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PATH—Partners for Advanced Transit and Highways—is a collaboration between the California Department of Transportation (Caltrans), the University of California, other public and private academic institutions, and private industry.

PATH's mission: applying advanced technology to increase highway capacity and safety, and to reduce traffic congestion, air pollution and energy consumption.

CALIFORNIA PATH

Developing Magnetic and GPS-Aided Inertial Navigation for PATH's Vehicle Guidance System

Jay Farrell, UC Riverside

Imagine computing a moving vehicle's position to within two centimeters — the size of your thumbnail — from a satellite in a twenty-million meter orbit. A PATH project now makes such accuracy attainable via the Global Positioning System (GPS), through techniques referred to as carrier phase differential processing. Researchers from UC Riverside and the PATH staff are collaborating to develop a reliable and fault-tolerant navigation system capable of providing vehicle state information with position estimation accuracy at the centimeter level. The immediate application of such a system would be for vehicle lateral control; application to longitudinal control and to aircraft, ships, and satellites is also possible.

To be capable of detecting and isolating sensor faults, the system should incorporate at least three sensors. To prevent all sensors from failing simultaneously, the sensors should have distinct operating principles. The three sensing approaches selected were magnetometer, carrier phase differential GPS (CPDGPS), and inertial measurements.

The main objective of this research was to develop and analyze the methods and algorithms needed to combine the magnetometer, CPDGPS, and inertial measurements in a navigation system to calculate the full vehicle state at accuracies consistent with the goal of achieving cm position accuracy. Since the main application is vehicle control, the system had to output the vehicle control state information with a rate of at least 25 Hz.

PATH has used a magnetometer sensing approach for over a decade with a high degree of reliability and success. Using an array of magnetometers mounted on a vehicle, the magnetic navigation system is capable of measuring the vehicle's distance from a path of magnetic markers embedded in the roadway with approximately 1.0 cm accuracy. The system also provides a measurement of trajectory relative vehicle heading.

Carrier phase differential GPS was being routinely used for post-processed surveying applications by the mid 1990s. A GPS receiver maintains phase lock to the carrier signal

continued on next page

generated by each GPS satellite. CPDGPS uses this phase measurement to compute the range between the antennae of the user and satellite. The main complicating factor is that this range is initially biased by the integer number of wavelengths of the carrier between the user and satellite antennas at the time that the receiver "locked" onto the satellite. This "integer ambiguity" must be estimated before the carrier phase can be used as a range estimate. Post-processed CPDGPS applications are now commonly and reliably used, since the integer ambiguities can be estimated and verified across an entire dataset. GPS real-time kinematic (RTK) research focuses on the development of methods to accurately and reliably estimate the integer ambiguities of a set of satellites in real-time for a moving GPS antenna.

Inertial navigation for vehicle control dates back to the 1940s. The advantages of an inertial navigation system (INS) are that the sample rate is fixed and can be quite high (kHz) and that the accuracy is unaffected by external fields. However, inertial systems for aviation and military applications are too expensive to be feasible for automotive applications. Two of the major factors for the high cost are low production volumes and the high cost of accurate inertial instruments. Recent advances in micro-electromechanical systems (MEMs) technology have resulted in solid-state accelerometers and gyros with potential costs of only tens of dollars in high production volumes. However, such solid-state inertial instruments, even when temperature compensated, tend to have high bias drift rates relative to traditional navigation specifications.

***Figure 1.* GPS antenna mount on PATH test vehicle.**

When this project began in 1995, pseudorange differential GPS-aided inertial navigation systems achieving 2 m accuracy were commercially available. Off line CPDGPS-aided inertial navigation had been implemented via post-processing, but there had been no demonstration of a real-time implementation, as is required for vehicle control. In May 1997, a team of researchers from the University of California at Riverside and the Stanford Research Institute demonstrated a real-time CPDGPS-aided INS that achieved 2.5 cm accuracy at 100 Hz. This navigation state vector was processed to produce a control state vector at approximately 30 Hz. In September 2000, a team of researchers from UC Riverside and PATH demonstrated reliable high-speed vehicle control using the CPDGPS-aided INS. In May 2001, reliable and accurate vehicle state estimation and control using the (triple redundancy) magnetometer and CPDGPS-aided INS was demonstrated.

This triplicate redundancy navigation system provides vehicle position, velocity, acceleration, attitude, heading, and angular rates at 150 Hz with accuracies (standard deviation) of 1.5 cm, 0.8 cm/s, 2.2 cm/s/s, 0.03 deg, 0.1 deg, and 0.1 deg/s. The system is designed to operate reliably whether or not GPS and magnetometer measurements are available. The May 2001 lateral vehicle control demonstration included the following situations: both CPDGPS and magnetometer-aided INS, CPDGPS-aided INS, magnetometer-aided INS, and switching between CPDGPS and magnetometer aiding of the INS at random times. The control demonstrations involved basic trajectory following as well as trajectory relative maneuvering (i.e., tracking sinusoidal perturbations and performing lane changes).

Sensor Package

Figure 1 shows a PATH Buick LeSabre instrumented with the magnetometer and CPDGPS-aided INS. The gray box on the left contains a Crossbow DMU-6X three axis inertial measurement unit, which includes a three-axis 2g solid-state accelerometer (100 Hz bandwidth) and a three-axis 100 deg/s solid-state gyro (10 Hz bandwidth). The DMU-6X performs anti-alias filtering, A/D conversion, start-up bias and axis-misalignment correction, and temperature compensation, and outputs the set of six inertial measurements by serial port at 150 Hz to the navigation computer. Commercial automotive applications would require similar inexpensive solid-state inertial instruments.

