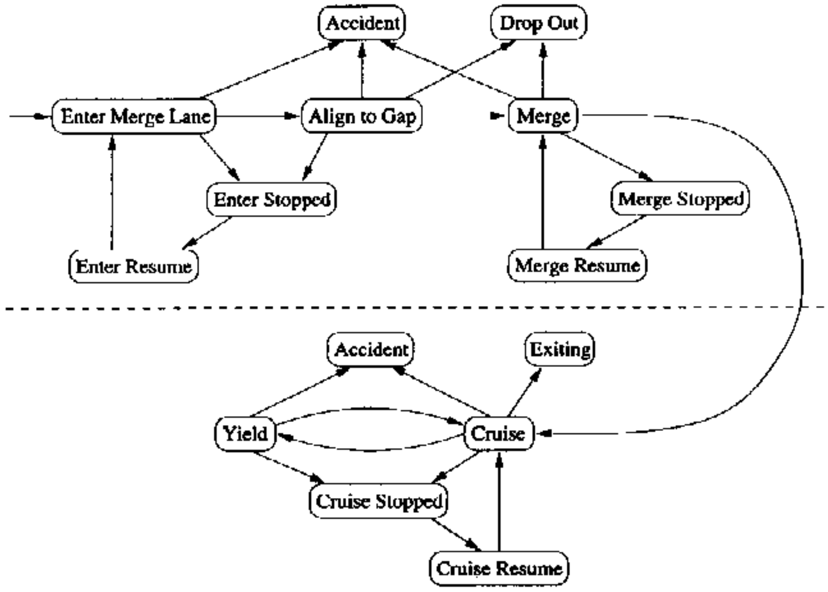
Control Objective

The objective of control consisted of a combination of several factors listed below in their priority order.

- Avoiding collisions
- Ensuring that merging vehicles are able to merge
- Maintaining the desired time headway between vehicles
- Maintaining the nominal speed for the lane (28 m/s was used as the nominal speed for the mainline.)

Controller Logic

Figure 2 shows the simplified logical behavior of the controller. Several states and transitions have been omitted corresponding to the book-keeping aspects of the controller behavior. More complete description of the controller is given in a companion paper (3). The vehicle begins in the *Enter Merge Lane* state at its initial speed. It moves to the *Align to Gap* state when it passes the physical barrier between the merge lane and the main lane. In this state it adjusts its speed to the mainline speed, looks for gaps and attempts to align itself with suitable gaps. When properly aligned, it enters the *Merge* state and changes lanes to the main lane. On completing the lane change, it moves to the *Cruise* state. When it encounters a merging vehicle that passes its yielding criterion, it moves to the *Yield* state. It increases its space headway until further yielding is no longer necessary. Then it moves back into the *Cruise* state. When the vehicle reaches its exit, it moves to the *Exiting* state and exits out of the simulation.



If the vehicle's speed reaches zero, it moves to the (respective) stopped state. Then, when sufficient space opens up in front of it, it resumes moving down the highway. Once it picks up sufficient speed, it moves back into a suitable state and continues its main operation. When a merging vehicle reaches the end of the merge lane without successfully completing the merge, it enters the *Drop Out* state. On detecting a collision, the vehicle moves into the *Accident* state. Vehicles in the collision state are dropped out of the simulation.

Table 3 shows the values of technology parameters assumed in the controller design.

Table 3: Technology Parameters

Parameter	Value
maximum acceleration	0.1 x g
maximum braking	-0.5 x g
sensor range	100m

Table 4 shows some of the state information maintained by the controller for decision making.

Table 4 Controller State Information (Distances are clipped to *sensor range*. In the absence of the related vehicle, nominal speed is used)

State	Description
same lane vehicle	vehicle immediately in front in the same lane
side lane vehicle	vehicle immediately in front in the side lane
yielding vehicle	for a vehicle in the merging lane, vehicle immediately in the back in the main lane
same lane gap	relative distance to same lane vehicle
side lane gap	relative distance to side lane vehicle
same lane relative speed	relative speed of same lane vehicle
side lane relative speed	relative speed of side lane vehicle
same lane ratio	same lane gap / (vehicle speed * desired time headway
side lane ratio	side lane gap / (vehicle speed * desired time headway

Control Laws for Acceleration and Braking

Let H_r denote headway ratio, V_{rel} denote relative speed, V denote vehicle speed and V_a denote nominal speed. H_r is given as

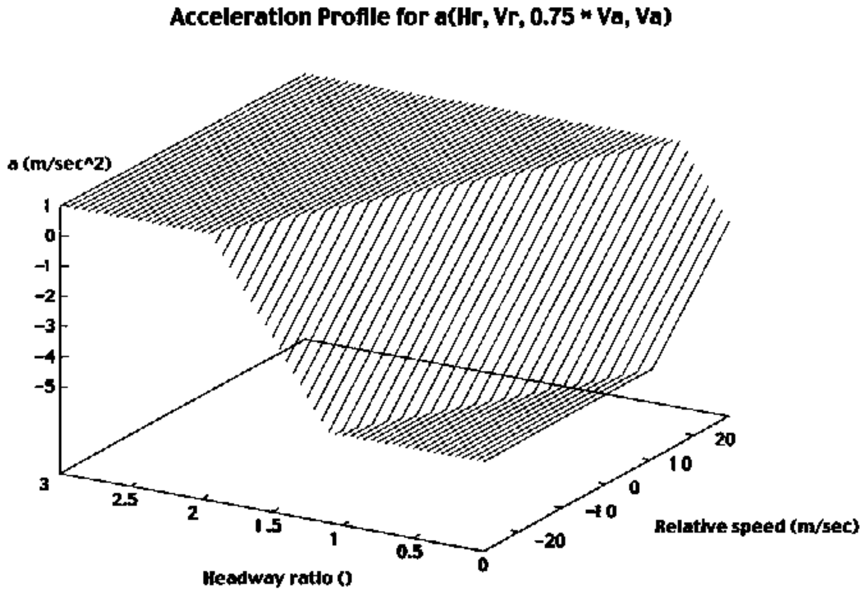
H_r = (gap/V)* (1/ *Desired Time Headway*)

Then, the raw desired acceleration is given by

$p_h (H_r - 1) + p_v V_{rel}$.

Here, p_h is the relaxation constant for headway errors and p_v is the relaxation constant for speed errors. We experimented with several values for p_h and p_v. The main idea was that the controller must respond rapidly to errors in the headway and relax smoothly to errors in the relative speed. We chose the following values for these parameters: $p_h = 7$ and $p_v = 0.2$. We converged on this choice after numerous trial simulations. This choice gave us the desired controller behavior with respect to safety and time headway keeping. At this time we are not able to give an analytical justification for these parameter values. This raw desired acceleration is clipped to *maximum acceleration* or *maximum braking* as the case may be. If the vehicle speed is positive and less than the nominal speed, the applied acceleration is this clipped acceleration. Otherwise, the applied acceleration is zero.

Thus, the applied acceleration is a function of H_r, V_{rel}, V and V_a, denoted $a(H_r, V_{rel}, V, V_a)$. Figure 3 shows the applied acceleration function.



The controller computes two accelerations:

same lane acceleration
= a(same lane ratio, same lane relative speed, vehicle speed, nominal speed) and

side lane acceleration
= a(side lane ratio, side lane relative speed, vehicle speed, nominal speed).

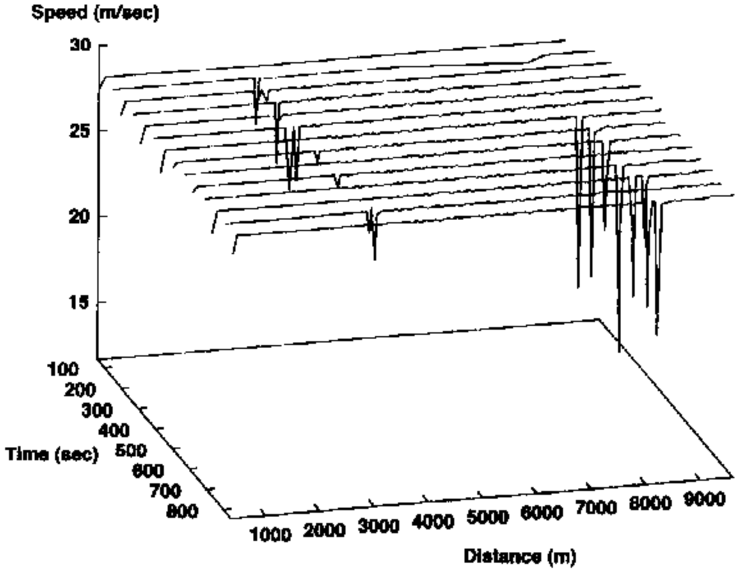
The same lane acceleration is used in headway keeping and the side lane acceleration is used during yielding and merging.

RESULTS

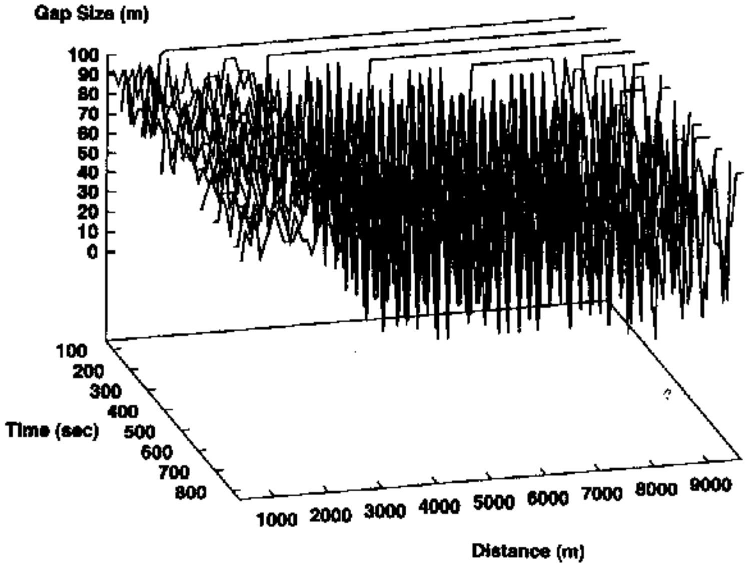
We ran the simulation with two levels of travel demand, the low intensity case and the high intensity case, and with two values for the desired headway, 1 sec and 3 sec. The results of the simulation runs for the one second time headway case are shown in Figures 4 and 5 for low intensity and Figures 6 and 7 for high intensity.

Each pair of figures (4 and 5, 6 and 7) show two measures of congestion. The first one is the speed profile over the highway stretch, indexed by time. The second is the gap profile with respect to the vehicle in front, indexed by time. The position of the merge junctions corresponds to the most congested spots on the corridor.

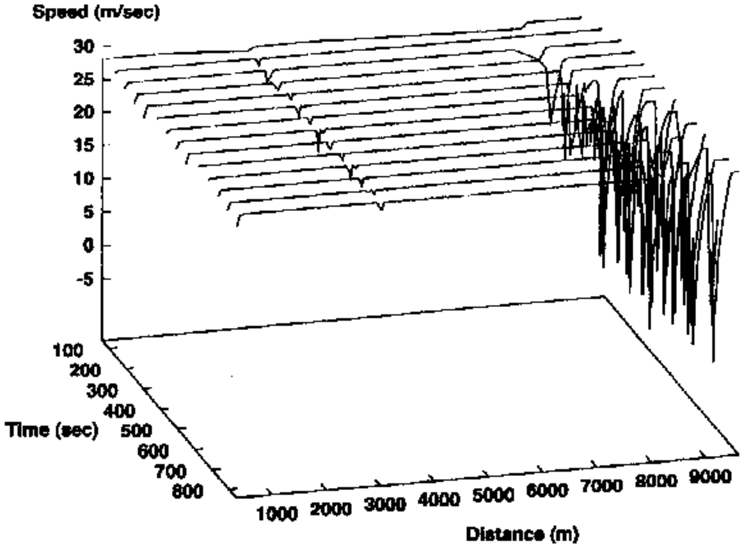
Distance vs Speed per Time



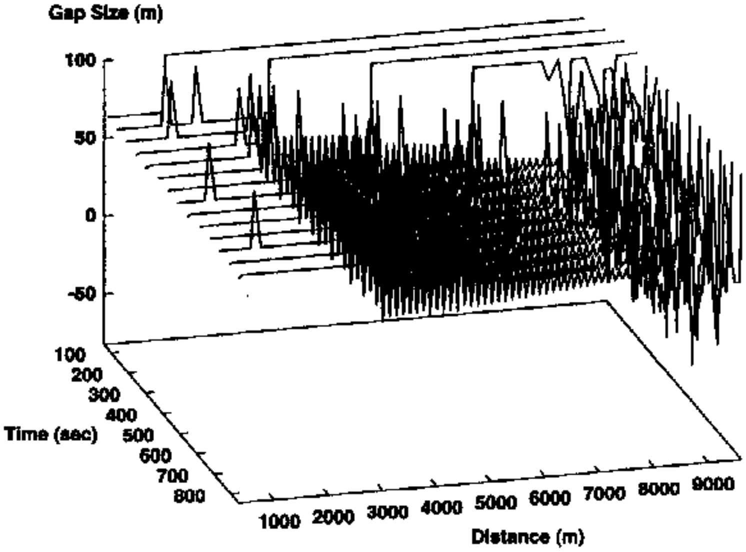
Distance vs Same Lane Gap per Time



Distance vs Speed per Time



Distance vs Same Lane Gap per Time



Other Results

- The average distance to begin merge was least in Entry 1 and highest in Entry 3.
- In the 1 second time headway case the maximum distance to complete merge was 200 m in the low intensity case and 220 m in the high intensity case.
- In all cases the number of drop outs was zero.
- In all cases the number of accidents for Entry 1 and Entry 2 was zero. Entry 3 exhibits accidents, particularly in the case of one second headway. The cause for these accidents is under instigation. Probable causes are

  1. $p_v = 0.2$: this implies that the relaxation constant for speed errors is 5 sec, which may be too large for maintaining 1 sec headway.

  2. Exiting protocol design: this is under investigation.

- Low intensity level of travel demand can be supported with no queue build up.
- High intensity level of travel demand cannot be supported without queue build up, indicating that ramp metering or some other strategy that lowers demand is essential. At Entry 1, in 15 minutes of simulation, 400 vehicles were admitted instead of 500. At Entries 2 and 3, in 15 minutes of simulation, 200 vehicles were admitted instead of 250. This indicates that the travel demand is not sustainable.

REFERENCES

(1) *NAHSC Milestone 2 Report (Task C2: Downselect System Configuration and Workshop #3).* 1996, Internal NAHSC document to be submitted to the U.S. Department of Transportation in 1997 as a formal program deliverable.

(2) Houston Metropolitan Transit Authority. *Houston Metro Corridor Data.* 1997

(3) M. Antoniotti, A. Deshpande, A. Girault. *Microsimulation Analysis of a Hybrid System Model of Multiple Merge Junction Highways and Semi-Automated Vehicles* , Proceedings of the IEEE Conference on Systems, Man and Cybernetics, Orlando, FL, U.S.A. October 1997

(4) A. Deshpande. *AHS Components in SHIFT.* 1997, Draft California PATH Research Report. (http://www.path.berkeley.edu/smart-ahs).

(5) A. Deshpande, A. Gollu, L. Semenzato. *SHIFT Programming Language and Run-Time System for Dynamic Networks of Hybrid Automata.* 1997, California PATH Research Report UCB-ITS-PRR-97-7. (http://www.path.berkeley.edu/shift)

(6) B. Ran. *O-D Matrices for Travel Demand in the Houston Metro Case Study.* 1997, Personal Communication.

APPENDIX B

Capacity Analysis of the Houston Katy Freeway Case Study

Luis Alvarez

Summary

The activity based theory of traffic flow is applied to evaluate highway capacity for four different concepts employing automated vehicles in the HOV lane of the Houston Katy Freeway. With these concepts, three increasing patterns of traffic demand are considered using SmartCap, a meso-scale software tool developed in the California PATH program as part of the NAHSC Tools effort, was used to simulate the highway behavior.

The four AHS concepts include three "independent" vehicle concepts, where each vehicle is assumed to operate in a car-following mode, gauging its position and velocity from the vehicle in front. The first concept, Independent Vehicle with Range and Range Rate Information (IVRR), assumes no intervehicle communication; the second concept, Independent Vehicle with Range and Range Rate and Warning Information (IVRRW), assumes communication only in cases of emergency, i.e., a sudden stop; the third concept,
Independent Vehicle with Range and Range Rate and Acceleration Information (IVRRA), assumes that the acceleration from the vehicle in front is know. The final concept, Platoon Organization (PO), assumes range, range rate and acceleration information in closely spaced, coordinated longitudinal groupings of up to 10 vehicles.

The resulting simulations indicate that the ***Platoon Organization concept provides smaller entry queues*** while sustaining a service time comparable or better to that provided by the Independent Vehicle concepts. ***This reduction on the size of the entry queues implies, in turn, a smaller required on-ramps to service the queues and a reduced impact in the collateral urban network.*** The reduction of the entry queues can be explained by the extra free highway space that is created after joins activities are executed.

For the Platoon Organization concept it was found that the factor that most limits additional reductions in service time is the size of the transition lanes in the off-ramps. Arbitrarily incrementing the platoon size does not provide any additional advantage and produces severe reductions on the velocity of the sections that precede an exit that must be taken by a high proportion of the through traffic.

1.0 Introduction

The capacity of the High Occupancy Vehicle (HOV) lane of the Katy Freeway is considered as a case study to test for the different concepts. Several concepts for implementing AHS have been proposed. The main differences between these concepts reside in the degree of vehicle's automation, the intensity of inter-vehicle collaboration and the highway infrastructure they require [1]. It is of prime importance to determine, in an accurate manner, the increment on highway capacity that each concept will produce.

Several patterns of origin-destination (OD) pairs of traffic flow are considered. These patterns correspond to expected volumes of traffic with low, mid and high cost modifications to the actual freeway and are composed by a mixture of cars and buses. This information was provided by the Houston Metropolitan Transit Authority. The simulations were executed with SmartCap[2,3,4], a meso-scale traffic simulator tool developed in AHS Task B5. The SmartCap design is consistent with the activity based theory of traffic flow developed in [2] and reported in [3].

This paper is divided into four sections. Section 2 describes the simulations and gives the most important data used for them. Section 3 discusses some simulations results. Finally, concluding remarks are presented in section 4.

2.0 Description of Simulation

2.1 Basic Freeway Layout

Three alternatives were considered to analyze the capacity of the Katy freeway HOV lane: low, medium and high cost. These alternatives differentiate mainly in the infrastructure in the on-ramps and off-ramps and in the total traffic of vehicles that is expected to flow through the freeway in each case. The size of the infrastructure and the volumes of traffic increase with the cost. The basic layout, however, is similar for the three alternatives. It consists of a single HOV lane with three on-ramps and three off-ramps. Figs. 1 and 2 correspond to the medium cost eastbound and medium cost westbound alternatives, respectively; the in-pointing arrows indicate entries while the out-pointing arrows indicate exits; the numbers in parenthesis are the length in meters of the different sections of the Freeway. For simulation purposes, the long sections of highway were partitioned into smaller sections of $\sim 450\text{-}650\ m$ each.

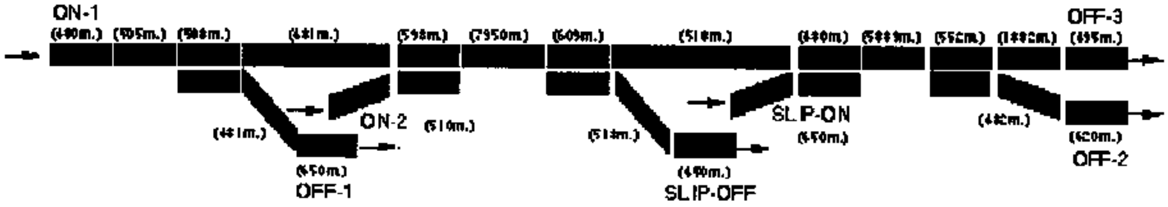


Figure 1. Eastbound Houston Katy HOV Lane Layout for the Medium Cost Scenario

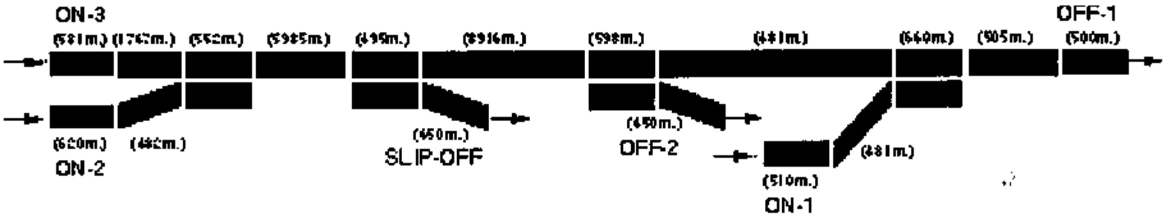


Figure 2. Westbound Houston Katy HOV Lane Layout for the Medium Cost Scenario

2.2 Concepts and Activities [1]

Four AHS concepts are analyzed:

1. Independent Vehicle with Range and Range Rate Information (IVRR).
2. Independent Vehicle with Range and Range Rate and Warning Information (IVRRW).
3. Independent Vehicle with Range and Range Rate and Acceleration Information (IVRRA).
4. Platoon Organization (PO).

2.2.1 Independent Vehicle Concepts [1]

The first three concepts, IVRR, IVRRW and IVRRA are similar. In each one vehicles are assumed to operate independently and measure its position and velocity relative to the vehicle in front. IVRR assumes no intervehicle communication, IVRRW assumes communication only in cases of emergency, i.e., a sudden stop, and IVRRA assumes that the acceleration from the vehicle in front is known.

There are three activities that completely describe the behavior of vehicles under these concepts:

1. *cruise*
2. *lane change right (LC-right)*
3. *lane change left (LC-left)*

Table 1 summarizes the space used by these activities, when the nominal speed is 30 *m/s*. Vehicles normally perform the activity *cruise*. The activities *LC-right* and *LC-left* are used for entering and exiting the highway.

AUTO					**BUS**				
Concept	Lane	Cruise	LC-right	LC-left	Concept	Lane	Cruise	LC-right	LC-left
IVRR	self	47	47	47	IVRR	self	202	202	202
	left	0	0	0		left	0	0	0
	right	0	47	0		right	0	202	0
IVRRW	self	45	16	16	IVRRW	self	199	68	68
	left	0	0	45		left	0	0	199
	right	0	45	0		right	0	199	0
IVRRA	self	43	14	14	IVRRA	self	198	62	62
	left	0	0	43		left	0	0	198
	right	0	43	0		right	0	198	0

Table 1. Space Demanded By Activities In The Independent Vehicle Concepts.

2.2.2 Platoon Organization Concept

Vehicle maneuvering in platoons is portioned in the following activities:

1. *leader*
2. *follower*
3. *join*
4. *split*
5. *AHS-entry*
6. *AHS-exit*

Vehicles entering the highway execute the *AHS-entry* activity that will accomplish a lane change. As soon they are in through lane of the highway the begin to perform the *leader* activity. In any particular section a *leader* can switch to the *join* activity if the average platoon size in that section is smaller than a given maximum platoon size. After a *join* is completed, vehicles switch to perform the *follower* activity. The *split* activity is executed considering the number of sections between the current vehicle position and its desired destination. The number of *splits* is such that when the proper destination is reached all the vehicles with that particular destination will be executing the *leader* activity or will be *followers* in a platoon that consist only of vehicles with that particular destination. The *AHS-exit* activity is executed to change the lane of the vehicles to the exit lane. Table 2 contains the space demanded by the activities in the platoon organization concept.

AUTO

Lane	leader	follower	join	split	AHS-exit	AHS-exit
self	66	7	37	37	30	30
left	0	0	0	0	66	0
right	0	0	0	0	0	66

BUS

Lane	leader	follower	join	split	AHS-exit	AHS-exit
self	205	20	110	110	98	98
left	0	0	0	0	205	0
right	0	0	0	0	0	205

Table 2. Space Demanded By Activities In The Platoon Organization Concept.

2.3 Input And Output Flows

The input flows used for the simulations in the Houston Katy Freeway are shown in Tables 3-5. The flow rates are constant and are sustained for an hour in all cases. The outputs have a capacity of 2000 *veh/hr* for the low cost scenario and 4000 *veh/hr* for the medium and high cost scenarios, respectively.

Eastbound (veh/hr)					**Westbound** (veh/hr)				
Input	Type	Destination			Input	Type	Destination		
		OFF-1	OFF-2	OFF-3			SLIP-OFF	OFF-2	OFF-3
ON-1	CAR	48.0	260.3	652.2	ON-3	CAR	324.5	324.5	551
	BUS	2.0	10.8	27.2		BUS	13.5	13.5	23
ON-2	CAR	0.0	137.4	342.9	ON-2	CAR	155.5	155.5	265
	BUS	0.0	5.7	14.3		BUS	6.5	6.5	11
SLIP-ON	CAR	0.0	82.6	205.4	ON-1	CAR	0.0	0.0	48
	BUS	0.0	3.4	8.6		BUS	0.0	0.0	2

Table 3. Low Cost Input Flow

Eastbound (veh/hr)					**Westbound** (veh/hr)				
Input	Type	Destination			Input	Type	Destination		
		OFF-1	OFF-2	OFF-3			SLIP-OFF	OFF-2	OFF-3
ON-1	CAR	96.0	607.7	1,216.3	ON-3	CAR	384.0	384.0	1,152
	BUS	4.0	25.3	50.7		BUS	16.0	16.0	48
ON-2	CAR	0.0	192.0	384.0	ON-2	CAR	192.0	192.0	576
	BUS	0.0	8.0	16.0		BUS	8.0	8.0	24
SLIP-ON	CAR	0.0	160.3	319.7	ON-1	CAR	0.0	0.0	96
	BUS	0.0	6.7	13.3		BUS	0.0	0.0	4

Table 4. Medium Cost Input Flow

Eastbound (veh/hr)					**Westbound** (veh/hr)				
Input	Type	Destination			Input	Type	Destination		
		OFF-1	OFF-2	OFF-3			SLIP-OFF	OFF-2	OFF-
ON-1	CAR	96.0	467.5	1,356.5	ON-3	CAR	600.0	600.0	1,20
	BUS	4.0	19.5	63.7		BUS	25.0	25.0	5
ON-2	CAR	0.0	245.8	714.2	ON-2	CAR	360.0	360.0	72
	BUS	0.0	10.2	29.8		BUS	15.0	15.0	3
SLIP-ON	CAR	0.0	245.8	714.2	ON-1	CAR	0.0	0.0	9
	BUS	0.0	10.2	29.8		BUS	0.0	0.0	4

Table 5. High Cost Input Flow

3.0 Simulation Results

The simulation results in this section are presented in two sets of plots. The first plot in each set shows the accumulated size of all the buffers in the entries to the highway, which is analogous to the entry queue resulting from the particular distribution of intelligence. These buffers result from applying the TMC entry plan described in section 4 that allows to put in the highway only the number of vehicles that will have space to perform their given activities in the entry sections. The second plot contains information about service time, defined as the sum of the traveling and waiting times. The traveling time measures the amount of time a vehicle spends on the highway and the waiting time is the time a vehicle spends in any input buffer before entering the highway. These values are averaged for all the vehicles in the highway and the addition of both averages, the average service time, is shown in the second plot of the sets.

The input flow is designed to last one hour. Therefore, the size of the buffers achieves its maximum at the end of that period of time for all the simulations. The simulations were subsequently extended until the buffers were completely emptied and the value of the average service time stabilizes; the amount of extra time required for this stabilization varies with the volume of flow, as expected.

The maximum speed for all the vehicles in the highway was set to 30 *m/s* = 108 *km/hr* ~67 *mi/hr* in all the scenarios.

3.1 Low Cost Scenario

The results for the low cost case are not included because they do not show any distinction between cost options. Input buffers never appeared in the simulations and the velocity was maximum for all vehicles in the four concepts.

3.2 Medium Cost Scenario

Figures 3 and 4 show the results for the simulation of the medium cost scenario. Recall, from Figures 1 and 2, that there are two points in which there is mixture of entry traffic. These points correspond to ON-1 and SLIP-ON for the eastbound direction and to ON-2 and ON-1 for the westbound direction. The α parameter, or the degree of cooperation which is manifested by mainline slowdown, was varied in each case. Different values were tried and the plots in Figures 3 and 4 show the results that achieve maximum performance for each concept. In the case of the intelligent vehicles concepts, this value is $\alpha = 0.95$ and for the platoon organization case the value is $\alpha = 0.60$. The platoon size is set to 10 in the platoon organization case.

The most significant difference in the simulation results for the eastbound direction in Figure 3 resides in the size of the buffers. The buffer size for the platoon organization concept is much smaller than the buffer size for the independent vehicle concepts. The service time does not differ significantly for the four concepts. This happens because in the platoon organization concept there is a velocity reduction in the sections that precede an exit that will be taken by a high volume of traffic.

For the westbound direction the platoon organization achieves both a smaller buffers' size and service time than the ones achieved with the independent vehicle concepts (see Figure 4).

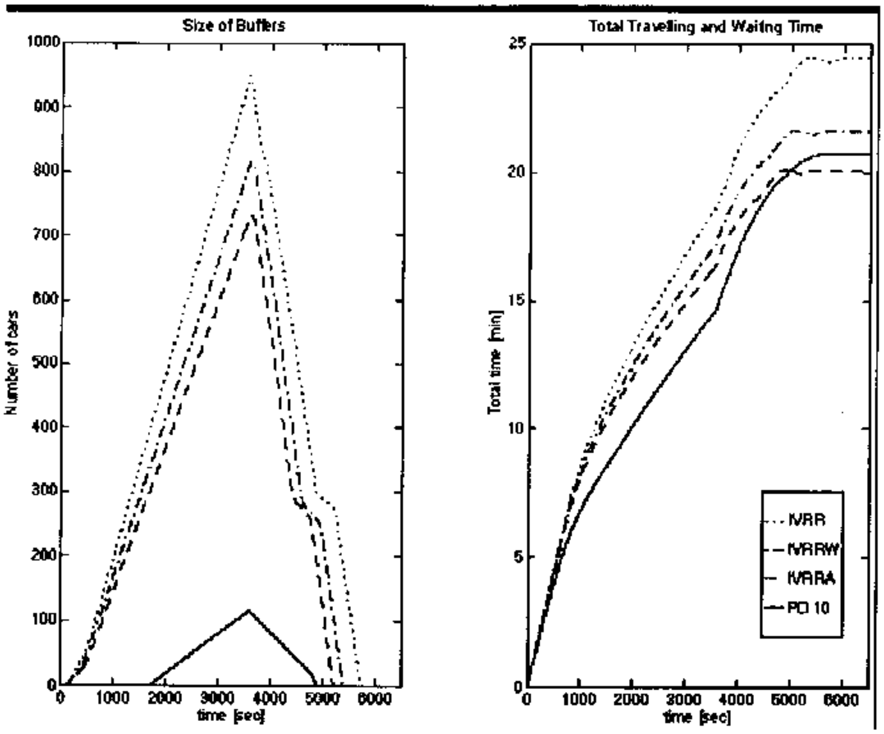


Figure 3. Simulation Results for Eastbound Medium Cost Scenario

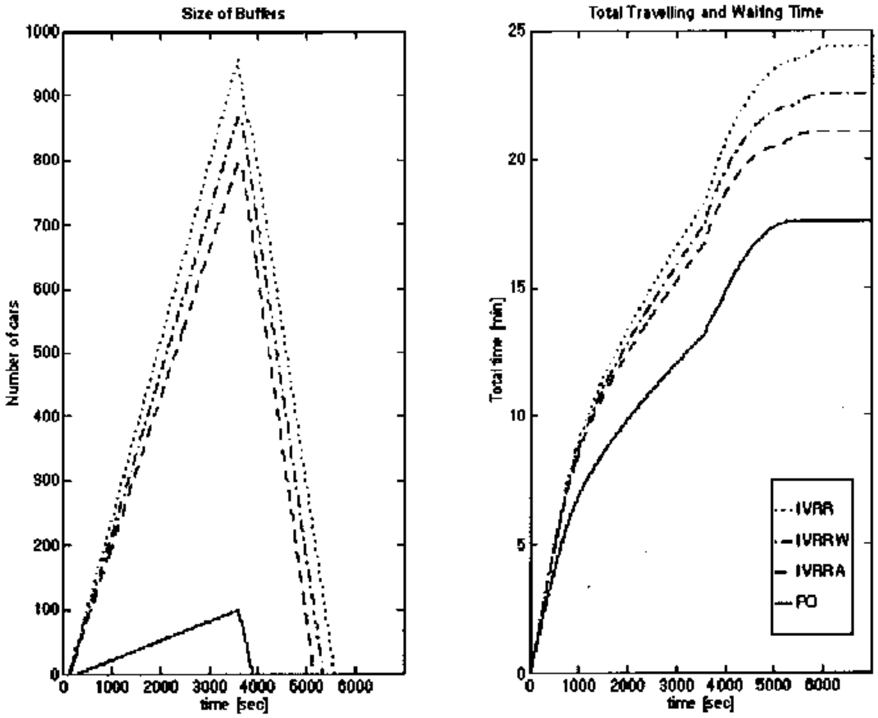


Figure 4. **Simulation Results for Westbound Medium Cost Scenario**

3.3 High Cost Scenario

The simulation results for the high cost scenario illustrated in Figures 5 and 6 are very similar to those discussed in the medium cost scenario. However, the size of the buffers is very large, even for the platoon organization concept that yields maximum buffer sizes of ~800 and ~600 vehicles for the eastbound and westbound directions, respectively.

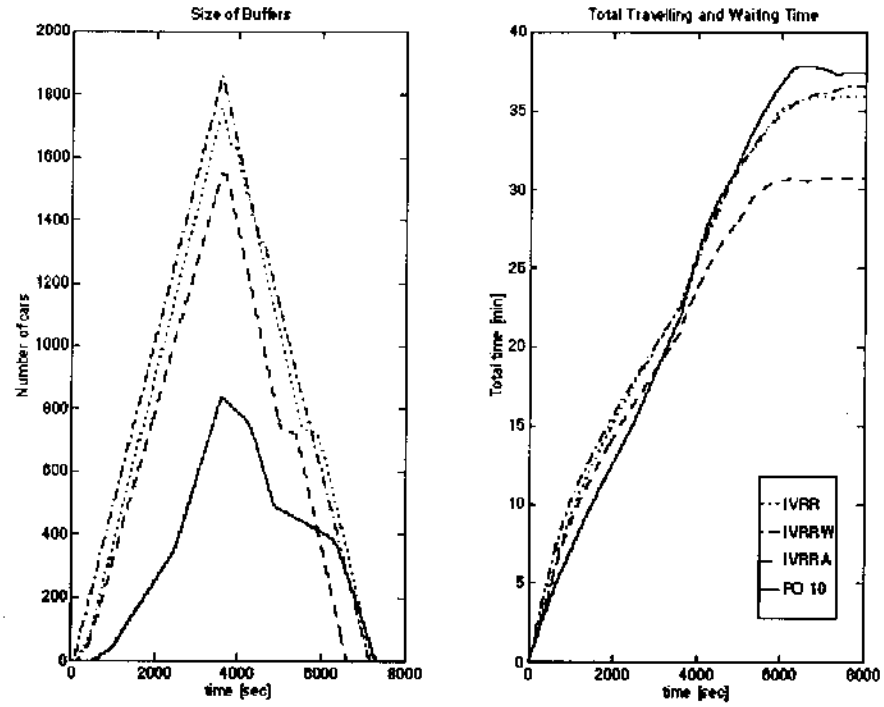


Figure 5. Simulation Results for Eastbound High Cost Scenario

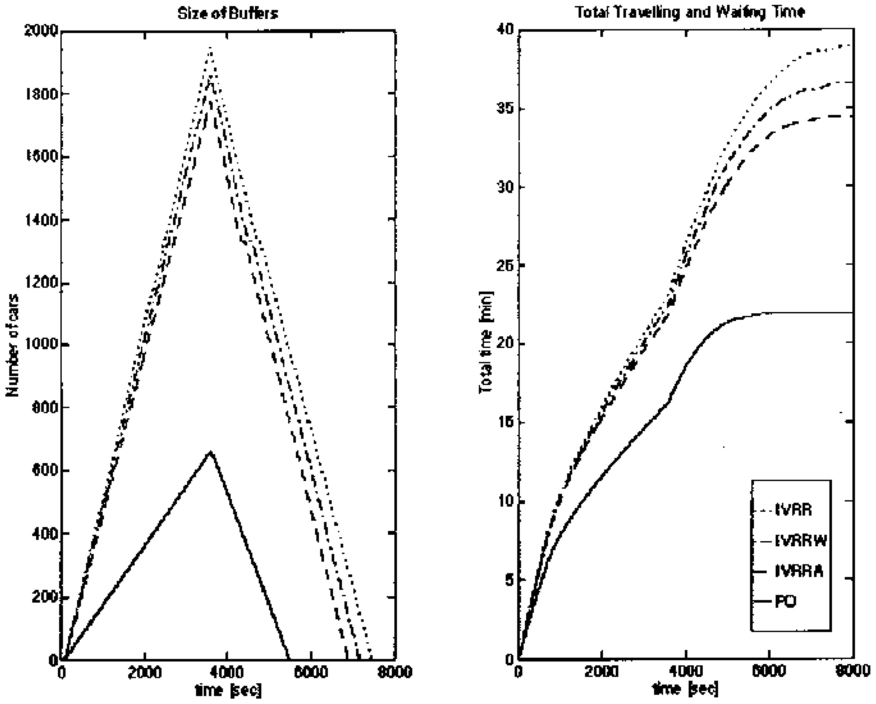


Figure 6. Simulation Results for Westbound High Cost Scenario

3.4 Platoon Size Effect

To evaluate the effect of the platoon size extra simulations were executed for the mid cost scenario, considering that in this case modest buffer size were achieved. Figures 7 and 8 show the simulation results for different values of the maximum average platoon size. It can be noticed from Figure 8 that increasing the maximum average platoon size to values larger than 10 does not provided any significant reduction in the size of the buffer and that the service time is almost independent of the platoon size.

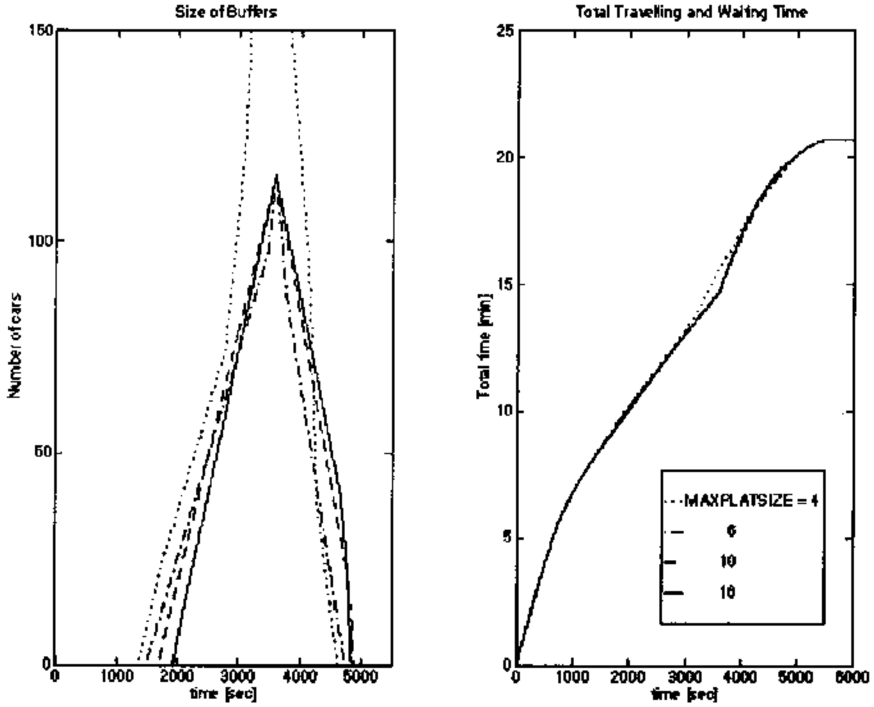


Figure 7. Effect of Platoon Size

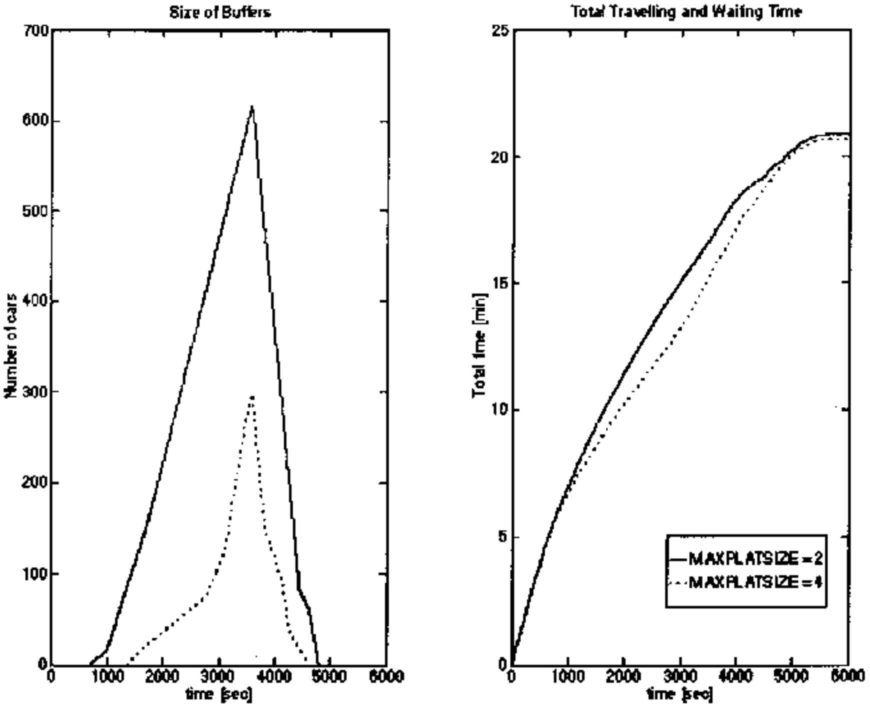


Figure 8. Effect of Platoon Size

3.5 Effect of Mixing Traffic

The effect on the choice of α is shown in Figures 9 and 10 for the independent vehicle concepts and the platoon concept, respectively. For the IV concept, Figure 9 shows that the buffer size increases when the value of α is reduced; however, this increase is small. This behavior can be explained as the velocity in the through direction of the HOV lane has to be reduced to accommodate a greater proportion of vehicles coming from the entry lane.

In the case of the platoon organization concept the results in Fig.10 indicate that the buffers' size is reduced when the value of α is reduced. The reason for this behavior is that the join activity in the previous sections to an entry reduces the demand of space in the through lane. The highway space that is freed by this joining process can be utilized by the entry flow.

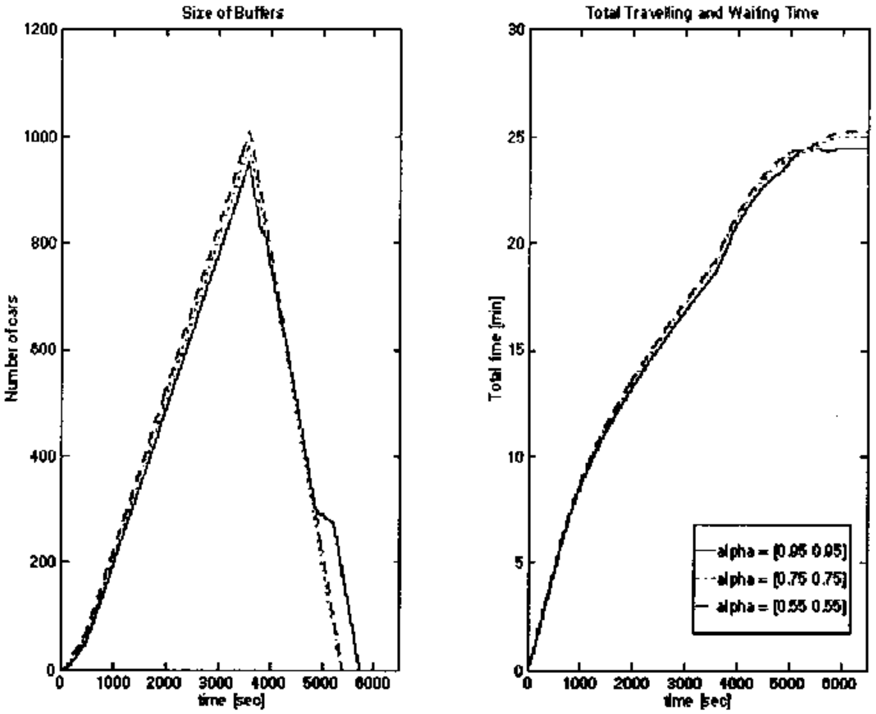


Figure 9. Effect of α on IV Concepts

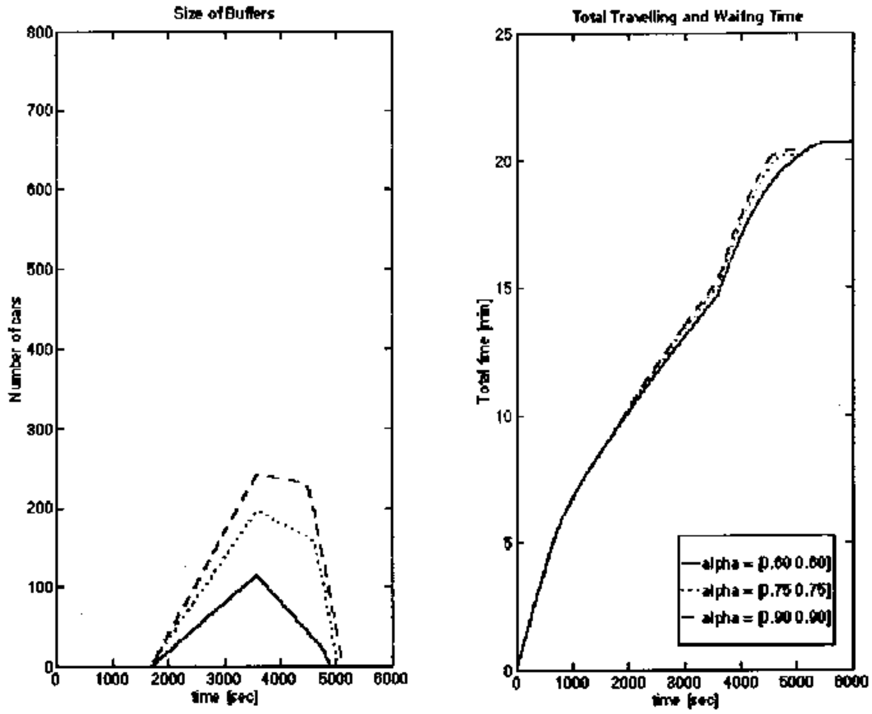


Figure 10. Effect of α on PO Concept

4.0 Conclusions

SmartCap, a tool developed through NAHSC Task B5, was used to simulate the behavior and estimate capacities of proposed applications of AHS on the Houston Katy Freeway HOV lanes. SmartCap is an activity-based traffic flow model using concept-dependent space filling policies, with entries simulated with first-come first-served queues. Different scenarios of infrastructure, traffic flows and concepts of AHS were input.

The resulting simulations indicate that the platoon organization concept provides smaller entry queues while sustaining a service time comparable or better to that provided by the independent vehicle concepts. This reduction on the size of the entry queues implies, in turn, a smaller required on-ramps to service the queues and a reduced impact in the collateral urban network. This reduction of the entry queues can be explained by the extra free highway space that is created after joins activities are executed.

For the platoon organization concept it was found that the factor that most limits additional reductions in service time is the size of the transition lanes in the off-ramps. Arbitrarily incrementing the platoon size does not provide any additional advantage and produces severe reductions on the velocity of the sections that precede an exit that must be taken by a high proportion of the through traffic.

Further analysis is required to refine the conclusions base on these simulations. In particular, more complex models for the entry flow are required as well as to study the sensitivity of the results to different values of the highway spaced demanded by the different activities and concepts.

Acknowledgments

The author wishes to thank Gabriel Gomes for his help with the simulations and in preparing the figures of this paper. Mireille Broucke provided the version of SmartCap that was used as based for the design of the TMC. John Haddon provided the activity space requirements for the four concepts and the initial description of the activity plan for the platoon organization concept.

References

1. NAHSC. NAHSC Automated Highway System Milestone 2 Report: Task C2, Downselect System Configurations and Workshop #3, June 1997.

2. M. Broucke and P. Variaya. A theory of traffic flow in automated highway system. Transportation Research, Part C: Emerging Technologies, 4(4):181-210, 1996

3. L. Alvarez. Activity based highway capacity analysis: a case study. *In Proceedings of IEEE-ITSC*, November 1997.

4. M. Broucke, P. Variaya, M. Kourjanski and D. Khorramabadi. SmartCap User's Guide. Technical Report, Department of Electrical Engineering and Computer Science, University of California, Berkeley, California, May 1996.