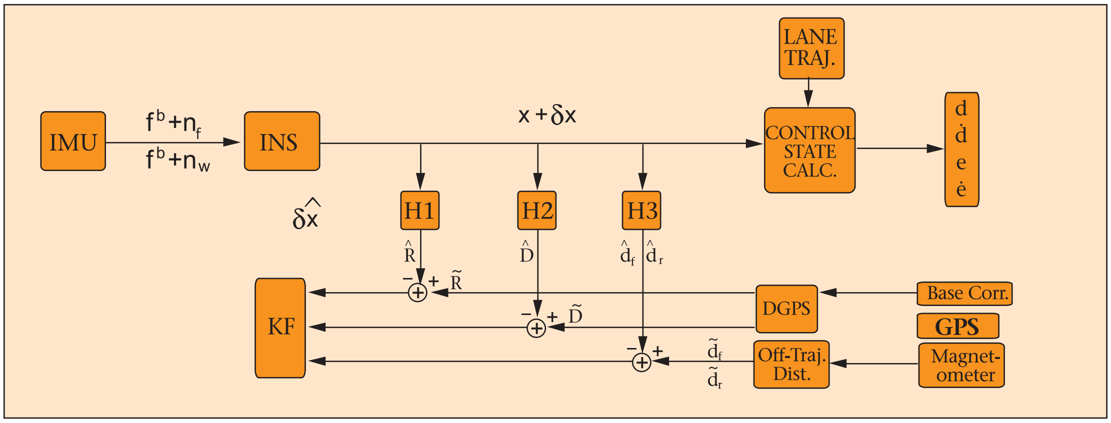


Figure 2. Complementary filter for integration of the magnetometer, carrier phase differential GPS, and inertial information.

Mounted on top of the gray box is the GPS antenna used for this project. Toward the front of the vehicle on the same mounting structure is a second GPS antenna that was used in selected attitude determination experiments. The tall antenna between the two GPS antennae is for the Freewave radio modem, used to communicate differential GPS corrections from a base station to the vehicle. A Novatel RT-2 GPS receiver (located in the trunk) processes the GPS antenna signal and sent pseudorange, Doppler, and carrier phase measurements via serial port to the navigation computer. The navigation computer (a Pentium notebook) implements the INS, complementary filter, and control state calculation equations.

Sensor Integration

Inertial, CPDGPS, and magnetometer measurements are integrated using a complementary filter (see Figure 2). In this approach, the angular rate information from the gyros is processed and integrated to compute a rotation matrix between the vehicle and tangent plane coordinate frames. Using that rotation matrix, the vehicle frame accelerometer measurements are processed and integrated to yield tangent frame velocity and position. This inertial state information is used to calculate predicted values for the CPDGPS and magnetometer measurements. The filter labeled KF is designed to attenuate the CPDGPS and magnetometer measurement noise and accurately estimate the INS state error. Then the estimated INS errors are fed back to correct the INS state. This estimation and error feedback can occur whenever GPS or magnetometer measurements are available. For the system discussed herein, the GPS and magnetometer measurements are incorporated at 1 Hz.

The INS state is computed at 150 Hz. INS computations continue regardless of whether magnetometer or CPDGPS measurements are available; therefore, the availability of the vehicle state for control computations is not affected by missed magnets or by loss of GPS satellite signals. The accuracy of the INS state information is affected by the amount of time since the last magnetometer or CPDGPS measurement. The error in the unaided INS grows in a polynomial fashion, reaching 0.5 meter error approximately 15 seconds after the last magnetometer or CPDGPS measurement. The complementary filter propagates error covariance matrices that characterize the accuracy of the INS state estimate. Therefore, in the event of sensor failure while in an automated mode of operation, the navigation system is able to warn the driver to resume manual operation with sufficient time for the driver to resume control.

Experimental Control Results

Figure 3 and Figure 4 show results of the instrumented vehicle performing maneuvers relative to the trajectory at the Crow's Landing test facility. The lane trajectory at Crow's Landing begins and ends with straight line segments. The middle section of

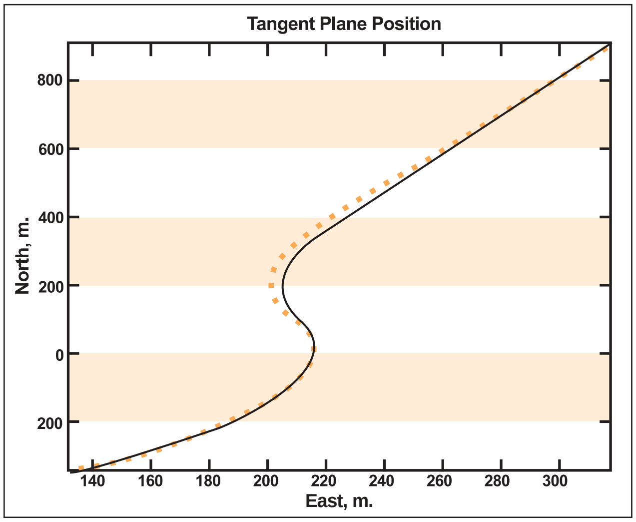


Figure 3. Tangent Plane Position. Plot of the north versus east coordinates of the vehicle performing a 3.6 m lane change maneuver along a curved section of the Crow's Landing test track.

the trajectory is composed of three 800-meter-radius turns that are constructed so that they connect smoothly to the straight portions of the trajectory. In Figure 3 the vehicle is traveling north to south. The southernmost curve and straight line segment have been cut off to improve the scale of the figure. The path of magnetic markers is indicated by the dashed line. The vehicle was commanded to perform a 3.6-meter lane change maneuver. Once the vehicle was more than 0.40 meter from the trajectory, the magnetometers were out of their effective range. The vehicle trajectory that resulted from this on-vehicle experiment is shown as the solid line in the figure. Note that this maneuver occurred at an arbitrary location.

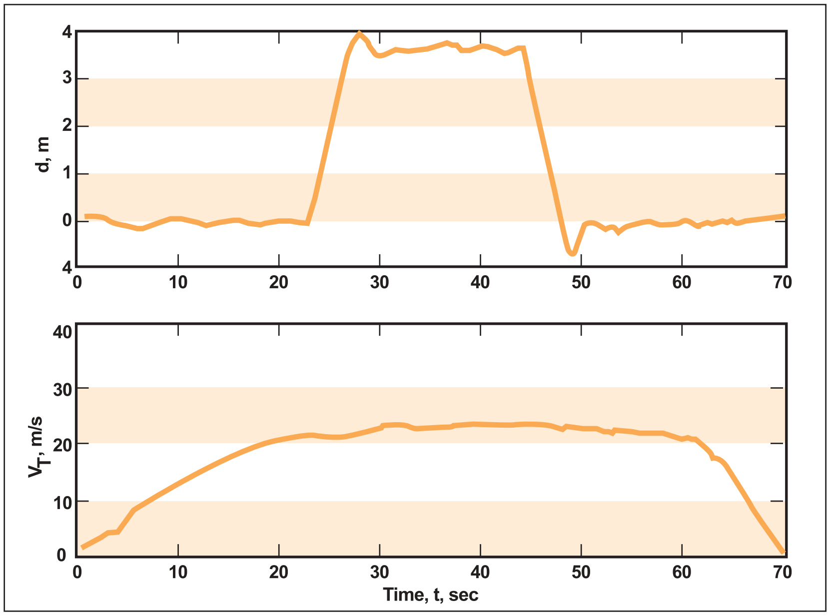
Magnetic and GPS-aided Inertial Navigation

The trajectory relative data is shown in Figure 4. The top graph is a time response plot of the distance *d* from the vehicle to the predefined trajectory. The bottom graph indicates the vehicle velocity tangent to the trajectory. The navigation system also computes velocity normal to the trajectory, trajectory relative heading and heading rate, and tangential and normal acceleration.

Figure 4. Trajectory relative data for the maneuver depicted in Figure 3.

Top—Plot of the calculated distance d, from the trajectory.

Bottom—Velocity tangent to the trajectory.



Significance and Future Applications

The main motivating application for our system is lateral vehicle control. However, the CPDGPS-aided INS portion is also applicable to air, sea, and space craft applications. The magnetometer and CPDGPS-aided INS has potential satellite-control applications.

In addition to the control state information required for lateral control, the navigation system also provides the tangential velocity information necessary for longitudinal control; therefore, a longitudinal control demonstration should be possible. This navigation system is also directly applicable to driver lane-departure warning and driver-assistance applications.

While roadway databases are available and used for a variety of purposes, the dominant roadway databases are only accurate to 15m, and do not store the altitude of the roadway. DaimlerChrysler and other research groups are developing methods to automatically incorporate position data from vehicles equipped with real-time kinematic (RTK) GPS into roadway databases. As the number of vehicles so equipped and the capabilities of these automated mapping methods increases, the development of a three dimensional centimeter-accuracy roadway database will be possible.

Another interesting application is the computation of relative vehicle state information for platooning or negotiating maneuvers with adjacent vehicles. Since each vehicle equipped with a magnetometer and CPDGPS-aided Inertial Navigation System is able to compute its own absolute position and velocity, the relative state information between any two vehicles can be computed by differencing the absolute state information of the two vehicles. The only additional hardware that would be required to support computation of vehicle relative state is a mechanism for communicating data between adjacent vehicles.

A variety of engineering projects (for example, vehicle system identification, tire slip estimation, and aerodynamic drag estimation) involve estimating particular aspects of a vehicle model. The accuracy of the estimated quantities is directly related to the accuracy of the sensors involved for measuring the dynamic state of the vehicle. The navigation system described in this article calibrates the inertial instruments and provides the vehicle state estimates at 150 Hz, with rates and accuracies better than any of the individual sensors involved. Perhaps the use of such integrated sensors in future projects involving the estimation of vehicle model parameters will allow more accurate estimation of the parameters of interest.

PATH Database Hits New Mark—World's Largest

Seyem Petrites, UC Berkeley

Entering the Database's 25,000th record were Barbara Post, Manager of Information Services for the Transportation Research Board, Nelda Bravo, Head of the National Transportation Library, PATH Database Manager Seyem Petrites and Database Librarian Michael Kleiber.

The California PATH Database recently reached yet another milestone—entry of its 25,000th fully-abstracted record into the Database. Attending a celebration of the event at UC Berkeley's Harmer E. Davis Transportation Library were PATH and Institute of Transportation Studies managers, researchers and staff. Two noted visitors from Washington, DC, Ms. Nelda Bravo, Head of the National Transportation Library, and Ms. Barbara Post, Manager of Information Services for the Transportation Research Board, were also on hand.

For the event, PATH Database Manager Seyem Petrites and Database Librarian Michael Kleiber joined Ms. Bravo and Ms. Post to virtually enter record number 25,000 into the Database. The record chosen for this honor was an Internet report entitled Other Road-Side Detectors, written by PATH researcher Dimitri Loukakos.

The PATH Database is the world's largest bibliographic database devoted to Intelligent Transportation Systems. Founded in 1988 by the Institute of Transportation Studies, the Database is maintained and managed by the Institute's Harmer E. Davis Transportation Library.

Internet access to the Database is provided through a partnership established in 1998 between the California PATH Program and the Transportation Research Board, with Database funding provided by Caltrans, the California Department of Transportation.

The PATH Database can be reached at:
http://www4.nationalacademies.org/trb/tris.nsf/web/path

CarLink II Wins National Transportation Award

John Wright, PATH

CarLink II program manager Susan Shaheen with ULEV Honda at Palo Alto Caltrain station.

PATH's innovative commuter-based carsharing program, CarLink II, was presented with the AASHTO (American Association of State Highway and Transportation Officials) President's Award for Intermodal Transportation on December 4, 2001. The President's Transportation Awards recognize an individual or team whose project has or could have a salutary impact on transportation nationwide or on a regional basis. Nominees for the award were in competition with people from across the country. The CarLink team is very honored and would like to thank AASHTO for the award. The team hopes more regions and states will follow the CarLink path!

Carlink II was formally launched August 23, 2001 at the California Street Caltrain Station in Palo Alto. Representatives from CarLink's partner agencies—PATH, the Institute of Transportation Studies at the University of California, Davis (ITS-Davis), Caltrans, Honda Motor Company, and Caltrain—shared the media spotlight with half a dozen new CarLink II users. Local officials and members of the public also came out in support of this innovative carsharing program.