APPENDIX C

Preliminary Emissions and Fuel Consumption Evaluation of Automated Highway Systems

Matthew Barth
College of Engineering
Center for Environmental Research and Technology
University of California
Riverside, CA 92521
barth@engr.ucr.edu

ABSTRACT

A preliminary evaluation has been carried out in estimating the emissions and energy use (i.e., fuel consumption) associated with an AHS using advanced simulation modeling tools. A detailed AHS microsimulation has been combined with a comprehensive modal emissions model to predict emissions and energy use for a modeled highway. The resulting AHS emissions and fuel consumption are compared to non-automated traffic at different levels of congestion, as well as idealized traffic flow. The results of this preliminary evaluation have shown that an AHS has slightly lower average fuel consumption than a non-automated highway operating at free-flow, and much lower average fuel consumption than a non-automated highway operating under congested conditions, because of its smoother traffic flow. Further, an AHS operating at 60 mph has substantially lower emissions per vehicle-mile traveled than non-automated traffic at the same average speed, again because of its smoother traffic flow. Vehicles that platoon in an AHS can expect an additional 5 - 15% fuel savings and emission reduction due to the aerodynamic drafting effect, which is dependent on the intra-platoon vehicle spacings.

1 INTRODUCTION

Automated Highway Systems (AHS) have the potential to substantially improve the safety and efficiency of highway travel. In addition, there are several potential benefits for the environment. Vehicle fuel consumption and emissions will be reduced due to smoother traffic flow (i.e., fewer accelerations/decelerations) and less congestion, resulting in shorter trip times. Further, if vehicles operate at very close spacings (i.e., platooning), the aerodynamic drag on the vehicles will be lower and fuel consumption and emissions will further be reduced.

In order to estimate the potential emissions and fuel consumption benefits of an AHS, preliminary experimentation has been carried out using advanced simulation tools. A detailed AHS microsimulation was combined with a comprehensive modal emissions model to predict emissions and energy use for a modeled highway. This highway was modeled after the Katy Corridor (Interstate Highway 10) of the Houston metropolitan region. For this case study, a single lane freeway with three merge junctions was examined. The resulting AHS emissions and fuel consumption are then compared to the cases of: 1) non-automated traffic at different levels of congestion; and 2) idealized traffic flow.

In Section 2, background information is given on the AHS microsimulation, the comprehensive modal emissions model, and the freeway congested cycles used for the non-automated traffic comparison. In Section 3, the methodology is briefly described, followed by the results given in Section 4. Conclusions and future work are described in Section 5.

2 BACKGROUND

2.1 AHS Microsimulation

The AHS microsimulation was implemented using the SmartAHS framework developed at PATH [Deshpande, 1997a]. SmartAHS provides the infrastructure elements for simulating vehicle-highway systems. It contains simulation models for highway layout, traffic sources and sinks, vehicle models at different fidelity levels, actuator models, physical level controller models, sensor models, and communication models.

SmartAHS is provided as a collection of libraries written in the SHIFT programming language [Deshpande et al., 1997b]. SHIFT is a programming language for describing dynamic networks of hybrid automata. Such systems consist of components which can be created, interconnected and destroyed as the system evolves. Components exhibit hybrid behavior, consisting of continuous-time phases separated by discrete-event transitions. Components may evolve independently, or they may interact through their inputs, outputs, and exported events. The interaction network itself may evolve.

For this case study, the highway layout was built using the SmartAHS highway models and simple kinematic vehicle models were used. For these simple kinematic vehicle models, the controller provides acceleration and brake inputs to the vehicles. A single lane freeway was examined with three merge junctions, modeled after the Katy Corridor (Interstate Highway 10) of the Houston metropolitan region. For further details on the actual microsimulation setup, please refer to [Antoniotti et al., 1997].

2.2 Comprehensive Modal Emissions Modeling Project

The current emission-factor models developed for large regional areas (i.e., EPA's MOBILE and CARB's EMFAC models) are inappropriate for application to detailed vehicle microsimulation models. Much better suited are *modal* emissions models, i.e., models that predict emissions (and fuel consumption) as a function of vehicle operating mode (i.e., idle, steady-state cruise, various levels of acceleration/deceleration, etc.). Researchers at the University of California, Riverside College of Engineering-Center for Environmental Research and Technology are currently developing a comprehensive modal emissions model for light-duty vehicles under the sponsorship of the National Cooperative Highway Research Program (NCHRP Project 25-11). The overall objective of this project is to develop and verify a modal-emissions model that accurately reflects impacts of speed, engine-load, and start conditions on emissions under a comprehensive variety of driving characteristics and vehicle technologies. The model is comprehensive in the sense that it will be able to predict emissions for a wide variety of Light Duty Vehicles (LDVs) in various states of condition (e.g., properly functioning, deteriorated, malfunctioning).

In this project, approximately 300 in-use vehicles are being randomly recruited and tested on a single roll 48" dynamometer over three different driving cycles: 1) the FTP (Federal Test Procedure); 2) the high-speed US06 cycle [EPA, 1995]; and 3) a specially designed modal emission cycle (MEC01, described in [Barth et al., 1997]). For each of these cycles, second-by-second engine-out and tailpipe carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NOx), and hydrocarbon (HC) emissions data are being collected. Based on these measured emissions data, a modal emissions model is being developed to estimate vehicle emissions under several operating modes.

Details on the comprehensive modal emissions model are given elsewhere (see, e.g., [Barth et al., 1996; Barth et al., 1997; An et al., 1997]), only a brief description is given here. The model employs a physical, power-demand modal modeling approach based on a parameterized analytical representation of emissions production. In such a physical model, the entire emissions process is broken down into different components that correspond to physical phenomena associated with vehicle operation and emissions production. Each component is then modeled as an analytical representation consisting of various parameters that are characteristic of the process. These parameters vary according to the vehicle type, engine, and emission technology. The majority of these parameters are stated as specifications by the vehicle manufacturers, and are readily available (e.g., vehicle mass, engine size, aerodynamic drag coefficient, etc.). Other key parameters relating to vehicle operation and emissions production are deduced from the comprehensive testing program. The model handles operating conditions of cold start, stoichiometric driving, power enrichment, and enleanment conditions. The later three conditions represent hot-stabilized operation.

It is important to note that for this preliminary AHS emissions and energy consumption case study, only a single LDV type is modeled (specifically, a 1996 Buick LeSabre). In future AHS emission analyses, better characterization of the vehicle fleet will be performed.

2.3 Freeway Congestion Cycles

In order to compare AHS emissions and fuel consumption to non-automated traffic, we make use of the US EPA's latest facility-specific congestion cycles. Under contract to the US EPA, Sierra Research [Sierra Research, 1997] has created several facility-specific congestion cycles based on matching speed-acceleration frequency distributions for a wide range of roadway types and congestion levels. These cycles have been developed based on a large amount of "chase car" and instrumented vehicle data collected in the cities of Spokane, Baltimore, Atlanta, and Los Angeles. The congestion level was recorded as different "Levels-Of-Service" (LOS) values based on the LOS measures developed by the Transportation Research Board (TRB, see [TRB, 1994]). FHWA currently employs these LOS measures for congestion. For freeways (i.e., non-interrupted flow), LOS is a function of both average vehicle speed and traffic flow rate. Primarily due to inter-vehicle interaction at higher levels of congestion (corresponding to LOS values of B, C, D, E, and F), vehicles will have substantially different velocity profiles under different LOS conditions. Under LOS A, vehicles will typically travel near the highway's free flow speed, with little acceleration/deceleration perturbations. As LOS conditions get progressively worse (i.e., LOS B, C, D, E, and F), vehicles will encounter lower average speeds with a greater number of acceleration/deceleration events.

Six driving cycles have been developed for freeway driving, ranging from high-speed driving (LOS A+, where vehicles have little or no interaction with other vehicles) to driving in near gridlock conditions (LOS F-). These cycles range from 4 to 12 minutes in length and were constructed to optimally match the observed speed-acceleration and specific power frequency distributions of the on-road vehicle data [Sierra Research, 1997]. These cycles are shown in Figure 1.

3 METHODOLOGY

The modal emission model calibrated to 1996 Buick LeSabre has been applied in several different fashions for this AHS analysis:

Application to Non-Automated Traffic

The six cycles described in Section 2.3 were used as input to the modal emission model to determine integrated emissions of CO, HC, NOx, and fuel consumption (all given in grams/mile). For all cases, it was assumed that all of the vehicles are in hot-stabilized operating condition (i.e., no cold start).

Application to Ideal Constant-Speed Traffic

Using the modal emissions model, emissions and fuel consumption were also predicted for ideal, constant-speed traffic flow. Several constant-speed "cycles" were created at 10, 20, 30, 40, 50, 60, and 70 mph. As before, integrated emissions of CO, HC, NOx, and fuel consumption were determined in grams per mile.

Application to the AHS microsimulation

The AHS microsimulation was run under different conditions of travel demand for the single lane Katy freeway as specified in [Antoniotti et al., 1997]. After the simulation was initiated, each run was allowed to "stabilize" for several simulation-minutes so that the average traffic speed was reasonably constant. At that point, the trajectories of every vehicle in the microsimulation were acquired (second-by-second velocity and acceleration). The modal emission model was then applied to these acquired trajectories and average fleet emissions and fuel consumption (in grams/mile) were calculated.

Simulation runs were performed for two cases:

1) an AHS *cooperative* scenario (described in [Antoniotti et al., 1997]) where vehicles coordinate their activities with each other, even when they are not within each other's sensor ranges. In this scenario, vehicles act as free agents, cooperating together for smooth merging and traffic flow. For this case, vehicles followed each other autonomously with a specified desired time headway of 1 second.
2) an AHS *platoon* scenario, where vehicles coordinate their activities as before, but also can group themselves into platoons for greater capacity. The intra-platoon spacings were set to 5 meters.

In order to account for the aerodynamic drag benefit when platooning, the modal emissions model assumed a near-constant spacing of 5 meters, and appropriately reduced the load (and subsequently emissions and fuel consumption) for the reported percentage of vehicles platooning at any point in time.

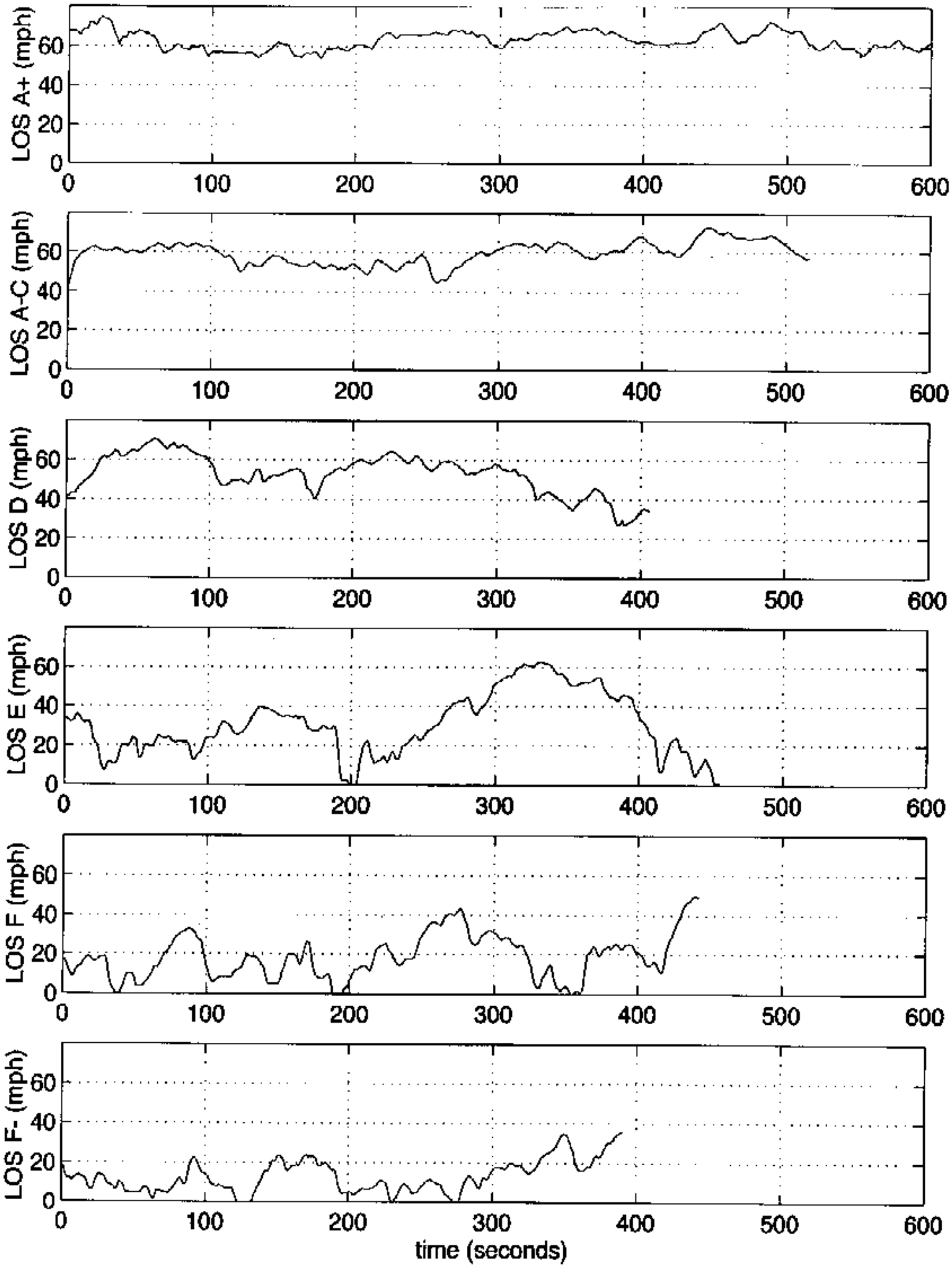


Figure 1. Freeway congestion cycles.

4 RESULTS

In Figure 2, fuel consumption per unit distance (given in grams per mile) per vehicle is shown as a function of average vehicle speed for the previously described scenarios of non-automated traffic, ideal constant-speed traffic, and AHS microsimulation. The solid line represents the non-automated traffic scenario, where the data points represent the average fuel consumption for the different congestion cycles described in Section 2.3. The dashed line represents the ideal constant-speed scenario (i.e., traffic without any acceleration/deceleration events) and represents the lower limit of emissions for the vehicle at different constant speeds. Results for the two AHS scenarios (cooperative and cooperative-platooned) are shown to lie between the ideal minimum and the non-automated traffic under light congestion. The platoon-based AHS has lower fuel consumption due to aerodynamic drag reduction when vehicles operate at close spacings.

In Figures 3, 4, and 5, HC, CO, and NOx emissions (given in grams/mile) are shown in a similar fashion. In these figures, the non-automated plots take on the typical parabolic shape of an emissions speed correction factor curve. This parabolic shape (high on both ends, low in the middle) comes about due to two factors. At low speeds, a vehicle has relatively low grams/second emission rate, however because it spends more time on the roadway for a given unit distance, it emits for a longer period of time (i.e., its grams/mile rate is higher). At high speeds, much greater loads are placed on the engine, drastically increasing the grams/second emission rate. The vehicle spends less time on the roadway for the given unit distance, but the increased grams/second rate overwhelms that factor. Emissions (in grams/mile) are typically lowest at medium speeds (i.e., 30 to 50 mph). Because fuel-consumption is not as sensitive to higher speeds as emissions, it only has a moderate increase at the high-end.

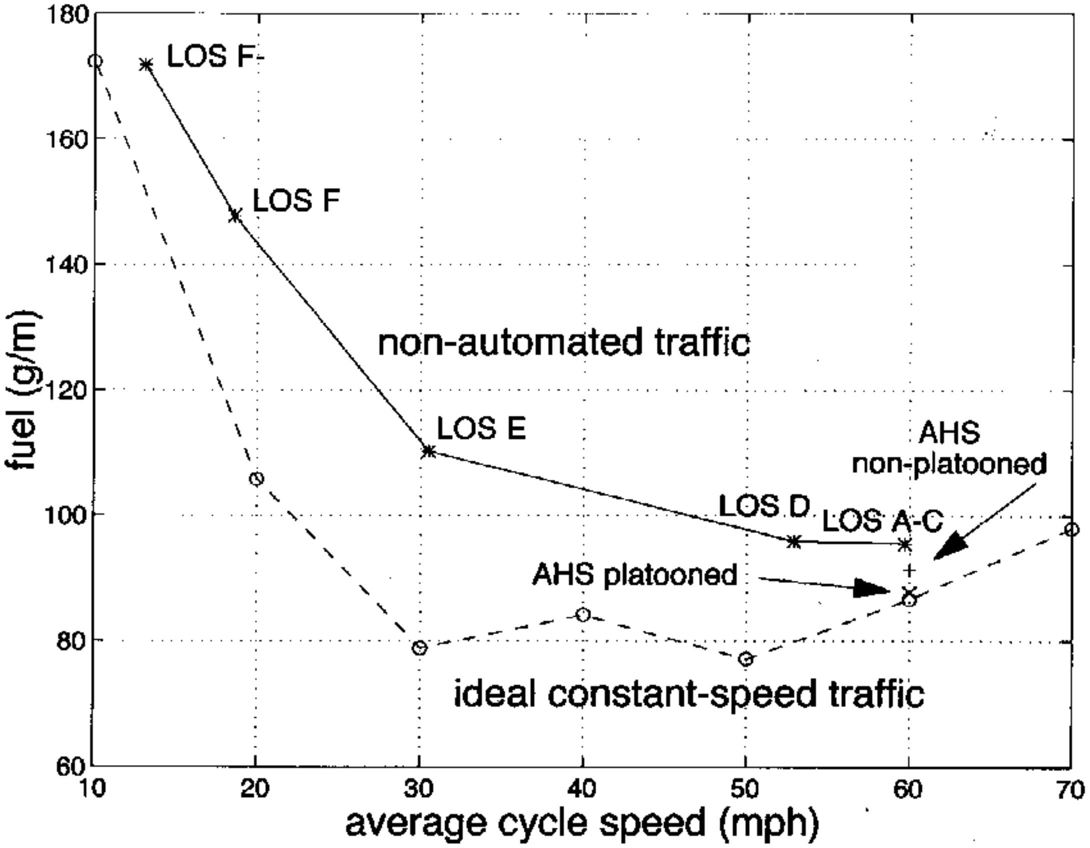


Figure 2. Fuel consumption versus average cycle speed.

It is interesting to note that the average vehicle HC and CO emissions for the LOS A-C case take a sharp turn upwards due to the emissions sensitivity to higher speeds. At the LOS A-C level, vehicles travel at high speeds with a limited amount of congestion-related acceleration/deceleration transients. Preliminary analysis has shown that the primary reason for higher HC and CO emission rates at higher speeds is due to very short enrichment events that occur when a vehicle only slightly accelerates at high speeds. For example, the modeled 1996 Buick LeSabre goes into enrichment only for 2 seconds for the LOS A-C cycle (total length is 516 seconds; vehicle goes enriched 0.3% of the time). As congestion increases, the average speed decreases, with greater acceleration/deceleration transients (see Figure 1). However, the load placed on the engine is not as great as it is at high speeds, even though the vehicle undergoes greater acceleration events.

Given the travel demand level for the Katy Freeway corridor case study, congestion will remain at the LOS F- level if no improvements are made. In Figures 6 - 9, we compare the fuel consumption and emissions for this LOS F- condition against other scenarios. If additional non-automated lanes are added to this corridor, congestion may return to the LOS A level, but the average HC and NOx emissions will remain approximately the same (average CO emissions may increase). The fuel consumption will be reduced to approximately 55% of the baseline non-automated case (a saving of 45%).

If automation in introduced into the traffic system, traffic will flow more smoothly, reducing fuel consumption by 47% (compared to LOS F-), HC emissions by 19%, CO emissions by 33% (compared to LOS A), and NOx by 5%. If vehicles are capable of platooning, the fuel consumption is reduced by 49%, HC emissions by 23%, CO emissions by 36% (compared to LOS A), and NOx emissions by 10%. For comparison, the idealized constant-speed traffic case is also shown.

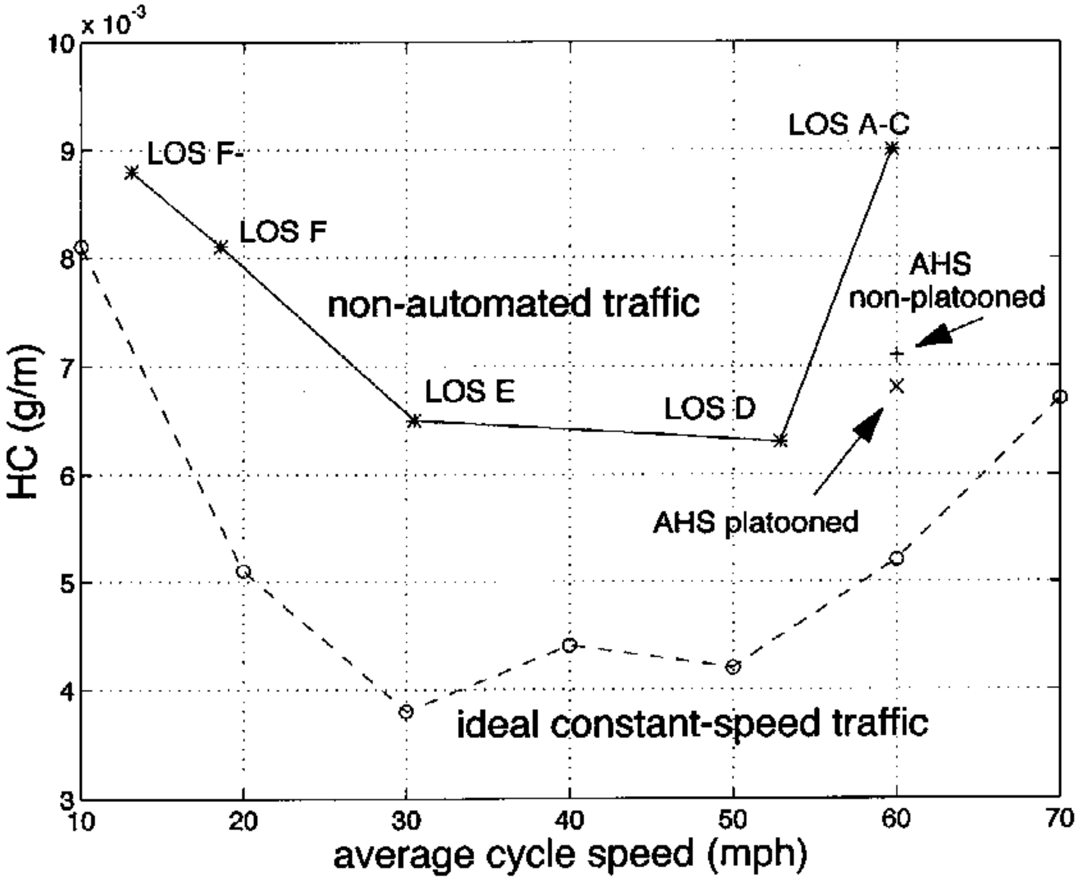


Figure 3. Average vehicle hydrocarbon emissions versus average cycle speed.

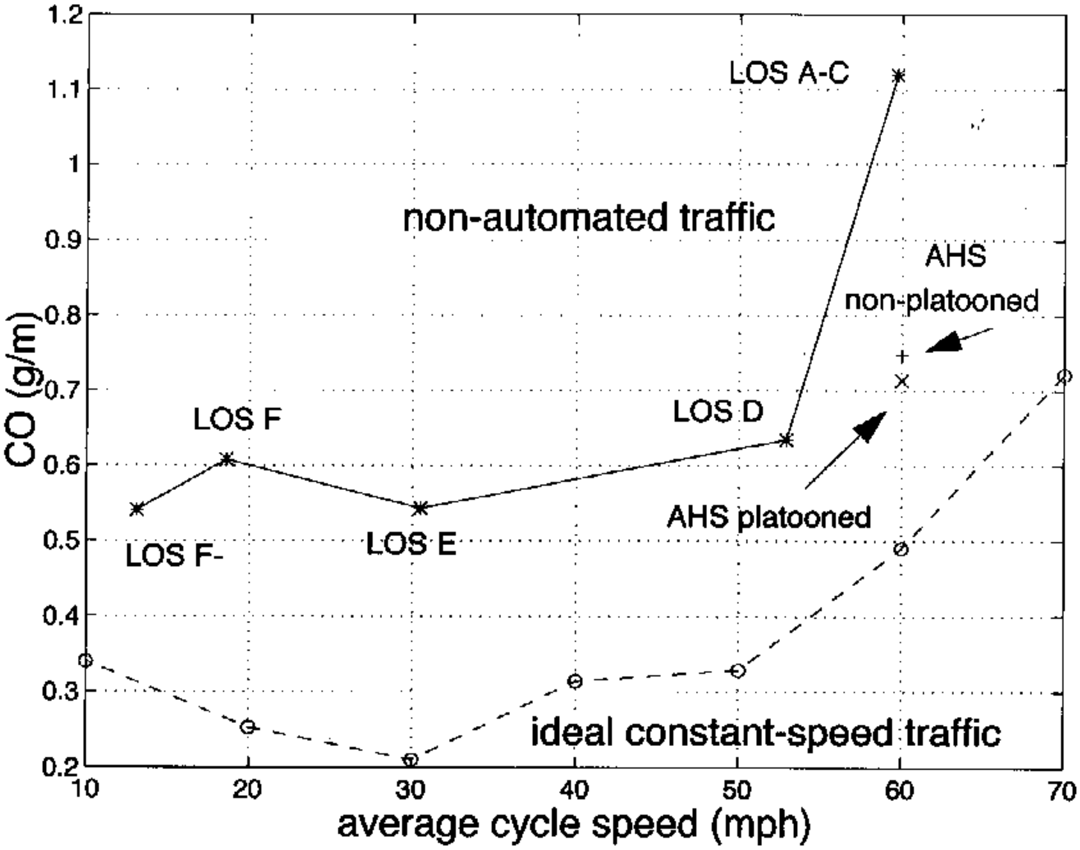


Figure 4. Average vehicle carbon monoxide emissions versus average cycle speed.

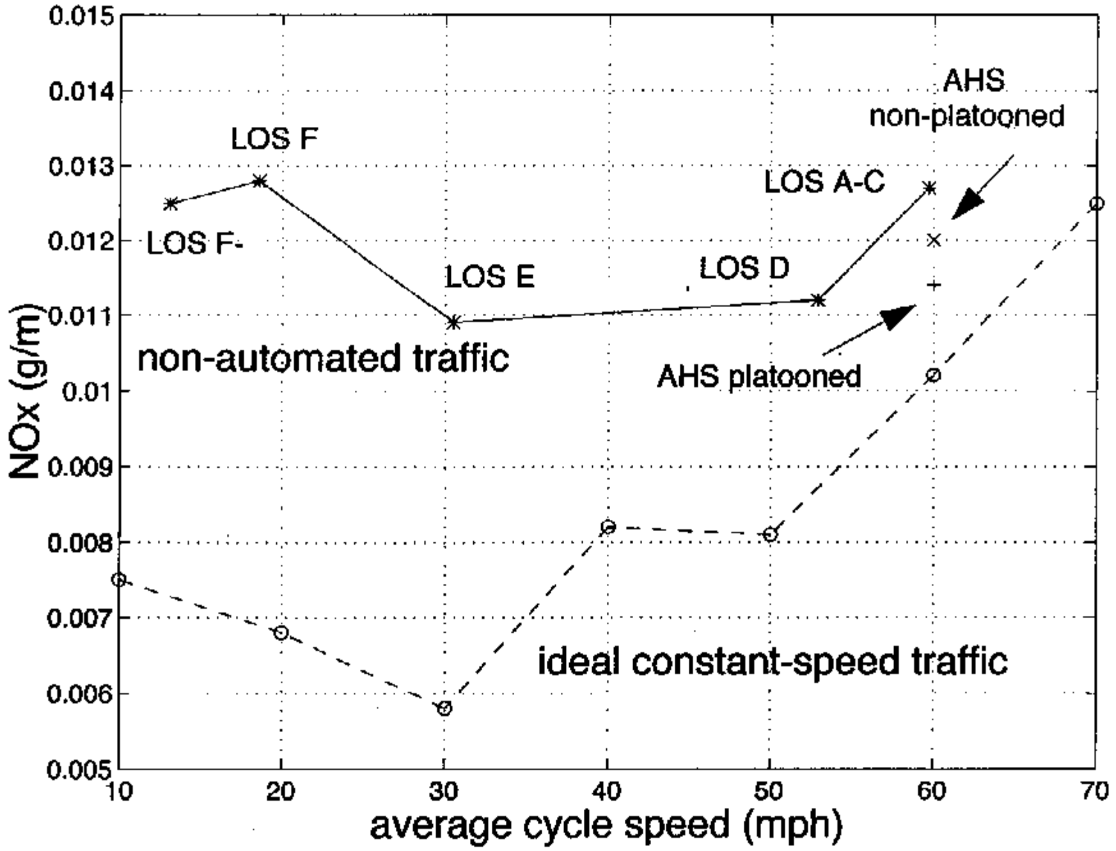


Figure 5. Average vehicle oxides of nitrogen emissions versus average cycle speed.

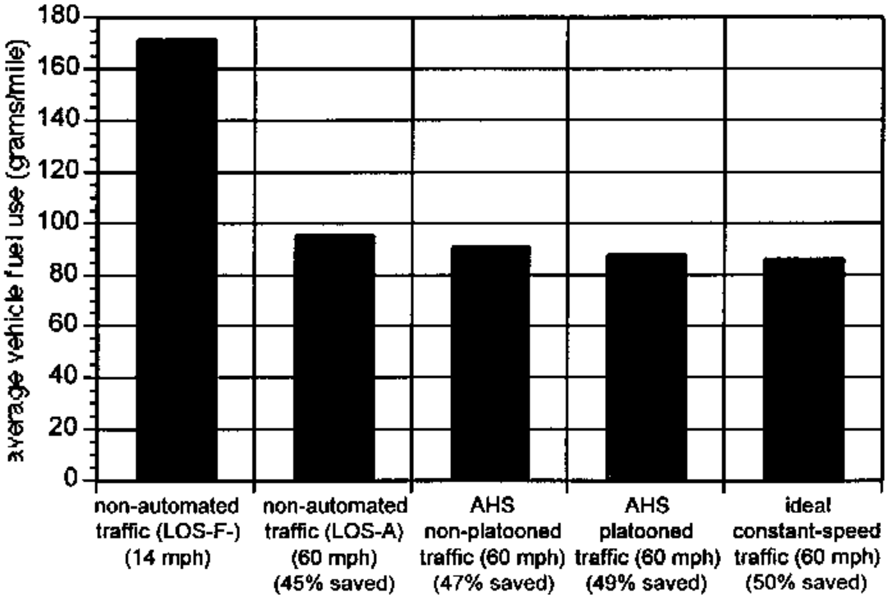


Figure 6. Fuel consumption comparison among various scenarios.

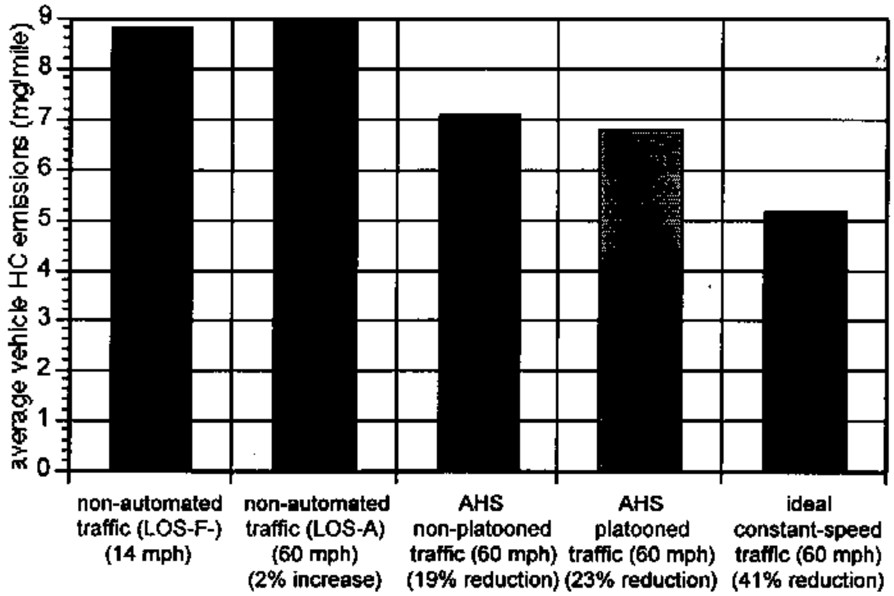


Figure 7. Hydrocarbon emissions comparison among various scenarios.

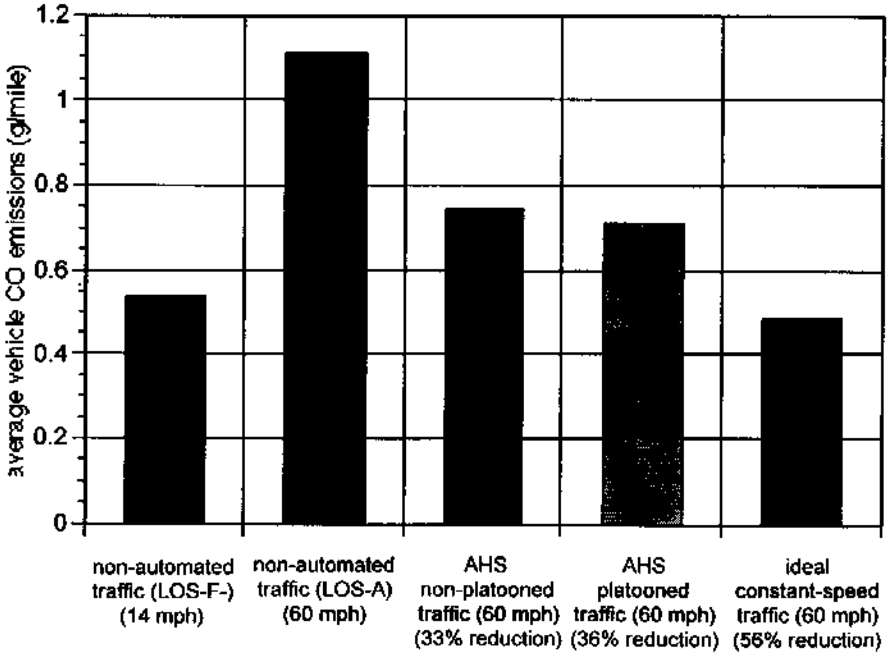


Figure 8. Carbon monoxide emissions comparison among various scenarios.

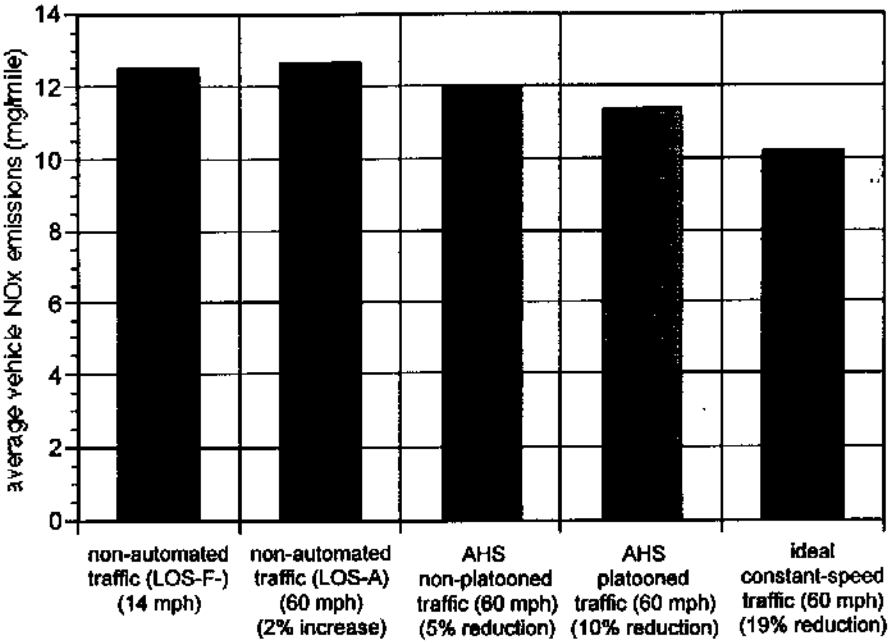


Figure 9. NOx emissions comparison among various scenarios.

It is important to note that these comparisons were made using only a single modeled vehicle. The results of other vehicles may vary greatly depending on numerous factors such as its emissions control strategy, age of the vehicle, emission certification level, etc.

5 CONCLUSIONS AND FUTURE WORK

Based on this preliminary set of comparisons using a single modeled vehicle, we can make the following general conclusions:

- An AHS has slightly lower average fuel consumption than a non-automated highway operating at free-flow, and much lower average fuel consumption than a non-automated highway operating under congested conditions, because of its smoother traffic flow.
- An AHS operating at 60 mph has substantially lower emissions per vehicle-mile traveled than non-automated traffic at the same average speed, because of its smoother traffic flow.
- Vehicles that platoon in an AHS can expect an additional 5 - 15% fuel savings and emission reduction due to the aerodynamic drafting effect, which is dependent on the intra-platoon vehicle spacings.

When the comprehensive modal emission model described in Section 2.2 is complete, it will be possible to perform the same comparisons using many different types of vehicles, including "composite" vehicles that represent specific vehicle/technology categories or even an average fleet. Also, the platooning analysis can be further refined, using variable vehicle spacings as part of the overall AHS strategy.

Another area of research to explore is to change the operating parameters of the AHS to minimize energy consumption and emissions, while still maintaining a high degree of safety and capacity.

6 REFERENCES

An, F., M. Barth, M. Ross, and J. Norbeck. 1997. "The development of a comprehensive modal emissions model: operating under hot-stabilized conditions", to appear, *Transportation Research Record* No. 1587, Transportation Research Board, National Academy of Science, October 1997.

Antoniotti, M., et al., "Microsimulation Analysis of Multiple Merge Junctions under Different ITS/AHS Policies", to appear, *IEEE Conference on Intelligent Transportation Systems*, Boston, MA, November 1997.

Barth, M., et al., "Modal Emissions Modeling: A Physical Approach", *Transportation Research Record* No. 1520, pp. 81-88, Transportation Research Board, National Academy of Science, August 1996.

Barth, M., T. Younglove, T. Wenzel, G. Scora, F. An, M. Ross, and J. Norbeck. "Analysis of modal emissions from a diverse in-use vehicle fleet", to appear, *Transportation Research Record* No. 1587, Transportation Research Board, National Academy of Science, October 1997.

Deshpande, A. *AHS Components in SHIFT.* California PATH Research Report, 1997a. http://www.path.berkeley.edu/smart-ahs

Deshpande, A. et al., *SHIFT Programming Language and Run-Time System for Dynamic Networks of Hybrid Automata*, California PATH Research Report, UCB-ITS-PRR-97-7, 1997b. http://www.path.berkeley.edu/shift

Sierra Research, "Development of Speed Correction Cycles", US EPA Document Number M6.SPD.001, June, 1997.

TRB, *Highway Capacity Manual - Special Report 209*, Transportation Research Board, National Academy of Science, 1994.

US EPA, "Support Document to the Proposed Regulations for Revisions to the Federal Test Procedure", US EPA technical report, Office of Air and Radiation, 1995.

RURAL AUTOMATED HIGHWAY SYSTEMS CASE STUDY

Greater Yellowstone Rural ITS Corridor

FINAL REPORT

By

Russ Gomke
Research Associate

Of the

Western Transportation Institute
Civil Engineering Department
Montana State University - Bozeman

Prepared for the

STATE OF MONTANA
DEPARTMENT OF TRANSPORTATION
RESEARCH AND DEVELOPMENT PROGRAM

In cooperation with the

NATIONAL AUTOMATED HIGHWAY SYSTEM CONSORTIUM,
CALIFORNIA DEPARTMENT OF TRANSPORTATION, AND
LOCKHEED-MARTIN, INCORPORATED

January 1998

DISCLAIMER

The opinions, findings and conclusions expressed in this publication are those of the author and not necessarily those of the National Automated Highway Systems Consortium, California Department of Transportation, Lockheed-Martin, Incorporated, Idaho Department of Transportation, Montana Department of Transportation, Wyoming Department of Transportation, or Yellowstone National Park. Alternative accessible formats of this document will be provided upon request.

ACKNOWLEDGMENTS

This report has been prepared in cooperation with Caltrans, MDT, IDT and WyDT. It was through the cooperation of the following individuals that the deliverables for this project were made possible.

- Jim Gaulke, Research Engineer - Wyoming Department of Transportation;
- Jim Richard, District Engineer - Idaho Department of Transportation;
- Dennis Hult, ITS Program Coordinator - Montana Department of Transportation; and
- Bill Cottrill, Traffic Engineer - National Park Service, Denver Office.

These agencies provided WTI with relevant information on the corridor to allow an accurate evaluation.

EXECUTIVE SUMMARY

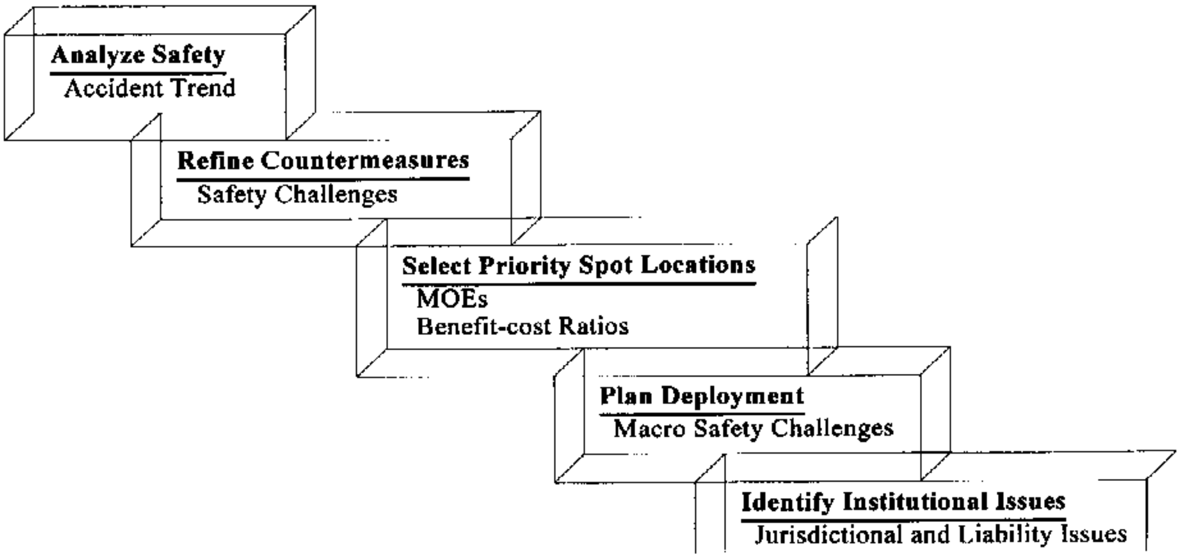
Introduction

In cooperation with the National Automated Highway System Consortium (NAHSC), case studies are being conducted on existing transportation corridors to determine the feasibility of AHS. Initial activities by the NAHSC have focused on urbanized areas. However, a need exists to investigate the applicability of advanced transportation technology and AHS in rural settings. AHS applications have primarily focused on problems associated with urban traffic congestion; secondary considerations have related to safety, air quality and energy conservation. These areas are also of concern to the rural transportation provider; however, the primary focus of the rural transportation provider is improved safety.

The Greater Yellowstone Rural Intelligent Transportation Systems (GYRITS) corridor comprises a loop roadway system traversing through Wyoming, Yellowstone National Park (YNP) and Grand Teton National Park, connecting Bozeman, Montana with Idaho Falls, Idaho. The combination of varied, often undesirable driving conditions with wildlife, unfamiliar drivers, a diverse traffic stream and a lack of communication infrastructure indicates an immediate and growing need for increased focus on safety. The problems experienced in the GYRITS corridor are common to many rural environments. Hence, it is an ideal location to showcase field operational demonstrations of advanced technologies.

The intent of this study was to recommend applications and consider implications of Automated Highway Systems (AHS) in a rural environment. This study focused on developing an applicable AHS for the GYRITS corridor that would ultimately increase safety and improve operation.

Figure I - Project Methodology



Rural AHS Vision

The system conceived for this project and used in the benefit-cost analysis assumes four incremental service levels: (1) Spot Application: locations where accidents are statistically over-represented will be implemented with technology to warning the driver of hazards via the infrastructure and dynamic messages; (2) Information Assistance: dangers warnings will be relayed to the driver via the vehicle; (3) Control Assistance: the vehicle warnings will be relayed to the driver and in the event the driver does not respond the vehicle will temporally assume control; and (4) Full Automation: in this instance the vehicle is fully autonomous.

Information Assistance, Control Assistance and Full Automation have three primary functions that assist with collision avoidance. These three functions are (1) longitudinal collision warning/guidance, (2) lateral collision warning/guidance and (3) intersection collision warning.

Institutional Issues

Challenges that may impede the deployment of AHS are institutional in nature. These include legal implications, public acceptance, procurement procedures, funding, operation and maintenance responsibility, privacy issues, environmental impacts, societal issues and jurisdictional coordination. Some public agencies are hesitant to get involved; the envisioned AHS system may be perceived as too futuristic. This is especially true in rural environments where agencies typically mitigate roadway problems using "low-tech, low-risk" solutions. Involving the rural transportation providers early in the planning, testing and evaluation phases will help promote the effectiveness of AHS, develop champions and achieve user buy-in. An incremental deployment strategy will help demonstrate early, visible, quantifiable safety benefits for potential users.

Accident Analysis

Accident rates were determined for each half-mile segment using a floating referencing system. Specifically, rates were determined on a half-mile basis, advancing along the route every tenth-mile. Additionally, severity rates were determined for each floating half-mile segment. Based on these rates, potential atypical accident locations were chosen for further study. These locations were analyzed to determine what, if any, accident trend(s) existed. Segments exhibiting trends were thought to have the best chance of maximizing benefits from AHS applications (see Table i).

Accident data, collected from Idaho, Montana, Wyoming and Yellowstone National Park, was standardized and assimilated to allow for spatial representation using Geographic Information Systems (GIS). Accident data was depicted both at spot locations and continuously along the roadway depending on the frequency and characteristics of the accidents. Before examining the accidents to determine geographic areas of focus, the corridor was separated into 18 major segments based on: changes in geometric alignment, city limits, mountainous areas, and state lines. Although state lines were assumed to be transparent, segments were broken along state lines for ease of analysis. The segment types included rural-flat, rural-mountainous, urban (within city limits), suburban (directly outside city limits until change in cross section), and semi-mountainous (only in Yellowstone National Park). The number of accidents for each accident trend, identified previously for half-mile locations, was determined for each of the 18 major segments. A geographic area was identified for focus if the area possessed two of the three following criteria: (1) a high percentage of the accidents in the area had a common trend; (2) a high number of the accidents in the area had the same common trend; and/or (3) half-mile atypical locations existed with the same trend (see Table ii).

Table i - Atypical Spot Locations

Milepost Range	Total Accidents	Total Trend	Milepost Range	Total Accidents	Total Trend
Montana U.S. Highway 191					
9.900-10.011	18	13	10.000-11.000	20	17
28.000-28.900	13	9	59.000-60.000	11	8
61.000-61.400	12	7			
Montana U.S. Highway 20					
1.000-2.000	10	6	8.619-8.946	11	7
Idaho U.S. Highway 20					
311.000-312.000	22	14	317.000-318.000	42	29
328.000-329.000	14	6	338.000-339.000	17	11
326.000	12	4	405.000-406.000	8	6
Idaho U.S. Highway 26					
335.000-336.000	23	12	336.000-337.000	34	24
338.000-339.000	16	11			
Wyoming U.S. Highway 89					
160.000-161.000	11	8	167.000-168.000	12	5
185.000-186.000	18	11	189.000-190.000	12	6
184.400-184.600	8	8	188.000-188.690	6	6
127.000-128.000	22	16			
Yellowstone National Park Highway 89					
21.034-21.834	18	9	21.334-21.834	5	5
43.122-43.672	9	5	66.180-67.780	20	9

In addition to considering spot and regional locations for the entire accident sample, two smaller groups were separated out for further analysis: (1) commercial vehicles and (2) in-state/out-of-

Table ii – Atypical Regional Segments

Milepost Range	Road Type	Total Accidents
Yellowstone Park U.S. Highway 89		
0.000-93.446	Park	426
Wyoming U.S. Highway 26		
0.000-2.370	Mountainous	7
Montana and Yellowstone Park U.S. Highway 191		
0.000-10.835	Level	88
10.836-66.826	Mountainous	276
66.827-81.903	Level	98
Idaho U.S. Highway 20		
308.717-353.050	Level Suburban	271
353.051-401.300	Level	117
401.301-406.300	Mountainous	18
Montana U.S. Highway 20		
0.000-3.000	Level	27
3.001-9.397	Mountainous	39
Idaho U.S. Highway 26		
335.255-338.069	Level Suburban	64
338.070-375.538	Level	134
375.539-402.500	Mountainous	63
Montana U.S. Highway 89		
0.000-51.812	Level	112
51.813-53.068	Level Suburban	44
Wyoming U.S. Highway 89		
118.32-152.090	Mountainous	304
155.211-165.000	Level	86
165.001-211.620	Mountainous	245

Table iii - Heavy Vehicle Accident Rates

Accident Type	Total Accidents	Accident Rate (R/MVMT)	National Average	Difference
Property Damage Only	54	97.39	75.00	+22.39
Injury Accidents	69	40.73	47.00	-6.27
Fatal Accidents	8	4.72	2.50	+2.22

state drivers. Targeting smaller groups within this sample may actually help to accelerate NAHSC's near-term deployment goals.