After five months of operation CarLink already has over eighty users sharing a fleet of up to twenty-seven Ultra Low Emission Honda Civics. Members drive the Hondas between their homes or worksites and the Caltrain station, then use Caltrain for most of their commute. Caltrain is a commuter rail system

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Institutional Aspects of Bus Rapid Transit

Mark A. Miller, PATH

Various facets of intelligent transportation system technology, grouped together under the rubric of Bus Rapid Transit (BRT), offer the possibility of enhancing transit bus operations and the quality of services delivered to transit riders. In concept, BRT combines the speed, comfort, and environmental efficiency of light rail systems with the flexibility, convenience, and relatively low cost of buses. Successful implementation of BRT technology in cities such as Curitiba (Brazil), Ottawa, and Pittsburgh has fueled interest in utilizing these low—or at least lower-cost—strategies to make bus transit more attractive and competitive.

In concept, Bus Rapid Transit combines the speed, comfort, and environmental efficiency of light rail with the flexibility, convenience, and relatively low cost of buses.

The most popular strategies for improving service are station area improvements, automated vehicle location systems, advanced passenger information systems, signal priority, and modifications to bus-stop spacing. BRT projects also are using articulated fleets and low-floor vehicles to expand capacity and reduce boarding times. With these and other implementation strategies such as electronic fare payment and automated passenger counting, improvements have been documented in terms of increased ridership, decreased travel times, and other performance measures.

Implementing BRT raises many challenging issues, technical, operational, and institutional issues. A recently completed PATH study investigated BRT institutional issues with respect to their relative level of importance and difficulty of resolution.

Our report investigates BRT through a macroscopic examination (comprising a literature review plus project members' own knowledge and experience), a survey of members of the US Bus Rapid Transit Consortium (http://www.fta.dot.gov/brt/) and several Canadian transit properties, and a more focused site-specific examination of three California BRT systems: the Santa Clara Valley Transit Authority, Alameda-Contra Costa Transit and Los Angeles County Metropolitan Transportation Authority.

Where appropriate and possible, our study also recommends strategies for these issues' resolution. The literature review provided insight into the history of bus rapid transit and helped identify potential institutional issues for further investigation. The survey provided information culled from the insights and experiences of planners, administrators, and engineers working for transit agencies, regional planning organizations, or highway and street departments. By design, the survey sample size was relatively small and thus even with a large response rate, survey response analysis was accomplished more descriptively than statistically. The result is an assessment of current opinions on this topic held by people who are most familiar with bus rapid transit systems in their communities, rather than a statistical or scientific study.

Survey Instrument: Design, Administration, and Analysis

By surveying field practitioners, our study gathered real-world experience and a broad understanding of the institutional issues affecting organizations involved with BRT systems. Several dozen issues were identified, grouped as follows, forming the basis of the survey instrument:

- intergovernmental and inter-organizational,
- intratransit property,
- political,
- public relations and marketing,
- funding and finance,
- labor,
- safety and liability,
- planning and land use, and
- physical environment.

The survey was administered to members of the US Bus Rapid Transit Consortium and several Canadian transit agencies employing BRT systems. Survey responses were analyzed to identify the most important and most difficult issues to resolve overall and with respect to two distinct BRT system operational settings (mixed traffic and exclusive facilities), and respondents' organizational affiliation (transit agencies, highway and streets departments, and planning agencies). Recommendations for resolving the issues were also considered.

Overall Findings

Survey responses identified several of the most common and site-independent institutional issues of bus rapid transit systems deemed to be the most important and most difficult to resolve:

- integration of multiple priorities, objectives, and agendas;
- finding political champions to support BRT;
- local and business community opposition to the removal of/restrictions on parking spaces for BRT use;
- availability and acquisition of right-of-way or physical space;
- impacts of BRT on roadway operations;
- concerns over long term funding commitments to BRT;
- gaining community support for transit-oriented development; and
- educating the public on BRT while managing perceptions and expectations.

Integration of Multiple Priorities, Objectives, and Agendas

Integrating multiple priorities, objectives and agendas is often the key to resolving institutional issues. When institutions discuss common-interest issues, each brings to the table their own organizational experiences, cultures, and goals. A "win-win" strategy might not always be achievable, but BRT project members need to acknowledge other agencies' concerns. Modal biases and agendas have historically infiltrated transportation planning. Recently, however, with the recognition that multi-modal transportation systems tend to be the healthiest, we have witnessed greater levels of cooperation. Many transportation organizations, however, still have responsibilities to their respective agencies or jurisdictions, and are still expected to protect their own interests. This enhanced cooperation and continuous dialogue should be encouraged to better understand stakeholders' concerns and attempt to address them throughout the BRT development and deployment process.

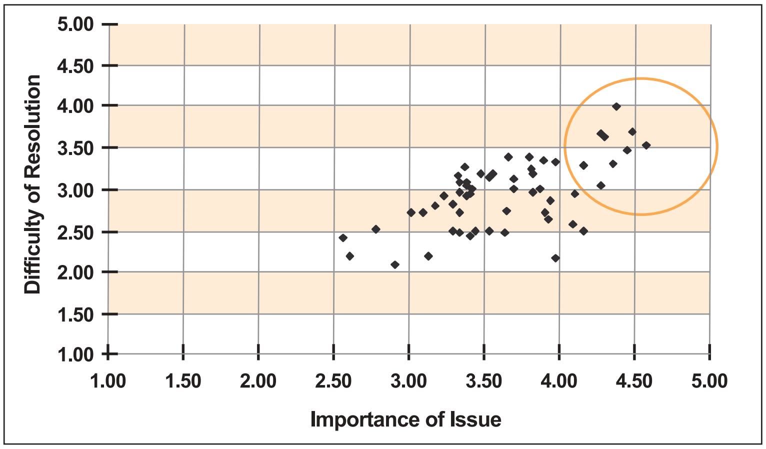

***Figure 1.* Survey responses were analyzed to identify the most important issues and those most difficult to resolve.**

Finding Political Champions to Support BRT

Gaining the ear and voice of influential politicians is one of the most often-cited means of achieving results in implementing a BRT system. Public support is critical though usually not attainable through transportation agencies alone. Finding a political champion to support a BRT initiative may be critical in gaining public support, since politicians are typically the final decision makers, with the clout to produce results.