Heavy vehicles were involved in approximately 10 percent of all accidents within the corridor, resulting in 28 percent of the fatality accidents and five percent of injury and property damage only accidents (see Table iii). Nationally, heavy vehicles accounted for 12 percent of all traffic fatalities and three percent of all accidents resulting in injury and property damage only. [10] The aforementioned statistics, which indicate that heavy vehicle accidents in the GYRITS corridor exceed the national averages, support the notion that a safety problem exists related to commercial vehicles in the corridor. However, the low frequency of accidents made it statistically difficult to sort heavy vehicle related accidents into trends. Instead, heavy vehicle accident rates appeared to be distributed randomly through mountainous and flat regions; indicating driver error may be the primary problem, while alignment and terrain are secondary contributors.

Traveler origin information was examined to determine if accidents within the corridor were a product of unfamiliar out-of-state travelers or local residents. It was hypothesized that this information would be helpful in determining target groups for early operational testing and evaluation. Tables iv and v describe the differences among in-state and out-of-state crash involvement rates for each geographic area of focus. The accident data from Idaho and Wyoming allowed for the determination of the causing party. Hence, each accident could be traced to a single in-state or out-of-state party; the proportion of in-state travelers and out-of-state travelers involved in an accident summed to one. Montana's accident data did not reflect causing party information but rather accident involvement. Hence, the proportion of in-state travelers and out-of-state travelers summed to greater than one.

Benefit-cost Analysis

Table vi presents realistic benefit-cost ratios based on predicted vehicle fleet market penetration as indicated in the deployment vision. Note the importance of vehicle fleet penetration and AHS service level on benefit-cost ratios for full-scale regional deployment. Many regions were deemed inappropriate for the installation of AHS infrastructure due to low benefit-cost ratios, likely resulting from the relatively low vehicle fleet market penetration. Lower accident reduction factors also resulted in lower benefit-cost ratios for the Information Assistance service level.

Table iv - Origin of Vehicle Causing Accident

State	Route	Segment	% In-state	% Out-of-state
Wyoming	89	total corridor section	51	49
	89	158.82 to 204.85	41	59
Idaho	20	total corridor section	68	32
	20	308.717 to 353.05	84	16
	20	353.06 to 406.30	37	63
	26	total corridor section	73	27

Table v - Origin of Vehicles Involved in Accident

State	Route	Segment	% In-state	% Out-of-state
Montana	20	total corridor section	65	94
	89	total corridor section	123	36
	191	total corridor section	71	48
	191	0 to 10.493	49	56
	191	10.494 to 81.903	60	36

Next Steps

This section recommends several areas for possible early field operational testing (FOT)with low-level AHS technology. The intent of the recommended FOTs is to provide the driver with more information and more time to react. It is hypothesized that this additional information and time will help the driver avoid many collisions. Through the benefit-cost analysis, sites with the greatest potential were selected for AHS technology deployment in continuing efforts. The candidate sites include:

Friction/Ice Detection and Warning System

(Montana U.S. Highway 191, milepost 9.900 to 10.011 and 10.000 to 11.000;

Table vi - Benefit-cost Ratio Based on Deployment Vision

	Benefit-cost Ratios	
Location	**Information Assistance** 20% penetration after 10 years	**Control Assistance** 50% penetration after 20 years
Montana U.S. Highway 191		
MP 0.000 – 10.835	3:1	23:1
MP 10.836 – 66.826	2:1	17:1
MP 66.827 – 81.903	4:1	34:1
Montana U.S. Highway 89		
MP 0.000 – 51.812	0.007:1	0.07:1
MP 51.813 – 53.068	5:1	37:1
Montana U.S. Highway 20		
MP 0.000 – 3.000	2:1	14:1
MP 3.001 – 9.397	0.02:1	0.2:1
Idaho U.S. Highway 20		
MP 308.717 – 353.050	7:1	36:1
MP 353.051 – 401.300	3:1	32:1
MP 401.301 – 406.300	0.7:1	5:1
Idaho U.S. Highway 26		
MP 335.255 – 338.069	20:1	137:1
MP 338.070 – 375.538	2:1	17:1
MP 375.539 – 402.500	1:1	10:1
Wyoming U.S. Highway 26		
MP 0.000 – 2.370	0.2:1	2:1
Wyoming U.S. Highway 89		
MP 118.320 – 152.090	4:1	34:1
MP 155.211 – 165.000	4:1	36:1
MP 165.000 – 211.620	1:1	9:1
Yellowstone National Park U.S. Highway 89		
MP 0.000 – 93.446	1:1	9:1

Intersection Crossing Detection

- Idaho U.S. Highway 26, milepost 336.000 to 337.000;
- Idaho U.S. Highway 20, milepost 317.000 to 318.000 and 311.000 to 312.000;

Animal-Vehicle Collision Avoidance

- Wyoming U.S. Highway 89, milepost 160.000 to 161.000 and 189.000 to 190.000;

Horizontal Curve Speed Advisory

- Wyoming U.S. Highway 89, milepost 127.000 to 128.000.

These sites were estimated to have the greatest potential for improving safety in the GYRITS corridor through the deployment of AHS. However, before any of the above sites are designated as FOTs, further investigation of the police accident records, the site, and the transportation providers' perspectives needs to occur.

TABLE OF CONTENTS

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The intent of this study was to recommend applications and consider implications of Automated Highway Systems (AHS) in a rural environment. This study focused on developing an applicable AHS for the Greater Yellowstone Rural Intelligent Transportation Systems (GYRITS) corridor (see Appendix A) that would ultimately increase safety and improve operation of the GYRITS corridor.

Initial activities by the National Automated Highway System Consortium (NAHSC) have focused on urbanized areas (see Figure 1). However, a need exists to investigate the applicability of advanced transportation technology and AHS in rural settings. AHS applications have primarily focused on problems associated with urban traffic congestion; secondary considerations have related to safety, air quality and energy conservation. These areas are also of concern to the rural transportation provider; however, the primary focus of the rural transportation provider is improved safety.

There are many safety benefits potentially realized through the application of AHS technologies to the existing transportation infrastructure, particularly through advanced driver warnings. It is estimated that if a driver were warned of an impending collision one half second earlier, 50 percent of rear-end and cross-road crashes and 30 percent of head-on crashes could be avoided. If an additional second is provided to the driver, 90 percent of all crashes could be avoided. Experts estimate that advanced transportation technologies will potentially save 11,500 lives, 442,000 injuries, and $22 billion in property damage nationally by 2010. [2]

The selected corridor represents a vital transportation link for the trucking industry, connecting the Northwest and Canada with Intermountain and Southwest markets. Approximately 20 percent of the traffic traversing the GYRITS corridor is commercial. [3] Commercial vehicles

Figure 1 – Typical AHS Environment

use this route to transport goods between the aforementioned markets and markets within the corridor (e.g., mining, forestry, and agricultural industries). Because much of the corridor is two-lane highway, many dangerous passing situations result involving large trucks, recreational vehicles, tourists and slow-moving farm machinery. Poor sight distance, limited by the winding road and canyon walls, exacerbates the danger.

The corridor presents an environment filled with unique challenges that must be confronted when developing a viable transportation system. The corridor receives about 80 to 90 inches of snow in a typical winter (see Figure 2). Temperatures can reach 65 degrees below zero (Fahrenheit) and a 40 to 50 degree temperature shift from day to night is not unusual. Winter conditions typically last about eight months. However, it has been known to snow in the higher elevations in the summer months.

Figure 2 – Typical Corridor Snowfall

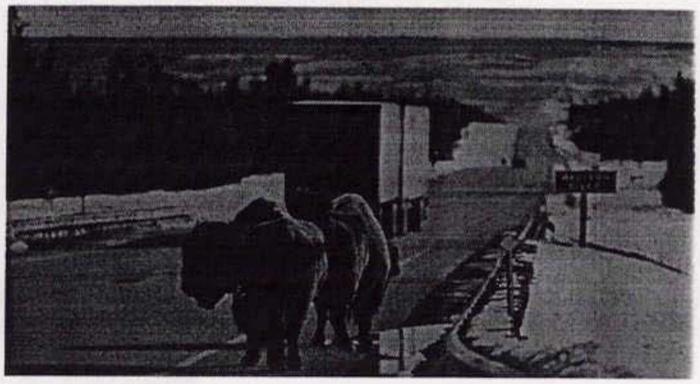


Figure 3 – Potential Animal-vehicle Conflict

The corridor encompasses migration routes and habitat for deer, elk, bison and moose. Periodically, these animals can be found on the roadway, presenting a potential animal-vehicle conflict (see Figure 3). Over a recent three-year period, 367 animal-vehicle collisions were reported. Non-reported animal-vehicle collisions likely increase this number substantially.

Because much of the corridor abuts mountain ranges, many sections of the corridor are not covered by cellular phone service. The canyon walls also preclude the reception of AM or FM radio band signals throughout much of the corridor.

The combination of varied, often undesirable driving conditions with wildlife, unfamiliar drivers, a diverse traffic stream and a lack of communication infrastructure indicates an immediate and growing need for increased focus on safety. The problems experienced in the GYRITS corridor are common to many rural environments. Hence, it is an ideal location to showcase field operational demonstrations of advanced technologies.

Background

In the last couple of decades, the transportation community has seen the emergence of new transportation technologies. Many agencies across the country have implemented and demonstrated the use of advanced transportation technologies but with little or no national coordination, standards or strategic direction. The congressional enactment of the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) restructured the United States Department of Transportation (USDOT) and made provisions for the development of an advanced technology program titled "Intelligent Vehicle-Highway Systems (IVHS). The USDOT was required to develop a national strategic plan and a grant program for the research, development and deployment of advanced transportation technologies. Later IVHS evolved into Intelligent Transportation Systems (ITS). This evolution presented ITS as a *transportation* consortium rather than a *highway* consortium. In 1992, the nation's first strategic plan, outlining the goals and objectives of the development of the national ITS architecture, was developed. [4]

Automated Highway Systems (AHS) reside within one of the three major study areas of ITS. Specifically, AHS is part of the Advanced Vehicle Control and Safety Systems (AVCSS) branch. Figure 4 depicts the three primary study areas of ITS.

Figure 4 - ITS Areas of Focus

ISTEA allocated resources to ITS and mandated an AHS technology feasibility demonstration in 1997, now known as *Demo 97*. To meet this goal, the National Automated Highway Systems Consortium (NAHSC) was created. The National Automated Highway Systems Consortium is a government-industry-academia collaboration working to apply AHS technology to our nation's highways to enhance efficiency and safety. This group led the efforts to meet the 1997 AHS demonstration goal.

The National Automated Highway System Consortium was charged with specifying, developing and demonstrating a prototype Automated Highway System (AHS). The specifications will provide for an evolutionary deployment that can be tailored to meet regional and local transportation needs. The NAHSC evolutionary deployment will: (1) provide for early introduction of vehicle and highway automation technologies to benefit all surface transportation; (2) incorporate public and private stakeholder views; and (3) involve stakeholder decision-making organizations.

Vehicle and highway automation is not new. The concept has been in existence for the last 50 years. As the vehicle has evolved, it has been automated (i.e., electric starters). As early as the 1950s and 1960s, General Motors and RCA experimented and demonstrated automated control of vehicle steering and speed on test tracks using analog vacuum-tube electronics. From the mid-1960s to about 1980, Ohio State University continued AHS research under the sponsorship of the Bureau of Public Roads and its successor, the Federal Highway Administration (FHWA). During this same timeframe, private sector companies such as TRW, Calspan and General Motors also studied AHS issues.

AHS was resurrected in 1986 by the California Department of Transportation (Caltrans) when they organized a conference on "Technology Options for Tomorrow's Transportation. " At this time, Caltrans also founded the Partner for Advanced Transit and Highways (PATH) program. Through PATH, Caltrans was able to promote advanced transportation technologies to meet California's growing need for greater highway capacity. In 1988, an informal working coalition, called Mobility 2000, was formed. Mobility 2000 defined the framework for the national program to develop, deploy and evaluate AHS technology. Mobility 2000 helped lead the development of ITS America, which in turn coordinated, funded and solidified the nation's AHS effort. [5]

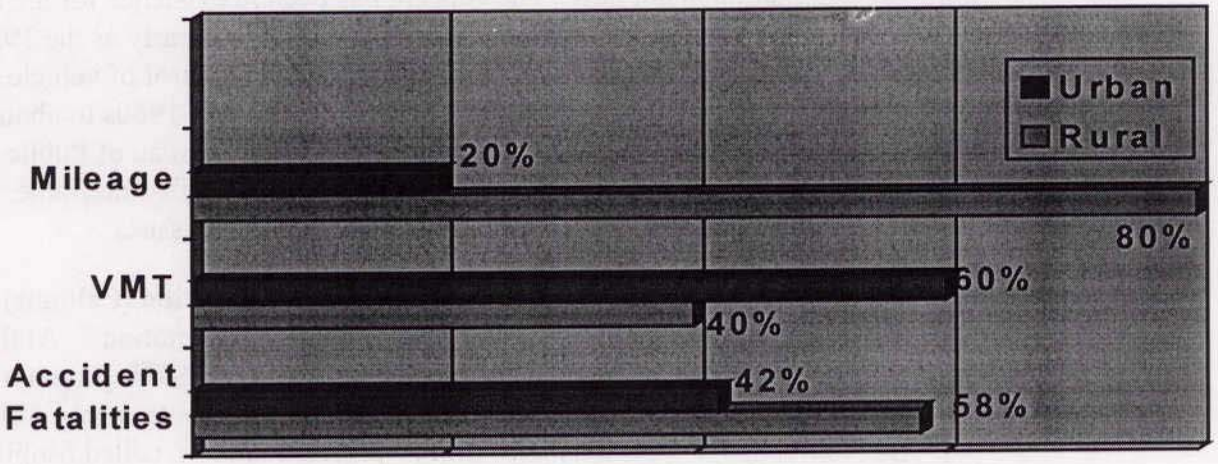
Given that much of the historical advanced transportation technology development came about in response to urban traffic congestion, it is important to understand the different characteristics of the rural and urban environment. As the transportation community is now learning, advanced transportation technologies designed for the urban setting cannot necessarily be mirrored to the rural setting.

Project Goals and Objectives

The goal of this project is to enhance the quality of life for rural residents and travelers through more safe and efficient movements of goods and people using judicious applications of advanced vehicle control technologies. An evolutionary deployment process will be followed, which allows transportation system users and providers to gradually realize the tangible benefits of deploying advanced vehicle control technologies.

The rural community is faced with many unique challenges and opportunities to develop sustainable transportation systems that address the needs of the rural traveler. Some of the rural transportation needs are in vast contrast to the urban transportation needs. Urban problems encompass congestion, mobility air quality, noise, safety, and energy issues. While rural areas struggle with many of these same issues, they have a rural-specific focus that differs. Rural safety issues are the highest priority. Two-lane rural highways are the backbone of the rural transportation network. These roads carry local traffic as well as commercial vehicles, transit vehicles, school buses, recreational traffic and commuter traffic destined for metropolitan areas. Rural roads account for 80 percent of the nation's total mileage. Only 40 percent of the national vehicle-miles traveled occur in rural areas. However, rural areas account for 58 percent of the accidents causing fatalities (see Figure 5). [1]

Figure 5 – Rural and Urban Travel Characteristics Corridor Description



Source: FHWA 1994 "Highway Statistics"

This section provides an overview of rural transportation problems specific to the GYRITS corridor. The focus of this report is safety as it relates to roadway alignment, human factors and weather. Figure 6 portrays the interaction of these elements in the project methodology.

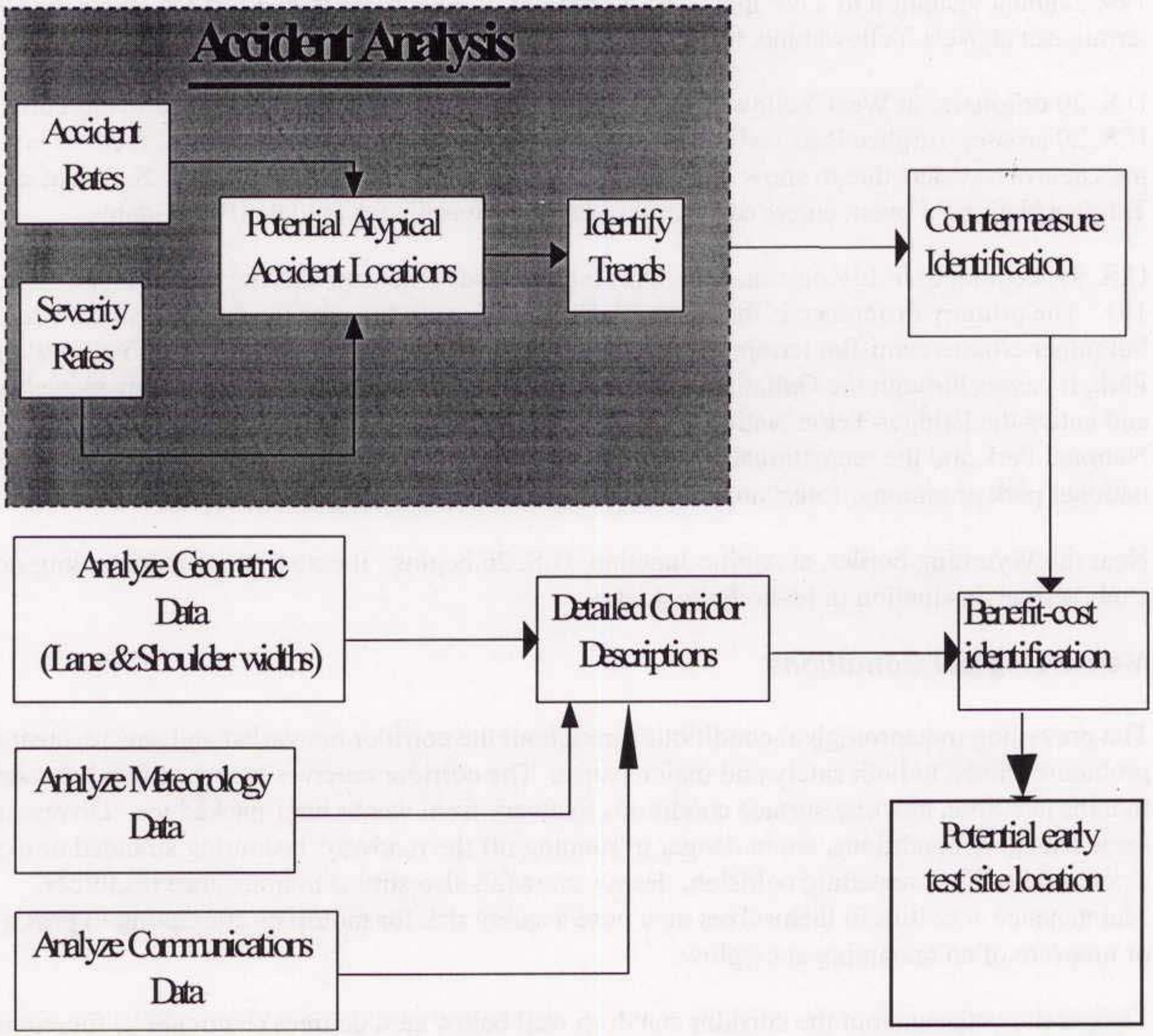


Figure 6 - Project Methodology

Roadways

The corridor contains several roadways; a description of each roadway follows (see Appendix A). In the northern portion of the corridor, U.S. 191 originates in Bozeman, Montana and continues south for fifty miles through the Gallatin Canyon following the Gallatin River. The Gallatin Canyon hosts a wealth of industries such as logging, recreation and tourism. Big Sky Ski and Summer Resort lies 35 miles from Bozeman, Montana, north of U.S. 191, offering abundant summer and winter recreational activities. U.S. 191 also travels through the Gallatin National Forest, which is used extensively by recreational travelers and commercial vehicles supporting the timber industry. Continuing south, U.S. 191 leaves Gallatin Canyon and enters Yellowstone National Park (YNP), home to thousands of elk, deer, moose and bison. YNP is also the location of an increasing number of year-round tourists. Between 1988 and

1992, annual visitation to YNP increased 40 percent, to total more than 3 million. [6] U.S. 191 terminates at West Yellowstone, Montana.

U.S. 20 originates at West Yellowstone, Montana and continues southwesterly to Idaho Falls, Idaho. U.S. 20 crosses Targhee Pass and the Continental Divide at an elevation of 7,072 feet. Every year, this pass delays travelers due to snow and other winter-related driving difficulties. U.S. 20 passes through Targhee National Forest, enters east central Idaho and terminates at Idaho Falls, Idaho.

U.S. 89, beginning in Livingston, Montana (for this study) presents driving conditions similar to U.S. 191. The primary difference is that U.S. 89 does not directly traverse the foothills of Paradise Valley, but rather crosses semi-flat terrain. Approximately 53 miles before U.S. 89 enters Yellowstone National Park, it passes through the Gallatin National Forest. It then continues though Yellowstone National Park and enters the Bridger-Teton National Forest in Wyoming. U.S. 89 continues through Grand Teton National Park and the recreational community of Jackson, Wyoming. U.S. 89 passes through either national park or national forest areas continually to the western Wyoming border.

Near the Wyoming border, at Alpine Junction, U.S. 26 begins. It enters Idaho and continues on to the study's final destination in Idaho Falls, Idaho.

Meteorological Conditions

The prevailing meteorological conditions throughout the corridor are varied and severe, creating problems related to both safety and maintenance. The corridor receives heavy snowfall for several months at a time, creating surface conditions that vary from wet to hard-packed ice. Drivers, unaware these changing conditions, are in danger of running off the roadway, becoming stranded or experiencing a potentially life-threatening collision. Heavy snowfall also strains maintenance resources. Maintenance activities in themselves may pose a safety risk for motorists attempting to pass a snowplow or unaware of an oncoming snowplow.

Temperatures throughout the corridor can drop well below zero degrees (Fahrenheit) for extended periods of time, creating dangerous conditions for motorists who become stranded and are unable to obtain help in a timely manner. Temperature changes of 50 degrees in a single day are not unusual and can create unexpected changes in the road surface conditions.

Windy conditions throughout the corridor are commonplace; gusts can occur unexpectedly creating hazardous situations. Travelers may experience blinding conditions or be forced to take an unfamiliar route due to a wind-related road closure. Wind can also create maintenance concerns in the form of downed signs or debris in the roadway.

The corridor is located in an active seismic region. The seismic activity, coupled with the diverse weather conditions, can create rockslides in the mountainous regions, which can block roadways, strike vehicles or cause vehicular collisions.

Meteorological data was collected at various locations throughout the corridor. The data included average maximum and minimum monthly and yearly temperatures, average annual precipitation, average annual snowfall, design wind speed and seismic zones. Temperature, precipitation and snowf data, from January 1, 1995 to May 31, 1996, was obtained through the Western Regional Climate Center. [7] Design wind speed and seismic zone data was obtained from the 1994 Uniform Building Code. [9] The wind speed values were based on the highest recorded velocity averaged over the time it takes for one mile of air to pass a given location. Seismic zones give a generalized representation of the seismic activity in a region. These zones were ranked from one to four, with four being the most seismically active.

Appendix B provides corridor conditions by route and city. The meteorological data is city-specific. It was assumed that average conditions existed along the route between any two cities.

Communication Infrastructure

Information related to the corridor communication infrastructure was difficult to obtain. However, some facts were determinable:

- cellular service is limited and spotty in some locations;
    - Gallatin Canyon has almost no service, service resumes near West Yellowstone, Montana and continues strongly to Idaho Falls, Idaho
    - Yellowstone National Park has no service
    - U.S. Highway 89 has spotty service throughout
- most areas in the mountainous regions are unable to receive AM or FM band radio signals; and
- most areas rely on some type of hardwire communication system for phone service and power.

Geometric Characteristics

Geometric data collected for the corridor included number of lanes, lane width, length of each segment, physical configuration of each on- and off-ramp, shoulder width, and median width. Much of the corridor consisted of two-lane highways with limited stretches of three- and four-lane highways near major cities. Lane widths were typically 12 feet, except for a 14-foot section along Idaho U.S. Highway 20 from milepost 360.3 to 360.6 (a four-lane segment of highway). In addition, 10-foot auxiliary lanes (mostly left turn lanes) existed in some areas along Wyoming U.S. Highway 89. Paved shoulders varied from zero to 14 feet in width and occasionally had additional unpaved shoulders. Most of the corridor's highways had at-grade intersections with rural collectors and driveways. The only section of roadway that had limited access was U.S. Highway 20 from Idaho Falls, Idaho (milepost 307) to northeast of Idaho Falls, Idaho (approximately milepost 347). Along this segment of roadway, only diamond interchanges existed. Detailed geometric characteristics are provided in Appendix C by milepost.

Project Partners

This study encompassed four principal jurisdictions and numerous local jurisdictions. The four principal jurisdictions and their respective contacts were:

- Montana Department of Transportation - Dennis Hult, ITS Program Coordinator;
- Idaho Department of Transportation – Lance Holmstrom, Senior Transportation Planner;
- Wyoming Department of Transportation – Jim Gaulke, Traffic/Research Engineer; and
- Yellowstone National Park – Jack Roberts, Road Maintenance Supervisor.

These jurisdictional representatives provided the research team with relevant and timely corridor information.

RURAL AHS VISION

Automated Highway Systems (AHS), according to the National Automated Highway Systems Consortium (NAHSC), "will safely operate properly equipped vehicles under automated control on properly equipped lanes." [11] This is the long-term goal of the NAHSC. However, before this goal can be achieved, AHS will have to be incrementally deployed. For AHS to successfully evolve, the systen must present clear and obvious advantages and benefits to the users. If no tangible benefits can be presented, then potential users will likely be unwilling to invest in AHS. This will be particularly true if capital costs are significant. The evolutionary approach will allow users to gradually use and accept AHS technology. With staged successes, users will be able to segmentally experience AHS and develop confidence in AHS safety and reliability.

This incremental approach will permit rural agencies the necessary time to fund and develop advanced technology applications to their transportation system. Generally, rural transportation providers operate with limited resources. Typical characteristics of rural transportation providers are:

- fewer finical resources which to operate;
- more lane-miles per capita to operate and maintain;
- smaller personnel base; and
- wider variety of weather extremes, particularly in the GYRITS corridor.

Rural highways were built to provide high-speed, long-distance travel to all vehicle types. The rural driving environment is unique from the urban driving environment in that rural highways posses the following characteristics:

- longer trips, often through unfamiliar areas;

- 78 percent of rural trips greater than 150 miles are for pleasure [12];
- areas of irregular terrain and road alignment, many times the irregular terrain dictates a less than desirable geometric road design;
- higher traffic speeds coupled with lower traffic volumes;
- longer trips, resulting in inattention, disorientation or fatigued conditions and lengthening driver reaction times;
- more motor vehicle fatalities and higher fatality rates;
- more older drivers, the average age is 45.8 and 18 percent of rural drivers are over 64 years of age [1];
- more severe effects of bad weather;
- more miles of unlit roadways;
- unexpected hazards, such as animals and slow-moving vehicles (farm machinery);
- fewer alternative routes; and
- generally more roadside obstructions and limited clear zones, particularly scenic areas.

For this rural case study, the AHS definition has been tailored to more adequately define the needs of the rural traveler and the evolutionary deployment vision. This case study has defined AHS to be "any application that assists the driver with avoiding any type of impending collision through the use of collision avoidance technology. " This includes any type of audio or visual warning that will provide the driver with a few more seconds of reaction time. This concept best suits the rural environment due to the limited right-of-way and funding. On rural two-lane, limited access highways, dedicated AHS lanes are not a feasible option.

Near-term rural strategies will consist of collision avoidance technologies applied at spot locations where a statistically high number of recurring accidents. Information will be communicated to the driver via roadside dynamic message signs or warning sign beacon mountings.

Long-term rural solutions consist of collision avoidance/driver assistance technology implemented in the vehicle. This will allow infrastructure to vehicle communication and vehicle to vehicle communication, resulting in a "smart" highway system.

The System

The system conceived for this project and used in the benefit-cost analysis assumes four incremental service levels. The service levels are:

1. **Spot Application**: locations where accidents are statistically over-represented will be implemented with technology to warning the driver of hazards via the infrastructure and dynamic messages.

2. **Information Assistance**: dangers warnings will be relayed to the driver via the vehicle.

3. **Control Assistance**: the vehicle warnings will be relayed to the driver and in the event the driver does not respond the vehicle will temporally assume control.

4. **Full Automation**: in this instance the vehicle is fully autonomous.

Information Assistance, Control Assistance and Full Automation have three primary functions that assist with collision avoidance. These three functions are (1) longitudinal collision warning/guidance, (2) lateral collision warning/guidance and (3) intersection collision warning.

Longitudinal Collision Warning/Guidance

The longitudinal warning function is designed to detect when a vehicle is traveling too fast for an oncoming roadway segment. The longitudinal warning system utilizes a vehicle's dynamic state and performance data in conjunction with current pavement condition and roadway geometric alignment data to calculate a maximum safe speed. If a vehicle is exceeding the maximum safe speed, the vehicle will alert the driver of the danger so that he/she may take appropriate action to avoid a crash. In the case of Control Assistance, a vehicle may automatically decelerate to a safe operating speed. The longitudinal warning function also detects slow-moving and fixed objects at a sufficient distance to allow the driver to stop or safely maneuver around the object. Once again, Control Assistance may intervene if a driver does not react or if the distance is to short to permit a driver adequate reaction time.

Lateral Collision Warning/Guidance

The lateral warning system is designed to detect when a vehicle is departing a travel lane. The lateral warning system utilizes data about the dynamic state of a vehicle in conjunction with information about an oncoming roadway geometric alignment to determine if a vehicle's current position and orientation will likely lead to a lane departure. If the likelihood of lane departure exceeds a particular threshold, an audio or visual alarm alerts the driver of danger to avoid an accident. In the case of Control Assistance, a limited amount of steering torque will be applied to reposition the vehicle in the center of the driving lane.

Intersection Collision Warning

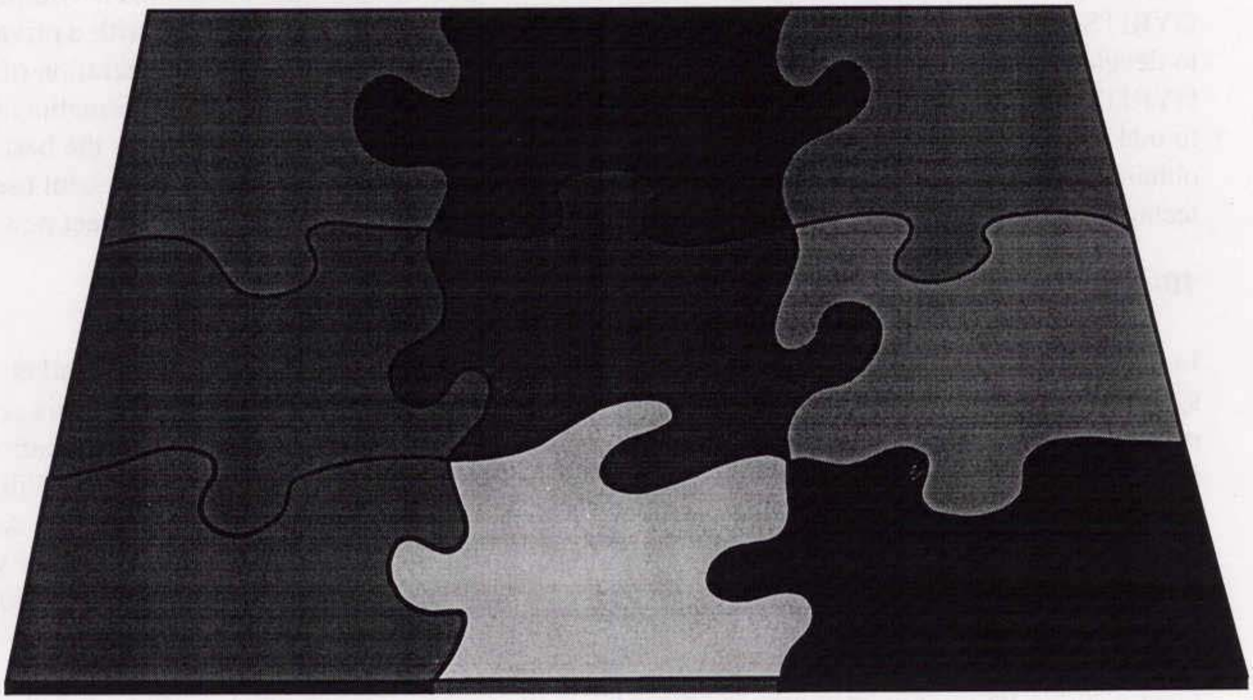
The intersection warning system is designed to detect the presence of vehicles on major roadways and relay the information to vehicles waiting to cross on minor roadways. Sensors or loop detectors placed on either side of the intersection in the major road determine when crossing, left turn or right turn maneuvers are safe. The American Association of State Highway and Transportation Officials (AASHTO) provides safe distance values for all three maneuvers (i.e., crossing, left turn, right turn).

Safe crossing information is relayed to the driver through stop sign-mounted beacons or through in-vehicle displays.

Deployment Vision

Limited quantification of AHS benefits and slow market penetration (i.e., vehicles equipped with advanced vehicle control systems) makes it difficult to clearly envision AHS deployment. However, it is recommended that AHS development in this corridor be incremental. Incremental deployment has been the "rule of thumb" for all AHS deployments. Most rural agencies will have to incrementally build an AHS infrastructure due to limited annual financial resources. This approach is referred to as "open architecture" - the use of incremental deployment with flexible design and regional tailorability (see Figure 7). An open architecture allows rural transportation providers to segment installation, remaining open to adapt evolving technologies yet tailor it to their specific needs.

Figure 7 - Incremental AHS Deployment



Unlike in urban areas, the element driving rural AHS is safety. Recurring congestion is generally not a problem in rural environments. This section does not determine the feasibility of implementing advanced vehicle control systems at the technical or institutional level, but instead proposes a near-term and long-term deployment vision.

5-year Vision

Within the next five years, field operational tests (FOTs) may begin in some of the spot locations with favorable benefit/cost ratios, assuming this effort is continued in subsequent phases. The fostering of FOTs in the next few years is important to winning AHS support from transportation users, providers and private agencies. Institutional/jurisdictional coordination between the project partners should solidify over the next few years as FOTs develop.

Lateral guidance technology will likely be installed in the infrastructure during this time period. The Montana Department of Transportation (MDT) is interested in demonstrating automated snowplow technology and may pursue this effort further in 1998. One of their target locations is within the GYRITS corridor - the Gallatin Canyon on U.S. Highway 191. If MDT partners with a private agency to develop their lateral control system, private-public partnerships may assist proliferation of AHS in the GYRITS corridor. As FOTs develop, it is important to initiate educational and informational programs to make the public aware of the benefits of advanced technology. Public outreach is the best way to obtain public support and make the public aware of the benefits of AHS by the successful use of the technology. Maintaining and increasing support for the system is the best way to attract new users.

10-year Vision

In the next ten years, AHS-Ready Vehicles (ARVs) will likely begin to penetrate the market. It is speculated that there will be approximately 20 percent fleet penetration by 2009. [13] It is assumed that rural fleet penetration will be somewhat lower. If MDT's automated snowplow demonstration comes to fruition, the lateral guidance system will exist throughout the entire Gallatin Canyon providing an advanced vehicle control foundation for the ARVs. The ARVs will likely use Information Assistance for the driver via audio and visual danger warnings. Institutional coordination will improve within this timeframe, leading to the proliferation of lateral guidance infrastructure systems to both Wyoming and Idaho.

Fleet vehicles will likely be equipped with AHS components. These vehicles will include local utility vehicles (i.e., power and telephone), emergency service vehicles, highway maintenance vehicles and commercial vehicles that use the route regularly. Little quantitative safety data will be available from equipped fleet vehicles; these vehicles are seldom involved in accidents within the corridor. Equipping fleet vehicles with advanced vehicle control systems will however provide qualitative data related to user satisfaction. As the use of AHS is augmented, public education on the emergence of new technology is particularly important.

20-year Vision and Beyond

Following a 20 year AHS effort, a greater number of vehicles will be using advanced vehicle control systems. It is predicted that by the year 2014, fleet vehicle penetration will be approximately 50 percent. [13] Once again, penetration rates in rural areas will likely be lower. In this same timeframe, ARVs will likely have advanced to Control Assistance.

On rural two-lane, uncontrolled access highways, AHS utilizing Control Assistance will likely be the pinnacle of development. Full automation is difficult to justify in the rural two-lane highway environment; the inability to dedicate a lane of travel to fully automated vehicles would result in fully automated vehicle mixing with non- or semi-automated traffic. In addition, uncontrolled access would result in many points of conflict that could have an adverse effect on fully automated AHS.

AHS Benefits

Automated Highway Systems (AHS) have the potential to address several different types of safety problems. AHS may be considered the tool of the future for engineers attempting to add to the safety and operation of a roadway where other traditional or conventional safety applications have fallen short. Unlike conventional safety applications, the goal of AHS is to achieve safety benefits through dynamic crash prevention countermeasures. Automated Highway Systems will provide dynamic warning and vehicle control information based on current roadway, traffic and environmental conditions.

Improving safety and security is the ultimate goal of this effort. As stated previously, approximately 90 percent of traffic accidents result from human error, generally related to fatigue, inattentive driving and excessive speed. [1] Automated Highway Systems will assist the driver and help reduce/eliminate human error accidents. In the GYRITS corridor, it is expected that collision avoidance systems with Information Assistance will help reduce the frequency of accidents while the advancement to Control Assistance will help reduce the rate and severity of crashes. If fully automated vehicles were provided on rural two-lane uncontrolled access highways, crashes could be eliminated. With an evolutionary deployment AHS can provide the rural traveler with:

- safer travel;
- more efficient travel;
- environmental benefits;
- additional mobility for the aging rural population; and
- reduced insurance rates due to the reduction in accident frequency and severity.

INSTITUTIONAL ISSUES

Probably the most prohibiting aspect of deploying an Automated Highway System (AHS) is the challenges presented to the state and local transportation providers. These two entities will likely inherit responsibilities related to maintaining and deploying AHS on the infrastructure within their jurisdictions. Furthermore, any testing or evaluating of AHS will likely be performed on state and local right-of-way. When the transportation network encompasses multiple jurisdictions, as this project does, the challenges are greater.

It is important that this study investigate the impacts of institutional issues as they apply to the rural community, and specifically, the GYRITS corridor. This section investigates the general issues and concerns that affect the successful development of AHS in the GYRITS corridor. Typical questions and concerns are:

- How will agencies procure AHS?
- Who will pay capital startup costs?
- Who will maintain and operate the system?
- Who will absorb possible liability claims?
- How are privacy issues dealt with?
- How will local agencies handle the technical demands?
- How is user acceptance established?
- Will the system be reliable?
- How will the new technology integrate with current state strategic plans?
- How will AHS affect the environment?
- Could public-private partnerships be successful?

Once these concerns have been isolated, they can be manageably addressed through outreach efforts to local governmental agencies and public stakeholders. Ultimately, both groups will be AHS users. Champions can be identified from each group who can help facilitate the maturation of AHS in pursuit of the AHS long-term goals and vision.

Some public agencies are hesitant to get involved; the envisioned AHS system may be perceived as too futuristic. This is especially true in rural environments where agencies typically mitigate roadway problems using "low-tech, low-risk" solutions. Involving the rural transportation providers early in the planning, testing and evaluation phases will help promote the effectiveness of AHS, develop champions and achieve user buy-in. An incremental deployment strategy will help demonstrate early, visible, quantifiable safety benefits for potential users.

General Issues

AHS is a long-term, futuristic concept with the objective of developing autonomous vehicles, particularly in urban regions. Much of the technological know-how to make this futuristic concept a reality exists today. Near-term applications can be augmented to synergistically attain the ultimate AHS goal.

Challenges that may impede the deployment of AHS are institutional in nature. These include:

(legal implications;

(public acceptance;

(procurement procedures;

(funding;

(operation and maintenance responsibility;

(privacy issues;

(environmental impacts;

(societal issues and

(jurisdictional coordination.

All of these issues are concurrent problems in the rural and urban environments. However, some of these issues pose a greater challenge in the rural environment, creating disinterest and disincentive to commit agency resources. Key differences are highlighted in Table 1.

Legal Issues

The legal concerns of the urban and rural environment are quite comparable when approaching the issue from the transportation provider perspective. The salient concerns of the transportation providers are how to mitigate the impeding legal ramifications of transferring vehicle control from the driver to the infrastructure. The goal of AHS is to assist and eventually remove the driver from the decision making process. Consequently, some party other than the driver may be responsible if an accident occurs.

Table 1 - Rural and Urban Institutional Issue Focus

Issues	**Rural**	**Urban**
Legal Issues	〈 Liability	〈 Liability
Public Acceptance	〈 High Tech Change 〈 User Costs	〈 User Costs
Procurement Procedures	〈 Staffing Resources 〈 Technical Resources 〈 Technology Obsolescence	〈 Technology Obsolescence
Funding	〈 Low Levels of Funding	
Operation and Maintenance Responsibility	〈 Funding Resources 〈 Technical Support	
Privacy Issues	〈 Use of Individuals Data	〈 Use of Individuals Data
Environmental Impacts	〈 Aesthetics	〈 Air Quality 〈 Energy Conservation
Societal Issues	〈 Economy 〈 Land Use	〈 Mobility 〈 Economy 〈 Land Use
Jurisdictional Coordination	〈 Agency Coordination	〈 Agency Coordination

Liability

One of the principal concerns transportation providers have when installing safety hardware on their roadway is liability. The governing laws are typically known as tort liability laws. The definition of tort liability is:

〈 **Tort** – A civil wrong or injury committed to a person or a person's property. It is an act or a failure to act that gives rise to a legal obligation, enforceable by a civil court, to pay money damages to those who suffer damage. [18]

〈 **Liability** – An obligation by law to be responsible for an activity or action. A liability is a court-enforceable duty of a person or entity (city, township, state, or private corporation). [18]

There are two categories of tort law: (1) injury law and (2) damage law. Most tort laws are developed and enforced at the state level, with differing sets of governing laws. Most states have tort compensations limits. Idaho, Montana and Wyoming all have tort limits that cap the amount of compensation per claim against the state. These limits are as follows:

Montana	$750,000 per claim and $1.5 million per occurrence.
Idaho	$500,000 per occurrence.
Wyoming	$250,000 per claim and $500,000 per occurrence.

State and local transportation providers are responsible for providing "reasonably safe highways". Most courts use the following definition of this responsibility:

> "Persons using highways, streets and sidewalks are entitled to have them maintained in a reasonably safe conditions for travel. One traveling on a highway is entitled to assume that his way is reasonably safe, and although a person is required to use reasonable care for his own safety, he is neither required nor expected to search for obstructions or dangers." [18]

Most transportation providers are considered with areas termed "high-risk." High-risk areas typically have a potential for high frequencies of accidents. The following items are considered high-risk:

- work zones;
- signs, signals and pavement markings;
- clear zones;
- structures;
- guard rails; and
- intersections.

AHS may be considered high-risk by transportation providers, particularly during the initial stages of demonstration and evaluation. During the initial development of AHS, much of the technology will be infrastructure based, placing much of the responsibility on the local transportation provider. As AHS matures and becomes more regional in scope, AHS technologies will shift from infrastructure based to vehicle based, reducing the responsibility of the transportation provider.

AHS is intended to enhance highway safety; thus liability claims in the aggregate should reduce. Legal issues may be mitigated at the legislative level by adjusting tort liability compensation levels or instituting individual state "sovereign immunity" laws that protect transportation providers from unreasonable liability claims.

Public Acceptance

Public acceptance may prove to be more of a barrier in the rural environment than in the urban environment. It is human nature to resist change and fear what is not fully understood. Historically, urban areas have been at the forefront, demonstrating and deploying components of advanced transportation technologies. Consequently, urban users have been exposed to new transportation technologies and may be more adaptable to the continued growth of AHS.

Rural transportation providers have been more reluctant to expand their transportation "toolbox" to include AHS applications, due to lack of financial and technical resources. The rural driver may be resistant without education and quantifiable, tangible travel and safety benefits.

Procurement Procedures

Procurement of advanced transportation technologies presents another difference between urban and rural transportation providers. Most urban transportation systems have reached or exceeded their capacity; transportation providers have been searching for ways to enhance their transportation capacity with AHS applications. These urban agencies typically have large planning and procurement departments and financial resources.

Rural agencies generally have little to no financial resources dedicated to advanced transportation technologies. Rural transportation agencies have vast transportation networks to maintain with limited economic resources. Consequently, rural agencies seek low-cost, low-tech, and low-risk near-term solutions to provide an adequate level of service to their customers.

Funding

Most rural transportation providers operate on limited budgets with little to no funds set aside for the development of AHS. Many rural agencies rely on volunteers to perform public safety functions. Rural agencies' poor economy is explained through their vast highway system coupled with their low populations and consequent small tax base. Much of the federal funding allocated to states is a reflection of the state's population.

Rural areas may be an ideal testbed for the effectiveness of public/private partnerships. The current economy may not permit rural transportation providers to deploy AHS. The private sector may supplement through both financial resources and technical sophistication unavailable in the public sector.

Operation and Maintenance Responsibility

Operation and maintenance is another issue impacting rural transportation providers more than urban transportation providers, given current funding levels and technical support. It is speculated that priva or federal agencies will be the primary participants in early AHS deployment efforts, especially during testing and evaluation. State agencies would assume operation and maintenance responsibilities once the system is functional. [19] The critical question is - will rural transportation agencies have the financial and technical resources to assume operation and maintenance responsibilities? Currently, they do not possess the financial or technical means; it is doubtful that the future will bring about significant change.

Privacy Issues

Privacy issues affect rural and urban transportation providers equally. Standards and guidelines should be developed defining the control and use of motorist-related data gathered through AHS. Standards and guidelines should address individual and vehicle identification, storage and access of the information, and any secondary uses of the information. Proper standards and guidelines will help to foster public acceptance.

Environmental Impacts

Generic issues within this category that affect both the rural and urban environment include air quality, energy and resource conservation. Aesthetic issues may capture more national attention in the rural environment given that most rural areas host many national parks, national forests and recreational centers.

Aesthetic issues may provide an even greater impact to this study due to the fact that it encompasses a treasure of natural resources, two national parks, several national forests and hundreds of campgrounds.

Societal Issues

Societal issues will impact both the rural and urban sectors to different degrees. Societal issues will impact community mobility, local economy, land use, social equity and other transportation issues. The gamut of impact will vary depending on community development goals or master plans.

Jurisdictional Coordination

Jurisdictional coordination poses a hurdle for both rural and urban transportation providers. Roadway jurisdiction is fragmented between state and local agencies. Any decision making process may involve governors, mayors, state legislatures, city councils, and local transportation coordinating committees. Furthermore, rural communities do not have Metropolitan Planning Organizations (MPO). Guidelines should be developed to mitigate jurisdictional conflicts and streamline coordination between the many agencies involved.

The roadway network for this study encompasses over 500 miles of roadway in three states and two national parks. The chore of uniting the multiple jurisdictions has thus far proven challenging. The Greater Yellowstone Steering Committee, who oversee the Greater Yellowstone Rural ITS Corridor project, may provide the multi-jurisdictional organizational structure needed to carry these initial AHS efforts to fruition. Thus, coordinating the Greater Yellowstone Rural ITS Corridor project and this stud will help develop a seamless rural architecture and provide a tangible product.

Project Partner Concerns

This study facilitated an early discussion of institutional issues of concern to the project partners. Appendix M provides the survey instrument that was used to gather feedback from each partner. Surveys provided partners with a forum to voice their concerns. The findings are summarized in Table 2 and discussed below.

Montana Department of Transportation (MDT)

The Montana Department of Transportation (MDT) was unable to respond to the questionnaire. However, MDT tends to be proactive and is investigating ways to guide snowplows through the GYRITS corridor in cooperation with 3M.

Table 2 – Concerns from Project Partners

Issues	IDT	WyDOT	YNP
Legal Issues	No concern, now	No concern, now	No concern, now
Public Acceptance	Some concern	Some concern	Little concern
Procurement Procedures	Need more data	Need more data	Need more data
Funding	Need more data	Need more data	Need more data
Operation & Maintenance Responsibility	No concern	Would be problem	No concern
Privacy Issues	No concern, now	Some concern	No concern, now
Environmental Impacts	Need more data	Need more data	Need more data
Societal Issues	Some concern	Need more data	No concern, now
Jurisdictional Coordination	Adequate	Adequate	Adequate

* No survey was received from the Montana Department of Transportation

Idaho Department of Transportation (IDT)

The Idaho Department of Transportation (IDT) is interested in what AHS technology can do, but is hesitant to get directly involved. IDT may not completely understand the AHS concept. Further outreach and education may solicit IDT's participation.

Planning and Outreach

To implement AHS in Idaho, all state and local transportation providers need to be involved, including state and local police. IDT currently has a transportation improvement plan that includes advanced transportation systems; information related to specific applications was unavailable. The IDT planning office would monitor all AHS research-related activities on their highways. IDT favors an evolutionary approach to slowly achieve public support.

Demonstrating, Deployment and Operation

IDT's desire is that AHS deployment be simple and incremental. The effectiveness of the technology must be proven to the local transportation providers and users. The pursuit of advanced technologies such as AHS is part of Idaho's state transportation improvement plan. However, it is premature for them to begin deploying any AHS technologies. IDT is willing to train appropriate personnel to maintain and operate any AHS. If AHS deployment were made possible through the continuation of this study, IDT would be willing to operate and maintain the system.

Financing and Legal Issues

Currently, IDT is not willing to commit funds to deploy any advanced transportation technologies until the systems are thoroughly proven and cost-effective.

Wyoming Department of Transportation (WyDOT)

The Wyoming Department of Transportation (WyDOT), similar to IDT, has adopted a "wait-and-see" approach before committing to AHS. While WyDOT wants to remain an involved player in AHS and ITS activities, they are hesitant to demonstrate the benefits of AHS on their transportation system. Outreach efforts may encourage a more intimate involvement from WyDOT.

Planning and Outreach

WyDOT would be the principal agency involved in any planning and deployment of AHS. City involvement may be required if AHS is deployed within their jurisdiction.

AHS could be adapted into Wyoming's state transportation plan if WyDOT views AHS as an agency goal or objective. In other words, if the system presents tangible benefits to all users, WyDOT would be interested in incorporating the technology into their transportation "toolbox."

The Wyoming Department of Transportation (WyDOT) maintains roads in Wyoming and in Grand Teton National Park; both agencies coordinate and exchange information. However, communication between these two agencies could be improved.

Demonstrating, Deploying and Operation

WyDOT is not proactive in pursuing new and innovative technologies to solve their transportation problems. Limited financial resources may explain their hesitancy to stray from basic maintenance and familiar, conventional countermeasures. However, WyDOT does want to have some level involvement, but prefers to take a wait-and-see approach. WyDOT wants to witness tangible benefits before committing any resources.

Currently, WyDOT would not be willing to deploy AHS in their fleet vehicles. They would prefer to see the technology demonstrated first. WyDOT does not have adequate technical staffing to maintain and operate AHS. They are willing to train their employees if WyDOT deploys an AHS. WyDOT is willing to assume control of an AHS after a "successful" demonstration.

Financing and Legal Issues

WyDOT is willing to financially support AHS if tangible benefits are demonstrated and they decide to adopt the technology as part of their transportation "toolbox." WyDOT would encourage public-private partnerships that would help finance AHS. WyDOT's principal concerns involving technology are system reliability and privacy issues.

Yellowstone National Park (YNP)

Yellowstone National Park (YNP) is very proactive in seeking advanced transportation solutions. Resistance from Park management may be minimal depending on public reaction to AHS requirements and ecological impacts. YNP is ready to move forward toward developing and deploying AHS components for testing and demonstration.

Planning and Outreach

The Department of the Interior is the roadway authority; representing both Yellowstone National Park (YNP) and Grand Teton National Park. A fluent line of communication exists between the Park Managers and their staff.

A review process exists which requires both Park Managers to approve any AHS deployment initiatives. Any AHS proposals that have been accepted by Park management can readily be adapted to their transportation plans. Each of the two national parks have maintenance and planning divisions that would be responsible for monitoring the AHS planning and deployment process.

The Department of the Interior needs a better understanding of what AHS is and what it can do for them. Some of their questions may be answered in this report. However, additional outreach efforts may facilitate better user education and interest.

Demonstrating, Deploying and Operation

Yellowstone National Park would prefer to have a proactive role in the development of AHS. YNP is open to any advanced transportation technologies that will help improve the Park's visitor experience by reducing traffic congestion and reducing motor vehicle accidents.

YNP is very interested in participating in an AHS demonstration project and demonstrating the effectiveness of AHS in their fleet vehicles. They have over 700 vehicles; implementation would depend on system requirements.

If AHS can demonstrate tangible benefits and reliability, Yellowstone National Park would commit to controlling, operating and maintaining the system. Currently the Park maintains radio communication systems and numerous computer systems. With training, the Park's staff should be able to operate and maintain the advanced transportation system. It is premature to measure resistance to installing advanced transportation technologies and equipment in the right-of-way until a system is designed and elements such as location, unit size, and electrical and communication requirements are determined.

Lacking within the YNP jurisdiction is an inadequate communication and electrical infrastructure.

Financing and Legal Issues

Yellowstone National Park has no barriers restricting them from fostering private-public partnerships. However, it is too early in the preplanning stage for YNP to predict any financial amount they would be willing to channel toward deploying AHS. It would depend on system reliability and capabilities.

ACCIDENT ANALYSIS

The fundamental objective of AHS is to address the limitations of human-based vehicle systems by:

- warning the driver of potential conflict, thus increasing the time for the driver to react;
- assisting the driver in potential collision situations by partially relieving the driver of the driving task; and
- providing autonomous vehicles.

To effectively determine where AHS technologies would produce the highest level of tangible benefits; traffic accidents for the GYRITS corridor were analyzed at spot locations (microanalysis) and roadway segments (macroanalysis). Safety is of paramount concern in the rural environment. By focusing this study on the safety applications of AHS, a greater acceptance can be achieved from the rural stakeholders. This section describes the accident analysis methodology and results.

To target high benefit areas, traffic accidents for the corridor were analyzed. A total of 2,538 accidents were analyzed for a three-year period: 1993 to 1995 for Montana and Idaho and 1994 to1996 for Wyoming. These accidents resulted in an economic impact to society of $131,242,436 (see Appendix G). Accidents within the city limits of Jackson, Wyoming and Livingston, Montana were ignored to focus on typical rural environments. The accidents that occurred within the city limits of these small cities paralleled accidents typical of large urban traffic centers caused by stop/go and merge/diverge traffic.

Accident rates were determined for each mile or half-mile segment along the corridor. It should be noted that Yellowstone National Park segments varied from 0 to 6 miles because of the node/sheet data format. High accident areas (i.e., locations in the corridor with a statistical over-representation of accidents when compared to the volume of traffic traversing the road) are referred to as "atypical" locations in this report.

Severity rates were also determined for each mile or half-mile segment. Potential atypical accident locations were chosen on the basis of severity in addition to accident frequency.

High accident and severity rates were used as indicators to target areas where accidents were occurring as the result of recurring contributing circumstances (i.e., accident trends). Areas experiencing accident trends were thought to have the best chance of maximizing benefits from AHS safety countermeasures.

Micro Accident Analysis

Accident rates were determined for each half-mile segment using a floating referencing system. Specifically, rates were determined on a half-mile basis, advancing along the route every tenth-mile. Additionally, severity rates were determined for each floating half-mile segment. Based on these rates, potential atypical accident locations were chosen for further study. These locations were analyzed to determine what, if any, accident trend(s) existed. Segments exhibiting trends were thought to have the best chance of maximizing benefits from AHS applications.

Accident Rates

Accident locations were identified as "atypical" if their accident rate showed a statistical over-representation of accidents. Over-representation was defined as being two standard deviations from the mean accident rate. Accident rates were determined for each half-mile segment using a rate per milli vehicle-miles traveled (R/MVMT). Average annual daily traffic (AADT) from the nearest traffic counting station was estimated by averaging the AADT over the three-year timeframe. The accident rates for all segments were compared along each route. Routes were compared by alignment (i.e., level, rolling or mountainous) (see Appendix D). The objective of this analysis was to determine the best site for further research or operational testing and to quantify corridor challenges; not necessarily to determine the most accident-prone locations in the corridor.

Severity Rates

Severity rates were calculated in the same manner as the accident rates, except that accidents were weighted based on their severity. Fatalities were weighted by a factor of eight, injuries were weighted by a factor of three, and property damage only accidents were weighted by a factor of one. These weighting factors were taken from "Traffic and Highway Engineering." [9] A factor of eight was used for fatalities instead of the suggested factor of 12 to prevent random singular fatalities from skewing the severity rates in particular half-mile segments. Severity rates did not yield significantly different results from the atypical locations identified by the accident rates.

Accident Trends

Each half-mile segment that was identified as atypical was analyzed for accident trend. For the purpose of this study, a trend was defined as an area having more than 25 percent of the same type of accident but not less than four total accidents.

The atypical accident locations identified through this microanalysis are listed in Table 3. Greater detail is provided in Appendix E. The accidents presented in Table 1 are typically a result of "speed too fast for conditions," "icy/slippery roads," "animal-vehicle collisions," "failure to yield right-of-way," and "moving vehicle collisions."

Table 3 - Atypical Spot Locations

Milepost Range	Total Accidents	Total Trend	Milepost Range	Total Accidents	Total Trend
Montana U.S. Highway 191					
9.900-10.011	18	13	10.000-11.000	20	17
28.000-28.900	13	9	59.000-60.000	11	8
61.000-61.400	12	7			
Montana U.S. Highway 20					
1.000-2.000	10	6	8.619-8.946	11	7
Idaho U.S. Highway 20					
311.000-312.000	22	14	317.000-318.000	42	29
328.000-329.000	14	6	338.000-339.000	17	11
326.000	12	4	405.000-406.000	8	6
Idaho U.S. Highway 26					
335.000-336.000	23	12	336.000-337.000	34	24
338.000-339.000	16	11			
Wyoming U.S. Highway 89					
160.000-161.000	11	8	167.000-168.000	12	5
185.000-186.000	18	11	189.000-190.000	12	6
184.400-184.600	8	8	188.000-188.690	6	6
127.000-128.000	22	16			
Yellowstone National Park Highway 89					
21.034-21.834	18	9	21.334-21.834	5	5
43.122-43.672	9	5	66.180-67.780	20	9

Macro Accident Analysis

Accident data, collected from Idaho, Montana, Wyoming and Yellowstone National Park, was standardized and assimilated to allow for spatial representation using Geographic Information Systems (GIS). Accident data was depicted both at spot locations and continuously along the roadway depending on the frequency and characteristics of the accidents.

Before examining the accidents to determine geographic areas of focus, the corridor was separated into 18 major segments based on: changes in geometric alignment, city limits, mountainous areas, and state lines (see Appendix D). Although state lines were assumed to be transparent, segments were broken along state lines for ease of analysis. The segment types included rural-flat, rural-mountainous, urban (within city limits), suburban (directly outside city limits until change in cross section), and semi-mountainous (only in Yellowstone National Park). The number of accidents for each accident trend, identified previously for half-mile locations, was determined for each of the 18 major segments. A geographic area was identified for focus if the area possessed two of the three following criteria:

- a high percentage of the accidents in the area had a common trend;
- a high number of the accidents in the area had the same common trend; and/or
- half-mile atypical locations existed with the same trend.

Table 4 presents the results of the macroanalysis. Appendix F provides a more detailed description.

Stratified Accident Analysis

The previous accident analyses considered the entire accident sample when determining potential AHS deployment locations. Targeting smaller groups within this sample may actually help to accelerate NAHSC's near-term deployment goals. Hence, two smaller groups were separated out for further analysis: (1) commercial vehicles and (2) in-state/out-of-state drivers.

Commercial Vehicles

Commercial vehicles or heavy vehicles were targeted because they provide a smaller market group and market penetration may be fostered more easily. Heavy vehicle accidents were sorted and stratified with the following objectives:

- to determine the characteristics of crashes involving heavy vehicles;
- to determine if heavy vehicles are over-represented in crashes in the corridor;
- to identify causal factors for heavy vehicles; and
- to link causal factors to trends.

With the stratified accident data, a microanalysis and macroanalysis were performed to characterize and geographically locate trends and challenges related to heavy vehicles.

Microanalysis

After careful analysis, no spot locations where heavy vehicles were over-represented in the accident trends were identified. Most heavy vehicle accidents were randomly distributed throughout the corridor. AHS near-term applications related to heavy vehicles at spot locations would be inappropriate.

Table 4 – Atypical Regional Segments

Milepost Range	Road Type	Total Accidents
Yellowstone Park U.S. Highway 89		
0.000-93.446	Park	426
Wyoming U.S. Highway 26		
0.000-2.370	Mountainous	7
Montana and Yellowstone Park U.S. Highway 191		
0.000-10.835	Level	88
10.836-66.826	Mountainous	276
66.827-81.903	Level	98
Idaho U.S. Highway 20		
308.717-353.050	Level Suburban	271
353.051-401.300	Level	117
401.301-406.300	Mountainous	18
Montana U.S. Highway 20		
0.000-3.000	Level	27
3.001-9.397	Mountainous	39
Idaho U.S. Highway 26		
335.255-338.069	Level Suburban	64
338.070-375.538	Level	134
375.539-402.500	Mountainous	63
Montana U.S. Highway 89		
0.000-51.812	Level	112
51.813-53.068	Level Suburban	44
Wyoming U.S. Highway 89		
118.32-152.090	Mountainous	304
155.211-165.000	Level	86
165.001-211.620	Mountainous	245

Table 5 - Heavy Vehicle Accident Rates

Accident Type	Total Accidents	Accident Rate (R/MVMT)	National Average	Difference
Property Damage Only	54	97.39	75.00	+22.39
Injury Accidents	69	40.73	47.00	-6.27
Fatal Accidents	8	4.72	2.50	+2.22

Macroanalysis

Heavy vehicles were involved in approximately 10 percent of all accidents within the corridor, resulting in 28 percent of the fatality accidents and five percent of injury and property damage only accidents (see Table 5). Nationally, heavy vehicles accounted for 12 percent of all traffic fatalities and three percent of all accidents resulting in injury and property damage only. [10]

The aforementioned statistics, which indicate that heavy vehicle accidents in the GYRITS corridor exceed the national averages, support the notion that a safety problem exists related to commercial vehicles in the corridor. However, the low frequency of accidents made it statistically difficult to sort heavy vehicle related accidents into trends. Heavy vehicle accident rates were stratified by road type (i.e., mountainous, rolling, level, etc.), hypothesizing that roads with mountainous alignment would have higher accident rates. This hypothesis could not be statistically verified (see Appendix H). Instead, heavy vehicle accident rates appeared to be distributed randomly through mountainous and flat regions; indicating driver error may be the primary problem, while alignment and terrain are secondary contributors.

Montana U.S. Highway 191 consistently exceeded the national average in all three severity rating categories (i.e., property damage only, injury and fatality rates). Particular segments included milepost 10.836 to milepost 66.826 (Gallatin Canyon) and milepost 66.826 to milepost 81.903 (a level section of highway between Bozeman, Montana and Gallatin Canyon). The accidents in these milepost ranges resulted in 74 total accidents with the following frequent "first harmful event":

〈 28 motor vehicle in transit;

〈 15 animal-vehicle conflicts;

〈 11 fixed object; and

〈 12 overturns.

Most frequent "first harmful event" categories for all heavy vehicle accidents in the corridor are provided in Table 6.

Table 6 - CVO Accidents: First Harmful Event

First Harmful Event	Percent Occurred
Motor Vehicle in Transit	30%
Animal-vehicle Conflict	16%
Run-Off-Road	8%
Hit Fixed Object	7%
Overturn	6%
None	6%
Other	27%

The leading categories of "contributing circumstances" for the 74 heavy vehicle accidents along Montana U.S. Highway 191 were:

- 22 driver inattentive;
- 18 speed too fast for conditions (i.e., weather conditions); and
- 13 icy surface conditions.

Most accidents were human error, and resulted in the driver leaving the appropriate travel lane. Most frequent "contributing circumstances" categories for all heavy vehicle accidents in the corridor are provided in Table 7.

In all, heavy vehicles accounted for 54 property damage only accidents, 69 injury accidents and 8 fatal accidents from 1993 to 1995. These accidents, resulting in 9 fatalities, 84 injuries and 165 property damage cases, resulted in an economic cost to society of $29,288,056. These economic costs were also stratified by road type and reduced to a cost per mile for each segment (see Appendix H). Montana U.S. Highway 191 consistently ranked the highest in this category, as did Montana U.S. Highway 20.

Table 7 - CVO Accidents: Contributing Circumstances

Contributing Circumstance	Percent Occurred
Inattentive	25%
Speed Too Fast For Conditions	19%
Icy	9%
Failure To Yield	8%
Failure To Have Vehicle Under Control	5%
Following Too Close	4%
Improper Pass	4%
Other	26%

With respect to AHS deployment, commercial vehicles will require targeting on the macro level by determining commercial carriers that consistently use the corridor as a common route to transport goods and services. Carriers that use Montana U.S. Highway 191 may be a good target group, since this highway may provide enough data to statistically quantify benefits.

Traveler Origin

Traveler origin information was examined to determine if accidents within the corridor were a product of unfamiliar out-of-state travelers or local residents. It was hypothesized that this information would be helpful in determining target groups for early operational testing and evaluation. Specifically, if the origin data indicated a statistical accident over-representation of either of the two aforementioned groups, this group could be isolated and targeted for various AHS applications.

The information presented here represents only vehicles involved in accidents within the corridor and does not represent the percent of total out-of-state/local travelers traversing the highways. The data was stratified by state and was only reduced to a macro level; the low frequency of accidents at most locations would not yield statistically valid findings in a microanalysis. The accident data from Idaho and Wyoming allowed for the determination of the causing party. Hence, each accident could be traced to a single in-state or out-of-state party; the proportion of in-state travelers and out-of-state travelers involved in an accident summed to one. Montana's accident data did not reflect causing party information but rather accident involvement. Hence, the proportion of in-state travelers and out-of-state travelers summed to greater than one.

Macroanalysis

Tables 8 and 9 summarize the proportion of in-state/out-of-state vehicles causing accidents and involved in accidents for geographic areas of focus.

Table 8 - Origin of Vehicle Causing Accident

State	Route	Segment	% In-state	% Out-of-state
Wyoming	89	total corridor section	51	49
	89	158.82 to 204.85	41	59
Idaho	20	total corridor section	68	32
	20	308.717 to 353.05	84	16
	20	353.06 to 406.30	37	63
	26	total corridor section	73	27

Table 9 - Origin of Vehicles Involved in Accident

State	Route	Segment	% In-state	% Out-of-state
Montana	20	total corridor section	65	94
	89	total corridor section	123	36
	191	total corridor section	71	48
	191	0 to 10.493	49	56
	191	10.494 to 81.903	60	36

Wyoming U.S. Highway 89

On Wyoming U.S. Highway 89, vehicles with out-of-state plates were the involved in approximately 51 percent of the accidents, while vehicles with Wyoming license plates were involved in 49 percent. Using a 95 percent confidence interval, no statistical difference was found at this location between in-state or out-of-state travelers.

The section of U.S. Highway 89 that traverses through Grand Teton National Park was examined separately to determine if out-of-state travelers influenced the number of accidents. In this 46-mile section of roadway, vehicles with out-of-state license plates were involved in 59 percent of the accider while vehicles with Wyoming plates were involved in 41 percent. The percent of unfamiliar drivers is likely greater than 59 percent since all Wyoming drivers may not be local to this specific route. On this 46-mile section of roadway there were 243 accidents. The first harmful event in these accidents were as follows:

- 108 animal-vehicle conflicts;
- 73 motor vehicle in transit;
- 31 vehicle overturned; and
- 31 other.

Note that 44 percent of these accidents resulted from animal-vehicle conflicts. This is an overwhelming number resulting from one causal factor.

Idaho U.S. Highway 20

On Idaho U.S. Highway 20, vehicles with Idaho license plates were involved in 68 percent of the accidents, while out-of-state vehicles accounted for 32 percent of the accidents. The accident data was stratified by roadway type to determine if driver origin characteristics were attributable to the location or type of facility. The first 44-mile section of highway leaving Idaho Falls, Idaho is a divided four-lane structure with a suburban surrounding. Vehicles with Idaho license plates were involved in 84 percent of the accidents, while the remaining 16 percent involved vehicles with out-of-state plates. The remaining 53-miles of roadway is a rural undivided two-lane structure. Vehicles with out-of-state plates were involved in 63 percent of the accidents, while vehicles with Idaho plates accounted for the remaining 37 percent. Once again, the number of unfamiliar drivers in the area is speculated to be greater than 63 percent since all vehicles with Idaho plates are likely not local to this route.

Idaho U.S. Highway 26

The accidents on Idaho U.S. Highway 26 involved vehicles with Idaho license plates 73 percent of the time and vehicles with out-of-state plates 27 percent of the time.

Montana U.S. Highway 20

The accidents on Montana U.S. Highway 20 involved out-of-state vehicles 94 percent of the time and vehicles with Montana plates 65 percent of the time.

Montana U.S. Highway 89

The accidents on Montana U.S. Highway 89 involved out-of-state vehicles 36 percent of the time and vehicles with Montana plates 123 percent of the time. It was hypothesized that Montana U.S. Highway 89 hosted a high level of local travelers, since many people living in Gardiner, Montana travel to Livingston, Montana (the two cities at each end of this route) for work and shopping.

Montana U.S. Highway 191

The accidents on Montana U.S. Highway 191 comprised 71 percent vehicles with Montana plates and 48 percent out-of-state vehicles. Highway 191 was split into two segments: (1) milepost zero to 10.493 and (2) milepost 10.494 to 81.903. Milepost zero to 10.493 had an accident involvement rate of 49 percent for vehicles with Montana plates and an accident involvement rate of 56 percent for vehicles with out-of-state plates. Statistically, there was no difference between in-state and out-of-state involvement rates. Milepost 10.494 to 81.903 had an accident involvement rate of 60 percent for vehicles with Montana plates and an accident involvement rate of 36 percent for out-of-state vehicles.

With respect to AHS applications, accidents involving out-of-state travelers likely occur because of their lack of familiarity with the road they are traveling. For this reason, unfamiliar travelers need extra information or guidance. The extra information or guidance could be provided as safe speed warnings and slippery condition warnings via dynamic message signs or by partial vehicle automation. Early operational testing of vehicle automation can target out-of-state travelers through vehicle-rental agencies. Further, investigation should take place to determine accident involvement rates for rental vehicles.

Atypical accident areas involving in-state travelers may result because local commuters become familiar with a section of commonly traveled roadway and begin to overdrive. In a sense, they become inattentive; not concentrating on driving as much as someone would on an unfamiliar section of roadway. The same countermeasures could be applied in this situation, however local commuters present a much larger, varied target group. The quantification of benefits may be challenged without sizable market penetration.

POTENTIAL AHS COUNTERMEASURES

This section briefly discusses the AHS requirements in the Greater Yellowstone Rural ITS (GYRITS) corridor. Many of the system-related requirements are a direct result of the adverse weather conditions in this corridor. A discussion of potential AHS countermeasures is provided below which includes a description of the equipment, system justification, predicted benefits and estimated costs.

Spot Location Countermeasures

This section presents technology applications appropriate for spot locations (i.e., roadway segments of one mile or less). The intent of these applications is to communicate potentially dangerous situations to the driver. Both advanced technology applications and traditional countermeasures are reviewed.

Road Surface Conditions Monitoring

Systems presented here are intended for unsafe situations resulting from icy road conditions. Typically, drivers are unaware of the slipperiness of the road or are inattentive and driving too fast for conditions.

New Technology: Friction/Ice Detection and Warning Systems

Tire-to-road friction is an important factor in vehicle control; adequate frictional forces are required to keep a vehicle on the road. Drivers must reduce their speed when friction levels are low to have adequate stopping distance. The envisioned friction/ice detection warning system would calculate a safe advisory speed and display the speed on a roadside mounted changeable message sign (CMS) (see Figure 8). The CMS would be placed far enough in advance of the problem area to allow the driver time to adjust their speed. The system would determine a coefficient of friction through measured weather conditions, road surface characteristics, and road grade. A processor would calculate an advisory speed based on the coefficient of friction and display the speed on the CMS, hence creating a dynamic operational system.

Justification: (This technology is to be applied to locations where the numbers of accidents due to icy conditions are statistically over-represented.

Benefits: (Drivers are warned of areas with icy conditions in advance. Dynamic signs placed sufficiently in advance of recurring slippery areas would allow drivers adequate deceleration distance before entering slippery areas. "Too fast for condition" accidents should be reduced.

Costs: (The estimated cost for this system is $111,620 which includes estimated installation costs, a four-point detection system with weather station and processing, and one changeable message sign.

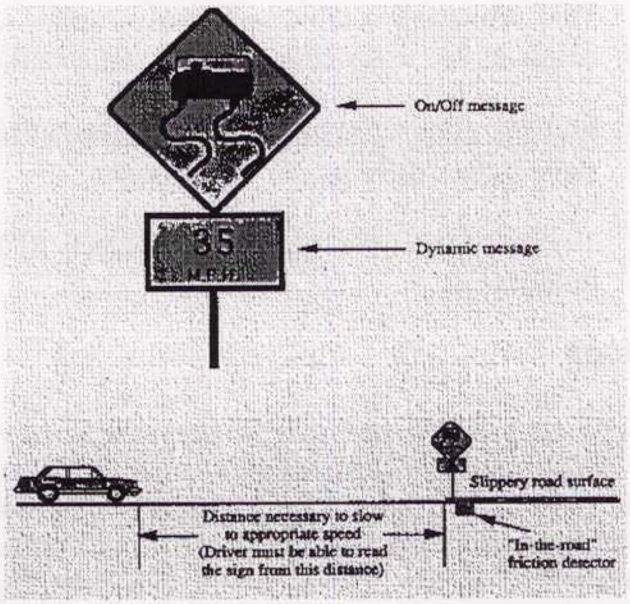


Figure 8 - Ice Detection Schematic

Traditional Countermeasure: Static Ice Warning Sign

The traditional method of informing motorists of recurring icy conditions is with a static ice warning sign (see Figure 9). Static signs have typically been over used. Many state agencies place these signs on every bridge and other areas where ice may form. Thus, many times these signs inform the driver of nonexistent icy conditions. This violates driver expectancy and over time, drivers begin to ignore warning signs, making them ineffective. Nonetheless, this countermeasure is attractive because of its low cost.

Figure 9 - Slippery Warning Sign

Justification: (This technology is to be applied to locations where the numbers of accidents due to icy conditions are statistically over-represented.

Benefits: (Initially, static signs may affect the speed of local drivers, but over time static signs may lose their effectiveness.

Costs: (The total cost of the sign is approximately $108 including material and installation.

Intersection Warnings

An intersection warning system is designed to detect the presence of vehicles on major roadways and relay information to vehicles waiting to cross on minor roadways. Sensors or loop detectors placed on either side of the intersection in the major roadway determine the safest time for crossing or turning. The American Association of State Highway and Transportation Officials (AASHTO) provides safe distance values for three maneuvers (i.e., crossing, turning left, turning right). Safe crossing information is relayed to motorists with beacons mounted on stop signs or through in-vehicle displays.

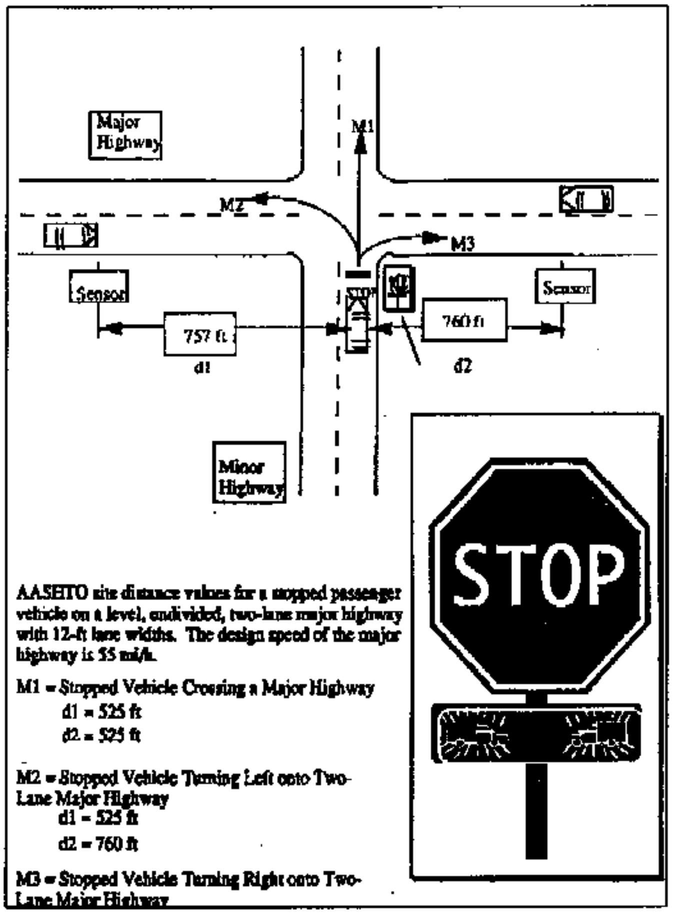
<u>New Technology: Crossing Detection</u>

An intersection crossing detection system is intended to enhance the driver's ability to safely enter the intersection of a major road from a minor approach. The system is intended to address crossing-path accidents at intersections controlled by stop signs on the minor road (see Figure 10). Stop signs on the minor roads would be equipped with displays indicating the presence of vehicles on the major road. The indicator would inform the driver if the vehicles on the major road are approaching from the left or right. Sensors or loop detector would be placed on either side of the intersection in the major road. The time required for a maneuver depends on design speeds, geometric alignment of the intersection and vehicle type factors.

Justification: (This technology is to be applied along rural high-speed highways where intersection control consists of two-way stop signs on the minor approach, there is a statistically high number of crossing-path accidents and traditional countermeasure are unable to mitigate the problem.

Benefits: (At the stop sign, drivers are warned that vehicles on the major roadway are close enough to the intersection that any maneuver the driver wants to make from the minor approach is unsafe. However, the driver ultimately makes the final decision on when to proceed and may not heed the warning. Hence, total accident elimination is unlikely.

Costs: (The estimated cost for this system is $34,590, which includes two inductive loop detectors, two sign controllers, two signs with illuminated vehicle icons and estimated installation costs.



AASHTO site distance values for a stopped passenger vehicle on a level, undivided, two-lane major highway with 12-ft lane widths. The design speed of the major highway is 55 mi/h.

M1 = Stopped Vehicle Crossing a Major Highway
d1 = 525 ft
d2 = 525 ft

M2 = Stopped Vehicle Turning Left onto Two-Lane Major Highway
d1 = 525 ft
d2 = 760 ft

M3 = Stopped Vehicle Turning Right onto Two-Lane Major Highway

Figure 10 - Crossing-Path Detection Schema

Traditional Countermeasure: None

After making site visits and examining intersection crossing-path accident records, no notable traditional countermeasures were discovered.

Animal-vehicle Collision Avoidance

Animal-vehicle collisions are numerous in the rural environment. While rarely resulting in human fatality, animal-vehicle collisions result in extensive property damage and almost always result in the death of the animal. Most animal-vehicle collision avoidance systems rely on object recognition and warning.

New Technology: Radar Detection Activation

Radar detection activation is intended to inform the driver of in-road objects that the driver is unable to see because of low visibility or poor geometric alignment. This system would activate any current, commercially available radar detector to warn the driver of a hazard. A transmitter is placed along the roadway where there are a high number of animal-vehicle accidents. The transmitter has a detection range of one mile in each direction. If an animal is detected, the transmitter would send a signal to an in-vehicle radar detector commonly used to identify police. On older detectors, the K-band alert will sound. New detectors under development will transmit variable text. Fixed messages would be stored in the newer detectors that would provide the driver with more details about the hazard. One drawback of this spot location application is that it is only effective for vehicles equipped with radar detectors.

Justification: (This system is intended for use in areas where animal-vehicle collisions are statistically over-represented.

Benefits: (Drivers are warned in advance of animals or objects on the roadway, providing drivers with the necessary time to slow down and make the appropriate maneuver to avoid a collision. This technology may be very useful in the GYRITS corridor national parks where there are many animal-vehicle collisions. Radar detectors could be loaned or leased to tourists as they travel inside the park boundaries.

Costs: (The estimated cost for this system is $3,800, which includes one transmitter, one solar pack and estimated installation costs.

Traditional Countermeasure: Fences, Reflectors, Repellents, Etc.

There are many traditional treatments for animal-vehicle collisions including wildlife fences, wildlife reflectors, repellents, increased hunting, reduced vehicle speeds, public education, vegetation clearance and improved vehicle lighting. Most traditional countermeasures focus on preventing the animal from crossing or accessing the roadway, which is either not feasible, ineffective or disturbs the natural aesthetics of the area.

Horizontal Curve Speed Advisory

Horizontal curve speed advisory systems are intended to provide the driver with real-time information about their ability to safely negotiate a roadway curve given their travel speed and the roadway surface conditions.

New Technology: Dynamic Variable Message Sign

The objective of this application is to help drivers negotiate horizontal curves at speeds safe for the design radius of curvature, the super-elevation and the frictional characteristics of the roadway. A dynamic message sign would display the calculated safe speed to the driver far enough in advance for the driver to react and decelerate to the appropriate speed (see Figure 11). Pavement monitoring sensors and processors may be added to monitor icy/slippery conditions.

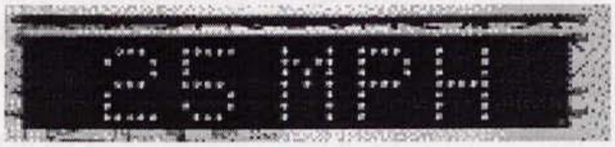


Figure 11 - Variable Message Sign

Justification: (This system is intended for use at spot locations where run-off-the-road accidents due to horizontal alignment are statistically over-represented.

Benefits: (Drivers are warned in advance of a horizontal curve and provided with a recommended speed to safely negotiate the curve.

Costs: (The estimated cost for this system is $4,000 for the sign and installation; a power source was assumed to exist.

Traditional Countermeasures: Static Curve Warning Signs

Two of the most common traditional countermeasures for horizontal curve accidents are "curve ahead" advisory signs and chevrons. As with the static ice warning sign, this traditional countermeasure is appealing because of its low cost. The combination of a static curve ahead sign and chevrons may be the most feasible application at this time. Chevrons cost approximately $27 for each sign and approximately $75 for installation. Six signs would total $615.

Regional Countermeasures

This section of the report briefly discusses regional countermeasures for the Greater Yellowstone Rural ITS (GYRITS) corridor AHS. Regional countermeasures were considered from a rural transportation provider perspective. Namely, what would the local and state transportation departments be responsible for? It was hypothesized that transportation providers would be responsible for providing the in-pavement lateral sensing technology. Specifically, it is assumed by the time AHS vehicles penetrate the market, most of the necessary components (i.e., sensors, processors, and longitudinal guidance systems) will be in the vehicles.

These countermeasures consider the adverse weather conditions presented in this corridor. If during typical winter, the lateral sensors can no longer locate the lateral position of the vehicle, or the longitudinal headway control can no longer measure headway and obstacles, serious safety problems will result.

Longitudinal Sensing

The most effective technology for longitudinal guidance was investigated for the GYRITS corridor. Many sensors are capable of longitudinal detection using: vision, ultrasonic, Laser Radar (LIDAR) and radar. The advantages and disadvantages of some of the systems are presented in Table 10.

Given the severe weather encountered in this region, system-related literature recommended radar as the best alternative for the GYRITS corridor. The accuracy of radar systems is sufficiently accurate for collision detection and warning. The system has a reported accuracy of ± 1 meter for ranges between 15 and 100 meters (49.21 and 328.08 feet).

Lateral Sensing

Factors affecting sensor selection include their capabilities in addressing poor road delineating, low temperatures, obscure pavement, reduced visibility conditions and mountainous road conditions. Several technologies are available for lateral guidance, which use vision, roadway referencing, radio wave signals, magnetic sensors and roadway magnetic markers and global positioning. Hybrids of these systems also exist. The advantages and disadvantages of some of the systems are presented in Table 11.

Due to the severe winter conditions and the mountainous environment, magnetic pavement markers currently seem to be the best technology for lateral sensing. Two magnetic systems were reviewed for this project: (1) PATH's magnetic nails and (2) 3M's magnetic tape. One concern with using magnetic nails is their effect on flexible pavements. How will inserting a rigid nail into a flexible pavement affe the properties of the pavement? Flexible pavements tend to distort with temperature variations and loading, causing cracking and rutting. Will the nails cause additional cracking? In colder climates, where frequent freeze-thaw cycles occur throughout the winter months, there are concerns that the rigid nails will be the nuclei for surface cracking. Conversely, how will the "flexing" of the pavement affect the performance of the nails? The 3M magnetic tape seems more suitable for colder climates, but is more expensive to install. The PATH magnetic nails have yet to be tested in cold climate flexible pavements.

Table 10 - Longitudinal Sensing Technology

Sensor Technology	Advantages	Disadvantages
Radar	〈 Accurate range and range rate (for Doppler radar) when performing optimally 〈 Low susceptibility to poor weather conditions 〈 Longer range sensing capability than infrared or vision systems	〈 Problems with very short range 〈 Susceptible to multi-path and clutter 〈 For high accuracy may require cooperative target (e.g., reflectors on vehicle bumpers) 〈 Higher cost sensor, and larger size 〈 Frequency allocation uncertainties 〈 Interference from other radar-equipped vehicles 〈 Potential health concerns from electromagnetic emissions exposure
Laser Radar	〈 Significantly lower sensor cost than radar, and smaller size 〈 Accurate range measurements at short range. Maximum detection range ~ 100 m in good conditions with target retro-reflector 〈 More focused beam than radar	〈 Sensitive to rain and very limited in fog 〈 Lower accuracy at longer range (for acceptable power levels) 〈 At longer ranges, requires cooperative target (retro-reflector) 〈 Difficulty detecting mud-covered vehicles 〈 Requires target reflectors for reliable performance 〈 Positioning of source and target must be "favorable" 〈 Power output limited by safety concerns
Vision systems	〈 Passive sensor 〈 Can potentially provide both lateral and longitudinal control information 〈 Interference not a problem 〈 Can detect obstacles 〈 Can differentiate between lanes	〈 Degraded performance in poor weather and low lighting conditions 〈 Processing intensive 〈 Very high relative cost 〈 Much further development required

Source: [14]

Table 11 - Lateral Sensing Technology

Sensor Technology	Advantages	Disadvantages
Magnetic roadway sensors and markers	〈 Precise lateral control technology 〈 Low-cost, passive sensor 〈 Very low data rate transfer of roadway turn information via magnetic marker polarity 〈 Low susceptibility to poor environmental conditions	〈 Susceptible to electromagnetic interference from vehicle an other sources
GPS	〈 Provides highly accurate, 3-D absolute position and velocity for both lateral and longitudinal control from single sensor 〈 Extremely accurate time 〈 Passive sensor 〈 Absolute position enables direct mapping to upcoming roadway characteristics in stored roadway database 〈 Most processing for information needed by control system performed by the sensor 〈 Commercially available, receiver costs decreasing rapidly	〈 Differential correction network required 〈 Requires augmentation with other sensors or pseudolites in areas where satellites are obstructed 〈 Initialization period required to achieve high accuracy 〈 Susceptible to multi-path errors

Source: [14]

New Technology: Magnetic Nails

The discrete magnetic nails developed by PATH are passive requiring no power, extremely durable, and will provide guidance in all weather conditions (see Figure 12). The sensors are installed along the centerline of the travel lane and are sensed by a magnetometer aboard the vehicle. The vehicle sensors detect the magnetic field; a processor determines the vehicle's deviation from the centerline. The polarity of the magnetic nails can be varied and encoded to provide the vehicle with limited amounts of information on the upcoming roadway alignment and characteristics. This technology was demonstrated in San Diego at *Demo 97*. The magnetic nails are proven, inexpensive and low cost to install. The cost for the magnetic nails is approximately $17,000 per lane per mile. This cost includes 20 percent for magnets, 40 percent for surveying and 40 percent for installation. The magnetic nails are provided by All Magnetics, Incorporated from Placentia, California.

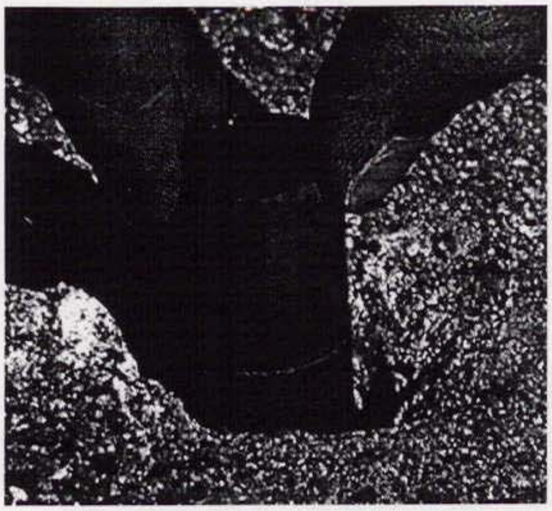


Figure 12 - Magnetic Nail

New Technology: Magnetic Tape

3M offers a continuous magnetic tape with a permanent magnetic field. The magnetic tape is also very durable, passive and relatively low cost. The magnetic tape functions similarly to the PATH's nails. The advantage of the tape over the nails is that the tape has been proven successful in cold climates, having been used and tested on several projects in Minnesota. The tape is a little more expensive than the nails. For a tape quantity between 5 to 10 miles, the cost is $26,400 per lineal lane mile; for a tape quantity greater than 10 miles, the cost is $23,760 per lineal lane mile.

Both systems require minimal maintenance. Presently, the principal maintenance consideration is highway overlays. If highways are directly overlain, the magnetic sensors may have to be raised if the pavement depth above the magnetic sensors exceeds a predetermined threshold. If milling operations are performed the sensors may have to be removed and reinstalled. The magnetic sensors life cycle greatly exceeds the life cycle of the pavement and maintenance on the magnetic sensors is negligible.

BENEFIT-COST ANALYSIS

Benefit-cost analysis is a monetary valuation of the impact of deploying projects. This technique is used by many public and private sector organizations to justify a project or to rank projects. In transportation engineering, benefit-cost analysis involves analyzing the advantages, benefits and cost reductions associated with a proposed transportation system enhancement as they apply to the system providers and users. The costs associated with the benefits of the enhancement are then directly compared to the capital expenditures required for providing the proposed transportation enhancement. Enhancements are generally safety-related or capacity-related with the goal of saving lives and/or increasing levels of service (LOS).

This analysis considered system costs to local transportation providers; it was assumed that the costs for vehicle upgrades would be distributed to the consumer. Specifically, this analysis assumed transportation providers would only be responsible for the purchase and installation of the magnetic lateral warning and guidance systems discussed previously.

The benefit-cost analysis was performed on a regional basis to better determine the magnitude of AHS impacts in the GYRITS corridor. The benefit-cost analysis was also performed separately on each corridor section (see Appendix D), where the roadway segments were separated and categorized by roadway type. The benefit-cost analysis consequently indicated the relative magnitude of benefits experienced along particular sections of roadway. The identification of relative impacts among corrid segments was intended to assist in the ranking of projects for field operational tests. The sites were analyzed and ranked only if a feasible countermeasure existed – either advanced or traditional.

Assumptions

The objective of this analysis was not to determine the performance of AHS at the technical or institutional level. The analysis assumes that the technologies perform as anticipated and as indicated in the literature.

Safety benefits resulting from AHS were difficult to predict for two reasons: (1) system reliability is unproven and (2) success relies often on driver response. Accident reduction factors (ARFs) were adopted from previous research or were assumed by hypothesizing that a certain percentage, less than 100 percent, of human error accidents could be reduced.

For the regional analysis, it was assumed that AHS technologies would be helpful in mitigating the following types of accidents, categorized by longitudinal assistance, lateral assistance, intersection assistance and other.

Longitudinal Assistance

- rear ends
- animal-vehicle conflicts
- following too close
- motor vehicle parked along roadside

Lateral Assistance

- head on collisions
- sideswipes
- overturned (after leaving the roadway)
- ran off road
- struck another motor vehicle in transit
- struck fixed object
- struck guard rail
- struck ditch
- struck cut slope
- struck tree
- struck sign
- struck fill slope
- not in right lane
-

Intersection Assistance

- disregard traffic control
- failure too yield

Other

- inattentive
- traveling too fast for conditions
- fell asleep
- illegal lane change
- illegal backing maneuver
- fail to signal
- over corrected
- improper pass

The appropriate ARFs were applied to each functional classification to determine the reduction in accidents and ultimately the resulting benefits. The ARFs used in this analysis were adopted from Yokota, Tokuyama and Ueda. [15] It is important to remember that the ARFs and consequent benefits from AHS are theoretical values. Field operational testing is required to confirm the accuracy of the theoretical ARFs. The ARFs applied regionally by each evolutionary stage are summarized in Table 12. The ARFs applied at spot locations are summarized in Table 13. In each case, the ARF value represents the proportion that accidents are reduced. For example, an ARF of 0.20 indicates that accidents are predicted to reduce by 20 percent.

Table 12 – Regional Accident Reduction Factors

System	Accident Reduction Factors		
	Information Assistance	**Control Assistance**	**Full Automation**
Longitudinal Assistance	0.65	1.0*	1.0
Lateral Assistance	0.30	0.85	1.0
Intersection Assistance	0.75	0.90	1.0
Other	0.30	0.85	1.0

* 0.90 used for Animal-vehicle Collisions

Table 13 - Spot Location Accident Reduction Factors

System	Accident Reduction Factors
Friction/ice detection and warning systems	0.45
Static ice warning sign	0.23 [16]
Intersection crossing detection	0.50 [17]
Animal-vehicle collision warning system	0.20
Dynamic variable message sign (speed advisory)	0.75
Chevrons	0.25

The friction/ice detection and warning system accident reduction factor (0.45) was derived by assuming that half of the 90 percent human error accidents would be eliminated. [1] With this system, it is still largely to the driver to decide on an appropriate response. The intersection crossing detection system ARF (0.50) was adopted from an FHWA report 93-080. [17] The animal-vehicle collision warning system ARF (0.20) was assumed to be low; many vehicles may not be equipped with radar detection devices and the driver is once again responsible for the final response. The dynamic variable message sign (speed advisory) ARF (0.75) was assumed to be high; the system is proving very successful in field applications (i.e., Roosevelt Tunnel in Colorado). The ARFs for the traditional applications - warning signs (0.23) and chevrons (0.25) - were taken from Agent, Stamatiadis and Jones. [16]

Spot Location Benefit-cost Analysis

Spot location benefits, costs and benefit-cost ratios are estimated below.

Benefits

Tables 14-19 approximate the financial benefits to be gained at site-specific locations through countermeasure deployment. A detailed description of the benefit estimation process using FHWA's economic costs is provided in Appendix I. Accidents likely mitigated by the countermeasures were separated from unrelated accidents. For example, this analysis assumed that AHS would have negligible effects on drivers who are chemically intoxicated. These "target" accidents were then multiplied by the appropriate ARF. Costs were assigned to the accident reduction. All benefits are expressed in annual terms.

Table 14 - Annual Benefits With Friction/Ice Detection

Location	Annual Cost Contributed By Trend	Annual Benefit
Montana U.S. Highway 191		
MP 9.900 – 10.011	$910,133	$409,560
MP 10.000 – 11.000	$903,666	$406,650
MP 59.000 – 60.000	$138,600	$62,370
MP 61.000 – 61.400	$6,733	$3,030
MP 1.000 – 2.000	$12,666	$5,700
Idaho U.S. Highway 20		
MP 405.000 – 406.000	$47,393	$21,326

Table 15 -Annual Benefits with Static Ice Warning Sign

Location	Annual Cost Contributed By Trend	Annual Benefit
Montana U.S. Highway 191		
MP 9.900 – 10.011	$910,133	$209,330
MP 10.000 – 11.000	$903,666	$207,843
MP 59.000 – 60.000	$138,600	$31,878
MP 61.000 – 61.400	$6,733	$1,548
MP 1.000 – 2.000	$12,666	$2,913
Idaho U.S. Highway 20		
MP 405.000 – 406.000	$47,393	$10,900

Table 16 - Annual Benefits with Intersection Crossing Detection

Location	Annual Cost Contributed By Trend	Annual Benefit
Idaho U.S. Highway 20		
MP 311.000 – 312.000	$411,203.67	$205,601.83
MP 317.000 – 318.000	$713,591.67	$356,795.83
MP 328.000 – 329.000	$184,238.67	$92,119.33
MP 338.000 – 339.000	$232,965.00	$116,482.50
Idaho U.S. Highway 26		
MP 335.000 – 336.000	$144,845.67	$72,422.83
MP 336.000 – 337.000	$1,329,263.33	$664,631.67
MP 338.000 – 339.000	$320,417.67	$160,208.83

Table 17 - Annual Benefits with Animal-Vehicle Collision Warning

Location	Annual Cost Contributed By Trend	Annual Benefit
Montana U.S. Highway 191		
MP 28.000 – 28.900	$600.00	$120.00
Wyoming U.S. Highway 89		
MP 160.000 – 161.000	$27,363.33	$5,472.66
MP 167.000 – 168.000	$4,000	$800
MP 185.000 – 186.000	$7,333.33	$1,466.67
MP 189.000 – 190.000	$26,030.00	$5,206
Yellowstone National Park U.S. Highway 89		
MP 21.034 – 21.834	$5,333.33	$1,066.67

Table 18 - Annual Benefits with Dynamic Variable Message Sign

Location	Annual Cost Contributed By Trend	Annual Benefit
Wyoming U.S. Highway 89		
MP 127.000 – 128.000	$502.656.33	$376,992.25

Table 19 - Annual Benefits with Chevrons

Location	Annual Cost Contributed By Trend	Annual Benefit
Wyoming U.S. Highway 89		
MP 127.000 – 128.000	$614	$125,664

Costs

Table 20 provides the approximate capital cost for each system considered for spot location deployment. Each cost was developed assuming the existance of a power source, if needed. These costs, in combination with the aforementioned monetary benefits, were used to estimate benefit-cost ratios.