Roadway-related Issues

The following three issues may be covered under the umbrella of roadway-related issues:

- Local/business community opposition to removal of/restrictions on parking spaces for BRT use
- Availability and acquisition of right-of-way or physical space
- Impacts of BRT on roadway operations

BRT is intended to provide the high-quality service associated with rail transit at a much lower price. In many BRT projects this is accomplished by providing buses with exclusive or nearly exclusive right-of-way, so operations are unaffected by urban-street congestion. However, obtaining the required right-of-way may be difficult. Most BRT projects operate at least partially in developed urban areas where physical space for transportation improvements may be scarce. In several projects this space comes from currently utilized roadway lanes or from existing parking lanes. BRT roadway facility operators (typically municipal street departments or state

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Putting the Microscope on Freeway Traffic Data

Juan Carlos Muñoz, Carlos F. Daganzo
UC Berkeley

Figure 1.
Site description and stations locations.

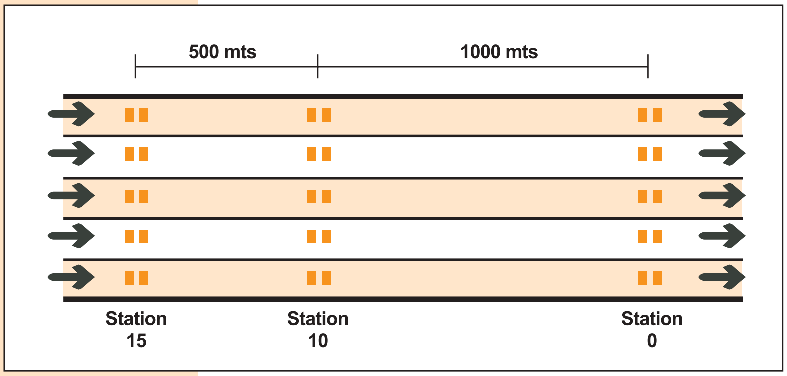
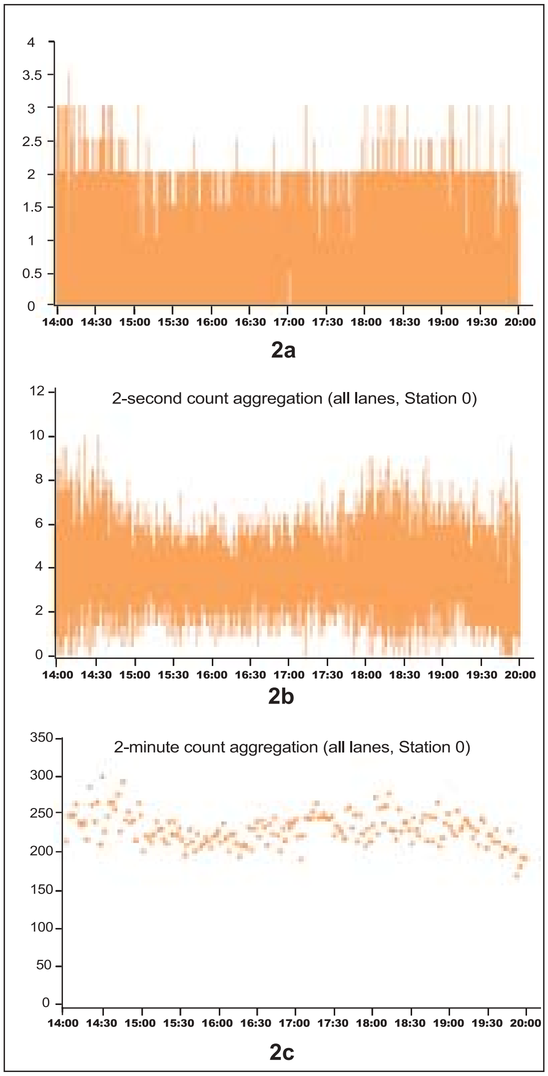


Figure 2.
Counts at station 0 vs. time of day: (a) 2-second counts at a single detector; (b) 2-second counts at all detectors; (c) 2-minute counts at all detectors.



Commuters generally agree that congestion has reached an intolerable level. To reduce congestion, transportation engineers need highly detailed traffic information, information that is also prized by traffic researchers as a prerequisite for improving the theoretical understanding of how traffic flows—or doesn't. Ideally, researchers and engineers could know the position of every vehicle on a particular road at every moment in time. However, the technology of recording space-time vehicle trajectories on a massive scale is in its infancy; therefore, analysts must work with much less data than they would like.

Many freeways are equipped with primitive sensors that can record only the anonymous presence of vehicles at specific locations, coded in a time series of 0s and 1s. Typically, these simple inductive loop detectors are installed on all lanes at sites, called stations, spaced about 500 meters to one kilometer apart. Despite this anonymity, and the spatial discreteness of the measurements, a treasure trove of detailed information can be recovered from 0-1 detector data if one analyzes the data with the right tools. In this article, we will illustrate the use of these tools using real traffic information from a section of Interstate 880 in Oakland, California (see Figure 1).

Figure 2a shows a time series of vehicle counts from a single detector at a single station on the left lane (number 1) of a section of Interstate 880 in Oakland, California. The counts cover a six-hour period bracketing the afternoon rush, in two-second intervals. Very little information can be obtained from this graph because the data include the effects of lane changes, driver differences, etc. If one aggregates all the two-second counts of all the station's detectors, as if a single detector were recording all vehicles across all lanes, lane-changing noise is eliminated (see Figure 2b). Some patterns emerge, but it is still impossible to detect the behavior of individual vehicles. Even if the data are aggregated over longer time periods, this difficulty remains (see Figure 2c). However, if the data are compared across stations, more patterns emerge.

Synchronized cumulative counts (known as N-curves) are the most informative way for researchers and engineers to visualize and compare data from multiple stations. Using one curve per station, N-curve diagrams display the cumulative number of vehicles that have passed over a series of stations over time. As a station counts vehicles, it generates data points, so each station generates its own curve. Each N-curve diagram displays a set of curves for a set of stations in a given time interval. The counts are initialized at each station with the passage of a reference vehicle. Figure 3a is an example. By comparing the curves, new information is obtained. Trip times between stations are given by the horizontal separation between curves, and vehicular accumulation by the vertical separation. Other traffic features, such as the average flow at a station in any interval of time, given by the slope of the N-curve, can also be visualized easily.