Benefit-cost Ratios

Tables 21 through 26 present the benefit-cost ratios for each of the spot location countermeasures. The benefit-cost ratios were developed by dividing the projected annual benefits by the projected annual cost (see Appendix K). The spot locations with the highest benefit-cost ratio should be targeted as early deployment locations.

The traditional, low-tech countermeasures had high benefit-cost ratios, skewed primarily by their extreme relative low cost of materials and installation and their long cycle life. Most of the more advanced countermeasures have favorable benefit-cost ratios, but not as high as the traditional countermeasures. The ARFs used for estimating advanced technology benefits were conservative; higher accident reductions may be realized when the technology is deployed and evaluated.

Table 20 - Estimated Spot Location System Costs

System	Cost
Friction/ice detection and warning systems	$111,620
Traditional "icy warning sign"	$107
Intersection crossing detection	$34,589
Animal-vehicle safety warning system	$3,800
Dynamic variable message sign (speed advisory)	$4,000
Chevrons	$614

Table 21 - Benefit-cost with Friction/Ice Detection System

Location	Benefit-cost Ratio
Montana U.S. Highway 191	
MP 9.900 – 10.011	25:1
MP 10.000 – 11.000	24:1
MP 59.000 – 60.000	4:1
MP 61.000 – 61.400	0.18:1
MP 1.000 – 2.000	0.34:1
Idaho U.S. Highway 20	
MP 405.000 – 406.000	1:1

Table 22 - Benefit-cost with Static Ice Warning Sign

Location	Benefit-cost Ratio
Montana U.S. Highway 191	
MP 9.900 – 10.011	14,659:1
MP 10.000 – 11.000	14,554:1
MP 59.000 – 60.000	2,232:1
MP 61.000 – 61.400	108:1
MP 1.000 – 2.000	204:1
Idaho U.S. Highway 20	
MP 405.000 – 406.000	763:1

Table 23 - Benefit-cost with Intersection Crossing Detection

Location	Benefit-cost Ratio
Idaho U.S. Highway 20	
MP 311.000 – 312.000	40:1
MP 317.000 – 318.000	69:1
MP 328.000 – 329.000	17:1
MP 338.000 – 339.000	23:1
Idaho U.S. Highway 26	
MP 335.000 – 336.000	14:1
MP 336.000 – 337.000	129:1
MP 338.000 – 339.000	31:1

Table 24 - Benefit-cost with Animal-Vehicle Collision Warning

Location	Benefit-cost Ratio
Montana U.S. Highway 191	
MP 28.000 – 28.900	0.21:1
Wyoming U.S. Highway 89	
MP 160.000 – 161.000	10:1
MP 167.000 – 168.000	1.4:1
MP 185.000 – 186.000	3:1
MP 189.000 – 190.000	9:1
Yellowstone National Park U.S. Highway 89	
MP 21.034 – 21.834	2:1

Table 25 - Benefit-cost with Dynamic Variable Message Sign

Location	Benefit-cost Ratio
Wyoming U.S. Highway 89	
MP 127.000 – 128.000	632:1

Table 26 - Benefit-cost with Chevrons

Location	Benefit-cost Ratio
Wyoming U.S. Highway 89	
MP 127.000 – 128.000	1540:1

Regional Analysis

Regional benefits, costs and benefit-cost ratios are estimated below.

Benefits

Table 27 approximates the financial benefit for each regional section of highway. Benefits vary depending upon the service level of AHS (i.e., information assistance, control assistance, full automation). The benefit data presented here assumes 100 percent market penetration at each service level. The benefits were estimated using the same methodology used for the spot location applications, but a broader subset of accidents were assumed to be mitigated. Appendix J provides a more detailed breakdown of benefits by accident causal factor. Again, all benefits are expressed in annual terms.

Costs

Table 28 approximates the capital cost for the infrastructure installation of lateral magnetic guidance and warning systems, under consideration for deployment at regional sections. These costs were combined with the aforementioned monetary system benefits to produce benefit-cost ratios.

Benefit-cost Ratios

Table 29 presents the benefit-cost ratios for each of the regional highway segments. These calculations assume 100 percent vehicle fleet market penetration.

AHS, with lateral warning and assistance systems, are attractive countermeasures for improving safety within the GYRITS corridor due to their ability to mitigate a wide range of accidents. The collision avoidance systems can help reduce the severity and frequency of accidents within the corridor, saving both money and lives.

Table 27 - Annual Regional Benefits with AHS

	Annual Financial Benefit		
Location	**Information Assistance**	**Control Assistance**	**Full Automation**
Montana U.S. Highway 191			
MP 0.000 – 10.835	$ 482,716	$1,154,983	$1,345,000
MP 10.836 – 66.826	$ 1,647,950	$4,448,683	$5,198,000
MP 66.827 – 81.903	$1,124,166	$2,339,500	$2,581,333
Montana U.S. Highway 89			
MP 0.000 – 51.812	$643,683	$1,576,183	$1,828,666
MP 51.813 – 53.068	$ 113,700	$212,600	$227,333
Montana U.S. Highway 20			
MP 0.000 – 3.000	$98,416	$193,800	$220,333
MP 3.001 – 9.397	$312,516	$874,183	$1,027,333
Idaho U.S. Highway 20			
MP 308.717 – 353.050	$ 5,205,932	$7,340,406	$8,197,450
MP 353.051 – 401.300	$ 2,765,106	$7,090,389	$8,237,174
MP 401.301 – 406.300	$60,570	$108,483	$120,871
Idaho U.S. Highway 26			
MP 335.255 – 338.069	$992,358	$1,778,401	$2,026,710
MP 338.070 – 375.538	$1,349,893	$2,876,419	$3,268,250
MP 375.539 – 402.500	$498,579	$1,241,874	$1,433,647
Wyoming U.S. Highway 26			
MP 0.000 – 2.370	$8,712	$22,801	$26,707
Wyoming U.S. Highway 89			
MP 118.320 – 152.090	$2,179,625	$5,324,161	$6,124,796
MP 155.211 – 165.000	$672,246	$1,637,940	$1,873,090
MP 165.000 – 211.620	$962,665	$2,033,252	$2,310,630
Yellowstone National Park U.S. Highway 89			
MP 0.000 – 93.446	$2,055,447	$4,016,507	$4,500,617

Table 28 - Infrastructure Costs for Lateral Guidance

System	Cost
PATH magnetic nails	$17,000 per lane per mile
3M magnetic tape	$26,000 per lane per mile for 5-10 miles $23,760 per lane per mile for 10.1 miles or more

Table 29 - Benefit-cost Ratio with Regional Deployment

	Benefit-cost Ratios		
Location	**Information Assistance**	**Control Assistance**	**Full Automation**
Montana U.S. Highway 191			
MP 0.000 – 10.835	9:1	21:1	25:1
MP 10.836 – 66.826	6:1	16:1	18:1
MP 66.827 – 81.903	15:1	31:1	34:1
Montana U.S. Highway 89			
MP 0.000 – 51.812	2:1	6:1	7:1
MP 51.813 – 53.068	18:1	33:1	36:1
Montana U.S. Highway 20			
MP 0.000 – 3.000	6:1	13:1	15:1
MP 3.001 – 9.397	10:1	27:1	32:1
Idaho U.S. Highway 20			
MP 308.717 – 353.050	23:1	33:1	37:1
MP 353.051 – 401.300	11:1	29:1	34:1
MP 401.301 – 406.300	2:1	4:1	5:1
Idaho U.S. Highway 26			
MP 335.255 – 338.069	70:1	125:1	142:1
MP 338.070 – 375.538	7:1	15:1	17:1
MP 375.539 – 402.500	4:1	9:1	11:1
Wyoming U.S. Highway 26			
MP 0.000 – 2.370	1:1	2:1	2:1
Wyoming U.S. Highway 89			
MP 118.320 – 152.090	13:1	31:1	36:1

MP 155.211 – 165.000	14:1	33:1	38:1
MP 165.000 – 211.620	4:1	9:1	10:1
Yellowstone National Park U.S. Highway 89			
MP 0.000 – 93.446	4:1	8:1	10:1

Deployment Vision Benefit-cost Analysis

Benefit-cost ratios on the basis of the deployment vision are estimated below.

Benefits

In an effort to more accurately project AHS impacts, assumptions from the deployment vision were included in the analysis. The Information Assistance service level is projected out 10 years assuming a four-percent inflation rate and a 20 percent vehicle fleet penetration (see Table 30). The Control Assistance service level is projected out 20 years assuming a four-percent inflation rate and a 50 percent vehicle fleet penetration. The Full Automation service level was omitted; it was assumed inappropriate for rural two-lane highways.

Costs

The capital costs previously estimated for the regional benefit-cost analysis (i.e., the infrastructure installation of the lateral magnetic guidance and warning system) were used here. These costs were combined with the aforementioned deployment vision monetary benefits to produce benefit-cost ratios.

Benefit-cost Ratios

Table 31 presents more realistic benefit-cost ratios based on predicted vehicle fleet market penetration as indicated in the deployment vision.

Note the importance of vehicle fleet penetration and AHS service level on benefit-cost ratios for full-scale regional deployment. Many regions were deemed inappropriate for the installation of AHS infrastructure due to low benefit-cost ratios, likely resulting from the relatively low vehicle fleet market penetration. Lower ARFs also resulted in lower benefit-cost ratios for the Information Assistance service level.

Table 30 - AHS Benefits with Deployment Vision

	Annual Financial Benefit	
Location	**Information Assistance** 20% penetration after 10 years	**Control Assistance** 50% penetration after 20 years
Montana U.S. Highway 191		
MP 0.000 – 10.835	$142,907	$1,265,353
MP 10.836 – 66.826	$487,872	$4,873,799
MP 66.827 – 81.903	$332,807	$2,563,062
Montana U.S. Highway 89		
MP 0.000 – 51.812	$190,561	$1,726,803
MP 51.813 – 53.068	$33,660	$232,916
Montana U.S. Highway 20		
MP 0.000 – 3.000	$29,136	$212,319
MP 3.001 – 9.397	$92,519	$957,720
Idaho U.S. Highway 20		
MP 308.717 – 353.050	$1,541,205	$8,041,856
MP 353.051 – 401.300	$818,604	$7,767,946
MP 401.301 – 406.300	$17,931	$118,850
Idaho U.S. Highway 26		
MP 335.255 – 338.069	$293,785	$1,948,345
MP 338.070 – 375.538	$399,633	$3,151,290
MP 375.539 – 402.500	$147,603	$1,360,548
Wyoming U.S. Highway 26		
MP 0.000 – 2.370	$2,579	$24,980
Wyoming U.S. Highway 89		
MP 118.320 – 152.090	$645,273	$5,832,938
MP 155.211 – 165.000	$199,017	$1,794,461
MP 165.000 – 211.620	$284,995	$2,227,550
Yellowstone National Park U.S. Highway 89		
MP 0.000 – 93.446	$608,511	$4,400,325

Table 31 - Benefit-cost Ratio Based on Deployment Vision

	Benefit-cost Ratios	
Location	**Information Assistance** 20% penetration after 10 years	**Control Assistance** 50% penetration after 20 years
Montana U.S. Highway 191		
MP 0.000 – 10.835	3:1	23:1
MP 10.836 – 66.826	2:1	17:1
MP 66.827 – 81.903	4:1	34:1
Montana U.S. Highway 89		
MP 0.000 – 51.812	0.007:1	0.07:1
MP 51.813 – 53.068	5:1	37:1
Montana U.S. Highway 20		
MP 0.000 – 3.000	2:1	14:1
MP 3.001 – 9.397	0.02:1	0.2:1
Idaho U.S. Highway 20		
MP 308.717 – 353.050	7:1	36:1
MP 353.051 – 401.300	3:1	32:1
MP 401.301 – 406.300	0.7:1	5:1
Idaho U.S. Highway 26		
MP 335.255 – 338.069	20:1	137:1
MP 338.070 – 375.538	2:1	17:1
MP 375.539 – 402.500	1:1	10:1
Wyoming U.S. Highway 26		
MP 0.000 – 2.370	0.2:1	2:1
Wyoming U.S. Highway 89		
MP 118.320 – 152.090	4:1	34:1
MP 155.211 – 165.000	4:1	36:1
MP 165.000 – 211.620	1:1	9:1
Yellowstone National Park U.S. Highway 89		
MP 0.000 – 93.446	1:1	9:1

NEXT STEPS

Candidate Field Operational Tests

Field operational tests (FOTs) encourage support for the deployment of advanced transportation technologies. Through field operational tests, "proof of technology" can be demonstrated. The proliferation of AHS will not emerge until components of AHS are successfully demonstrated. Through the successful demonstration of "showcase" projects, AHS can win the support of both transportation providers and users. Automated Highway Systems must demonstrate tangible safety benefits to support the theoretical accident reduction claims made by researchers.

This section recommends several areas for possible early field operational testing with low-level AHS technology. The intent of the recommended FOTs is to provide the driver with more information and more time to react. It is hypothesized that this additional information and time will help the driver avoid many collisions. Through the benefit-cost analysis, sites with the greatest potential were selected for AHS technology deployment in continuing efforts. The candidate sites include:

Friction/Ice Detection and Warning System

- Montana U.S. Highway 191, milepost 9.900 to 10.011 and 10.000 to 11.000;

Intersection Crossing Detection

- Idaho U.S. Highway 26, milepost 336.000 to 337.000;
- Idaho U.S. Highway 20, milepost 317.000 to 318.000 and 311.000 to 312.000;

Animal-Vehicle Collision Avoidance

- Wyoming U.S. Highway 89, milepost 160.000 to 161.000 and 189.000 to 190.000;

Horizontal Curve Speed Advisory

- Wyoming U.S. Highway 89, milepost 127.000 to 128.000.

These sites were estimated to have the greatest potential for improving safety in the GYRITS corridor through the deployment of AHS. However, before any of the above sites are designated as FOTs, further investigation of the police accident records, the site, and the transportation providers' perspectives needs to occur.

Measures of Effectiveness

As stated earlier in the deployment vision, the objective of this effort is to make travel within the GYRITS corridor safer. This objective will predictably be attained through the systematic application of advanced transportation technologies. Specific measures of effectiveness (MOEs) should be developed to gage the attainment of the longer-term objective. Specifically, MOEs serve to:

- assess the system improvements;
- quantify associated benefits and costs; and
- communicate deployment results to technical and non-technical audiences.

For this study, system effectiveness centers on improving safety, including reducing accidents and reducing vehicle speeds. Selection of the MOEs is critical in determining system effectiveness. For the GYRITS corridor, there were four spot location advanced technologies considered for deployment. At these four locations, the following MOEs are recommended to determine system performance.

Goals:
- Increase safety

Objectives:
- Assess accident causal factors
- Assess driver/roadway operation characteristics
- Assess impact of weather on accidents
- Assess impact of vehicle mix on safety

MOEs:
- Accident rates per million vehicle-miles traveled
- Total accident reduction
- Speed reductions

Each of these MOEs should be evaluated with statistically valid before-after analyses (see Appendix L).

Similar MOEs can be developed for the regional deployment sections. Because regional deployment measures affect a broader range of accident types, a broader base of MOEs should be used to evaluate system performance. Regional MOEs may include:

- number of annual crashes
- number of annual fatalities
- annual fatality rates
- annual number of injuries
- annual injury rates

- annual injury rate
- injury severity index
- accident rates per million miles traveled (kilometer miles traveled)
- annual cost of injuries
- infrastructure damage

The MOEs presented above provide a method to quantify the safety improvements resulting from AHS deployments in the GYRITS corridor. Quantitative analysis considers system performance from an equipment-related perspective, as well. Did the system operate within the guidelines and specifications that were intended? Qualitative methods may also be used to evaluate system performance from a human factor perspective. The qualitative evaluation is non-technical but evaluates any possible improvements in quality of life for the transportation users and/or providers.

REFERENCES

1. United States Department of Transportation. Fatal Accident Reporting System. 1994.

2. The Diebold Institute for Policy Studies. Transportation Infrastructure , the Development of Intelligent Transportation Systems. 1995.

3. Hult, Dennis. Montana Department of Transportation, Telephone Interview. 9 July 1997.

4. "Intelligent Transportation Systems: The National Program." www.wsdot.wa.gov/comission.ATTP/04National.htm. Online. 10 April 1997.

5. "Historical Background of Automated Highway Systems." nahsc.volpe.dot.gov/history.html. Online. National Automated Highway System Consortium, 1 Dec. 1997.

6. BRW, Inc. Alternative Transportation Modes Feasibility Study: Yellowstone National Park. Volume III. United States Department of the Interior, July 1994.

7. "Western Regional Climate Center." wrcc.sage.dri.edu/. Online. 11 March 1997.

8. International Conference of Building Officials. Uniform Building Code. 1994.

9. Garber, J. Nicholas, and Lester A. Hoel. Traffic and Highway Engineering. Minnesota: West Publishing Company, 1988, 140-141.

10. National Highway Traffic Safety Administration. Traffic Safety Fact. United States Department of Transportation, 1996.

11. National Automated Highway Systems Consortium. System Objectives and Charateristics. 5 Oct. 1995.

12. JHK. Preliminary Assessement of Rural Applications of Advanced Traveler Information Systems.

13. "Cost/Benefit Analysis of Automated Highway Systems." ahs.volpe.dot.gov/psadocs/task/task_p/patexc_p.html. Partners for Advanced Transit and Highways, 29 Dec. 1997.

14. SRI. Precursor System Analyses of Automated Highway Systems: Lateral and Longitudinal Control Analysis. FHWA-RD-95-052, Federal Highway Administration, 1995.

15. Yokota, Toshiyaki, Hideo Tokuyama and Satshi Veda. Cost-Benefit Analysis for Implementation of Automated Highway Systems. Fourth Annual World Congress on Intelligent Transportation Systems, ICC Berlin, Germany. 21-24 Oct. 1997.

16. Agent, Kenneth R., Nikiforos Stamatiudis and Samantha Jones. Development of Accident Reduction Factors. June 1996.

17. Fancher, P., L. Kostyniak, D. Massie, R. Ervin, K. Gilbert, M. Reiley, C. Mink, S. Bogard, P. Zoratti. Potential Safety Applications of Advanced Technology. FHWA-RD-93-080, Federal Highway Administration 1995.

18. Kilareski, Walter P. Tort Liability Workshop. Federal Highway Administration.

19. Delco. Precursor System Analyses of Automated Highway Systems: Institutional and Societal Aspects. FHWA-RD-95-151, Federal Highway Administration, Jan. 1996. 14-30.

20. Battelle. Precursor System Analyses of Automated Highway Systems: Institutional and Societal Aspects. FHWA-RD-95-045, Federal Highway Administration, Jan. 1996. 67-85.

21. Calspan. Precursor System Analyses of Automated Highway Systems: Institutional and Societal Aspects. FHWA-RD-95-135, Federal Highway Administration, Jan. 1996. 12-46.

22. BDM. Precursor System Analyses of Automated Highway Systems: Institutional and Societal Aspects. FHWA-RD-96-046, Federal Highway Administration, Jan. 1996. 12-30.

23. Battelle. Precursor System Analyses of Automated Highway Systems: Urban and Rural AHS Analysis. FHWA-RD-95-043, Federal Highway Administration, Jan. 1996.

24. Deeter, D. and C. E. Bland. Technology in Rural Transportation: "Simple Solutions." FHWA-RD-97-108. Federal Highway Administration, July 1997.

25. Euler, Gary W. and H. Douglas Robertson. National Intelligent Transportation Systems Program Plan. Volume I. Virginia: ITS America, March 1995.

26. Advanced Rural Transportation Systems. Strategic Plan. Washington: United States Department of Transportation, Aug. 1997.

27. Najm, Wassim G. and August L. Burgett. Benefits Estimation for Selected Collision Avoidance Systems. Fourth Annual World Congress on Intelligent Transportation Systems, ICC Berlin, Germany. 21-24 Oct. 1997.

28. Pomerleau, Dean. Charles Thorpe and Lloyd Emery. Performance Specification Development For Roadway Departure Collision Avoidance Systems. Fourth Annual World Congress on Intelligent Transportation Systems, ICC Berlin, Germany. 21-24 Oct. 1997.

30. PATH. Preliminary Cost/Benefit Factors Analysis of Automated Highway Systems. FHWA-RD-95-155. Federal Highway Administration, 1994.

31. Calspan. Preliminary Cost/Benefit Factors Analysis of Automated Highway Systems. FHWA-RD-95-135. Federal Highway Administration, 1995.
32. "Current AVCS Deployment."ahs.volpe.dot.gov/avcsdoc/inuse.html. 31 Dec. 1997.

33. National Automated Highway System Consortium. "AHS Objectives and Characteristics." nahsc.volpe.dot.gov/sect2.html#A1. 1 Dec. 1997.

C3 Interim Report

10.6 Consensus

Includes:
10.6.1 Meeting Minutes from Conferences
10.6.2 Stakeholder Forum Summary Report
10.6.3 Post Demo Survey

NAHSC

10.6.1 Meeting Minutes from Conferences

One-Page Executive Summary

I. The questionnaires worked.
Our basic approach of presenting stakeholder-friendly formats to stakeholders and asking them to rank them and provide other information proved very successful in generating a great deal of useful information.

II. The stakeholders ranked the six Choices in reasonable ways that could be analyzed to produce useful results to support Consortium decisions -- to make Consortium development user-driven, needs-driven.
The results presented in Section II below demonstrate that we can get meaningful prioritizations over Stakeholder Choices from stakeholder responses to a questionnaire. We were also able to consolidate the ranking rationales based on many stakeholder responses. Those rationales showed the prominence of safety and need in prioritization, as well as several reasons why most but not all stakeholders favor vehicle-only Choices over Choices involving infrastructure or cooperative vehicles. That last finding is quite important for our planning: Yes, at some ideal level users shouldn't care if infrastructure is involved or not, but in fact, even when the performance advantages of infrastructure assistance and vehicle cooperation were pointed out, there was a pronounced vote in favor of vehicle-only Choices.

III. 26% of the stakeholders wanted to know more than the information provided in the format in order to rank Stakeholder Choices by attractiveness. And they told us what they wanted to know.
However, the only specific information identified as desirable was cost and a specification of the obstacles that could be detected. It's a judgment call, but I feel that as soon as that information can be meaningfully specified, at least at the example level for example Stakeholder Choices, we should try out adding it in to the formats. We can specify the obstacle detection performance by fiat. We can specify example costs by fiat, too, though we might want to experiment with error bars on that.

IV. 64% of stakeholders want us to specify performance, and they told us what they wanted specified.
We should try specifying that performance, but we should do that carefully, since we don't want to make the stakeholder-friendly formats too complex. Many of the performance specifications requested by the stakeholders are fairly technical. Here is the list of those specifications requested by at least two respondents:

- distance ranges of detection, and corresponding required reaction times.
- reliability, Mean Time Between Failure (MTBF), are they fail-safe.
- false alarm rates.
- estimated % reduction in accidents by driver type, situation; % deaths avoided; associated savings.
- safe usage speed
- types of obstacles that can be detected, including a pedestrian?
- operational under what roadway conditions, i.e., weather such as snow, rain, fog, etc.

V. 66% of the respondents had ideas about the presentation formats
The primary recommendations: use pictures and graphics, use a graphic designer, use a clearer layout and less technical language, consider using a short video for each Choice scenario.

VI. 53% of the respondents listed User Services they would be "most interested in."
Section VI below lists those User Services. There were no clear insights gained except the list itself.

VII. The miscellaneous responses, while interesting, did not provide any clear insights.

The reader is referred to the "Misc" sheet of the attached spreadsheet to read those responses.

Introduction

We presented a questionnaire at the ITS Midwest meeting in Chicago April 25. A copy of that questionnaire is included as Appendix A. This memo summarizes my analysis of the results of that questionnaire. This memo will be transmitted to you two ways:

- Fax, since that is the easiest way to present to you the spreadsheet printout of the responses.
- Email, two files: This memo as attached Word 6.0, then the spreadsheet itself, which is sheeted such that you can printout the first seven sheets and get the same results as are faxed to you. The last sheet is the complete spreadsheet.

I've removed the name/address/phone information from what I'm sending you, but will send you a fax of that information if you request it.

The Results section presents seven sections of results, summarized on one page in the Executive Summary above. Appendix A presents the questionnaire. The fax version includes the presentation sheets from the spreadsheet of the 59 responses.

Results

I. The questionnaires worked.

- 59 of the about 65 people in the audience turned in responses, about 90%.
- 58 of those 59 ranked the six "User Services" (That's what we called them, but we should have named them something else. For want of a better term, I'll call them Stakeholder Choices here.). 14 of those 58 ranked them even though they said that the descriptions did not tell them enough to rank them.
- 49 of those 58 listed rationales for their rankings.

Those response rates are phenomenal. While we need to work on the formats (as we shall see in this analysis), clearly the basic idea is sound. We are planning the June Forum not around questionnaires but around group elicitation, because that is the best protocol for the time available. Still, the response rate to these questionnaires shows our basic idea is sound: stakeholder-friendly formats of "Stakeholder Choices" (whatever we call them, and they are not pure User Services or Market Packages) and asking for ranking and other information.

II. The stakeholders ranked the six Choices in reasonable ways that could be analyzed to produce useful results to support Consortium decisions -- to make Consortium development user-driven, needs-driven.

These results are based on Questions 3 and 4:

3. To the extent that you can rank the user services based on what we have told you, please rank them, with 1 being the most attractive, 6 being the least attractive, and ties allowed.
4. Why? That is, please explain your ranking.

Remember that the six Stakeholder Choices were not picked to represent "the six things the Consortium is considering developing", but were picked to form a constructive basis for eliciting preferences from stakeholders. So the significance of these results is not only that "Lane-Change Warning - vehicle only" came out on top (though that and the rest of the ranking information is significant), but also that this format and these types of questions can yield useful results.

We'll start out with a table summarizing the ranking information by stakeholder group:

Question #:				3: Rank		Best 1		Best 2		Best 3	Best 4	
		Obstacle		Closing Rate		Lane Change					L-V	
		vehicle	infra	vehicle	infra	vehicle	coop'v		L-V	L-V	R-V	
Stakeholder		only	assist'd	only	assist'd	only	veh's	L-V	R-V	R-V	O-I	Stakeholder Group Name
Group	N	O-V	O-I	R-V	R-I	L-V	L-C	R-V	L-C	O-I	L-C	Explanation
PDU	15	4	5	3	6	1	2	1	1	1	1	Private Direct User
DOT	17	5	4	3	6	1	2	1	1	1	1	
MPO	1	4	6	3	5	1	2	1	1	1	1	
Toll Auth	2	1.5	4.5	3	6	1.5	4.5	1.5	1.5	1.5	1.5	
Transit Op'r	2	5	6	3.5	3.5	1.5	1.5	1.5	1.5	1.5	1.5	
CVO	2	5	5	1	2	3	5	1	1	1	1	Commercial Veh Operator
Veh Elec	6	3	1	4.5	4.5	2	6	2	2	1	1	Veh Electronics Manufacturer
InfraDes/Bld	9	3.5	6	1	5	2	3.5	1	1	1	1	Infra Designer / Builder
Reg'lLUPlng	1	6	5	4	3	2	1	2	1	2	1	Regional Land Use Planner
University	2	3	4	5	6	1	2	1	1	1	1	
ProjMgtCns	1	5	1.5	5	5	3	1.5	3	1.5	1.5	1.5	Project Management Consultant
Business	1	5	6	4	3	2	1	2	1	2	1	
SUM =	59	O-V	O-I	R-V	R-I	L-V	L-C					
max =		6	6	5	6	3	6	3	2	2	1.5	
rank of max =		4.5	4.5	2	4.5	1	4.5					
Average =		4.2	4.5	3.3	4.6	1.8	2.7	1.5	1.2	1.3	1.1	
rank of average =		4	5	3	6	1	2					
N-weighted average =		4.1	4.4	2.9	5.3	1.4	2.8	1.2	1.1	1.1	1.0	
rank of N-weighted avg =		4	5	3	6	1	2					
		underlined cells = improved ranking by adding last service										

In the body of the table, each cell entry is a rank averaged over the individual respondents in the stakeholder group. The "Best 2" through "Best 4" columns show the highest rank for each stakeholder group for that combination of Stakeholder Choices. The "max" through "rank of N-weighted avg" rows at the bottom should be self-explanatory.

Note first that the ranking of Stakeholder Choices by average rank is the same whether we average over the 12 stakeholder groups (rank of average) or the 59 respondents (rank of N-weighted average):

1. Lane-Change Warning vehicle only
2. Lane-Change Warning cooperative vehicles
3. Closing-Rate Warning vehicle only
4. Obstacle Warning vehicle only
5. Obstacle Warning infra assisted
6. Closing-Rate Warning infra assisted

In fact, this ranking is the same as for Private Direct User considered alone, and is only one reversal away from the DOT stakeholder group considered alone.

Note second that the vehicle-only version of each Choice is ranked above the infrastructure-assisted or cooperative-vehicle version everywhere in the table, for all stakeholder groups, except for three one-person groups and for the Obstacle Warning for the DOT and Vehicle Electronics groups.

But that isn't the only thing we are interested in. We are perhaps more interested in Breadth of Support over stakeholders. That can be measured by the maximum (lowest, i.e., highest-numbered) rank, presented in the "max" row, since a good indicator of breadth of support is how well-served is the stakeholder group that is <u>least</u> well-served by the Choice. That is sobering, in that all but one of the Choices is the least favorite or second least favorite of at least one stakeholder group! If we limit the Breadth of Support measures to the Market Setters (the max ranks of the top six stakeholder groups), and we break the two ties with industry (Veh Elec and InfraDes/Bld) Breadth of Support, then we get the following ranking:

1. Lane-Change Warning	vehicle only
2. Closing-Rate Warning	vehicle only
3. Obstacle Warning	vehicle only
4. Lane-Change Warning	cooperative vehicles
5. Closing-Rate Warning	infra assisted
6. Obstacle Warning	infra assisted

That ranking only conflicts once with the InfraDes/Bld group, conflicts three times with the Veh Elec group, and conflicts twice with those two industry groups taken together.

But now let's get strategic and look at what combinations (portfolios) of Choices provide the best Breadth of Support. Those are indicated in the table as "Best 1," Best 2," "Best 3," and "Best 4." Those are derived by the Breadth of Support logic presented above, but now assuming each stakeholder group judges the portfolio by the Choice within that portfolio that best serves it. So with that we get:

Best 1:	Lane-Change Warning	vehicle only
Best 2: add	Closing-Rate Warning	vehicle only
Best 3: add	Obstacle Warning	infra assisted
Best 4: add	Lane-Change Warning	cooperative vehicles

This strategy results in a very different Choice selection by the Consortium than the ones presented earlier, since it is based not on average desirability, but on the more strategic idea of picking a portfolio of Choices that, taken together, has the broadest appeal across stakeholder groups. Strictly speaking, going by ranks alone the Best 3 should be different from the one listed here, but we weighted the improvement in rank by Veh Elec (six people) from 6 to 1 as more important than two other smaller (from 2 to 1) improvements to minor, single-person stakeholder groups.

But now let's look behind the rankings to see the rationales typically cited by the stakeholders for their rankings. The rationales are closely paraphrased and typically copied verbatim on the "<u>Rankings</u>" sheet of the spreadsheet (sorted by stakeholder group), attached as an optical-fax page and as an emailed spreadsheet. I will only summarize comments made by more than one respondent of the 48 respondents who stated rationales:

- 16 respondents:
    - Safety: critical to, potential for injury and/or fatality, leading cause of accidents, probability
- 11 respondents:
    - perceived need, experience as a driver, "most drivers have serious problems with," "most significant problem," "critical function with very high priority," "most commonly encountered."
    - anti-infra and pro-veh-only: sometimes cited reasons:

        pro-veh-only: ease of implementation, easiest/fastest to get done, most cost effective, driver services rather than giving control to an automated system, "more feasible due to controlled environment in veh as opposed to inclement weather, cost is born by veh owner, cost effectiveness more efficient under private ownership, charge actual users who want those features," "perceived less cost, least amount of gov infra to support (both physical and administrative infra)."

        anti-infra: "can't seem to have the necessary added value," "No $ to equip infra."
- 6 respondents:
    - where assistance is most helpful, where driver most in need of assistance, frequency of occurrence

and difficulty of "manual" detection:

- 2 respondents:
  - pro-infra: Infra seems to add more benefits; for this system to work right, infra needs to work with veh.
  - importance, function, effectiveness for driver
  - tech feasibility, possibility in near term
  - perceived value vs perceived cost and operational burdens including false alarms (FAs); benefit/cost ratio (B/C).

III. 26% of the stakeholders wanted to know more than the information provided in the format in order to rank Stakeholder Choices by attractiveness. And they told us what they wanted to know.

These results are based on Questions 1 and 2:

1. Do these descriptions of services tell you enough for you to rank them by how attractive each of them is to you? Yes___ No___.
2. If "No," what else do you need to know?

- 15 of 58 answered Question 1 "No," and provided ideas in answering Question 2.
- 43 of 58 answered Question 1 "Yes," though of those, 11 still provided ideas in answering Question 2.
- All responses are provided (with some paraphrasing) on the "<u>NeedKnow</u>" sheet of the spreadsheet (sorted by stakeholder group), attached as an optical-fax page and as an emailed spreadsheet. I will only summarize comments made by more than one respondent:

What else do stakeholders need to know for them to rank Stakeholder Choices?

- 11 respondents:
  - Cost: Using words ranging from "would help" to "a major issue."
    7 of them had answered "No" to Q1, 4 had answered "Yes" to Q1.
    We'll abbreviate that as 7 requireds and 4 helpfuls.
- 3 respondents:
  - Details are not enough. Services are not well defined. Need detail on what devices.
  - Must define "obstacle." pedestrian/car/animal/chuckhole, would it also warn of unsafe closing rate?
- 2 respondents:
  - Errors. Explain reliability of friction estimates.
  - Nature of alarms (e.g., visual, audio).
  - False alarm rates.
  - Relative feasibility, what can practically be done.

IV. 64% of stakeholders want us to specify performance, and they told us what they wanted specified.

These results are based on Questions 5 and 6:

5. Would you prefer that we specify approximate performance for each of the above user services? Yes___ No ___
6. If "Yes," for each user service, in what terms would you like performance specified, and what levels or types of performance would you like that service to have on each of those dimensions?

- 35 of 55 answered Question 5 "Yes," and 26 of those provided ideas in answering Question 6.
- 20 of 55 answered Question 5 "No," though of those, 5 still provided ideas in answering Question 6.
- All responses are provided (with some paraphrasing) on the "<u>Perf'c</u>" sheet of the spreadsheet (sorted by stakeholder group), attached as an optical-fax page and as an emailed spreadsheet. I will only summarize comments made by more than one respondent. Note that the answers to this question overlap with those

in Result III above, about what other information would the stakeholder want to know in order to rank items.

In what terms would you like performance specified? Of the 31 respondents who provided ideas:

- 9 respondents:
  - distance ranges of detection, and corresponding required reaction times.
- 6 respondents:
  - reliability, mean time between failure (MTBF), are they fail-safe?
- 5 respondents:
  - false alarm (FA) rates.
- 4 respondents:
  - estimated % reduction in accidents for various driver groups and driving situations, % deaths avoided, associated savings.
- 3 respondents:
  - safe usage speed
  - types of obstacles that can be detected, including a pedestrian?
- 2 respondents:
  - operational under what roadway conditions, i.e., weather such as snow, rain, fog, etc.

V. 66% of the respondents had ideas about the presentation formats

These results are based on Question 7:

7. How could we make these presentation formats clearer?

- 39 of 59 provided ideas. 5 of those said the formats were clear enough; The other 34 had suggestions.
- All responses are provided (with some paraphrasing) on the "Format" sheet of the spreadsheet (sorted by stakeholder group), attached as an optical-fax page and as an emailed spreadsheet. I will only summarize comments made by more than one respondent. Note that the answers to this question overlap with those in Result III above, about what other information would the stakeholder want to know in order to rank items.

How could we make these presentation formats clearer? Of the 39 respondents who provided ideas:

- 12 respondents:
  - use pictures, diagrams, a simple graphic/picture for each scenario, enlist a graphic designer.
- 7 respondents:
  - Needs a clearer layout: Unclear if have separate items or duets. Provide better alignment or "bullets" to focus on each change condition, warning condition and action/reaction. Copy is difficult to read. Page is too busy. Don't like comment boxes. Boxes don't guide reader -- indentation would help reader understand the structure. Add wording or examples as to how the User Service can actually aid driver.
- 5 respondents:
  - Clear enough, keep it as it is, it's clearly simple. Giving more info may make the decision too complex. It is manageable, if not slightly confusing.
- 4 respondents:
  - Show a short animation video for each scenario
  - Need to describe conditions in terms more understandable to the general public. More detailed scenario descriptions. Many terms are too complex. Use full sentences. Use clearer language.
- 2 respondents:
  - Indicate cost, practical achievability.

VI. 53% of the respondents listed User Services they would be "most interested in."

These results are based on Question 8:

8. What user services would you be most interested in?

- 31 of 59 responded.
- All responses are provided (with some paraphrasing) on the "Usr Svcs" sheet of the spreadsheet (sorted by stakeholder group), attached as an optical-fax page and as an emailed spreadsheet. I will only summarize comments made by more than one respondent.

What user services would you be most interested in? Of the 31 respondents who provided ideas:

- 4 respondents:
  - lane departure and road departure warning
- 3 respondents:
  - aids to driver fatigue: wake me up with alarm if I fall asleep, lateral control re fatigue.
  - night visibility/detection: night vision, adjustable, via windshield? (older driver issue plus $ for lighting, NIMBY, urbanization concerns)
  - Lane-Change Warning.
- 2 respondents:
  - control of "other" motorist: control the "dumb" motorist in residential areas, keep idiot speeder/lane-changer under group management control.
  - trip guidance
  - detect road conditions. Such as pavement or bridge conditions, icing. Could be wholly infra-based, such as to prompt de-icing strategy.
  - Obstacle Warning.

VII. 22% of the respondents had "Miscellaneous Responses"

- 13 of the 59 respondents made written comments that did not fit well under any one question.
- All of those responses are provided (with some paraphrasing) on the "Misc" sheet of the spreadsheet (sorted by stakeholder group), attached as an optical-fax page and as an emailed spreadsheet. Only one issue was touched on by more than one respondent:
- 2 respondents:
  - There are no $ avail. to maintain basic roadway surface -- Therefore creating systems which depend on more infra are doomed in this environment. No $ to equip infra.

A-V. Obstacle Warning - Vehicle Only

Sounds alarm when obstacle detected

Obstacle detection limited to line - of - sight.

Driver can turn it off.

Scenario: Obstacle is detected in lane: Alarm warns you.

A-I. Obstacle Warning - Infrastructure Assisted

Same as Vehicle-Only, except in addition:

When in specially-equipped lane, sounds alarm even when obstacle not visible, around curve.

Specially-equipped lanes:

Roadside devices to detect and transmit obstacle location to upstream vehicles.
Those roadside devices are technically challenging to install and maintain.

B-V. Warning of Unsafe Closing Rate with Vehicle in Front - Vehicle Only

Several levels of alarm for successively more hazardous closing rates.

Accounts for road friction.

Driver can turn it off.

Scenarios: Car in front suddenly brakes: Alarm warns you
(the more hazardous the case, the more urgent the alarm).
Car cuts in front of you: Alarm warns you
(the more hazardous the case, the more urgent the alarm).

B-I. Warning of Unsafe Closing Rate with Vehicle in Front - Infra

Same as Vehicle-Only, except in addition:

When in specially-equipped lane, accounts for road friction better.

Specially-equipped lane:

Roadside devices to detect and transmit road friction to upstream vehicles.
Those roadside devices are technically challenging to install and maintain.

C-V. Unsafe Lane Change Warning - Vehicle Only

Sounds alarm when driver turns on blinker to change lanes or to merge,
if a vehicle is detected in that lane, including a vehicle in driver's "blind spot,"
or a vehicle in adjacent lane is overtaking from behind.

Driver can turn it off.

Scenarios: You want to change lanes.
As soon as you turn on your blinker to do that, the alarm sounds.
The system has detected a car coming up quickly from behind
in your target lane, making it unsafe for you to make your lane change.
You are merging on to a freeway. Your blinker is on.
As you start to merge, the alarm sounds.
The system has detected a car in your "blind spot."

C-C. Unsafe Lane Change Warning - Vehicle-Vehicle Cooperation

Same as Vehicle-Only, except in addition:

Able to detect and warn if specially-equipped vehicle two lanes over
is planning to change into the same lane you are.

Appendix A: Answer representing your particular stakeholder group. Page 2

Check One:

___ Vehicle Manufacturer
___ Vehicle Electronics Manufacturer
___ DOT
___ MPO
___ Societal Impacts, Environment
___ Other(please specify:)_______________
___ Infrastructure Designer / Builder
___ Transit Operator
___ Transit User
___ CVO
___ Insurance
___ Private Direct User

1. Do these descriptions of services tell you enough for you to rank them by how attractive each of them is to you?
   Yes___ No___.

2. If "No," what else do you need to know? (Use the back of the page if required.)

3. To the extent that you can rank the three user services based on what we have told you, please rank them, with 1 being the most attractive, 6 being the least attractive, and ties allowed:

A-V. vehicle-only ___	B-V. vehicle-only ___	C-V. vehicle-only ___
A-I. with infrastructure___	B-I. with infrastructure___	C-C. with vehicle-vehicle coop'n___

4. Why? That is, please explain your ranking:

5. Would you prefer that we specify approximate performance for each of the above user services?
   Yes ___ No ___

6. If "Yes," for each user service, in what terms would you like performance specified, and what levels or types of performance would you like that service to have on each of those dimensions? (Use the back of the page if required.)

7. How could we make these presentation formats clearer? (Use the back of the page if required.)

8. These user services are examples. We are developing a comprehensive list of user services. What user services would you be most interested in? (Use the back of the page if required.)

Optional but strongly preferred: Please give us your name, affiliation and phone #:

AUTOMATED HIGHWAY SYSTEM (AHS) PROGRAM

NAHSC WASHINGTON D.C. STAKEHOLDERS FORUM SUMMARY REPORT

JUNE 5-6, 1997

National Automated Highway System Consortium
3001 West Big Beaver, Suite 500
Troy, Michigan 48084

Table of Contents

1. Summary

The National Automated Highway System Consortium (NAHSC) held its Third Annual Stakeholder Forum in Washington, DC, in conjunction with the ITS America Annual Meeting. The forum, held on June 5-6, 1997, was attended by 100 stakeholder representatives and provided stakeholder interaction to gain industry-specific input on user needs and potential building blocks toward the implementation of automated highway systems (AHS). Attendees were also given a briefing on the Consortium's recent progress, and the upcoming Proof-of-Technical-Feasibility Demonstration.

Gene McCormick's opening remarks highlighted political support for the AHS program, and insights into the pending federal transportation legislation -- the NAHSC is a Congressionally mandated program requiring annual renewal.

The AHS program has been in existence for more than two years. Steve Carlton addressed the overall AHS program objectives and the current status of the program.

Bob McQueen, Jim Reynold, Evelyn Wagner and Chris Bausher provided technical presentations on the Consortium's user-driven approach to developing user needs into technical requirements and corresponding technology packages.

Breakout sessions with the stakeholders were facilitated by Consortium members and stakeholder representatives. These sessions allowed stakeholders to contribute to what is known about user needs and services, and further define who the potential users of AHS are. Stakeholders provided opinions on the Consortium's overall approach and methods of stakeholder involvement. This valuable input will be incorporated into future work plans.

The stakeholders were also presented with several examples of market packages -- the building blocks of AHS implementation. Feedback was extensive, showing that stakeholders are eager to be more involved in the Consortium's technical work as well as in the consideration of near-term market developments for planning the implementation of AHS.

The Consortium will continue to involve the stakeholder community in a needs-driven approach to the program. Future forums will focus on confirming user needs and the responding system architecture, specification and prototype of the National Automated Highway System.

2. Agenda

THURSDAY	JUNE 5, 1997
11:30-12:00	General Session
12:00-1:15	Working Lunch: "New Emphasis, New Vision"
1:15-1:30	Break
1:30-2:45	"Progressive Deployment, AVCSS, AHS User Services"
2:45-3:00	Break
3:00-4:15	Technical Breakout Groups on User Services
4:15-4:30	Break
4:30-5:30	Demonstration '97
5:30	Adjourn

FRIDAY	JUNE 6, 1997
8:00-9:00	Breakfast and General Session: "AVCSS and AHS Market Packages"
9:00-10:45	Technical Breakouts on Market Packages
11:00 - 12:00	Stakeholder Group Organizational Breakouts
12:00-12:15	Break
12:15-1:45	Working Lunch with Breakout Session Report Presentations
1:45	Adjourn

Technical Breakout Groups

Consumer
Commercial Vehicle Operators
Transit
Infrastructure
Cross-cutting

Stakeholder Breakout Groups

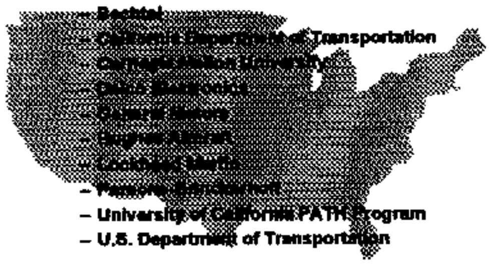
Government Agencies
Transit Operators
Highway Industry
Vehicle Electronics Industry
Vehicle Industry
Insurance Industry
Trucking Operators
Transportation Users

3. New Emphasis, New Vision

The National Automated Highway System Consortium is a group of 10 Core Participants working together to specify, define and prototype an automated highway system (AHS). Together with 124 Associate Participants, the Consortium is increasing their focus on early stages of progressive implementation. Some of the near-term goals of the Consortium is to build on the National ITS Architecture, add detail to the Advanced Vehicle Control and Safety Systems (AVCSS) and develop a staged implementation plan.

In the future the Consortium will increase emphasis on achieving near-term benefits with staged implementation market packages which will service user needs. The NAHSC will work more closely with NHTSA and put more emphasis on the earlier stages of an AHS. The Consortium will continue to conduct Case Studies in areas around the United States, the most promising of which may evolve into field tests. These Case Studies will work with public and private sector partners to evaluate feasibility and real world benefits. The long-term vision for the Consortium is to achieve a fully automated highway system through a staged implementation of market packages.

National AHS Consortium



- **10 Core Participants**
  - Bechtel
  - California Department of Transportation
  - Carnegie Mellon University
  - Delco Electronics
  - General Motors
  - Hughes Aircraft
  - Lockheed Martin
  - Parsons Brinckerhoff
  - University of California PATH Program
  - U.S. Department of Transportation
- **Plus 114 Associate Participants**

The Potential for AHS . . .

☑ **Improved Highway Safety**
- No Collisions in the Absence of System Malfunctions
- Fail-Safe System Design

☑ **Increased Highway Throughput**
- Double to Triple Today's Capacity per Lane
- Less Capacity Reduction Due to Incidents

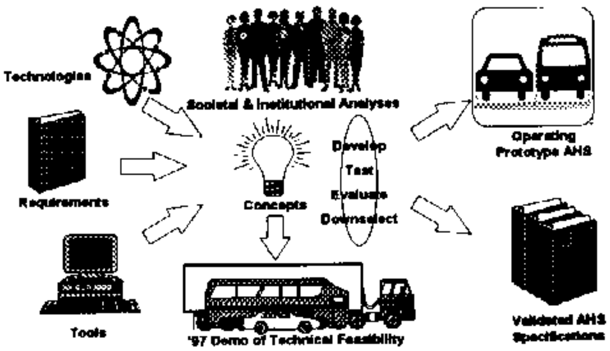
☑ **Enhanced Mobility**
- Shorter, More Predictable Trip Times for People and Freight
- Easier, More Reliable Travel in Inclement Weather

☑ **Reduced Environmental Impact**
- Less Need for Additional Highway Lanes
- Reduced Fuel Consumption and Exhaust Emissions

Mission

- **Specify, develop and demonstrate a prototype Automated Highway System. The specifications will provide for evolutionary deployment that can be tailored to meet regional and local transportation needs.**
- **Seek opportunities for early introduction of vehicle and highway automation technologies to achieve early benefits for all surface transportation users.**
- **Incorporate public and private stakeholder views to ensure that the AHS is economically, technically and socially viable.**

Program Elements



Concept Development

- A Three Stage, Five Year Effort to Produce a Complete AHS Concept that is-
  - Technically Feasible
  - Economically Viable
  - Socially Acceptable
  - Meets Goals for Safety, Mobility and the Environment
- Stages One and Two are Now Complete
- Stage Three is Focused on Selecting Specific Concept Attributes and Producing a Concept Design for Prototype

Key Concept Attributes

- Distribution of Intelligence
- Traffic Mix
- Vehicle Separation Policy
- Obstacle Management
- Role of Driver
- Deployment Sequencing

Operations Concept

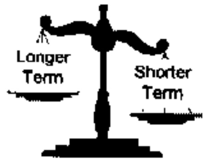
- Version I Distributed December 20, 1996
- Version II Draft Distributed March 26, 1997
- Two Operational Modes
  - Mixed Manual and Automated Vehicles
  - Dedicated Lanes for Automated Vehicles only
  - Fully Automated Vehicle Control
- Scope
  - Mature AHS
  - Bridge from SOC to Functional and Physical Design
  - Not Substitute for System Specification
  - No Requirements for Values in Operations Concept
- Editorial
  - NOT Compare Options (Benefits or Challenges)
  - Options with Variations (Not Prescriptive)
  - Evaluation Framework (Not "THE" AHS)

Functional Decomposition

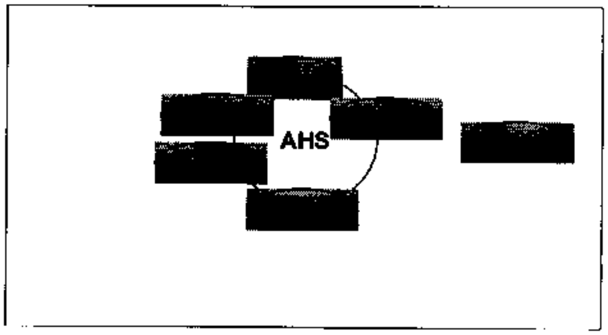
- Version I Draft Distributed March 31, 1997
  - Hierarchical Decomposition to 4th level
  - Functional interfaces
  - Four Major Functions
    - Initiate Automated Operation
    - Disengage Automated Operation
    - Moving under AHS Control
    - Managing the AHS
  - Four External Elements
    - Driver
    - TMS
    - Specially Equipped Vehicles
    - Obstacles
- Functional Requirements
  - Incorporation into SEDB and System Specification

Focus on Progressive Deployment

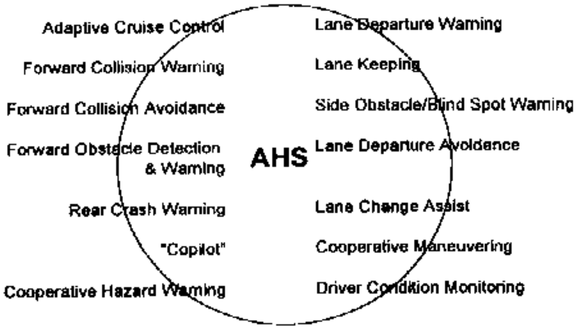
- Build on National ITS Architecture
  - Maintain Compatibility
  - Add Detail for Advanced Vehicle Control and Safety Systems
- Develop Staged Deployment Plan
  - More Emphasis on Earlier Stages
  - Achieve Near Term Benefits
  - Use AHS as the Long Term Vision



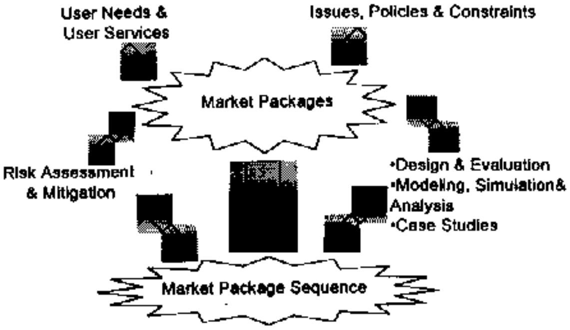
AHS in the Context of ITS



AVCSS User Services



Policy Redirection Implementation



Developing User Services and "Market Packages" for Automation

- Assess User Needs, Desires and Benefits
  - 114 Associate Participants
  - Technical Analysis and Evaluations
  - Case Studies
- Seek Stakeholder Consensus
  - Workshops and Forums
  - Case Studies
- Evolve Promising Case Studies to Field Tests
  - With Public Sector and Private Sector Partners
  - Evaluate Feasibility and Real World Benefits
- Encourage Special Applications

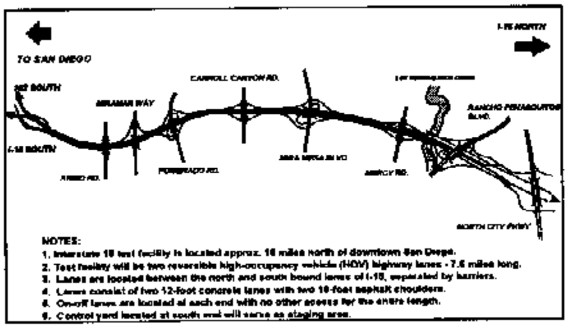
DEMO '97

The Big Picture:

- Four day event August 7-10, 1997
- San Diego, California
- SAE Technical Conference
- Exposition
- Vehicle Demonstrations
- Ancillary Events
- VIP and Media

1997 Demonstration Site

I-15 HOV Lanes - San Diego



NOTES:
1. Interstate 15 test facility is located approx. 10 miles north of downtown San Diego.
2. Test facility will be two reversible high-occupancy vehicle (HOV) highway lanes - 7.6 miles long.
3. Lanes are located between the north and south bound lanes of I-15, separated by barriers.
4. Lanes consist of two 12-foot concrete lanes with two 10-foot asphalt shoulders.
5. On-off lanes are located at each end with no other access for the entire length.
6. Control yard located at south end will serve as staging area.

DEMO '97

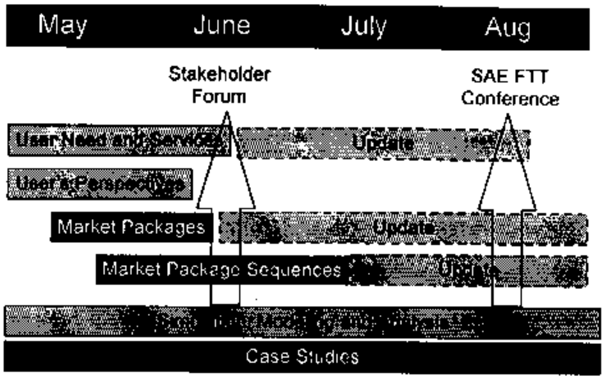
I-15 Vehicle Demonstrations:

- Maintenance and Operation
- Multi-Platform Free Agent
- Truck
- Alternative Technology
- Evolutionary
- Control Transition
- Platoon

Associates' Demonstrations

- **Houston Metro Autonomous Buses**
- **Eaton-Vorad Adaptive Cruise Control Class 8 Truck**
- **Ohio State University Vision & Radar Reflective Tape**
- **Honda Free-agent Autos Showing Transition of Control**
- **Toyota Free-agent Autos Showing Evolution of AHS**

Near Term Milestones -- 1997



May June July Aug

Stakeholder Forum

SAE FTT Conference

User Need and Services — Update

User's Perspective

Market Packages — Update

Market Package Sequences — Update

[illegible]

Case Studies

4. Progressive Deployment, AVCSS, AHS User Services

The presentation "What Do You Want From AHS", given by Bob McQueen, Jim Reynold, Chris Bausher and Evelyn Wagner provided an overview of AHS user needs and user services. The group explained user services and their relationship to the development process, presented the process being used to define and confirm AHS user needs and user services and presented an introduction to the breakout groups that were to follow the presentation.

User-driven development was a recurring theme. The users were asked to review and comment on the current lists of user needs and user service labels. They were then asked to separate into their respective user groups to go through the process of defining a user service.

Applying User Services In AHS

June Stakeholder Forum
June 5, 1997

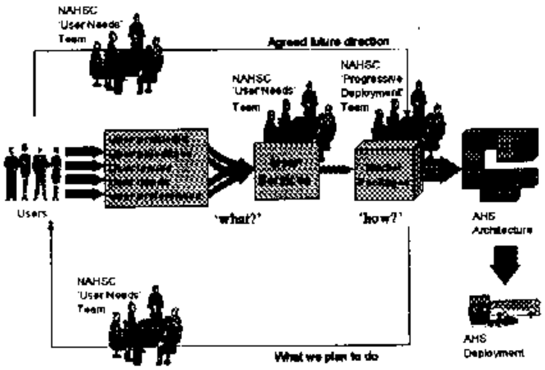
Objectives

- To support an iterative cooperative development approach to AHS
- To engage the user groups in intense interaction leading to the definition of a complete set of User Services and full descriptions of those User Services

Agenda

- Review of where we are
- User Services
- 'So What?' Analysis
- What will happen at the forum
- What will happen after the forum

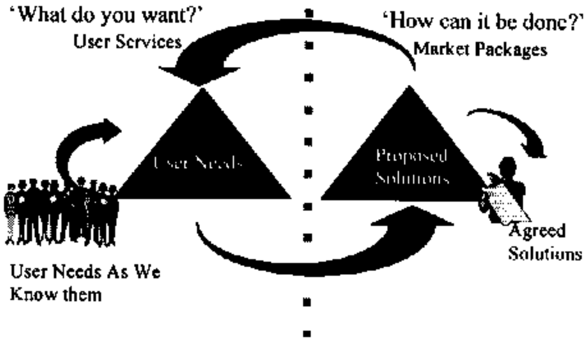
Overall Process



What are ITS User Services?

- Concise description of 'what' the Automated Highway System will have to do, or provide, if you are going to consider it successful
- Encapsulation of user problems, objectives, issues, needs, and preferences

The User Services Approach



User Service Set

- User Service Label
- Description
- 'Shall' statements

What Will Happen At The Forum

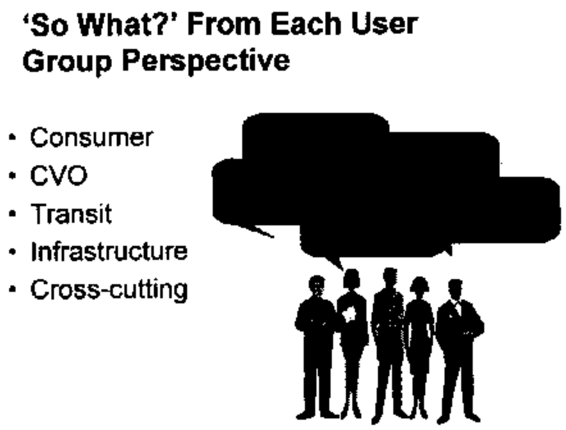
- Confirm / modify user groups
- Confirm and add to user needs
- Brief users on our objectives and the User Service development process
- Work a short 'So What?' Analysis example to give users some actual experience in user service definition and development
- We won't have time to complete the analysis

The User Services Development Approach

- Begin with user needs and User Service labels
- Perform 'So What?' Analysis
- Prepare User Service Description
- Prepare "Shall" Statements

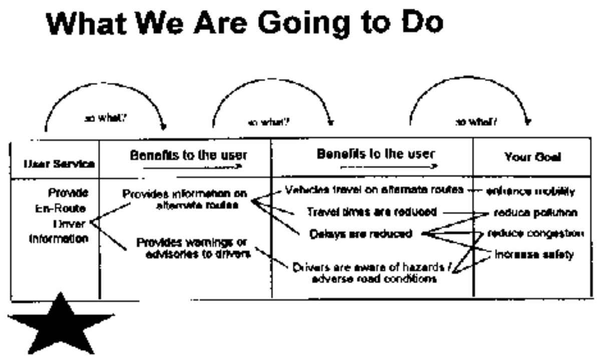
'So What?' Analysis

- Why Bother?
  - Identification of potential benefits to the user
  - Identification of irreducibles or goals which the User Service addresses
  - Facilitates generation of User Service descriptions
  - Provides the basis for briefing the system developers with 'shall' statements (contracts)
  - Validates the User Service



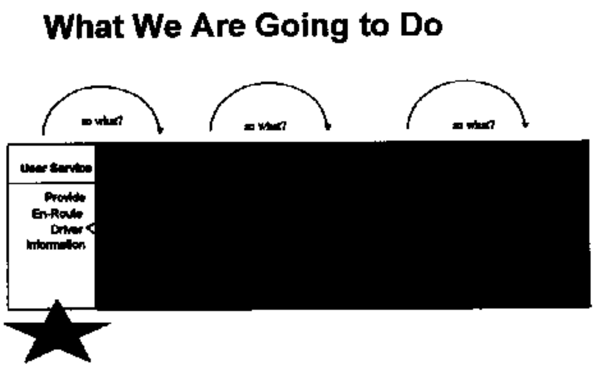
'So What?' From Each User Group Perspective

- Consumer
- CVO
- Transit
- Infrastructure
- Cross-cutting



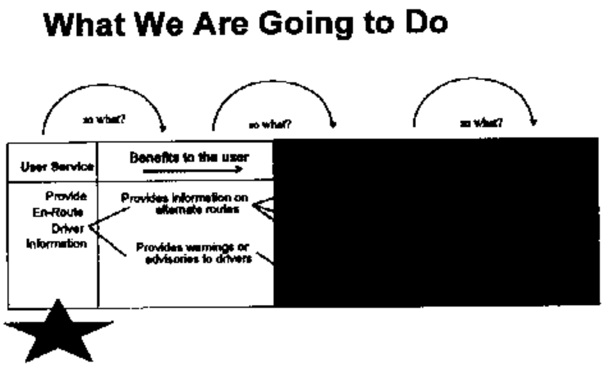
What We Are Going to Do

User Service	Benefits to the user	Benefits to the user	Your Goal
Provide En-Route Driver Information	Provides information on alternate routes Provides warnings or advisories to drivers	Vehicles travel on alternate routes Travel times are reduced Delays are reduced Drivers are aware of hazards / adverse road conditions	enhance mobility reduce pollution reduce congestion increase safety



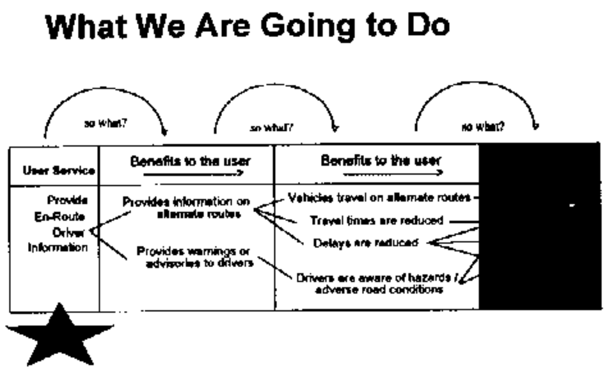
What We Are Going to Do

User Service
Provide En-Route Driver Information



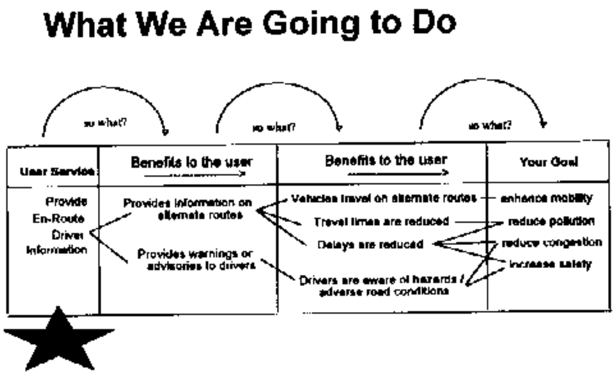
What We Are Going to Do

User Service	Benefits to the user
Provide En-Route Driver Information	Provides information on alternate routes Provides warnings or advisories to drivers



What We Are Going to Do

User Service	Benefits to the user	Benefits to the user
Provide En-Route Driver Information	Provides information on alternate routes Provides warnings or advisories to drivers	Vehicles travel on alternate routes Travel times are reduced Delays are reduced Drivers are aware of hazards / adverse road conditions



What We Are Going to Do

User Service	Benefits to the user	Benefits to the user	Your Goal
Provide En-Route Driver Information	Provides information on alternate routes Provides warnings or advisories to drivers	Vehicles travel on alternate routes Travel times are reduced Delays are reduced Drivers are aware of hazards / adverse road conditions	enhance mobility reduce pollution reduce congestion increase safety

What Will Happen Afterwards

- The 'so what' analysis completed in smaller groups (s)
- Each group drawn from a particular user group
- Each group may need several sessions to complete the work
- User needs team can provide support
- Results from analysis passed back to user needs team
- Turned into user service set

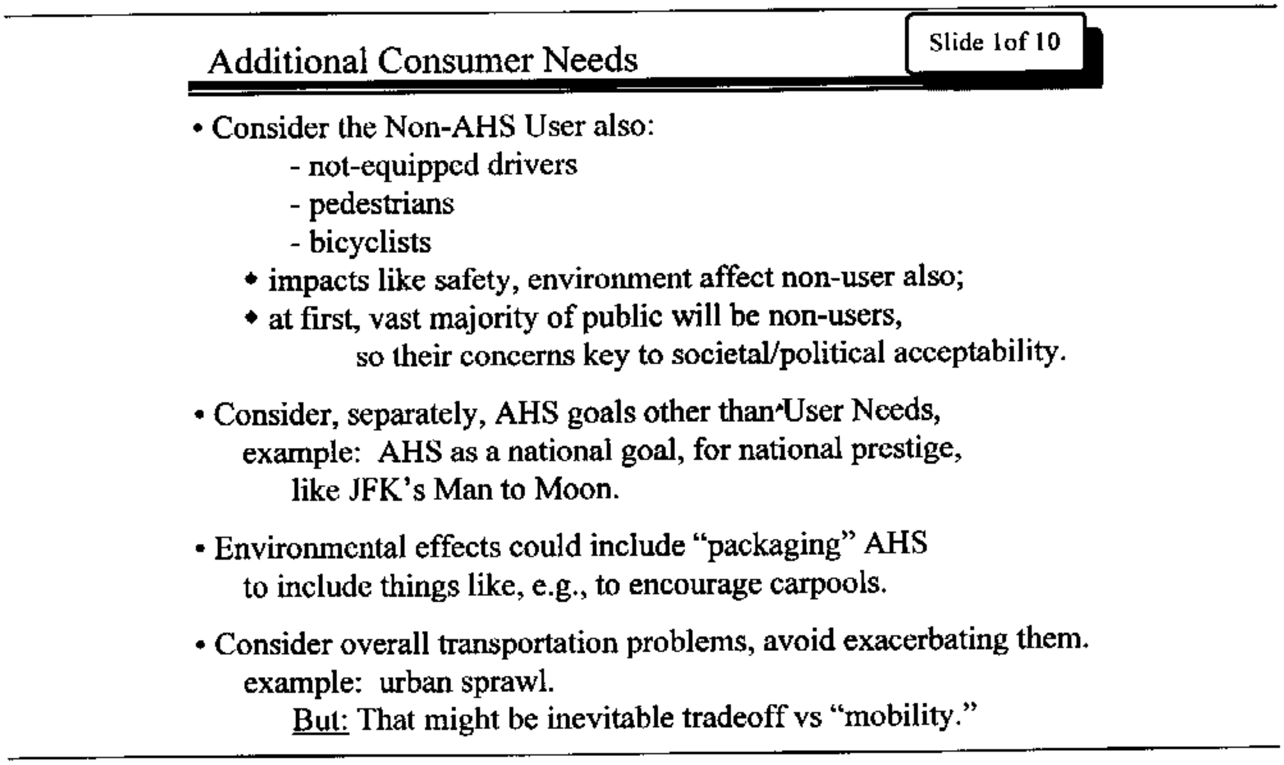
Tentative Schedule

- Stakeholder Forum
  - support the 'what / 'how' cycle
- Perform the 'So What?' Analysis for all the User Service Labels
- San Diego Demo
  - have completed the entire 'So What?' Analysis to be used for Description and 'Shall' Statement development

5. Technical Breakout Groups on User Services

5.1 Consumer Breakout Group

This brief report is based on the overheads produced on June 6 reporting the results of the Consumer Breakout Group to a plenary session of the Stakeholder Forum. In fact, this report is simply images of those overheads, with most of the images followed by text that explains and interprets points that may not be clear from the image alone.

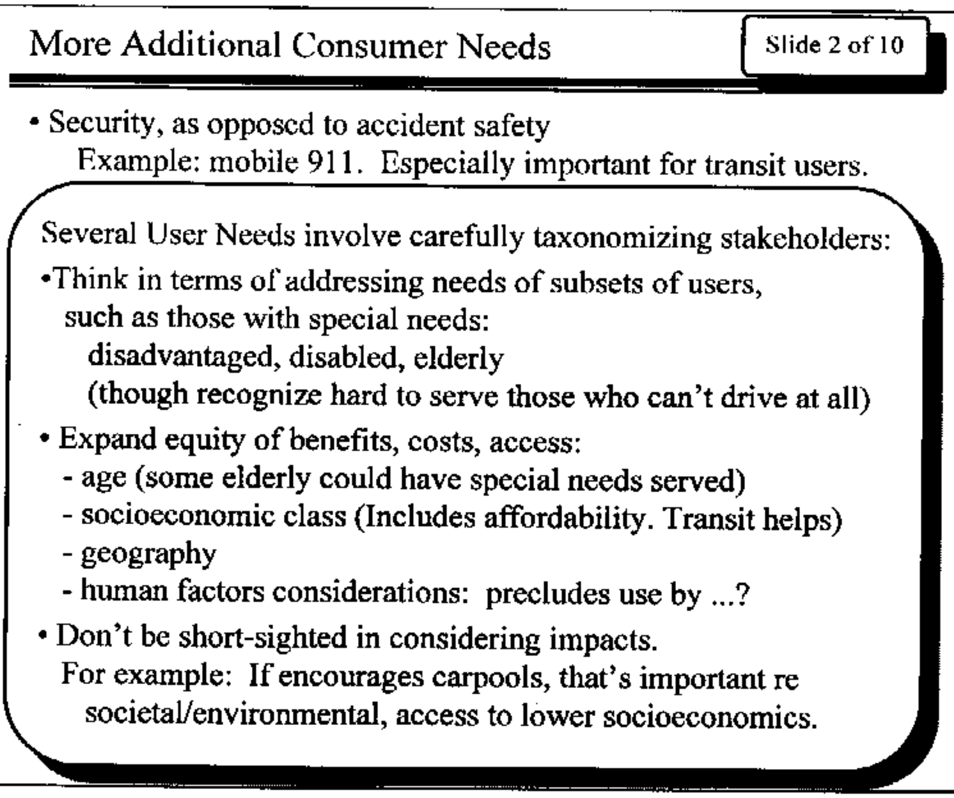


Additional Consumer Needs

Slide 1of 10

- Consider the Non-AHS User also:
  - not-equipped drivers
  - pedestrians
  - bicyclists
  - impacts like safety, environment affect non-user also;
  - at first, vast majority of public will be non-users, so their concerns key to societal/political acceptability.
- Consider, separately, AHS goals other than User Needs, example: AHS as a national goal, for national prestige, like JFK's Man to Moon.
- Environmental effects could include "packaging" AHS to include things like, e.g., to encourage carpools.
- Consider overall transportation problems, avoid exacerbating them. example: urban sprawl. <u>But:</u> That might be inevitable tradeoff vs "mobility."

One of the most significant things about this first slide is that the participants immediately went into an "evaluation" mode, i.e., developing not solely Consumer Needs but more broadly performance/impact measures, including both benefits (i.e., partially fulfilled needs) and costs/burdens/impacts. That was in spite of the fact that the participants were specifically prompted to generate Consumer Needs, with some explanation of Consumer Needs and general reminders of the explanatory material defining User Needs that had been presented in the previous plenary session. Once the stakeholders adopted an evaluation perspective and paid some attention to impacts, it was natural for them to start with another step away from User Needs by considering the Non-AHS User, since most of the first impacts could be impacts to non-Users (first bullet). They also adopted another perspective when they worded one item in terms of goals (second top-level bullet). While any goal could be reworded into a User Need, a participant specifically called for "AHS goals other than User Needs." The intent of the this step in the User Needs / User Services / Market Package framework is to identify User Needs, i.e., those needs that can be at least partially fulfilled by the system. That limits the discussion to the "positive" side of the evaluation, i.e., those things that the system can do positively for the user, leaving costs/impacts/burdens to be discussed later. However, this breakout group (and in fact others) did not follow that framework, and instead went directly into a full evaluation mode, i.e., considering both benefits and costs/impacts/burdens.



More Additional Consumer Needs

Slide 2 of 10

- Security, as opposed to accident safety
  Example: mobile 911. Especially important for transit users.

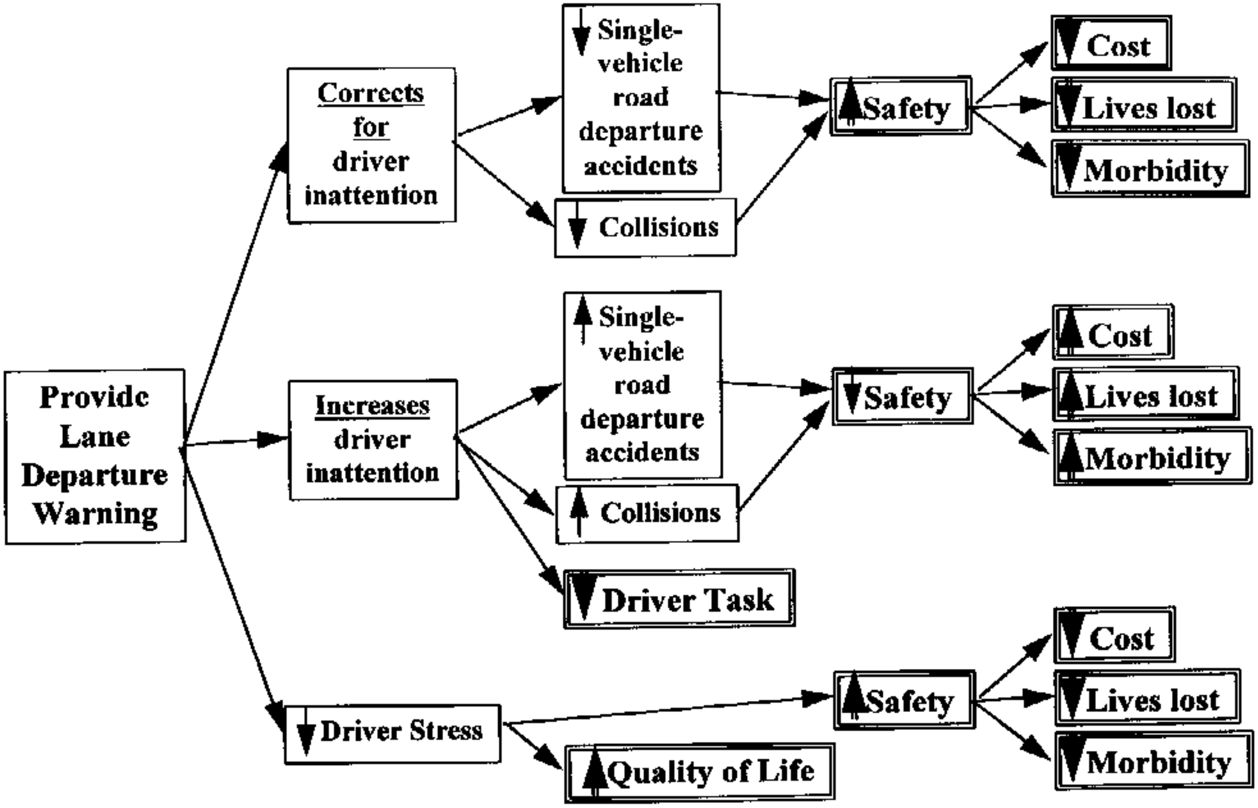
Several User Needs involve carefully taxonomizing stakeholders:

- Think in terms of addressing needs of subsets of users, such as those with special needs:
  disadvantaged, disabled, elderly
  (though recognize hard to serve those who can't drive at all)
- Expand equity of benefits, costs, access:
  - age (some elderly could have special needs served)
  - socioeconomic class (Includes affordability. Transit helps)
  - geography
  - human factors considerations: precludes use by ...?
- Don't be short-sighted in considering impacts.
  For example: If encourages carpools, that's important re societal/environmental, access to lower socioeconomics.

(No explanatory text called for.)

"So What" on Lane Departure Warning

(Would like to do Lane Keeping as the next User Service in a logical sequence)



Provide Lane Departure Warning

Corrects for driver inattention
- ↓ Single-vehicle road departure accidents
- ↓ Collisions
- ↑ Safety
  - ↓ Cost
  - ↓ Lives lost
  - ↓ Morbidity

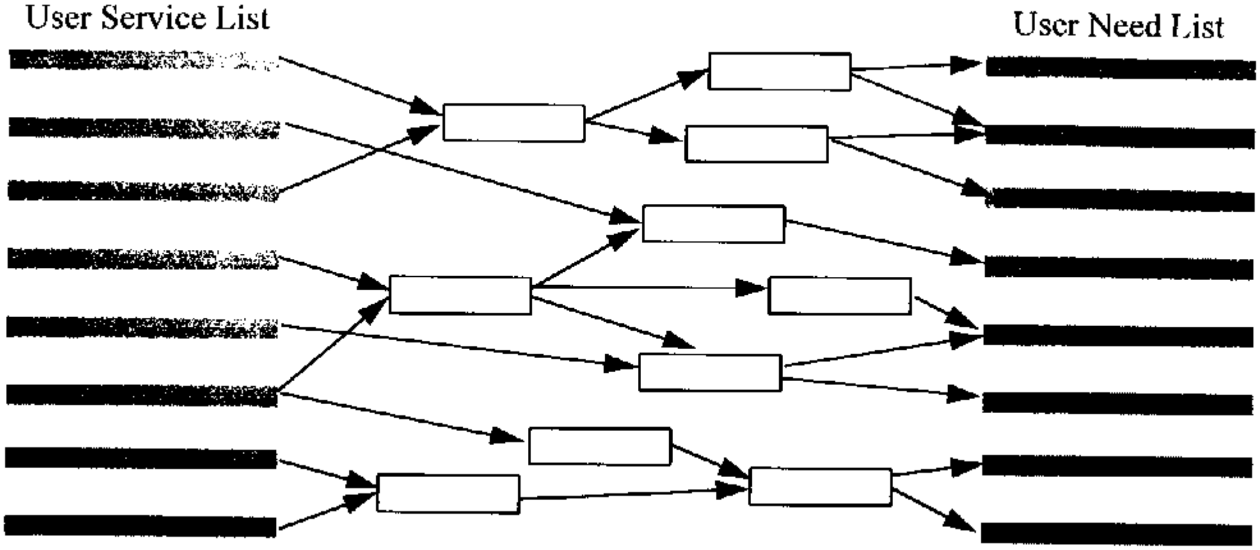
Increases driver inattention
- ↑ Single-vehicle road departure accidents
- ↑ Collisions
- ↓ Safety
  - ↑ Cost
  - ↑ Lives lost
  - ↑ Morbidity
- ↓ Driver Task

↓ Driver Stress
- ↑ Safety
  - ↓ Cost
  - ↓ Lives lost
  - ↓ Morbidity
- ↑ Quality of Life

In this graphic, we tried to stay as close as possible to the graphics of the example "So What" analysis presented in a plenary. We boxed the items and used arrows for clarity and brevity. The double-line boxes depict "irreducible," or goals. That would seem to be contradicted by the two levels of double-lined boxes concerning Safety. That reflects a difference among the participants as to whether Cost/Lives Lost/Morbidity were the irreducible "So Whats" of Safety, or if those aspects simply define Safety. This graphic represents a deliberate effort to keep things at a simple level, since a more complete analysis would turn it into a "bushy mess," and would not build insight into the "So What" of Lane Departure Warning. The top two of the three main branches of the graphic reflect the fact that the participants felt that Lane Departure Warning would have in fact two countervailing effects: to correct for and to increase driver inattention.

An Idea for Structuring "So What" "Analyses"

Slide 4 of 10



But what's "The Point"?

To lay out "requirements" so that the AHS meets User Needs

This graphic was suggested by the participants as a way to answer the question of one participant: "Why are we doing this 'So What" analysis?" The answer: To keep straight what should be User Services and what should be User Needs, to relate the list of User Services to the list of User Needs, and to test the list of User Services to see how well a corresponding set of "requirements" (simply rewording User Services as requirements) meets User Needs.

5.2 Commercial Vehicle Operators Breakout Session

NAHSC STAKEHOLDER FORUM (5 JUNE 97)

Day 1 User Services 'So What?' Analysis

Commercial Vehicle Operations User Group

CVO Group

- Dave Barry (NPTA)
- Steve Hay (Univ. of Minn.)
- Dan Guzman (GM)
- Gordon Fink (ITS America)
- John MacGowan (FHWA)
- Bob McQueen (NAHSC)
- Bjorn Klingenberg (Consultant)
- Carol Jacoby (NAHSC)
- Greta Huang (NAHSC)

'So What?' Analysis

- User Service Label
- 1. Automatically keeping a Safe Stopping Distance

1.1 Prevents collision

- 1.1.1 Avoids pain and suffering for all parties
- 1.1.2 Reduce property damage (vehicle, infrastructure)
- 1.1.3 Reduce insurance costs (premiums)
- 1.1.4 Schedule adherence
- 1.1.5 Avoid truck damage
- 1.1.6 Reduces downtime

1.1 Prevents collision

- 1.1.7 Reduces incidents/congestion
- 1.1.8 Improve industry name/trust
- 1.1.9 Driver security
- 1.1.10 Increase driver recruitment/retention
- 1.1.11 Reduce transport/operations cost
- 1.1.12 Protects cargo/increase customer satisfaction
- 1.1.13 Hazardous Materials management (less clean-up, protects environment)

1.2 Reduce fatigues/stress

- 1.2.1 Reduce accidents
- 1.2.2 Increase alertness
- 1.2.3 Positively affect hours of service
- 1.2.4 Driver wellness (physical and psychological)
- 1.2.5 Decrease health insurance costs
- 1.2.6 Increase recruitment

1.3 Increase fuel economy

- 1.3.1 Reduce cost
- 1.3.2 Environment (reduce emissions, preserve natural resources)
- 1.3.3 Fewer stops
- 1.3.4 Reduce "wear & tear"
- 1.3.5 Increase profit
- 1.3.6 Longer equipment life

1.4 Reduce "wear & tear"

- 1.4.1 Lower maintenance cost
- 1.4.2 Increase competitiveness
- 1.4.3 "Customer Loyalty" (product customers along entire "chain")

Issues

- Intermodalism
- Need to show "how" as well as "what"
- Domestic vs. Global Market ("User Services")
- Give insight to products available
- Accounting for "disincentives"

5.3 Transit Breakout Session

Transit User Group

Additional User Needs

Additional User Needs

- Improve bus docking precision
- improve safety under all conditions
- improve maintenance operations
- improve maintenance labor productivity
- increase flexibility to meet future demands
- increase driver's availability for non-driving tasks

Additional User Needs

- Reduce driver stress
- improve perceived security
- approach rail-like disciplined operations
- achieve fail safe rail approaches
- improve support vehicle operations
- improve inter modal safety
- provide fast emergency service

User Service Process - 'so what?'

- A very good and useful process for improving understanding of user needs
- the process must...
  - involve experienced experts
  - involve multi disciplinary interactions

5.4 Infrastructure Breakout Session

Infrastructure

Stakeholders' Forum
Breakout Group #1
June 5, 1997

User Needs

- Modify previously-listed need to read:
  Identifiable, acceptable, quantifiable risks
- Add new Needs:
  - Provide traffic surveillance
  - Provide diagnostics to identify weather-related and other factors that affect traffic flow
    - Detect continuity breaks
  - Provide info for current and predicted travel times

New Needs (cont.)

- Provide system status and road conditions
- Provide for Mayday capability
- Be designed for easy, affordable maintenance (acceptable cost)
  - Minimize hard-wired electronics
- Manage, minimize liability exposure
- Improve incident detection and management
- Provide TMC or TMC-augmentation

New Needs (cont.)

- Provide way to acquire, protect, use data
- Provide revenue-generating capability to offset costs
- Assure security of system
- Be capable of operation by/management by infrastructure owners/institutions
- Increase accessibility
- Balance needs of infrastructure & adjacent land uses

New Needs (cont.)

- Support existing land uses and land use and economic development plans
- Balance public equity in allocation of private vehicle and public costs
- Obstacle warning
- Provide for spot/critical location deployability
- Identify advisory speed in dangerous locations
- Control/govern speed in dangerous locations (CVO)

User Services

- Optimize Traffic Flow
- Adjust & Balance Lanes
- Detect and Respond to Incidents
- Manage Infrastructure Maintenance

- **Use "So What?" to Identify Costs as well as Benefits**

User Services: Optimize Traffic Flow

- Increase Throughput
  - Save capital costs
  - Reduce diversion to local streets
  - Achieve planning/design capacity
  - Decrease CO, HC

    but also:
  - Increase maintenance costs
  - Impact access roads

Optimize Traffic Flow (cont.)

- Increase Throughput (cont.)
  - Increase VMT
  - Trigger latent demand
  - Increase NOX
  - Impacts on other modes
- Reduce energy consumption
  - Conserve resources
  - Improve air quality

Optimize Traffic Flow (cont.)

- Reduce energy consumption (cont.)
  - Less tax revenues
- Reduce traffic incidents
  - Less injuries, deaths
  - Lower insurance costs
  - Increased throughput
  - Reduced secondary incidents
  - Improve air quality/conserve energy

Optimize Traffic Flow (cont.)

- Reduce traffic incidents (cont.)
  - Increase trip time reliability
  - Reduce demand on public services, e.g. emergency services
  - Reduces economic costs to society from lost productivity
- Defers/offsets construction of new lanes
  - Less community disruption

Optimize Traffic Flow (cont.)

- Defers/offsets construction of new lanes (cont.)
  - Lower costs
- Reduce emissions
- Time savings
- Trip time reliability
- Reduce drivers' operating costs

5.5 Cross-cutting Breakout Session

Facilitator: Jim Reynold
Notetaker: Joy Pinne

PLEASE NOTE: The verbage that follows is based on the interpretation solely of the notetaker. Please forgive me if I have misrepresented any of the topics or missed something that was said during the breakout session. I have tried to add to certain areas to make them more clear, however, I have tried to leave the flavor of conversation as it was during the breakout session. jp

Attendees:

Name	**Organization**	**Phone**	**Fax**
Joy Pinne	Caltrans/NAHSC	916-657-4265	916-657-4580
Alan Arai	IMRA America	916-756-2813	
Dennis Foderberg	U of MN/MD DOT	612-626-8285	
John Mason	PTI/Penn State	814-863-1907	
Emilinno Lopez	VA DOT	804-786-0186	804-225-4978
Mike Martin	Martin Enterprises & Assoc.	703-391-7330	703-481-5667
Bob Neff	Eaton Vorad	248-354-2719	248-354-6962
Jeff Boehm	3M	612-736-3325	
Berry Ashby	Wave Band Corp	310-212-7818 x106	202-296-3840
Hiroshi Tsuda	ITS America	202-484-4134	202-484-3483
Kagutoshi Satoh	JSK (Japan)	81-3-3501-5676	81-3-3501-5685
Scott Adrews	Toyota Motorcorp (Japan)	81-565-23-9170	81-565-23-5742
Ron Frazzini	Honeywell Tech Center	612-951-7353	
Tom McKendree	Hughes/NAHSC	714-732-3228	
Wayne Sorenson	State Farm	309-766-3663	
Steve Weiland	Navigation Technologies	847-699-7063	847-699-8667

CROSS CUTTING NEEDS

- Highway Safety
- Economical
- Return on investment
- Little or no environmental impact
- No introduction of unacceptable risks

Purpose of breakout session is to develop user needs by completing the following:
Label
Description
Number

Point is to identify requirements that will become the basis to develop design requirements.

Who we are:

- Environmental
- Insurance
- Vehicle Suppliers
- Electronics
- Enforcement
- Emergency Services

Identifiable groups left out:

- non-user - people who are politically sensitive (political, money providers, captive ridership that can't afford AHS) We need to think about this as we develop the benefits. These people may benefit from the system even though they don't use it. Example: HOV lanes benefit the non-HOV lanes by freeing up space on the conventional highway.
    Need representation for non-users
    Political representatives may be able to speak for these people
    Look at who is going to picket against us. There is a whole contingent of people who think that the money should be spent elsewhere. We need to address these people and show them that they will benefit from the program in ways that they have not previously understood Non users and stakeholders may want to spend the money on other things.
    OPONENTS OF AHS - could be neutral or have competing agendas
        We may choose alternatives that may impact them less, so they are important to recognize

    Competing stakeholders
    Stakeholders in alternative solutions
    Light rail people may be opposed.What do we call them and who will represent them.
    FRA - platoon of trucks in competition with rail
- Taxpayers
- Societal issues
- Social equity
- Economical equity
- Different perception of benefits from each user group. They may be captured in other groups.
- Standard setters/Architecture - standards follow - regulations are different. We have to follow this, however, standards don't have to be followed. Product will not be taken off the shelf just because it did not follow standards. If it sells and makes money it will remain on the market.
- Other vested interests
- Regulatory bodies
- Standard setting bodies

Market is always ahead of regulation. It may stifle growth of innovative solutions.

All of these groups are trying to meet consumers needs.

Labels:
(We tried to pick one of the ones that is less noticed rather that choose the obvious one)

Presupposition of the sequence of deployment - should we be more general?
There is a clear progression of thought that begins with warning systems with driver remaining in control. Evolution using these same sensors moving towards partial control to avoid collisions or obstacles, and then on to full automation. Don't feel bound by this.

The market place is not ready for full automation. Education is needed. The system needs to be extremely intuitive and come out in small steps.

User Services:

1.1 Avoid frontal and side collisions:

This is general enough to be applied in different stages from warnings to full automation.
What does this provide for us as users? What are the benefits?

1.1.1 Reduces accidents,
1.1.2 Infrastructure and property damage - repair costs are down
1.1.3 Fatalities
1.1.4 Reduces congestion
1.1.5 Litigation
1.1.6 Clean-up
1.1.7 Vehicle repairs
1.1.8 Insurance costs
1.1.9 Workman's comp
1.1.10 Quality of life
1.1.11 Improves reliability
1.1.12 Improves freight mobility
1.1.13 Medical costs
1.1.14 Frees up the police force from the accident scene

Note: Many industries will be affected and this can possibly harm the economy.

1.2 Reduces accidents:

1.2.1 Improves traffic reliability (Better traffic flow/more throughput)
1.2.2 Reduces congestion
1.2.3 Improves the confidents to travel this method
1.2.4 Reduces incident delays
1.2.5 An increase in through put may cause bottleneck at the end. We need to look at the
1.2.6 Whole system and not just the highways. Can't just look at one mile of roadway.
1.2.7 Improves travelers confidence
1.2.8 Adjacent/Secondary roads are improves - physical diversion of traffic into residential (can't reroute everyone into the same alternate route)
1.2.9 Reduces driver stress (Needs to be a more reliable system until people will be relieved of stress while giving up control of their vehicle. May increase stress significantly. People may be ready for adaptive cruise control, but they are still in charge of their car. They are not ready to take their hands and feed off.)
1.2.10 Reduces the number of secondary accidents
1.2.11 Reduces rubbernecking

From a personal point of view avoiding frontal and side collisions reduces all of the hassles of being involved in an accident. It improves our quality of life.

There is a difference between immediate stress and background stress. Avoiding frontal and side collisions involves a reduction of stress, but there is still an anxiety involved with giving control to a system that doesn't have the trust of society. Can this be attained prior to deployment?

Independent of a specific technology, a system that avoids frontal and side collisions reduces some stress, but also brings on some stress involved due to mistrust of the machine. Increases the technical dependency level. Older drives have a problem with this.

Robert Neff from Eaton Vorad uses adaptive cruise control during his daily commute and vouches for the reduction of stress. More confident and more comfortable. He said that it didn't take him long to get used to it. (It should be noted, however, that he works for the company that developed and markets it and could have had some impact on his trust in the system.)

Need to rationalize the degree of importance for each of the user services and organize with some parallelism. Need an outline format. This will be done in the formal report.

Reduction of accidents is a direct result of avoiding frontal and side collisions. Stress reduction is not a result of this, it is a result of less property damage which stems from avoiding frontal and side collisions.

The members of the cross cutting group feel that this is just an exercise and a listing of benefits. We are brainstorming and throwing out ideas. We cannot do it all today.

It would be more relevant to this group to break it down into the different user groups and list why reducing accidents affects each of these groups. They are trying to address issues and not be brainwashed by regurgitating the answers the stakeholders feel the Consortium wants. They would like tools that would help them sell the system to the end users. They would like us to show them what the consortium has done in the last 2 years and ask for their comments. A few feel that the forums the way they are currently organized is a waste of time and that we are brainwashing them. They feel that they have a lot more to offer and that by changing the format, we can be more productive at these meetings and get some information out of these sessions that can be used and incorporated in our work. They are on board and would like to be able to sell it to the policy makers. They need to justify the money that they spend. They need to make money. There is a public issue as well as making a profit. Private industry will not be involved unless there is a profit or some kind of motivation or incentive involved. We have to work together.

This is a massive long term program that the government can't do alone. The consortium needs help in developing incremental deployment. 30 user services developed by committee. User services is not a good process. The public doesn't understand. We just changed the name and called them user packages. Lets look at the real world. There is a high amount of risk involved. We could waste a lot of money (some say we already have and that many groups have already bailed out. General feeling is that the consortium is not listening) They feel that they should be evaluating what the consortium has done and not rehashing what they have heard before. Not much can be accomplished in a couple of hours of brainstorming. It would be preferable to provide the stakeholders with a package a few weeks prior to the forum for them to comment on and absorb. They could contribute much more during the meetings this way.

Consortium started out looking at full automation as their vision. Consortium has re-looked at the program and agreed that we need earlier market packages that come out in small steps instead of just the end product.

Eaton Vorad has done 6 case studies on there own and shown that there has been a reduction of 69% of accidents due to collision avoidance. Private industry is selling ITS through success stories. The feeling is that the Consortium doesn't want to envision anything except what they see as an AHS (full automation on dedicated lanes). Industry sees a different vision.

The benefit of a true AHS is not fully understood. It is hard to develop interim steps when the end vision is not agreed upon by industry. There are systems out there now that will accomplish what we are looking for and achieve 90% of the benefits. NAHSC and government needs to agree on what the end goal is and then develop the small steps to get from point A to point B.

We are obligated to demonstrate that our method will work. They want to see some numbers. They feel that Toyota and Honda will be leading the way. People need to understand what needs to happen and how to get there.

Government/Industry/Academia need to come together.

Need incentives from the government to encourage private industry to put money in this area.

Show us the benefits. No benefits, it is not going to work.

What are the costs associated with different levels of this (cost-benefit analysis). The system we should strive for should fall out by doing this.

SHOW ME THE BENEFITS!
What is in it for me? What do you tell your customer?

Back to the question of what "Avoiding frontal and side collisions" will do for each of the stakeholder groups:

Environment - Not as much pull as policy makers. May proliferate more users - could be negative.

Insurance - other opportunities: whoever builds system will need to be insured in the event of failure. Personal side, insurance rates will drops. Lawyers out of the system. Reduction of litigation. Proving the cause of accident.

Vehicle Manufacturers - Higher reliability will sell better. Improved feeling of ownership. Improve sales because of safety. Improves the quality of experience of owning and operating a car. Object of desire instead of destruction. Enhances the driving experience. Reduces the extent of required service and repair. May be more expensive to replace some of the systems, however, this may not have to be replaced as often. May increase litigation if we don't put a system like this on the car even though we have the technology (ex. ford and airbags) Reduces the service and repair infrastructure

Electronics Industry - Similar to Vehicle Manufacturers. Sell more product. Make money. Road conditions tied to vehicles - more money. Public image aspect of it. Helping society. Electronics that could detect if a vehicle WAS following too close. Could reduce litigation. Vehicle could contain a black box. What would that black box record. Could help the insurance industry. Some people like it and some people don't. May be a hard sell because of Big Brother watching over you.

Enforcement - Controlled pursuit. Reduce number of responses. Speed may not be an issue. Frees up resources.

EMS - reduce response time. Save money. Less severe accidents. Medical costs reduced.

Non Users -

Other vested interests

Regulatory bodies

Standard setting bodies

More meaningful by looking at each of the industries and looking at what the benefits would be.

Who we are...

- Environmental
- Insurance
- Vehicle Manufacturers
- Electronics Suppliers
- Enforcement
- Emergency Services
- *Non Users*
- *Other vested interests*
- *Regulatory bodies*
- *Standard setting bodies*

The User Service Exchange

- We understood the process
- We actively participated
- We got frustrated
  - amount of work required to obtain result
  - chaotic nature of brainstorming
  - seems consortium not listening
  - need to assume certain level of understanding
- We improved the process

The New Idea

- Use the user service template
- Perform the "so what" analysis
- Systematically poll the user representatives for input
  - Organize the input
    Provide more structure
  - More inclusive of ALL ideas
  - Get valid inputs from each stakeholder group

Discussion of Near Term Deployment

- Some felt current technology development was being disregarded
- Some felt the general issues of each stakeholder group were being rehashed
- Many felt that the economic realities will drive the program and the NAHSC is an incentive or catalyst

"Show me the benefits"

- What's in it for me?
- What do we tell our customers?
- How do we sell the products...
  - to the people?
  - to the politicians?