N-curves have a drawback, however, in portraying real traffic information encompassing many vehicles for long periods of time. Subtle but important features, such as slight changes in the rate at which vehicles are being counted—that is, speed—are obscured by the large scale required to display the data. This is shown in Figure 4a, where data for the three stations of our freeway have been displayed. (Notice that the stations are numbered in hundreds of meters upstream from station 0). For our purposes, this diagram is useless. Because the total number of vehicles passing through each station in the six-hour period is two orders of magnitude larger than the typical vehicle accumulation from one station to the next, the curves to all visual intents and purposes lie on top of each other.

This scaling problem can be overcome by plotting the N-curves on an oblique coordinate system, defined by two non-orthogonal families of individually labeled parallel lines. In our examples, these lines will be either vertical or slanted, as shown in Figure 3b, which displays the two idealized curves of Figure 3a. In Figure 3b and elsewhere in this article coordinate labels are shown in boldface for vertical (time) lines and in ordinary Roman type for slanted (number) lines. The reader is invited to verify that the pairs of N-curves in Figures 3a and 3b are graphs of the same data. Note that vehicle accumulation is still given by vertical separation between curves, and that trip times are now given by curve separations in the direction parallel to the oblique axis.

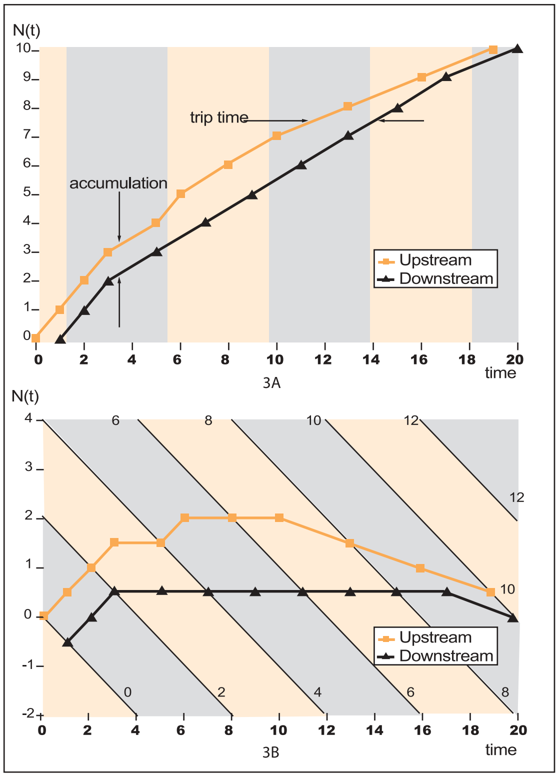


Figure 3.
Hypothetical N-curves at two locations:
(a) orthogonal coordinate system;
(b) oblique system.

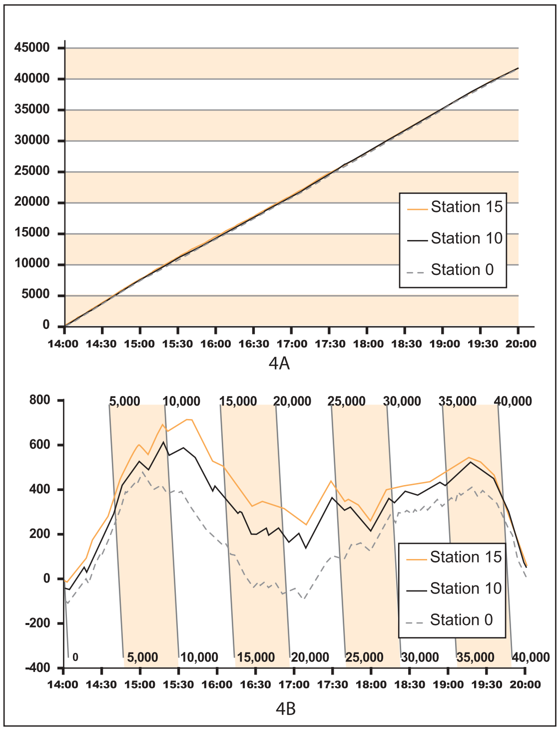


Figure 4.
N-curves for all lanes at stations 0, 10 and 15 between 14:00 and 20:00 hrs:
(a) orthogonal plot;
(b) oblique plot.

Figure 5.
Traffic conditions at stations 0 and 15 between 14:15 and 14:45 hrs.

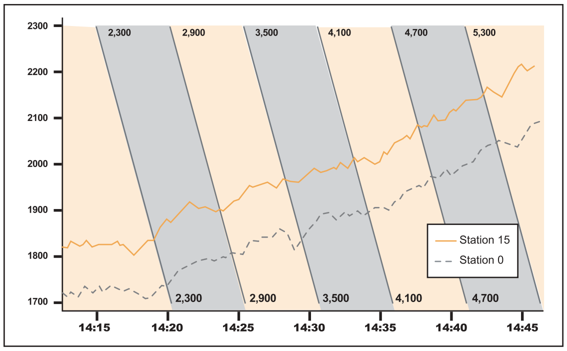
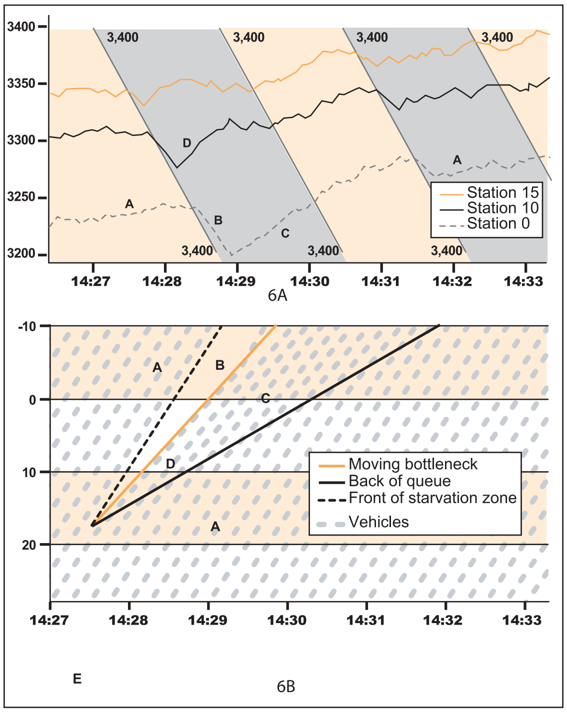


Figure 6.
Traffic patterns around a moving bottleneck:
(a) N-curve signature detected at stations 27, 22 and 12; (b) evolution in time and space.