Avoid frontal and side collisions

Environment

- not as much pull as other stakeholders
- AHS may proliferate vehicle use- could be negative

Insurance

- other opportunities: whoever builds system will need to be insured in the event of failure.
- Personal side, insurance rates will drop.
- Lawyers out of the system. Reduction of litigation.
- Proving the cause of accident.

Vehicles

- Higher reliability will sell better.
- Improved feeling of ownership.
- Improve sales because of safety.
- Improves the quality of experience of owning and operating an automobile.
- Reduces the service and repair infrastructure
- May increase litigation

Electronics

- Similar to vehicle manufacturers
- Sell more product
- Make money -Ex: Road conditions tied to vehicles
- Public image aspect- helping society

Enforcement

- Controlled pursuit
- Reduce number of responses
- Speed may decline as an issue

EMS

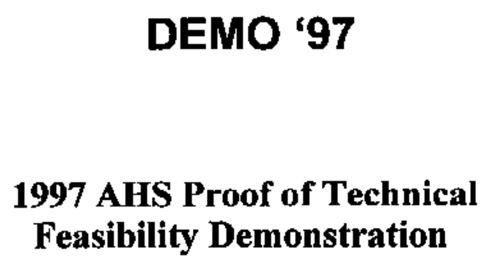
- Reduce response time.
- Save money.
- Less severe accidents.
- Medical costs reduced.
- Better deployment flexibility

Where do we go from here?

- NAHSC should take the first cut at needs, services and market packages and sequences
- Stakeholders review/amend
- Repeat steps 1 & 2
- Consensus

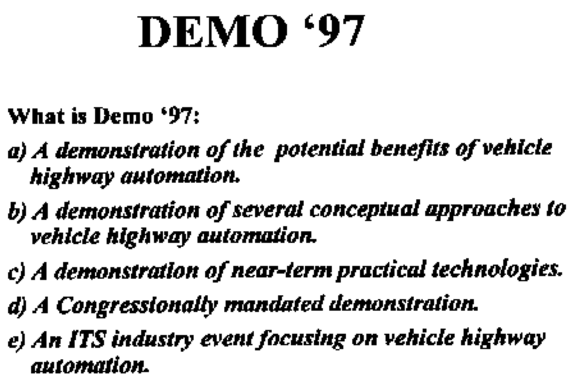
6. Demonstration ’97

Demo ’97 will present a look at the future of highway travel with a series of live demonstrations of automated highway system (AHS) technologies on Interstate 15 in San Diego, California. The NAHSC will demonstrate the technical feasibility of these AHS technologies and their near-term applications to substantially improve highway safety and efficiency. Demo ’97 includes seven on-lane vehicle scenario demonstrations and a nearby Exposition Center. The Demonstration will show currently available and emerging advanced vehicle control and safety system technologies and concepts that promise to be the building blocks of an AHS prototype. The Exposition Center will detail potential benefits and near-term deployment options of AHS technologies through exhibits, automated vehicle and equipment displays, computer simulations, vehicle demonstrations, presentations and literature.



DEMO ‘97

1997 AHS Proof of Technical Feasibility Demonstration



DEMO ‘97

What is Demo ‘97:

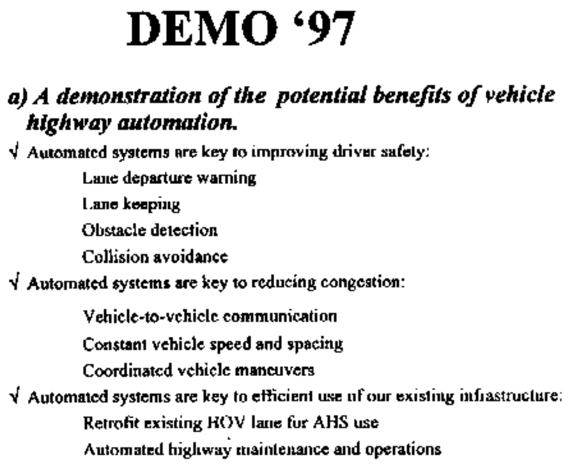
a) A demonstration of the potential benefits of vehicle highway automation.

b) A demonstration of several conceptual approaches to vehicle highway automation.

c) A demonstration of near-term practical technologies.

d) A Congressionally mandated demonstration.

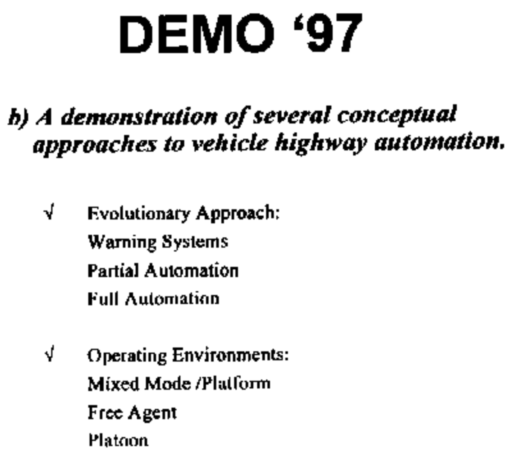
e) An ITS industry event focusing on vehicle highway automation.



DEMO ‘97

a) A demonstration of the potential benefits of vehicle highway automation.

√ Automated systems are key to improving driver safety:
  Lane departure warning
  Lane keeping
  Obstacle detection
  Collision avoidance
√ Automated systems are key to reducing congestion:
  Vehicle-to-vehicle communication
  Constant vehicle speed and spacing
  Coordinated vehicle maneuvers
√ Automated systems are key to efficient use of our existing infrastructure:
  Retrofit existing HOV lane for AHS use
  Automated highway maintenance and operations



DEMO ‘97

b) A demonstration of several conceptual approaches to vehicle highway automation.

√ Evolutionary Approach:
  Warning Systems
  Partial Automation
  Full Automation

√ Operating Environments:
  Mixed Mode /Platform
  Free Agent
  Platoon

DEMO ‘97

c) A demonstration of near-term practical technologies.

√ Radar
√ Image Processing
√ Magnetic Markers
√ Radar Reflective Stripe
√ Magnetic Stripe
√ Real-time Processing

DEMO ‘97

d) A Congressionally mandated demonstration.

√ Intermodal Surface Transportation Efficiency Act (ISTEA - 1991):

"The Secretary (of Transportation) shall develop an automated highway and vehicle prototype from which future fully automated intelligent vehicle-highway systems can be developed. .... The goal of this program is to have the first fully automated highway or an automated test track in operation by 1997".

DEMO ‘97

e) An ITS industry event focusing on vehicle highway automation.

√ Vehicle Demonstrations:
  NAHSC Core Members
  Eaton Vorad
  Honda R&D
  Houston Metro
  Ohio State University
  Toyota Motor Corporation
√ Exhibits:
  Over 33,000 sq. ft floor space
  Parking Lot Vehicle Demonstrations
√ Media:
  Network TV, Print, and Radio

DEMO ‘97

The Big Picture:

√ Four day event August 7-10, 1997
√ San Diego, California
√ SAE Technical Conference
√ Exposition
√ Vehicle Demonstrations
√ Ancillary Events
√ VIP and Media

DEMO ‘97

I-15 Vehicle Demonstrations:

√ Maintenance and Operation
√ Multi-Platform Free Agent
√ Truck
√ Alternative Technology
√ Evolutionary
√ Control Transition
√ Platoon

Control Transition

Honda R&D:

√ Two Automated Honda Sedans
√ Equipped With Automated Lateral (vision and magnet) and Longitudinal (Radar) Systems
√ Two Parts: Segment 1- Vision-Based Lateral Control
  Segment 2 - Magnet-Based Lateral Control
√ Demonstrates Obstacle Detection and Avoidance, Automated Lane Change, Automated Vehicle Following, Lateral Control Transition

Alternative Technology

Ohio State University:

√ Two Automated and One Conventional Sedans (Honda)
√ Both Automated Vehicles Equipped With Lateral Systems (Radar Reflective Tape and Vision) and Longitudinal Systems (Radar)
√ Demonstrates Obstacle Detection and Avoidance, Automated Lane Change, Automated Vehicle Following, Lateral Control Transition

Evolutionary Deployment

Toyota Motor Corporation:

√ Two Automated Toyota Sedans and Two Conventional Toyota Sedans
√ Equipped With Automated Lateral Control (vision) and Automated Longitudinal Control (Radar)
√ Two Parts: Segment 1 - In-Vehicle AHS Features used on Conventional Highway,
Segment 2 - Fully Automated Driving in Mixed Traffic
√ Demonstrates Evolutionary Deployment of Automated Systems, Adaptive Cruise Control, Lane Departure Warning, Blind Spot Warning, Obstacle Detection and Avoidance, Automated Passing, Automated Lane Change, Cooperative Vehicle Following

Truck Scenario

Eaton Vorad:

√ Class 8 Freightliner Tractor Trailer Truck and Sedan (GM)
√ Truck Equipped with Automated Longitudinal Control System (Radar). Passenger Car Conventional.
√ Highway Speeds with at Least 5 Vehicle length Spacing
√ Demonstrates Automated Obstacle Detection, Automated Blind Spot Collision Warning, and Automated Vehicle Following with Smart Cruise ® System

Platoon

Core Participants:

√ Eight Sedans (GM)
√ All Vehicles Configured Identically With Automated Lateral Control (magnets) and Longitudinal Control (Radar)
√ Separation Distances Will Be Less Than 4 Meters
√ All Vehicles Start in Formation and Accelerate to Highway Speed
√ Platoon Splits to form Two Smaller Platoons (Appx. 30 Meter Separation)
√ Two Smaller Platoons Join Again to Form One and slow to a Stop
√ Demonstrates Vehicle-to-Vehicle Communication and Automated Coordination

Integrated Multi-Platform Free Agent

Core Participants and Houston Metro:

√ Three Sedans (GM), Two New Flyer Buses
√ All Vehicles Equipped With Lateral (vision) and Longitudinal (Radar) Control Systems
√ Demonstrates Mixed Platform Adaptive Cruise Control, Automated Passing, Lane Departure Warning, Headway Warning, Automated Lane Change, Obstacle Avoidance, Coordinated Avoidance

Maintenance and Operations

Core Participants:

√ One mini van (GM)
√ Shows Infrastructure Inspection and Performance Verification
√ Vision-based Lateral Control and Conventional Cruise Control
√ ID Presence of Faulty or Missing Magnets and Obstacles and Mark Location
√ Notify Passengers and TMC in Real-Time
√ Non-Automated ORV(Obstacle Removal Vehicle) will Remove All Obstacles from Identified Locations

6.1 Questions and Answers

What can AHS offer in the near term?

Fully automated highway systems may be twenty years away, but many AHS applications are already road-ready or near ready. These include:

- Adaptive Cruise Control - This system senses vehicles ahead and alters speed accordingly.
- Obstacle/Collision Warning - Using radar, this system "sees" obstacles and other vehicles in the road and warns the driver and/or brakes.
- Lane Detection - This system uses sensors to track markers in/on the highway lane and warns the driver when he/she drifts across a lane or road boundary.

DEMO '97

Demo '97 is our opportunity to show the world what ITS is all about.

Come join us!

How can AHS improve safety?

Crashes on our nation's highways cause more than 40,000 fatalities and more than five million injuries each year, costing more than $150 billion. In nine out of ten crashes, human error plays a leading role. Fortunately, highway and vehicle automation promises to make highway travel significantly safer by reducing - or even eliminating - the element of driver error. Vehicles equipped with AHS technologies will be safer because they will:

- Detect and avoid obstacles, reducing the number and severity of crashes.
- Communicate with other vehicles, enabling coordinated maneuvers.
- Maintain lane position, reducing roadway departure crashes and sideswipes.

How can AHS reduce congestion?

AHS promises to reduce congestion by dramatically increasing the efficiency of today's highways. An AHS lane will be able to double or triple the capacity (in vehicles per hour) of a given stretch of highway. AHS can achieve this substantial improvement by:

- Providing uniform driving performance through eliminating erratic accelerations, decelerations and weaving typical on congested highways.
- Eliminating uneven traffic flow caused by human distractions, varying driver skills and impairments.

Do you have a question for the National Automated Highway System Consortium? Send email to comments@nahs.org.

7. AVCSS and AHS Market Packages

The NAHSC is moving quickly to focus more attention on partial automation systems which are believed to be almost market ready. As part of the focus, the Consortium is building more detailed descriptions of what these intermediate systems might be. The development of market packages for automated highway systems draws heavily from user services and stakeholder input and preferences. Ideally, all market packages should be derived from user services. Ultimately, all the market packages must be at least traceable to a user service. From a proposed list of market packages for AHS, there will be stage where each market package will be examined to determine the type of user service it serves, the expected benefits for each user service, the risk issues for the market package and what type of equipment the package has.

Stakeholder interaction with the Consortium was the main theme for this segment of the Forum. Tom McKendree gave an overview on the definition of a market package and where the NAHSC is at in developing market packages for AHS. His presentation covered some sample market packages that the NAHSC has developed and guidelines that were used in developing the market packages. After Tom's presentation, the group was then asked to separate into their respective user groups to discuss the sample market packages and suggest guidelines in the development of market packages.

Market Packages

Tom McKendree
Leader, Progressive Deployment Team
NAHSC

Agenda

- Objectives For This Morning
- What Are Market Packages?
- Where Is NAHSC In Developing Market Packages?
- Some Example Market Packages
- Example Guidelines for Market Packages
- How You Can Help

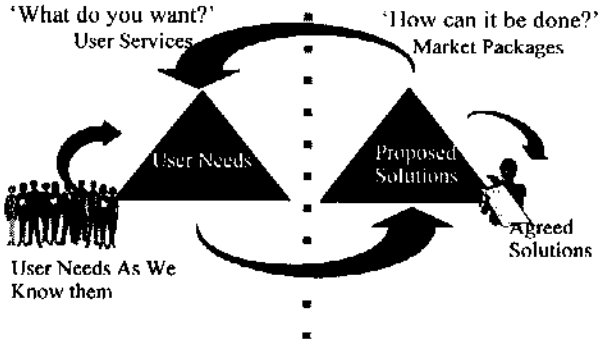
Objectives

- We Are Listening
  - Here to Collect Ideas from You
- This Presentation
  - Review the Idea of Market Packages
    - Applications to AHS
  - Discuss Some Examples That Will Be Reviewed In the Breakout
- The Breakout
  - Identify Stakeholder Issues and Constraints to Guide Development of Candidate Market Packages
    - Evaluation Factors
    - Suggestions for New Market Packages
    - Guidelines to Help In Defining Good Market Packages

What Are Market Packages?

- Bundles of Technology That Address One or More User Service
  - Each Seems Like a Single Product
- Building Blocks
  - Increments In Deployment
    - The System Grows by Adding Market Packages
    - Each Building Block Must Make Sense as a Step
  - Must Make Sense as a Set, Not Just Individually
    - The Set must be Complete
    - The Market Package should separate nicely
- Divisible Into Equipment Packages
  - The Total Equipment That Each Stakeholder Buys to Make a Market Package Happen

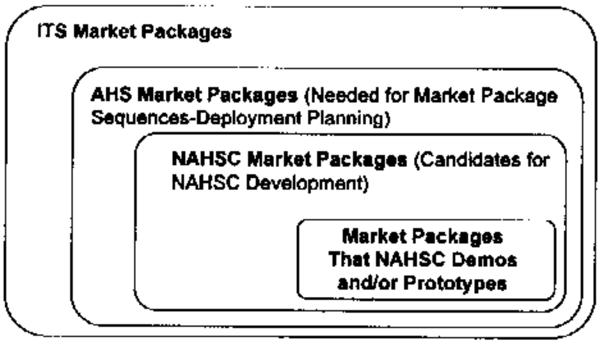
Market Packages and User Services



Why Are We Developing Market Packages?

- They Tangibly Respond to User Services and Facilitate Understanding
- They Present Building Blocks for Incremental Deployment and Early Benefits
- They Take Advantage of Synergies With Communications and Sensor Infrastructure
- They Provide Links With the ITS National Architecture
- Determine Things Which NAHSC Needs to Concentrate on
  - Analyze
  - Demo
  - Specify
  - Prototype
  - Operational Test

We Care about Different Groups of Market Packages



ITS Market Packages

AHS Market Packages (Needed for Market Package Sequences-Deployment Planning)

NAHSC Market Packages (Candidates for NAHSC Development)

Market Packages That NAHSC Demos and/or Prototypes

Market Packages Can Vary In Many Directions

- How Much Control (Warning to Full Automation)
- Who Controls (Driver, Vehicle, Infrastructure)
- What is Controlled (E.G. Lateral, Longitudinal, Obstacles)
- Who is Responsible (Driver to System)
- Environment (Mixed Lane, Protected, Dedicated)
- Incremental Step Size
- Tendency Towards Different Societal & Institutional Answers

Where is NAHSC in Market Packages

- A Good Understanding of the Vision, Full-Automation Market Packages from Previous Work
- Focused on Completing the set of candidate AHS Market Packages
  - Requires Indentifying and Fleshing out the nearer term Market Packages
  - Developing work from ITS
  - Most Concerned with developing NAHSC Market Packages to support further work
- Based on Current Understanding of User Needs
  - Looking forward to next iteration from this forum
- Meanwhile, developing guidelines for good Market Packages
  - Looking for ideas to help guide the development of Market Packages

Example Market Package: Cooperative Warning and Advice

- Exchange Information With Cooperative Vehicle
  - Talk Upstream
  - With Traffic in other directions
- Receive Information from Infrastructure
  - Roadside Beacons
  - Informed by Regional TMC
  - Informed by Local Sensors
- Example Information
  - Incidents
  - Obstacles
  - Stopped Vehicles
- Example Information [CONTINUED]
  - Poor Driving Conditions
  - Vehicle Data
  - Accident ahead
- Supports Preliminary AHS User Services, including
  - Monitor and Diagnose other driver behavior
  - Monitor and Diagnose other vehicles
  - Identify risks
  - Advise appropriate speed and actions

Example Market Package: Collision Avoidance

- Vehicle Automatically Maneuvers to avoid an imminent collision
- Accidents avoided
  - Collision with vehicle in front
    - Brake and PowerTrain only
  - Collision with an obstacle
  - Collision with vehicle on the side
  - Collision with an overtaking vehicle on the side
  - Run off the road
  - Combinations
- Driver can turn off and override
- Appropriate Driver Interface must be designed
- Supports preliminary AHS user services, including
  - Avoid frontal collisions with vehicle and obstacles
  - Avoid side collisions
  - Identify Risks

Example Market Package: Cooperative Control Data

- Transmit and Receive Information with Cooperative Vehicles
- Receive information from Infrastructure
- External information to aid Maneuver Decision and Maneuver Control
  - Could be an Augmented Version of any of the Collision Avoidance Market Packages
  - Could be Control Parameter Advisories (e,g, Emergency Speed Limits)
- Adaptive Cruise Control with Cooperative Vehicles
  - Instantaneous Speed and Acceleration
  - Performance Capability
- Information from
  - Other passing vehicles
  - Local sensors
  - Regional TMC
- Supports preliminary AHS User Services, including
  - Avoid frontal and side collisions
  - Monitor and Diagnose other vehicles
  - Identify risks

Example Market Package: Cooperative Automation on Protected, Mixed Lanes

- Mixed Lanes are Shared by Automated and Manual Vehicles
- Protected Lanes have Barriers, excluding most hazards
  - Cooperative Infrastructure Warns of Obstacles and other Hazards
  - Could be a single lane with no merging
- Variants
  - Adaptive Cruise Control and Frontal Collision Avoidance
  - Above, plus Lane Keeping
    - Protected lane required should driver disengage
  - Above, plus Automated Merge and Demerge Capability
- Support Preliminary AHS User Services, Including
  - Automate Appropriate Speed
  - Automate Lane Keeping
  - Automate Merging

Example Market Package: Full Automation

- Long Term Vision
- Driver-Disengaged Highway Driving
- Variants
  - High Throughput on Dedicated Lanes
    - Vehicle Platooning
  - Driver-Disengaged Full Automation on Ordinary Lanes
    - Very Advanced On-Board Sensors and Processing
- Supports Preliminary User Services, Including
  - Automate Appropriate Speed
  - Automate Lane Keeping
  - Automate Merging
  - Automate Lane Changing

Guidelines for Market Packages *(What We Will Be Asking You For)*

- Include Suggestions, Issues, Characteristics to Strive For and to Avoid, Rules of Thumb, and Design Rules
- Not Absolute
- Examples
  - A System That Automates Lateral and Longitudinal Control Must do the whole driving job - drivers will disengage
  - How you deploy can be more important that what you deploy
  - It has to work as well as the customer expects it to
  - Infrastructure deployment is project oriented
  - NAHSC should focus on systems that involve cooperation outside the vehicle - Others are looking at vehicle-only
  - Consider Environmental Impacts when evaluating alternatives

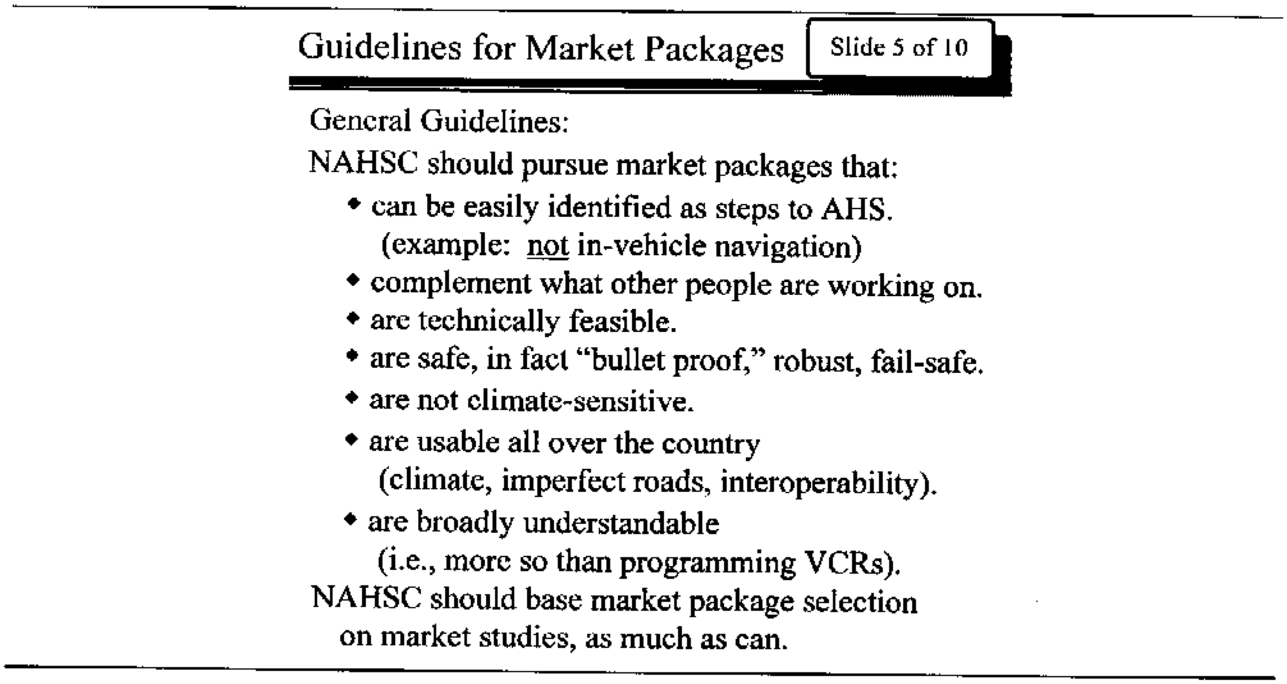
What We Want to Accomplish in the Breakout

- Suggest Guidelines for Market Packages
  - Issues
  - Constraints
  - Evaluation Factors
  - Suggestions for new Market Packages
  - Guidlines to help in defining good Market Packages
- Use the Market Packages as Examples to feed discussion
  - We are looking for what makes Market Packages better or worse more than criticism of specific Market Packages
  - Including advice on what sorts of Market Packages NAHSC should focus on
- Vague, Tentative, Partial and Caveated Advice is Allowed

8. Technical Breakouts on Market Packages

8.1 Consumer Breakout Session

These last six slides were not generated in the order indicated by the overheads or the lists on the overheads. Each sentence or bulleted item was developed in a scattered order during the breakout, then gathered into logical groupings and orders for the overheads.



Guidelines for Market Packages

Slide 5 of 10

General Guidelines:

NAHSC should pursue market packages that:

- can be easily identified as steps to AHS. (example: not in-vehicle navigation)
- complement what other people are working on.
- are technically feasible.
- are safe, in fact "bullet proof," robust, fail-safe.
- are not climate-sensitive.
- are usable all over the country (climate, imperfect roads, interoperability).
- are broadly understandable (i.e., more so than programming VCRs).

NAHSC should base market package selection on market studies, as much as can.

The guideline of the last bullet, "are broadly understandable," might have been more clearly worded as "with operation easily understood (i.e., more so than programming VCRs)."

Guidelines for Market Packages

Slide 6 of 10

Evaluation Factors: (other things being equal,) It's good if:

- uses established technology.
- perceived as inexpensive, low-maintenance, easy-to-fix.
- can tie to easily understandable benefits.
- clearly addresses clear need.
- delivers benefits across broad cross-section of users (example: indirect benefits of offloading).
- driver can select which features enabled.

Note some overlap between these guidelines on Slides 6 through 8 and the Consumer Needs of Slides 1 and 2. Note also in Slides 6 through 8 that with Market Packages, as with Consumer Needs, the participants slipped naturally into a pattern of evaluation factors, even though they had been specifically instructed to develop guidelines for market packages.

Guidelines for Market Packages

Slide 7 of 10

Evaluation Factors: (other things being equal,) It's good

- vehicle-based
  - easier turnover (quicker than capital
  - benefits on unequipped
  - not dependent on (provider, maintainer)
  - not dependent on standards.
- not dependent on vehicle-vehicle (and so not dependent on:
  - equipped-other-vehicle penetration,
  - standards).

(No explanatory text called for.)

Guidelines for Market Packages

Slide 8 of 10

Evaluation Considerations:

- societal value also important, besides marketability.
- consider impacts to non-AHS users
  - benefits, perceived benefits (ex: cell phones).
  - no negative impacts, minimize adverse side-effects.
- environmental impacts.

(No explanatory text called for.)

Even though the participants had not been told to consider Market Package sequences, but only to consider Market Packages in isolation, the participants chose to identify market package sequential, strategic considerations, as listed in Slides 9 and 10:

Slide 9 of 10

Market Package Sequential, Strategic Consids:

NAHSC should pursue a market package strategy that is
flexible, adaptive,
i.e., later market packages
shaped by earlier deployments.

Market Packages should each be independently sellable,
i.e. sell each step one at a time.

Early packages must deliver benefits in mixed traffic,
unequipped lanes.

Each package should be technically conservative,
so that successful as deployed,
have sequential credibility, "string of successes."

Slide 10 of 10

Market Package Sequential, Strategic Consids:

Market Packages should be attractive "step sizes,"
comprising a sequence strategy,
with stratified penetration,
that attractiveness being a function of:

- functionality (an attractive increment in functionality).
- price per that increment in functionality.
- insurability/liability (i.e., small step on those factors).
- compatibility (i.e., problems if 20 versions on the road).
- accessibility (i.e., accessible to broad cross-section).

By "stratified penetration," we mean that each Market Package may penetrate particular sub-markets (e.g., technology-leading consumers) first, then once that penetration has provided demonstration, proof-of-acceptance, and familiarity, the Package can penetrate other submarkets later.

In closing:

The participants did more than we asked them to. They developed many good ideas in both the Consumer Needs and Market Packages breakout sessions. They often deviated from, and in some cases went beyond, the patterns of responses that had been laid out for them as examples. The Consumer Needs they chose to develop were in fact along the lines of performance/impact measures. The "So What" analysis came out looking more like a decision-analytic influence diagram, and highlighted the challenge of doing a "So What" analysis on a User Service that has countervailing effects. They developed a good idea for structuring the "So What" analyses to relate a list of User Services to a list of User Needs. Many of the guidelines for Market Packages came out as evaluation factors and considerations. The participants specifically extended their thinking to Market Package sequences, developing good ideas for sequential, strategic considerations.

8.2 Commercial Vehicle Operators Breakout Session

Guidelines

- aim for the biggest bang for the buck (GM holds clinics with buyers before designing)
- market driven
- Develop a series of market packages as a whole, logical progression as defined by market needs, not technological progression....not independent packages that are not interdependent...more evolutionary
- Build upon what you have now in CVO, which is communications between vehicle and infrastructure
- next step is.....maybe keeping the driver from falling asleep.....then adaptive CC......then, vehicle to vehicle communication for platooning (lead vehicle controls

Guidelines

- Three principal interests for the 1997 Demo
  - Economics (fuel economy, fleet mgmt., productivity)
  - Safety
  - Mobility/Accessibility
  - Clean Air
- Detail should be focused on the Near Term with a some fuzziness of the future, instead of major focus on the far future

Guidelines

- Start with MPs that benefit all users
- initial market may be for trucks as they can make case for more expensive equipment
- later market has larger volume, support lower prices, wider use

Issues

- Transferring freight is fundamentally different than transferring people
- truck drivers travel more in one year that people in their lifetime
- Vast range of CV groups and application types (light duty, class 3-4 pick-up; medium duty, class 5-7 pick-up an delivery; heavy vehicle, class 8 vocational trucks, to heavy vehicle, class 8 long-hual trucks

Issues

- 5 year development cycle for vehicles
- Four phases (starts when designers get the idea....clay model....wind tunnel....great looking but "tooling" is not available (twisted fender)....validation and prototype mold....production
- Tooling is very expensive, volume is very important....
- 2.5 years for Eaton development cycle from design to production

Issues

- The biggest volition is deployment in trucks/transit vs. private passenger (e.g. roadside to vehicle communications)
- The cost of operating a truck is $1 a minute.....if you can reduce that based upon the market packages......value of safety
- Information sharing: if dedicated lanes, then yes, they'll provide but if not, guard against privacy ("Stay out of my cab")

Issues

- Consideration of Teamsters/Union Issues
- Take it one step further than Adaptive CC
- Profits this month; sales goals are immediate

Issues

- Three separate types of CVO (private, for hire, intermodal)
- These Mps may be used in other countries (eg parts manufactured in Canada are trucked to Mexico....lane keeping capability should be available from door to door)
- Market Packages are not just truck specific. ..they'll be of value of other user
- Deployment path focussed on initial deployment in trucks is more likely (cost, test bed)
- We need continual large incremental leaps in safety......insurance companies will give savings.....data can be misintrepreted (eg airbags problem)
- Earlier adopters (buyers) will get the benefits (eg. ABS)

New CVO MPs

- didn't define any, but have input on sequencing

Market Package Sequencing

- four primary packages
- 1. Lane keeping
- 2. Collision warning (take a big effect in insurance costs)
- 3. Driver Fatigue
- 4. "volunteer" Speed Control (roadside to vehicle speed warning is already available)

Control Regimes (Driver Control)

- 1st Warning
- 2nd Assistance
- 3rd Supplement (full)
- Infrastructure
- autonomous
- one-way
- interactive (two-way)

Follow On Actions

- Dave and Bjorn to provide support and access to CVO stakeholders
- planned teleconference to follow up and make plans
- want to here what other groups are planning

8.3 Transit Breakout Session

Transit Breakout Group

Market Package Discussion

Attendees

- Kan Chen
- Tom Lambert
- Ron Fisher
- Susan Beaty
- Ron Hearne
- Mark Miller

Guidelines

- avoid using technical jargon
- expand the "5 who's"
- think broadly & creatively about market applicability; applications to other modes
- identify incremental deployment paths from any given m.p. –start with lowest risk first to build public confidence, to avoid failure, increase measured risk incrementally
- link market package to case studies to demonstrate technology, i.e. have mini-demos

New Market Package

- call it "full automation"
  - very low speed (5 mph)
  - dedicated lane for maintenance
  - no drivers during servicing though service personnel are on the ground
  - vehicle location system via sensors

New Market Package -Continued

- lateral, longitudinal guidance for a guidance vehicle to tow bus through service area
- collision avoidance on tow vehicle
- last stages of bus parking task a driver would be needed
- manage timing of fueling process
- borrow automated process used manufacturing industry

Progressive Deployment Path(s)

- increase measured risk
- increase speed of vehicles
- decrease exclusivitiy of lanes

Strategies To Continue And Complete The Process

- ITSA Advanced Public Transportation Systems Committee
- APTA meetings
  - general manager's
  - bus ops & tech
  - rail rapid transit
  - bus safety audit
- TRB committees

8.4 Infrastructure Breakout Session

Infrastructure: Market Packages

Stakeholders' Forum
June 6, 1997

Market Packages in General

- Need roadmap for market packages (technology neutral), beginning with cruise control
  - such "roll-out" diagrams exist going back to 1989
  - NAHSC has developed technology roadmap
- Market packages and roadmap should specify appropriate infrastructure components, including resources required

Market Packages in General

- Institutional structure/options may be own set of market packages
  - But shouldn't prejudge institutional environment 10+ years from now
- Market package definitions should specify:
  - Precedent market packages assumed
  - Degrees of performance

Cooperative Warning & Advice

- Doesn't say vehicle-to-infrastructure, but wasn't intended to exclude
  - VDOT planning includes expectation of info from vehicles
- If some vehicles can communicate, others are dumb: is this problematic?
- There are different kinds of vehicle-to-vehicle communication

Cooperative Warning & Advice

- Value of vehicle-to-vehicle information may be of limited value to non-equipped vehicles, thus appropriately vehicle-based
- NAHSC has important role in tying vehicle developers and roadside operators
  - Best market packages will maximize use of what's already happening

Cooperative Warning & Advice

- Infrastructure-to-vehicle communication now common in info systems; NAHSC contribution should be in vehicle-to-vehicle and vehicle-to-infrastructure communications

Collision Avoidance

- Goes beyond NHTSA to take control
- Is really group of market packages
  - Not using cooperation yet
  - But taking control in emergency situation
- Not clear why Run-off-the-Road is in this package
- Good for all classes of vehicles

Collision Avoidance

- What is role of infrastructure
  - If includes intersections, must include infrastructure
- Perhaps, should be split into front-obstacle and side-steering control
- How about a market package that reduces severity of collision (e.g. through slow-down, stopping)?

Collision Avoidance

- Fleets (transit, CVO) in particular will need retrofit packages

Cooperative Control Data

- Add Communication
- Takes control in emergency situations: Question is who recognizes emergency first

Cooperative Automation on Protected, Mixed Lanes

- "I would pay $2000 for this for longer (5 hour) trips."
- Good for CVOs
- Reduces risk without restricting use of lane
- Too early to conclude that physical barriers are best way to separate/isolate lane
- Could be implemented as test by allowing instrumented vehicles on So. Cal. busways

Cooperative Automation on Protected, Mixed Lanes

- Change "avoidance" to "warning" + lane keeping
- When hazards do get inside barriers, they are more difficult to remove, e.g. debris, deer
- Will require shoulder for disabled vehicles, et al.

8.5 Cross-cutting Breakout Session

Facilitator: Jim Reynold
Notetaker: Joy Pinne

PLEASE NOTE: The verbage that follows is based on the interpretation solely of the notetaker. Please forgive me if I have misrepresented any of the topics or missed something that was said during the breakout session. I have tried to add to certain areas to make them more clear, however I have tried to leave the flavor of conversation as it was during the breakout session. jp

Any combination of these packages may work in one area quite well, but not in another area. Response is that it may sell in certain areas and can only be used in maybe the top 50 cities, and doesn't work anywhere else. Feeling is that it should work everywhere.

We should concentrate on one area instead of trying to do everything and make it work in all situations. They suggested we concentrate on the city to city approach first and make sure that if someone buys a system in LA, it will function the same in Miami and New York (Standardize).

Will this information be used, or will this be another report sitting on a shelf?

The consortium should be and is a catalyst to get the vehicle industry to sell cars and the DOT's to provide the infrastructure.

Need to come out and agree on how we develop a system in small incremental steps that everyone knows about and agrees on with government incentives provided to get us there.

The interstate system was mandated. Is this required for an AHS? or is there a way to get there without mandates?

We need to quit worrying about the chicken and egg problem between the auto manufacturers and infrastructure industries and decide on a path that the system will evolve through.

Some felt that there is a push from automakers to put intelligence in roadway and visa versa. Others felt that the automakers have been going along just fine without relying on the infrastructure until things become standard (such as lane lines and markers).

A vision system that relies on these markings will not always work in areas that snow, at night, in the rain, etc. Do we develop redundant systems? Do we go with a system that will work in all areas equally? Do we still do this if it becomes expensive comparative to creating redundant systems? Do we accomplish a system that will work in all areas by requiring redundant systems in all vehicles? Will this increase the cost too much?

AHS will have to survive on its own merits similar to rail etc. Prototype should set the stage in a real world setting showing us the benefits. How much will it relieve congestion? How much will it make the system safer? How much will it cost? Will we need to provide separated lanes? Do we take away from the existing roadway or buy new right-of-way?

The question is how are we going to get there, not just the benefits. It is a great idea, but there is no possible way to get there in one big leap.

Market Packages with ITS are not working!!!! We should not follow this method. No one understands them. Stick with what is working. Communications - government/infrastructure. Long control - vehicle.

First step is possibly adaptive cruise control. 80% of Americans use cruise control, only 8% of the population have it in Europe. The package must make sense in all markets.

It has been that industry develops something because they can make money, not just because it is needed. Apply as needed.

Market packages as being nice and clean. Each piece of the package needs to be a complete set. Something that needs nothing else to be whole. It also needs to be adaptable so that additions can improve. A "car" needs many other packages to make it work. Everything else has to follow along. Tent won't stand up if some of the ropes are missing.

Braking for collision warning - need to add product. If you can't implement that portion, will the market package collapse? If we were to build a "car" tomorrow, we would need to build the infrastructure, the insurance industry, gasoline, body shops, etc.

We all agree that we must develop a flow chart for how deployment can take place. Infrastructure, vehicle, user training (should be intuitive), components, auto manufacturers, highway construction.

A lot of parallel paths. What is the cost and what are the benefits? This is what we really want to do, but in order to get there, we may need to do something first that is not as good, but will get us there. Is it worth doing now, or should we go on without it. May include it, but it may not be necessary to the end product. Do it if we can afford it.

Progressive deployment must account for all pieces of the puzzle.

Consortium wants to build a picture of end product. Take small steps that we can do and the big picture will follow. Lets just worry about the technical issues right now. Other issues are out of our control.

Critical path approach - Which items are essential to get us there and which ones aren't?

Need to define the long term goal in order to define the requirements for the blocks.

Paradox: Products they are coming out with now need to be focused towards an ultimate goal of an AHS. To do this, we need to know what the ultimate goal is, otherwise we may make a wrong turn.

Suggestion as a method to get to fully automated control: System with an electric car that will go to LA or NY without stopping. Electric guideway similar to subway. Controlled with a Raytheon (or other radar) system. Each car maintained electronically. Input your destination and sit back and relax. Charges as it goes. Could get us toward the ultimate AHS. Put in existing HOV lanes or abandoned rail lines. Would have to build some infrastructure. Early systems studies that were done for AHS used guideways. Trying to put together with private industry. Much cheaper than gas. No patents. Could be a building block towards full automation.

Incremental approach is the path we are taking. We can't say what government or industry is going to do 15 years from now, but we must make some assumptions to get us going.

How much intelligence should be in the car vs the roadway? Where do we want to use it? Intercity to intercity? EX: San Diego to Las Vegas.

Maybe start with a system that is specifically on trucking corridors and have a dedicated lane.

Certain things have to happen at a certain point. Someone has to make a decision that out of these five options, it makes the most sense to go with this path.

We need to identify at which point in the flow chart, where the technical decisions need to be made and make that a standard uniformly throughout the country. This is the reason for a national consortium. Lack of that has driven the vehicle industry to develop based on a lack of infrastructure because they can't count on it. At some point, market will demand that pieces be added to the roadway to make system more affordable.

WHAT ARE THE BENEFITS!!!!

The NAHSC role is to tell the industry how to get from point A to point B.

What is realistic for vehicles? What is realistic for infrastructure? Most are not dependent on infrastructure. Once infrastructure becomes consistant everywhere, then we can look at products that depend on the infrastructure and the industry will start marketing products that use it. GPS is an example of a system that we are trying to get the public to accept and trust. Start systems that are building stones towards the ultimate goal. Currently within 25 meters for GPS is acceptable. Technology will follow.

No money in DOT's right now to even maintain the roads. Governments institutional framework doesn't allow participation unless money is earmarked for construction and maintenance. Vehicle industry has never depended on government money. They do it on their own.

Provide technical guideline

What We Did

- Can't adequately address Market Packages without preparation and detail prior to Stakeholder meetings
- Discussed broad range of issues related to AHS development and deployment
- Developed new process for development and evaluation of Market Packages

Recommended Market Package Development Plan

- NAHSC develops proposed Market Packages and Market Package Sequence
  - detailed description
  - public sector requirements
  - private sector requirements
  - technical requirements
  - improvements over prior Market Package steps
  - benefits and risks
  - where it fits in the big picture

Recommended Market Package Development Plan

- Distribute proposed Market Packages to Stakeholders 30 days prior to meeting
- Hold Stakeholder Forums to review and comment on proposed Packages and Sequences
- Modify and improve proposed Market Packages and Sequences

Observations

- As defined, Market Packages may not explain AHS to ALL Stakeholder groups
- The process tends to repeat a lot of generally understood information
  - Suggest separate new Stakeholder orientation process, to streamline main activities

Observations (cont.)

- PMOC representatives - good for policy level issues and program issues
- Forums - good for detailed review
  - technical stakeholder committees could be effective
- How do we break pattern of government and industry independence?

Observations (cont.)

- Progressive deployment must account for ALL of the pieces of the puzzle
  - A "car" is not a Market Package
- Sub-components of a Market Package may not be essential for successful deployment
- Critical path approach for each Market Package and each Market Sequence would help

SHOW ME THE BENEFITS!!!

9. Stakeholder Group Organizational Breakouts

9.1 Government Agencies

The first action for this breakout was for the group to decide on a new or continuing PMOC Stakeholder Representative and Alternate. It was decided to continue with the current representatives and alternate which are listed below:

J.R. Robinson	Representative
John Kiljan	Representative
Ray Pethtel	Alternate

These were the issues that were brought up in this breakout sessions:

- Keep Stakeholder Forums / Workshops
- Have NAHSC make more of an effort to keep stakeholders involved
- Doing excellent job of addressing program
- Private Sector must lead
- Public Sector must support/encourage
- Stakeholder can suggest areas to start
- Present Case Studies at Forum

There was a big concern with the new categories for this forum. This group didn't see that it was divided into equal representation and that the new groups were necessary. They also felt that emergency manager, police/state patrol should be included in this group.

There were several questions that were asked by the group to be answered by the Consortium:

- What do government agencies want from deployment?
- Do separate government agencies want different things?

Some comments about this Forum

- There should be a list about what to do in breakout sessions - specific questions to answer.
- Should receive information beforehand about what is being presented and what questions will be asked.
- The group felt that the first day of the forum was a waste of time - the forum should start with brainstorming then go on to reaction.
- One PMOC member should be assigned to stakeholder interests
- Stakeholder Reps should be there and help conduct program/meeting, record meetings, get material beforehand.
- NAHSC should not impose NAHSC agenda on stakeholders

Negative view of the Consortium

- Cursory view of technology
- Cursory view of societal and institutional issues
- No information on costs/negatives
- Not enough involvement with small, specialized systems

Positive view of the Consortium

- The concentration on safety, best program that is going
- The concentration on congestion

9.2 Transit Operators

Minutes were not turned in for this breakout session. The following people were voted for PMOC Stakeholder Representative and Alternate:

Robert G. MacLennan - Representative
Tom Lambert - Alternate

9.3 Highway Industry

John Mason, the Stakeholder Representative, was not available to run this session, but Ron Hearne, the NAHSC Liaison, moderated the session instead. Sarah Nolf was the recorder for this session. John Mason agreed the previous day to continue as Stakeholder Representative for this stakeholder category. The following person was elected as Stakeholder Representative with no objections from the members who attended this session:

John M. Mason - Stakeholder Representative

The following people attended the breakout session:

Amy Polk		
Jeff Boehm	-	3M
Bill Jeffries	-	Mitretek
Joe Beggan	-	Rizzo Associates, Inc.
Ron Hearne	-	Bechtel
Sarah Nolf	-	PB, NAHSC Program Office

The following is a summary of issues that were covered in the session:

There were concerns that the Consortium needs to look at other roads other than freeways, i.e. two lane rural roads and city streets. Market packages for these systems would be run-off road, early warning and land keeping.

There is a need to look at maintenance user services and market packages, i.e. automated snowplows, preventative maintenance of the infrastructure. This would benefit state operators.

There was a concern with the communications between automated highways and the TMC. Should the Consortium look at the interaction of the data coming into the TMC and the users of the TMC - perhaps some kind of software package to integrate the two systems.

Another idea for a user service if for the TMC and automated vehicles to have a predictability in congestion or weather conditions.

Listed below is a bulleted list of ideas that were talked about in the breakout session:

- There was concern that the Consortium didn't provide enough information about the market packages, there was not a base line to start from. The group needed to be shown something to get the brainstorming started.
- One of the packages mentioned a fully automated system in mixed traffic in the AVCSS Compendium. We need to talk about getting off of the freeway and something other than a dedicated lane.
- We need a backward-forward incremental addition to the vehicle like with cruise control, it is not only limited to freeways but is mostly used on freeways.
- The consortium should look at four lane highways and intersections.
- There would be some early benefits from looking at market packages outside of the freeways: Earlier deployment, increased safety and public acceptance.
- Is the Consortium looking at what the companies are going to come out with in the next few years and how it affects the role of the Consortium and the AHS?
- There needs to be standardization and that is what the Consortium is doing, they are looking at different technologies and advancing the most promising technologies. For example, 3M has been looking at a variety of products and has determined that magnetics is the best path for all different regions and weather.
- Is there something that the Consortium is missing (moderator)?
    - Automated Guidance on Snowplows
    - How about a maintenance package?
    - A package to let us know what the vehicle is doing
- That package is being looked at as a baseline standard function for all vehicles (moderator).
- Is there a preventative maintenance of the road/infrastructure for potholes or cracks being looking at for a user service/market package?
- IDV scenario for Demo '97 is looking at that, but it is within the vehicle. What about having Smart-Infrastructure? For example, having information about slippery road conditions on a bridge before vehicles even get there. Would this be cost effective and who would benefit from having this?
- Should this be in another market package or imbedded within the other ones. Should the Consortium be looking at this?
- The TMC has not been mentioned in the market package - software wise. Will there be a package to predict the problems and make adjustments through advisory signs on the freeway?

- Predictability is a good idea. The autonomous vehicles need to get info back to the TMC, is this idea being addressed?
- Also, can the data be shared from State/County/City operators?
- It would be great to be able to predict traffic for events and weather conditions. It is important that they system has a way to process the information and relay the problems.
- Should the Consortium be proactive to sort the data and create the market package or just provide the data and let the DOT's deal with the software?
- Smart - Infrastructure would be farther off in the future - what can be done to the infrastructure that would be cost effective and can be implemented quickly, get the biggest bang for the buck.
- Also need to look at the communications part of AHS, what will we do in rural areas - will we go wireless? Fiberoptics may be going down and the vehicles can use that as a way of communication.
- There may be an issue in combining types of communications technology - there needs to be consistency between the states.
- Should there be an obstacle detection market package for infrastructure - not only for vehicles?
- How does the TMC learn about crashes? Do the automated vehicles inform the TMC about incidents - what about rural areas?

9.4 Vehicle Electronics Industry

Jim Lewis, PMOC Liaison from Hughes, conducted the meeting for the Vehicle Electronics Industry stakeholder category. The notes below are the summary from the meeting that was presented at the breakout session presentation.

1. The vehicle electronics industry category is still looking for a stakeholder representative. The group was not able to identify a representative for the category at the second forum held in Boston, Massachusetts. It has been charged by the group to have John McComas (Delco PMOC) to check with the EIA to determine if someone from there is interested in representing this stakeholder category. As of now, John McComas will act as the interim representative.
2. The following list is what the stakeholders in this category would like to see
   - A written description of focus of the forum about a month before. For instance, information on market packages.
   - Would like to see a roadmap over time for the market packages
   - The group was very interested in discrete market packages which we will derive from our present global views.
   - As IVI is developed, the group would like continued updates on how vehicle automation fits in.