The separation between curves can now be amplified by reducing the vertical scale. Figure 4b displays the curves of Figure 4a on an amplified oblique system. Notice the appearance of previously hidden information. For example, from the change one can now clearly see (and quantify) a drop in flow at all stations between 15:00 and 15:30 hrs. The drop was first felt downstream, at Station 0, and later at the upstream stations. It is also easy to see how vehicle accumulation and trip times increased immediately after that flow reduction. The diagram shows that a queue grew from Station 0 to Station 15 and beyond, and that this queue began to dissipate around 17:30 hrs, starting at station 15.

Information in traffic moves as waves. We are all too familiar with a freeway accident causing a shock wave, a moving traffic jam that travels upstream: this is an excellent example of information traveling as a wave against the traffic stream. Upstream-moving waves, such as the one observed on our section of freeway between 15:00 and 15:30 hrs, reflect the presence of congested conditions. Uncongested conditions, on the other hand, are characterized by forward-moving waves that propagate with the traffic speed. They can be clearly seen in Figure 5, which displays data at stations 0 and 15, from 14:15 to 14:45 hrs. It can be clearly seen that (except for a discrepancy around 14:28 hrs) traffic conditions at station 15 define conditions 1.5 kms downstream very accurately, with less than a minute of delay, and that trip times remained quite constant despite the fluctuations in count.

The discrepancy at 14:28 hrs presents a new opportunity to show the potential of oblique plots. At first sight, it appears that station 0 may have malfunctioned, since it seems to have stopped recording vehicles for a short period. To look into this further let us rescale the oblique plot to achieve a desired magnification level (as with a microscope) and also add the curve for the intermediate station (see Figure 6a). Clearly the detectors at Station 0 were not malfunctioning: the interruption in flow is also recorded at Station 10. Because the interruption grew while moving downstream, other explanations, such as a traffic accident or a sudden drop and recovery in travel demand must also be ruled out. Such events would have left different signatures. The only plausible explanation for the observation is that the bottom of the "V" represents a clot, as it were, of slow vehicles moving downstream, caused by an obstruction moving forward with traffic. Inspection of the figure shows that the obstruction traveled slightly below the speed limit (88 km/hr). An observer at Station 0 would have observed normal flow conditions, followed by a 30-second period of extremely low flow, and then two minutes of flow at nearly the maximum rate for a 5-lane freeway. The most likely explanation for these patterns (high speed for the moving obstruction with negligible downstream flows) is that a highway patrol car with its lights flashing, traveling just under the speed limit, entered the road somewhere upstream of Station 15, when the vehicle count was about 3400. Even on the freeway, drivers would have hesitated to pass such a vehicle, which would thus block traffic behind it, causing a moving queue.

By looking at Figure 6a in more detail one can identify the flow downstream and upstream of the slow vehicle, as well as the speed of the transition zone between the upstream free-flowing traffic and the back of the moving queue. Furthermore, by comparing the flow in the queue after the slow vehicle passed through Station 10 and Station 0 (regions D and C of Figure 6a), the reader may be able to see that the flow was significantly higher at Station 10 than at Station 0. This suggests that the first hundred drivers tail-gated each other upon joining the queue, and later relaxed. The data also show that drivers who arrived later did not act in this way, since drivers labeled with higher numbers (up to N=3750) never experienced the high flows. This change in behavior maybe explained by proximity to the bottleneck when vehicles joined the queue. We speculate that the first drivers may have adopted very short spacings in the hope of getting through the bottleneck quickly, and that their motivation disappeared upon realizing that the queue would last for a while. Drivers who arrived later may not have seen the bottleneck and thus had no reason to follow so closely.

All this information has been condensed in Figure 6b, which also includes the "best-fit" space-time trajectories of the moving bottleneck and the affected vehicles. Labels A-D link traffic patterns found in Figure 6a with their respective space-time regions in Figure 6b. Note that the oblique plot technique reveals from noisy 0-1 data the precise time and place of the "moving bottleneck's" appearance (point E in the figure). Interestingly, and reassuringly, it turns out that there is an onramp without detectors at the point of appearance.

This illustration shows how much information can be obtained from seemingly poor data with a simple visualization tool. The detection of our moving bottleneck, and the quantification of its interesting regularities (including changes in driver behavior) was made possible only by the oblique plot technique. As a result of this new technique, we gain new insights into wave propagation in traffic, bottlenecks caused by freeway merges, bottlenecks caused by off-ramps, and transition zones at the back of freeway queues. Perhaps this technique can be useful in fields like fluid mechanics, where one could analyze a fluid's properties by checking them at different stations. It also might be applied in production processes, to track products as they move along conveyor belts, and in other fields where the unidimensional movement of objects is of interest.

Suggestions for further readings in oblique plots and related techniques:

Cassidy, M. J., and R. L. Bertini. 1999. "Observations at a Freeway Bottleneck." Proceedings of the Fourteenth International Symposium on Transportation and Traffic Theory (ISTTT). Jerusalem, Israel: Elsevier, July 1999.

Cassidy, M., and J. Windover. 1995. "Methodology for assessing dynamics of freeway traffic flow." Trans. Res. Rec. 1484, 73-79.

Daganzo, C. F. 1997. Fundamentals of Transportation and Traffic Operations. Oxford: Pergamon-Elsevier.