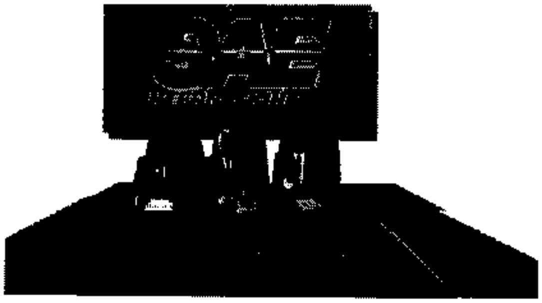
9.5 Vehicle Industry

Arlan Stehney, from SAE, lead the Vehicle Industry breakout session. The following people were reelected for stakeholder representative and alternate:

Bill Agnew, SAE - Representative
Arlan Stehney, SAW - Alternate

The slides below summarize the minutes from the breakout session.

NAHSC Stakeholder Forum
June '97
Vehicle Industry Stakeholder



Assumptions / Givens:

- "Real" AHS is not coming for at least 20 years
- Technology will change tremendously over the next 20 years (e.g. computer, communications)
- Manufacturers will offer products:
    - when consumers express "desire"
    - which manufacturers consider "safe"
    - not because of "industry pressure"
    - reluctantly to meet regulations

Recommendations:

- Embrace industry "evolution", as products will be introduced by vendors with technology
- Consider role of NAHSC until ultimate vision of AHS is closer to reality/implementation
- Focus NAHSC and government into the role of "umpire" versus "God"

9.6 Insurance Industry

Minutes were not turned in for this breakout session. The following people were voted for PMOC Stakeholder Representative and Alternate:

Wayne Sorenson, State Farm	-	Representative
John Werner, State Farm	-	Alternate

9.7 Trucking Operators

Minutes were not turned in for this breakout session. The following people were voted for PMOC Stakeholder Representative and Alternate:

Dave Barry, National Private Truck Council	-	Representative
Bjorn Klingenberg, Surface Transportation Association	-	Alternate

9.8 Transportation Users

Minutes were not turned in for this breakout session. The interim stakeholder representative from ITS America was agreed upon to still be the interim representative until another representative is found. The following people were voted for PMOC Stakeholder Representative:

Craig Roberts, ITS America	-	Representative

10. Breakout Session Report Presentations

All the presentations that were presented during this part of the forum are contained in the report for each breakout session. A handout was passed out for all the attendees to express their opinion on the forum. If you have not turned in your completed evaluation to the Program Office and would like to do so, please fax it to the following number : (248) 649-9569. Additional copies of the evaluation form are available within this report.

NAHSC
National Automated Highway System Consortium

11. AHS Stakeholder Forum Evaluation

Name (optional):______________________________

Thank you for participating in the AHS Stakeholder Forum. Your input is appreciated and we would like to know your opinion of the material that was presented to you during these two days. Please answer the following questions to help us in creating an AHS development process that is most useful to you.

1) Which user group(s) do you belong to? (Please circle)

Consumer CVO Transit Infrastructure Cross-Cutting

2) Do you feel the Consortium is listening to the users?__________What, if anything, would you change?______________________________

3) Do you feel that your user group is being considered equally in the process?______________________________

4) Do you have a clear understanding of User Services and Market Packages?______________________________

5) Did you find the breakout groups effective? __________ What would you change?______________________________

6) What, if any, comments do you have about the AHS market packages that have already been defined?______________________________

7) What, if any, comments do you have about the AHS User Services that have already been defined?______________________________

8) Other Comments

____

12. Comments, Questions and Concerns for the Consortium

If you have questions, comments or concerns about the AHS Program, please feel free to fax them to Sarah Nolf at (248) 649-9569. We will be posting all the comments with some answers from Core Participant Members on our web site (http://nahsc.volpe.dot.gov) and will also be sending out the finalized version to all our Associate and Outreach Participants. Some sample questions that were raised at last year's Boston Stakeholder Forum:

- What is the exact level of effort for the PMOC Representatives?
- Would it be more effective to build another freeway with Express Lanes instead of building a one lane dedicated AHS?
- What does Demo '97 intend to show that has not already been shown?

Your comments, questions and concerns:

Please fax or send this page to Sarah Nolf at the NAHSC Program Office, 3001 West Big Beaver, Suite 500, Troy, Michigan 48084, Fax: (248) 649-9569.

13. List of Attendees

Associates - 47 Attended

Alan Arai				
IMRA America, Inc.	2121 Second St., Building A, Suite 101 Davis, CA 95616		(916) 756-2813	(916) 756-2971
Arlan Stehney				
SAE International	400 Commonwealth Drive Warrendale, PA 15096-0001		(412) 772-7157	(412) 776-0243
Christopher Cluett				
Battelle	4000 N.E. 41st Street, P.O. Box 5395 Seattle, WA 98105-0395		(206) 528-3333	(206) 528-3552
D. Craig Roberts				
ITS America	400 Virginia Ave., SW, Suite 800 Washington, DC 20024-2730		(202) 484-2895	(202) 484-3483
Dave Barry				
National Private Truck Council	66 Canal Center Plaza, Suite 600 Alexandria, VA 22314		(703) 683-1300	(703) 683-1217
Dennis L. Foderberg				
University of Minnesota	511 Washington Ave., S.E., Suite 200 Minneaplois, MN 55455		(612) 626-8285	(612) 625-6381
Dr. Jacqueline Llanos				
Inrets - France DCEE - Polytechnic University	333 Jay Street - Bky New York, NY 11201		(718) 260-3433	(718) 260-3249
Dr. Wayne Sorenson				
State Farm Insurance Companies	One State Farm Plaza: Research D-4 Bloomington, IL 61701		(309) 766-3663	(309) 766-3662
Emiliano Lopez				
Virginia Department of Transportation	1401 E. Broad St. Rm. 207 Richmond, VA 23219		(804) 786-0186	(804) 225-4978
Frank Van Erkel				
Rijkswaterstaat Dutch DOT	P.O. Box 20906 2500EX The Hogue, The Netherlands		+31 70 351 8096	+31 70 351 8795
Gary Schneider				
Wilbur Smith Associates	1301 Gervais St., Suite 1600 Columbia, SC 29201		(803) 758-4500	(803) 251-2064
Hiroshi Doi				
SRI International	1611 N. Kent Street Arlington, VA 22209		(703) 247-8486	(703) 247-8569
Hiroshi Tsuda				
ITS America	400 Virginia Ave., S.W., Suite 800 Washington, DC 20024-2730		(202) 484-4134	(202) 484-3483

Hiroshi Ueno

Nissan Research & Development	39001 Sunrise Drive Farmington Hills, MI 48331	(810) 488-4099	(810) 488-3914
Homer Pettitt, Jr.			
DTS, Incorporated	4900 Seminary Road, Suite 701 Alexandria, VA 22311	(703) 379-4800	(703) 379-4901
James R. Robinson			
Virginia Department of Transportation	1402 East Broad Street, Suite 207 Richmond, VA 23219	(804) 786-6677	(804) 225-4978
Jeff Boehm			
3M	3M Center, 22-5-4N-14 St. Paul, MN 55144	(612) 736-3325	(612) 737-1055
Job Klynhout			
Rijkswaterstaat Dutch DOT	P.O. Box 1031 3000 BA Rotterdam, The Netherlands	+31 70 282 5902	+31 70 351-8795
John M. Mason, Jr.			
Penn State University	201 Research Office Bldg Transportation Operations University Park, PA 16802-4710	(814) 863-1907	(814) 865-3039
Joseph G. Beggan			
Rizzo Associates, Inc.	235 W. Central Street Natick, MA 01760	(508) 651-3401	(508) 651-1189
Jun Shibata			
ITS America	400 Virginia Ave., SW, Suite 800 Washington, DC 20024-2730	(202) 484-4135	(202) 484-3483
Kimberly Allyn Mastako			
Texas Transportation Institute	The Texas A&M University System College Station, TX 77843-3135	(409) 862-3928	(409) 845-6001
Mammen Daniel			
Daniel Consultants, Inc.	8950 Route 108 East Columbia, MD 21045	(410) 995-0090	(410) 992-7038
Michael R. Martin			
Martin Enterprises & Assocs.	2625 Steeplechase Dr. Reston, VA 20191	(703) 391-7330	(703) 481-5667
Michael Wolterman			
Toyota Technical Center	1410 Woodridge Ave. Ann Arbor, MI 48105	(313) 995-7117	(313) 995-7092
Mr. John Werner			
State Farm Insurance Companies	One State Farm Plaza: Research D-4 Bloomington, IL 61701	(309) 766-6172	(309) 766-3662
Nina Babiarz			
Technology Management Incorporated	7801 Mission Ctr. Ct #410 San Diego, CA 92108	(619) 298-7877	(619) 298-0115
Philip A. Reynolds			
Calspan SRL Corp.	150 North Airport Drive Buffalo, NY 14225	(716) 631-6715	(716) 631-6990
R. Barry Ashby			

Wave Band Corporation	1350 Eye St. N.W. (#1240) Washington, D.C. 20005	(202) 296-3840	(202) 682-0146
Raman K. Patel			
I-95 Corrider Coalition	NEC- One Penn Plaza Lit City, NY 10119	(212) 465-5502	(212) 465-5442
Randolph W. Hall			
University of Southern California	3715 McClintock Avenue, Room 247 Los Angeles, CA 90089-0193	(213) 740-4894	(213) 740-1120
Ray D. Pethtel			
Virginia Tech	312 Burruss Hall (0159) Blacksburg, VA 24061-0159	(540) 231-5199	(540) 231-3456
Rick Schuman			
ITS America	400 Virginia Ave., S.W., Suite 800 Washington, DC 20024-2730	(202) 484-4543	(202) 484-3483
Robert L. Neff			
Eaton Vorad Technologies	26101 Northwestern Highway, P.O. Box 765 Southfield, MI 48037-0765	(248) 354-2719	(248) 354-6962
Robert Larson			
Raytheon	7700 Arlington Boulevard Falls Church, VA 22046-1572	(713) 560-5000	(713) 208-1259
Robert R. Glass			
Jet Propulsion Laboratory	525 School St., S.W., Suite 203 Washington, DC 20024	(202) 426-9327	(202) 426-9355
Ronald Fisher			
Creative Transit Alternatives	6504 Stratton Place Falls Church, VA 22043	(703) 536-6430	(703) 534-4138
Scott Andrews			
Toyota Motor Corporation	1, Toyota-Cho Toyota, Aichi 471-71 Japan	81+565-23-9208	81+565-23-5742
Stephan Bahler			
Minnesota Department of Transportation	Mail Stop 320, Room 252, 117 University Avenue St. Paul; MN 55155-1899	(612) 215-0409	(612) 296-0152
Stephan G. Gehring			
ITS America	400 Virginia Ave., S.W., Suite 800 Washington, DC 20024-2730	(202) 484-4589	(202) 484-3483
Stephen Albert			
Western Transportation Institute	Montana State University, Bozeman Bozeman, Montana 59717-3900	(406) 994-6114	(406) 994-6105
Steven W. Hay			
University of Minnesota	511 Washington Ave., S.E. Minneaplois, MN 55455	(612) 626-1808	(612) 625-6381
Susan K. Beaty			
Houston Metro	1201 Louisiana Houston, TX 77208-1429	(713) 881-3029	
Susan Takami			
Navigation Technologies	10400 W. Higgins Rd., Suite 400 Rosemont, IL 60018	(847) 699-6523	(847) 699-8667

Susannah C. Scott

Jet Propulsion Laboratory	525 School St., SW, Suite 203 Washington, DC 20024	(202) 426-9336	(202) 426-9355

Takchiko Barada

Sumitomo Electric	3235 Kifer Road, Suite 150 Santa Clara, CA 95051	(408) 737-8517	(408) 737-0134

Tom Lambert

Houston Metro	1201 Louisiana St., P.O. Box 61429 Houston, TX 77208-1429	(713) 739-6808	(713) 759-9537

Core Participants - 33 Attended

Alan Lubliner

Parsons Brinckerhoff	One Penn Plaza New York, NY 10019	(212) 465-5412	(212) 465-5737

Aleks Gollu

University of California PATH	1357 S. 46th Street, Bldg 452 Richmond, CA 94804-4603	(510) 231-9466	(510) 231-9565

Bill Jeffrey

Mitretek	600 Maryland Ave., SW, Suite 755 Washington, DC 20024	(703) 285-1946	(703) 285-2264

Bill Spreitzer

GM ITS Program	30500 Mound Road Warren, MI 48090-9055	(810) 986-2916	(810) 986-9338

Bob McQueen

PB Farradyne	3200 Tower Oaks Blvd Rockville, MD 20852	(301) 816-5591	(301) 816-1884

Carol Jacoby

Hughes	Bldg. 617/AA306 ullerton, CA 92834	(714) 732-8224	(714) 732-2613

Celeste Speier

NAHSC	3001 W. Big Beaver Rd, Suite 500 Troy, MI 48084	(248) 816-3407	(248) 649-9569

Chris Bausher

PB Farradyne	3200 Tower Oaks Blvd Rockville, MD 20852	(301) 816-5590	(301) 816-1884

Daniel J. Guzman

GM - Advanced Tech. Vehicles	36852 Maas Drive Sterling Heights, MI 48312	(810) 680-5965	(810) 680- 5134

Don Orne

Parsons Brinckerhoff	535 Griswold, Suite 1940 Detroit, MI 48226	(313) 963-5760	(313) 855-8584

Evelyn Wagner

PB Farradyne	3200 Tower Oaks Blvd Rockville, MD 20852	(301) 984-6463	(301) 816-1884

George Percivall

Hughes Aircraft	1616 McCormick Drive	(301) 925-0368	(301) 925-0327

	Upper Marlboro, MD 20774		
Greg Larson Caltrans	1227 "O" Street, MS 83, P.O. Box 942873 Sacramento, CA 94273-0001	(916) 657-4369	(916) 657-4580
Greta Huang Bechtel	P.O. Box 193965 San Francisco, CA 94119-3965	(415) 768-0158	(415) 768-4560
Hamed Benouar Caltrans	P.O. Box 942873 Sacramento, CA 94273-0001	(916) 654-9768	(916) 657-4580
Jim Lewis Hughes Aircraft Company	Bldg 617/AA306 - P.O. Box 3310 Fullerton, CA 92634	(714) 732-8224	(714) 732-2613
Jim Misener California PATH	1301 S. 46th St., Bldg 452 Richmond, CA 94804	(510) 231-5651	(510) 231-9565
Jim Reynold Parson Brinckerhoff	5775 Blue Lagoon Drive, Suite 360 Miami, FL 33126	(305) 261-4785	(305) 261-5735
Joy Pinne Caltrans	P.O. Box 942873, MS-83 Sacramento, CA 94273-0001	(916) 657-4265	(916) 657-4580
Mark Miller California PATH	1357 S. 46th Street, Bldg. 452 Richmond, CA 94804	(510) 231-9465	(510) 231-9565
Marty Turner NAHSC	3001 W. Big Beaver, Suite 500 Troy, MI 48084	(248) 816-3400	(248) 649-9569
Pat McKenzie Lockheed Martin	P.O. Box 179, MS DC4350 Denver, CO 80201	(303) 977-0848	(303) 971-4093
Richard Bishop FHWA	6300 Georgetown Pike, Room T-201 McLean, VA 22101-2296	(703) 285-2680	(703) 285-2264
Roger Boothe PB Farradyne	3200 Tower Oaks Blvd Rockville, MD 20852	(301) 816-2777	(301) 816-1884
Ron Hearne Bechtel	45 Fremont St. San Francisco, CA 94105-1895	(415) 768-2604	(415) 768-2743
Sarah Nolf NAHSC	3001 W. Big Beaver, Suite 500 Troy, MI 48084	(248) 816-3411	(248) 649-9569
Steve Carlton Lockheed Martin	P.O. Box 179,MS DC4350 Denver, CO 80201	(303) 971-9563	(303) 971-4093
Steven Schuster			

Hughes Aircraft
Loc. FU, Bldg 675, M/S P343, 1801 Hughes Drive
Fullerton, CA 92633
(714) 732-1867 (714) 732-2613

Stuart Harvey

Caltrans
P.O. Box 85406
San Diego, CA 92186
(619) 467-3000

Thomas E. Marchessault

U.S. Department of Transportation
400 7th Street
Washington, DC 20590
(202) 366-5422 (202) 366-3393

Tom McKendree

Hughes
Bldg. 617/AA306, P.O. Box 3310
Fullerton, CA 92834
(714) 732-3228 (714) 732-2613

William B. Basset

Caltrans
1120 N. Street
Sacramento, CA 95812
(916) 654-2630

Yasuhiko Iwasaki

U.S.D.O.T. - F.H.W.A.
6300 Georgetown Pike
McLean, VA 22101-2296
(703) 285-2682 (703) 285-2264

Other Participants - 18 Attended

Adam S. Fine

Fine Research
12405 Wendell Holmes Rd.
Herndon, VA 20171
(703) 264-0018 (703) 264-0019

Amy Polk Bribbon

3549 Garfield
Minneapolis, MN 55409
(612) 823-5113

Bjorn Klingenberg

Surface Transportation Association
2111 Summit Drive
Lake Oswego, OR 97034
(503) 635-9416

Christopher K. Wilson

DaimlerBenz
1510 Page Mill Road
Palo Alto, CA 94304
(415) 845-2579 (415) 845-2555

Daniel Brand

Charles River Associates
200 Clarendon Street, T-33
Boston, MA 02116-5092
(617) 425-3310 (617) 425-3132

Edward Greene

Ford Motor Company
9810 Allen Road
Allen Park, MI 48101
(313) 594-3700 (313) 594-3700

Jonathan Slevin

Walcoff
12015 Lee Jackson Highway, Suite 500
Fairfax, VA 22033
(703) 218-1447 (703) 934-9866

Kan Chem

Kan Chen Incorporated (KCI)
2420 Skyfarm Drive
Hillsborough, CA 94010
(415) 375-8890 (415) 375-8582

Kazutoshi Sato

JSK
Toranomon-34-Mori Building
1-25-5, Toranomon, Minato-Ku, Toyko 105 Japan

Ling Yu	City of San Antonio	3500 N.W. Loop 410, Suite 321 San Antonio, TX 78229	(210) 733-4574	(210) 733-4576
Louis F. Sanders	APTA	1201 NY Avenue NW Washington, DC 20005	(202) 848-4086	
Mac Woodward	Izaac Walton League	699 Chapel Hill Rd Charlston, VA 22901-2943	804) 973-3708	(804) 973-2004
Michael P. Curran	Inside ITS	270 Lafayette Street, Suite 700 New York, NY 10012	(212) 925-1714	(212) 925-7585
Robert H Borcherts		1555 Washtenaw Ann Arbor, MI 48104	(313) 663-6758	(313) 662-0091
Robert S. Jaffe	Jaffe Engineering and Development Industries	POB 501, 17 Miller Avenue Shenorock, NY 10587-0501	(914) 248-8466	(914) 248-5840
Ron Frazzini	Honeywell Technology Center	3660 Technology Drive Minneapolis, MN 55418	(612) 951-7353	(612) 951-7438
Takashi Fukunaga	Panasonic Industrial Company	44768 Helm Street Plymouth, MI 48170	(313) 455-9290	(313) 455-9336
Yasu Ishiai	Panasonic	44768 Helm Street Plymouth, MI 48170	(313) 455-9089	(313) 455-9336

10.6.3 Post Demo Survey

AHS DEMO RIDER SURVEY **October 1, 1997**ahsdemo.sum
TASK C3: USER NEEDS ***Y.B. Yim & Ronald Koo***

EXECUTIVE SUMMARY OF PRELIMINARY FINDINGS

During a four-day demonstration of the automated vehicle and highway technologies in San Diego, a survey of demo riders was conducted at the Miramar College site. The purpose of the survey was to gain insights into the participants' perceptions of AHS technologies. A two page survey questionnaire was distributed to demo riders of each scenario by narrators or interviewers after completing their ride in returning vehicles from the demo site to the college. The riders were asked to fill out the questionnaire in-vehicle or at the drop-off site on campus. The survey covered four areas of revealed preference questions: 1) what did they like and dislike about the automated vehicle and highway technologies (referred to AHS technologies), 2) what are the perceived benefits of AHS to individual users and to society in general, 3) what concerns do they have with AHS, and 4) for what kind of driving or in what environment would they use AHS. The following is a summary findings of the demo survey.

Of the 1,200 survey forms distributed during the demo period from August 7-10, 1997, 974 riders completed the survey which resulted in an 81.1% return rate. This high return rate is significant from a statistical point of view because it suggests that the survey sample is highly representative of the demo rider population. Descriptive statistical techniques including Chi-square and t-tests were used in order to determine associations between responses and scenarios.

Due to the size and number of vehicles used in different scenarios, proportions of survey participants differed among scenarios (Table 1). The free agent bus scenario obtained the highest proportion of participants (56.9%) followed by the platooning scenario (24.5%). Although the sample size of some scenarios was fairly small, responses were crosstabulated by scenario to

determine the similarities and differences between rider perceptions of each scenario. The statistical analysis showed that rider responses were remarkably similar for the most part at the 95% confidence level (Chi-squire test and t-test of means and proportions).

Table 1. Distribution of survey participants

Scenario	Scenario color	No of participants	% of participants
Free-agent, multi-platform, passenger vehicle	Tan	43	4.4
Free-agent, multi-platform, bus	Red	554	56.9
Platooning	Green	239	24.5
Maintenance	Orange	21	2.2
Control transition	Blue	27	2.8
Heavy truck	Purple	35	3.6
Evolutionary	Gray	55	5.6
Total		974	100

FINDINGS

Reaction to the AHS technologies

An overwhelming majority of demo riders (98.5%) responded positively to the AHS. Their first reaction to it was 'great, terrific, super, very impressive.' The demo riders liked what they saw and experienced (94.6%) with the AHS technologies. Among the reasons were: 1) the good ride quality and ease of vehicle operation, 2) the safety and sense of security they felt while riding, 3) the reliability of the technologies, 4) the smooth transition from automatic to manual operation, 5) the vehicle's ability to change lanes and provide longitudinal control, 6) hands-free driving and automated cruise control, 7) the vehicle's maneuverability and its ability to respond, 8) the visual display, and 9) the interface between vehicles and drivers.

AHS attributes

With respect to specific questions regarding the AHS attributes, over 90% of the participants said that the ride felt smooth, safe, quiet and enjoyable. They also responded positively to the performance of the demo vehicles with regard to their ability to smoothly accelerate or decelerate and to maintain a comfortable temperature in the vehicle compartment. Over 80% of the participants said that the demo vehicles operated at the right speed and that they were comfortable riding them. The participants were also impressed with the design of the display and the audio quality. The majority of them said that the display looked like it would be easy to use (61.7%), it was well designed so that the information could be easily understood (65.2%) and the audio was pleasant and reassuring (57.8%).

Vehicle spacing for the platooning scenario

One question was concerned with the distance between vehicles during the platooning scenario since part of that experiment was to test how comfortable the drivers were with this aspect of an automated environment. The survey of those who participated in the platooning scenario found that the majority (73.5%) felt comfortable with the 20 foot distance between the vehicles driving at 60 MPH. Only 7.5% felt that the vehicles were too close and 6.8% said they were not sure.

Willingness to use the AHS technologies

When asked whether they would like to use automated vehicle and highway technologies, an overwhelming majority of the participants (95.2%) said they would like to use them. Only 2.5% said they would not and 2.4% said they did not know. Crosstabulations showed that age or gender was not closely associated with the willingness to use the AHS. This result is somewhat different from the focus group study conducted in the San Francisco Bay Area in 1996. The focus group study found that the older generation, age over 50 years, was much more enthused about the AHS than the younger generation was, age under 35. [1,2]

Environment suitable for the use of AHS

When asked about the suitability of the AHS for driving conditions, many believed that such technologies would be most appropriate for urban or rural freeway driving and also for long distance trips. About one-half of the participants thought that the AHS would be appropriate for commute trips as well as for driving at night or in fog.

Perceived benefits of AHS

The participants perceived that most important benefits of the AHS to them personally were stress reduction and making driving easier. They also viewed that AHS users could benefit from reduced travel time. Considering society in general, the most important benefits cited were increased safety and increased vehicle throughput. The participants also thought that the AHS would result in reduced air pollution.

Concerns about AHS

The most frequently mentioned concerns about the AHS for driving on a highway were the drivers' inability to control automated vehicles in emergency situations (30.1%) and to control hardware when it breaks down (19.2%). Some participants were also skeptical about whether the computer technology could make the right decisions for different driving conditions (15.6%). When asked about concerns that they have personally about the use of the AHS in general, some common responses were "giving up control of the vehicle to a computer," "it may encourage greater use of personal vehicles," and "the possible government invasion of their privacy."

Expected toll of automated highways

Since the cost recovery of the AHS infrastructure is of interest to providers, the participants were asked how much they are willing to pay for the toll of automated highways. For a trip approximately the same length as the demo ride, about 7 miles, the average toll they were willing to pay was $1.23 and the median toll was 70 cents.

Changes in the perception of the AHS after demo ride

With regard to the changes in the perception of AHS, a vast majority of the participants said that they had become more positive toward AHS (70.5%) while only 0.4% had become less positive. 15.6% of the participants indicated that the demo had not changed their perception at all.

Sample characteristics

The demo riders were from several different organizations but the transportation industry represented the largest proportion (31.1%) of the demo participants. 19.4% represented the public sector from local, state and federal governments, and 14% were from universities or research institutions. 8% were from the electronics industry and only 2.2 % were from the telecommunications industry. The majority of the participants were employed full time and the mean age of the survey participants was 45.8 years. There were four times as many male participants as there were female participants in the demo survey.

---

[1] 1. Yim, Youngbin, *consumer attitudes toward Automated Highway Systems*, ITS America 7th Annual Meeting, June 2-5,1997.
2. Yim, Youngbin, *a focus group study of Automated Highway Systems and Related Technologies*. the 8th International Federation of Automataic Control Symposium on Transportation Systems, Technical University of Crete, Greece, June 16-18,1997.

APPENDIX

AHS Demo Survey Preliminary Results

Sample size: 974 completed surveys

Q1. What is your initial impression of the automated vehicle and highway technologies that you experienced on this demo ride?

First reaction to AHS	**n**	**%**
Great, terrific, super, very impressed, very interesting	589	67.9
Positive comments on the AHS technologies	161	18.6
Very smooth, very comfortable	41	4.7
It works	39	4.5
Has useful safety features, felt safe	24	2.8
Negative comments on the AHS technologies	13	1.5
Total response(n)	**867**	**100**

Q2a. What did you like most about the demo ride?

	n	%
Liked everything	**27**	**3.4**
Liked about the AHS	**506**	**64.1**
- Technology	192	
- Vehicle performance, operation	56	
- Safety, sense of security	98	
- Ride quality	113	
- Design quality	47	
Liked about the demo	**257**	**32.5**
- Demo itself	152	
- Narrators	105	
Total response	**790**	**100**

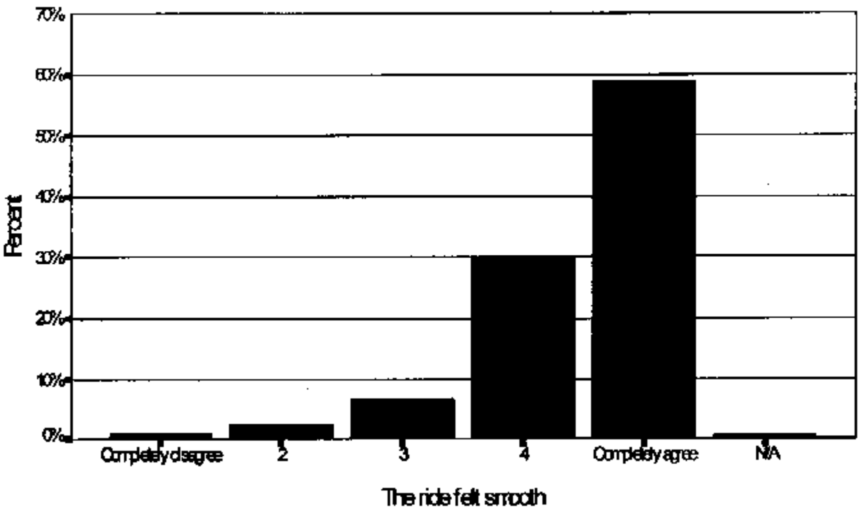
Q2b. What did you dislike most about the demo ride?

	n	%
Disliked nothing	(186)	**(35.9)**
Disliked about the AHS technologies	**142**	**42.8**
- Feeling loss of vehicle control	15	
- Braking complaints	14	
- Ride was noisy	9	
- Ride was "jerky," not smooth	43	
- Vehicle separation	17	
- Difficult to trust AHS in general	37	
- Auditory warnings not clear enough	7	
Disliked about the demo	**190**	**57.2**
- Demo too short, not enough maneuvers, unable to test more scenarios	98	
- Difficult to see the road ahead	42	
- Demo too highly choreographed	20	
- Demo logistics seemed in disarray	20	
- Unfavorable comment on the narrators	6	
- Cost concerns, too expensive	4	
Total response	**332**	**100**

Note that 14.6% of the total sample responded negatively to the demo experience regarding the AHS technology.

Q3. How would you rate the experience you just had riding the demo vehicle in terms of the following attributes?

3a) THE RIDE FELT SMOOTH

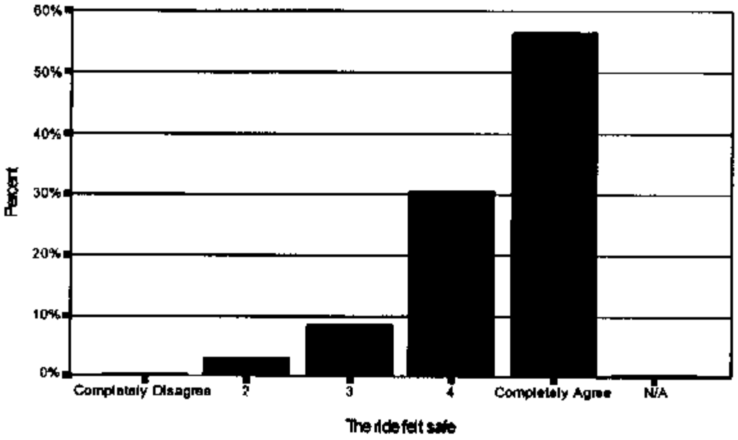


(Use a 1 to 5 scale, where 1 means you "completely disagree" with the statement and 5 means you "completely agree" with the statement. Feel free to use any number from 1 to 5 to express your opinion.)

1: Completely disagree:	0.9%
2:	2.7
3:	6.8
4:	30.1
5 Completely agree:	58.9
Not sure/ no answer	0.6

Total response n = 968

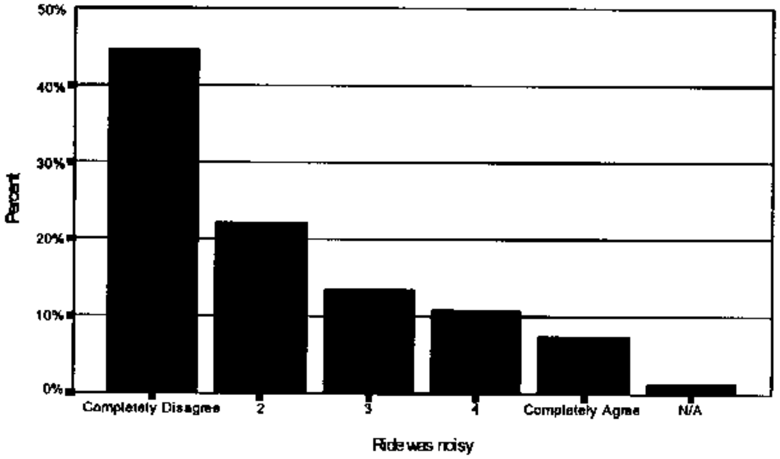
3b) RIDE FELT SAFE



1 Completely disagree	0.6%
2	3.0
3	8.7
4	30.7
5 Completely agree	56.6
Not sure/ no answer	0.4

Total response n = 970

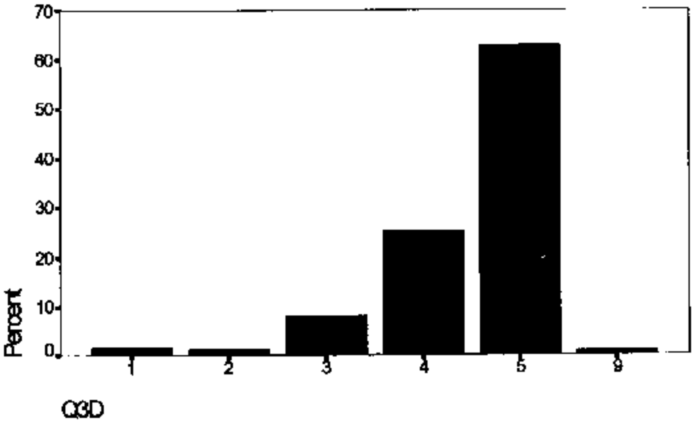
3c) RIDE WAS NOISY



1 Completely disagree	44.7%
2	22.2
3	13.3
4	10.9
5 Completely agree	7.5
Not sure/ no answer	1.4

Total response n = 960

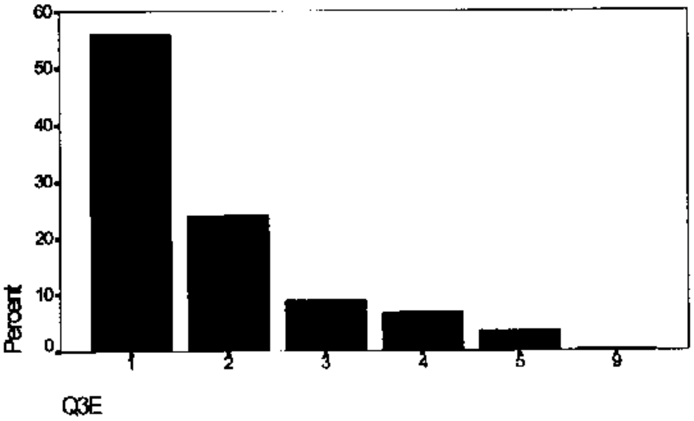
3d) RIDE WAS ENJOYABLE



1 Completely Disagree	1.6%
2	1.2
3	7.9
4	25.3
5 Completely Agree	62.9
Not sure/ no answer	1.0

Total response n = 964

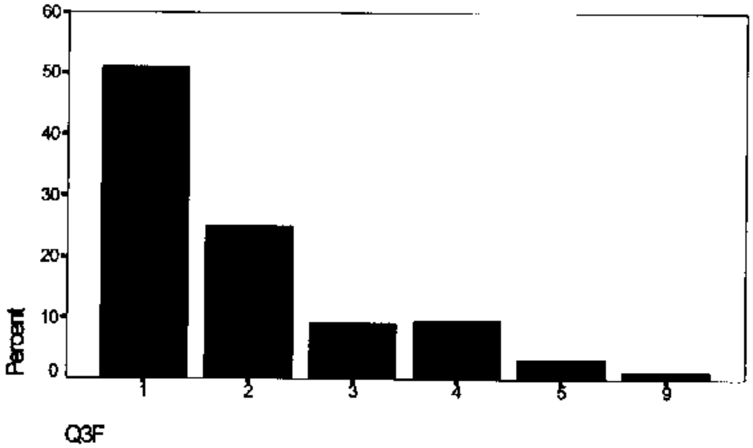
3e) ACCELERATION WAS TOO SUDDEN



1 Completely Disagree	56.1%
2	24.0
3	9.0
4	6.9
5 Completely Agree	3.5
Not sure/ no answer	0.5

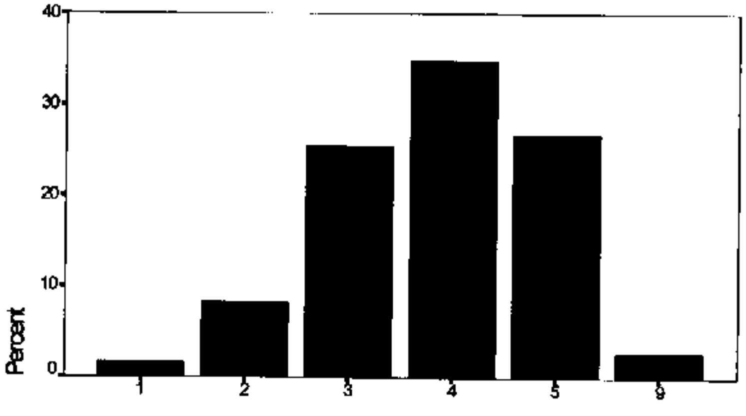
Total response n = 969

3f) DECELERATION WAS TOO SUDDEN



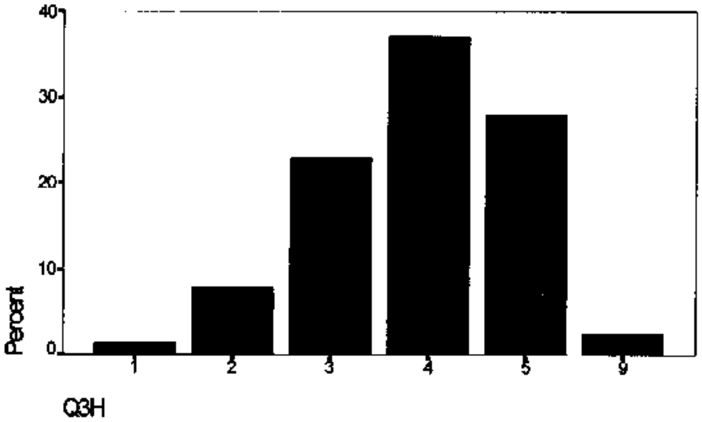
1 Completely Disagree	51.1%
2	25.2
3	9.3
4	9.8
5 Completely Agree	3.3
Not sure/ no answer	1.3
Total response N= 974	

3g) THE DISPLAY LOOKED LIKE IT WOULD BE EASY TO USE



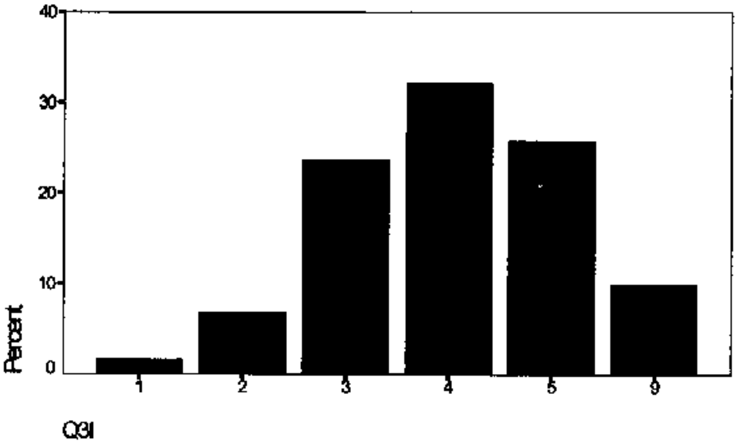
1 Completely Disagree	1.7%
2	8.3
3	25.5
4	34.9
5 Completely Agree	26.8
Not sure/ no answer	2.8
Total response N= 974	

3h) THE DISPLAY WAS WELL DESIGNED SO THAT THE INFORMATION COULD BE EASILY UNDERSTOOD



1 Completely Disagree	1.4%
2	7.8
3	23.0
4	37.3
5 Completely Agree	27.9
Not sure/ no answer	2.6
Total response N = 974	

3i) THE AUDIO WAS PLEASANT AND REASSURING



1 Completely Disagree	1.6%
2	7.0
3	23.6
4	32.1
5 Completely Agree	25.7
Not sure/ no answer	10.0

Total response N = 974

Q4. Did the car go too slow, too fast, or about the right speed?

Car went too slow	14.2%
Car went too fast	1.2
About right speed	83.3
Not sure/ no answer	1.3
Total response n = 961	

Q5. Was the car compartment too warm, too cold, or about the right temperature?

Car temp. too warm	4.3
Car temp. too cold	3.6
Car temp. about right	90.0
Not sure/ no answer	2.1
Total response n = 954	

Q6. Did the cars in front or behind you seem to be too close or far enough away?

Cars in front too close	7.5
Cars in front far enough	85.7
Not sure/ no answer	6.8
Total response n = 908	

Q7. After taking the demo ride, do you think you would like to use automated vehicle and highway technologies?

Would like to use AHS tech.	95.2
Would not like to use tech.	2.5
Not sure/ no answer	2.4
Total response n = 951	

Q8. For what kind or driving or in what situations would you use this technology?
(check as many as apply)

Urban freeways	71.3
Rural freeways	70.4
Long trips	90.1
Commute trips	54.5
Driving on surface streets	19.5
Driving at night or in fog	56.1

Other (specified)	5.6
Total response N = 974	

Q9. What are the most important benefits for you personally of vehicle automation for driving on a highway?

Most important (1)	
Increased privacy	0.9%
Reduced stress	27.4
Reduced travel time	10.5
Makes the driving task easier	21.6
Being able to do other things while driving	9.0
Other	13.8
Total response n = 32	

Second most important (2)	
Increased privacy	0.7%
Reduced stress	23.7
Reduced travel time	15.5
Makes the driving task easier	26.5
Being able to do other things while driving	10.8
Other	2.6
Total response n = 670	

Third most important (3)	
Increased privacy	1.6%
Reduced stress	17.7
Reduced travel time	16.9
Makes the driving task easier	15.6
Being able to do other things while driving	17.9
Other	4.4
Total response n = 418	

Q10. What are the three most important benefits in general of vehicle automation for driving on a highway?

Most important (1)	
Increased safety	61.4
Reduced pollution	1.6
Reduced noise	1.0
More vehicles can travel on an automated lane	13.7
Fewer new highways will be needed	4.8
Other	0.9
Total response n = 768	

Second most important (2)	
Increased safety	10.0
Reduced pollution	13.9
Reduced noise	1.8
More vehicles can travel on an automated lane	34.5
Fewer new highways will be needed	14.9
Other	1.3
Total response n = 338	

Third most important (3)	
Increased safety	7.5
Reduced pollution	19.2
Reduced noise	3.8
More vehicles can travel on an automated lane	12.1
Fewer new highways will be needed	25.3
Other	2.1
Total response n = 65	

Q11. After riding the demo vehicle, what concerns you personally about vehicle automation technology?

Greatest concern (1)	
Control of vehicles in emergency situations	40.8%
Automated control hardware breaking down	25.7
Trusting computer technology to make the right decision	16.0
Other	3.6

Total response n = 726

Second-greatest concern (2)	
Control of vehicles in emergency situations	20.8%
Automated control hardware breaking down	31.4
Trusting computer technology to make the right decision	17.7
Other	1.1

Total response n = 707

Third-greatest concern (3)	
Control of vehicles in emergency situations	13.0%
Automated control hardware situations breaking down	15.1
Trusting computer technology to make the right decision	31.4

Other 1.6

Total response n = 638

Fourth-greatest concern (4)	
Control of vehicles in emergency situations	0.1%
Automated control hardware breaking down	0.4
Trusting computer technology to	0.4
Other	1.1

Total response n = 73

Q12. What concerns you personally about vehicle automation usage in general?

Greatest concern (1)	
More air pollution will result	3.7
It encourages greater use of personal vehicles	18.5
Giving up control of the vehicle to a computer	35.8
Possible government invasion of privacy	9.8
Other 4.6	

Total response n = 249

Second-greatest concern (2)	
More air pollution will result	6.7
It encourages greater use of personal vehicles	15.5
Giving up control of the vehicle to a computer	12.9
Possible government invasion of privacy	9.3
Other	2.0

Total response n = 417

Third-greatest concern (3)	
More air pollution will result	10.7
It encourages greater use of personal vehicles	7.6
Giving up control of the vehicle to a computer	6.3
Possible government invasion of privacy	7.3
Other	0.9

Total response n = 542

Fourth-greatest concern (4)	
More air pollution will result	4.5
It encourages greater use of personal vehicles	1.2
Giving up control of the vehicle to a computer	0.6
Possible government invasion of privacy	7.0
Other	-.-

Total response n = 325

Q13. Would you be willing to pay a toll charge to use an automated highway system?

Yes	70.7%
No	17.5
Not sure/ no answer	11.8

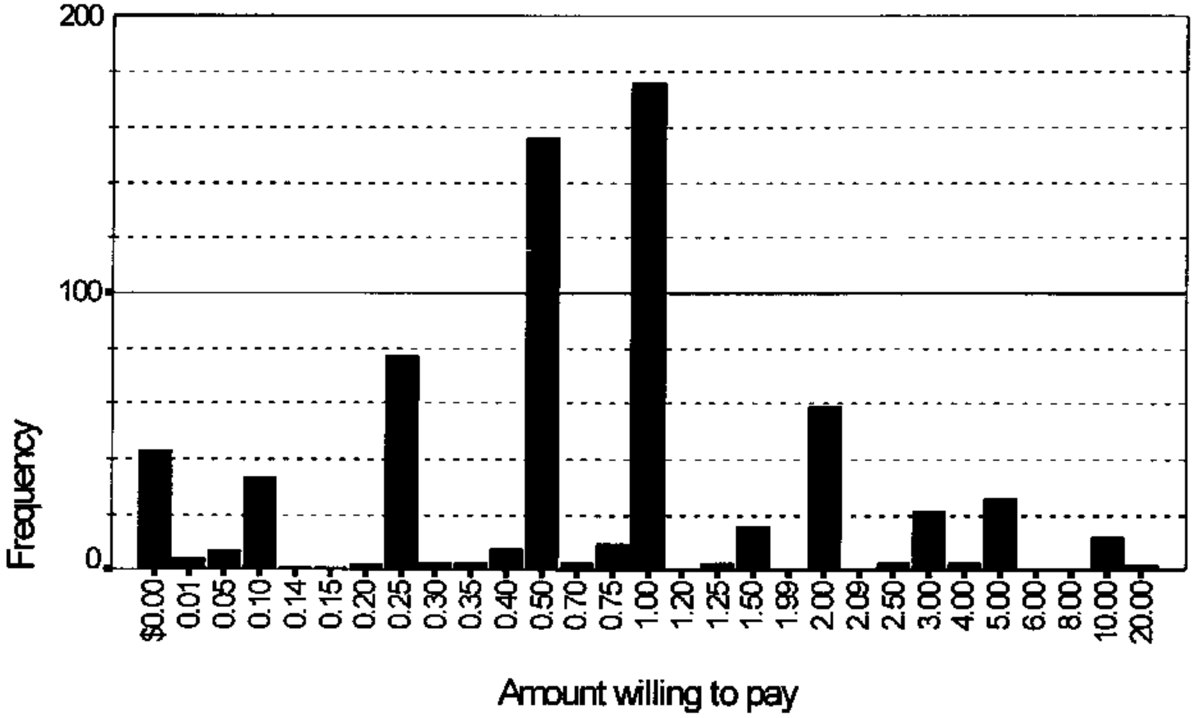
Total response N = 974

Q14. What toll charge would you expect to pay for a trip of approximately the same length as the demo ride?

Total response N = 974

mean $1.23
median$0.70

$0.00	4.4%
$0.10	3.5%
$0.25	7.9%
$0.50	16.0%
$1.00	18.1%
$2.00	6.1%
$3.00	2.3%
$5.00	2.7%



Q15. Which functions and features that you experienced at the demo would you like to have on your own vehicle?

	n	%
Cruise control, speed control	151	18.1
Collision avoidance radar	105	12.6
All of them	97	11.6
Lane control, distance spacing, platooning	71	8.5
Obstacle avoidance, proximity radar	57	6.8
Lane change, lance departure warning	53	6.3
Auto steering, hands-free	43	5.1
Lateral view, side view, blind spot warning	37	4.4
Other features: front view, front radar; rear view, real view avoidance radar; auto stop and go; display panel; auto braking; change from manual to automatic; navigation system, destination guidance; alarm, warning systems; the camera	77	9.2
Not sure	16	1.9
No answer	128	15.3
Total responses	**835**	**100**

Q16. As a result of the demo ride, how has your perception of automated vehicle and highway technologies changed?

Become more positive		70.5%
Become less positive	0.4	
Has not changed	15.6	
Not sure/ no answer	13.4	

Total response N = 974

Q17. What percent of your driving is on freeways?

mean:	51.1%
median:	50%
mode:	50%
st. dev.	25.0

Total response N = 974

Q18. Gender

Male	71.4%
Female	16.1
No answer	12.5
Total response N = 974	

Q19. Age Category

<18	0.7%
18-24	2.2
25-34	12.9
35-44	20.5
45-54	27.6
55-64	14.9
65+	4.7
No answer	16.4
Mean	45.8 years
Median	46
St. dev.	11.8
Total response N = 974	

Q20. Employment

Employed	78.6%
Retired	4.6
Neither	3.1
Other	13.7
Total response N = 974	

Q21. Which type of organization do you work for?

Transportation industry	31.1%
Public sector (local, regional, state or federal)	19.4
College, university or research organization	14.0
Electronics industry	8.0
Telecommunications industry	2.2
Other	10.2
No answer	15.2

Total response N = 974

Q22. In what country do you live?

United States	66.3%
Japan	9.0
France	2.4
Germany	2.1
Netherlands	1.6
England	1.2
Korea	1.1
Canada	0.7
Italy	0.6
Sweden	0.3
Belgium	0.2
Russia	0.2
Denmark	0.1
Switzerland	0.1
Other	0.6
No answer	13.3

Total response N = 974