Muñoz, J. C., and C. F. Daganzo. 2000. Experimental characterization of multi-lane freeway traffic upstream of an off-ramp bottleneck. University of California, Berkeley: Institute of Transportation Studies, California PATH Program. PATH Working Paper UCB-ITS-PWP-2000-13.

CarLink II Wins Award

continued from page 5

that runs from San Francisco to San José and its southern suburbs for approximately 75 miles (120 km). The cars at the worksites are then available for all registered employees during the day for meetings and errands.

CarLink II encourages the use of transit by providing preferential parking, reducing commute time from the station, and offering guaranteed rides in the case of emergencies. Operations staff at ITS-Davis and evaluators at PATH are able to track vehicle usage and the on-line reservations system using GPS and custom-built software; the PATH research team is also conducting extensive on-line surveys of the participants.

Randell Iwasaki (Acting Deputy Director, Region 4 Caltrans) also used the occasion to announce a new initiative among Caltrans, the Air Resources Board, and the California Energy Commission. This tri-agency partnership will develop synergistic solutions to the problems affecting transportation, energy, and environment in California.

Bus Rapid Transit

continued from page 7

Los Angeles County Metropolitan Transit Authority and the City of Los Angeles Department of Transportation have partnered to implement new Metro Rapid express bus lines. Metro Rapid service focuses on major destinations and transfer points, with stop intervals lengthened to every 0.8 to 1.0 miles. Expansion to corridors with exclusive busways is being considered.

Departments of Transportation) are interested in how BRT operations would affect their facilities. In cases where projects look to utilize roadway space that is currently on-street parking, businesses and residents may be opposed to the "loss" of parking, even if it is only during peak-periods. Therefore a major concern is the availability of physical space to accommodate BRT operations. Proper consideration must be given to identify if there are competing interests for space and how BRT operations may impact these facilities.

Concerns Over Long-Term Funding Commitments to BRT

Is BRT merely the "flavor of the month?" What are the implications for transit agencies should a BRT concept fall out of favor? Some BRT projects will require a great deal of capital investment, often requiring transit agencies to shoulder the risk of having greater capital to maintain without recovering sufficient additional revenue to cover those costs. Such operating and maintenance costs may make transit agencies reluctant to embrace BRT. Until there are domestic success stories and the federal government shows a firm commitment to the program, many transit agencies may proceed cautiously.

Gaining Community Support for Transit-Oriented Development

Many BRT projects have incorporated land use strategies to encourage and reinforce transit usage. However, for most outside the transportation and planning communities, the concept of transit-oriented development (TOD) is new. For many, higher density and mixed use means more crowding and greater congestion. Attempting to garner public support for TOD could be difficult, especially if there are not many local examples to aid the public's understanding. Proactively educating the public on this subject may bear fruit to avoid future public opposition. Allaying fear of the unknown is often a responsibility that must be borne when presenting an untested concept to the public.

Educating the Public on BRT, and Managing Perceptions and Expectations

Transit agencies must carefully present BRT to the public and to decision-makers in order to maintain support and interest for the program. Setting unrealistically high expectations can lead to disappointment and a loss of support. Agencies must balance between "hype" and actual results.

Operational Setting

The physical setting in which a BRT system operates, whether busway, expressway, bus lanes on arterials, or in mixed traffic, is an important system attribute. We investigated whether the operational setting raised specific institutional issues. Operational types were aggregated into two distinct families: mixed traffic and exclusive facilities. Each completed survey was identified with one of these two families, based on the predominant operational setting of the corresponding BRT project (since a BRT system might have different settings along its routes).

Mixed Traffic

Survey respondents representing mixed-traffic BRT systems identified the following issues: street and highway departments having to relinquish control of their infrastructure, reaching agreement or consensus on bus stop/station area enhancements, and capital costs associated with BRT. The first two issues are clearly associated with a mixed-traffic type of operational setting. Mixed-traffic systems tend to be upgrades of existing systems. Exclusive facility systems, however, tend to be new systems (often built on unused rail right-of-way) and their costs are more likely compared to such capital-intensive systems as light rail transit, so capital costs may be of greater importance for mixed traffic systems than for exclusive facilities.

Exclusive Facilities

Survey respondents representing exclusive facility BRT systems identified the following issues: viewing BRT as a top down solution to a problem, local and community opposition to BRT, lack of empirical evidence on BRT's effects on land use, and potential developers' perception of BRT's lack of permanence as compared to rail. These are more regional than local issues. Because exclusive facility systems are generally larger in scale and scope than mixed traffic systems, especially relative to required infrastructure and capital, it is not surprising that successfully implementing these systems requires a regional perspective on planning, development, and land use.

Organizational Type

Survey participants' responses reflect their organization, its objectives, agendas, and business cultures. We examined responses by organizational type to identify differing values, priorities, and perceptions. Organizational types included transit agencies, highway/street departments, and planning agencies.

For transit agencies, issues deemed the most important and difficult to resolve included responsibility for enforcement on bus lanes/ busways, and educating the public on BRT and managing perceptions and expectations. Maintenance responsibilities for shared infrastructure and hardware/software was one of the most important associated with street and highway departments. For planning agencies, the following issues were highlighted: reaching agreement or consensus on bus stop/station area enhancements, educating the public on BRT and managing perceptions and expectations, gaining community support for transit oriented development, and perceived or actual competition of BRT with rail transit.

Recommendations for Resolution of Issues

Respondents recommended action to help resolve their most important issues. They emphasized marketing and public relations, public outreach and education, stakeholder participation, creation of new institutional entities, and studying land use and planning policies. Reference was also made for the need to quantitatively document the impacts, both benefits and costs, of BRT. Calls were also made to develop solutions to various potential negative impacts or disbenefits of BRT, such as excessive noise, vehicle emissions, and safety-related problems. Respondents also thought it would be very important for study findings to be fully communicated both to local jurisdictional decision-makers and the public who live in the communities or along a specific corridor most impacted by a BRT system implementation. Also of particular import, from the respondents' perspective, is the need to welcome and solicit input from a multitude of stakeholders to build as large as possible a constituency of political supporters within the affected community for a proposed BRT system.

In Silicon Valley, the Santa Clara Valley Transit Authority's Line 22 "Bus Rapid Transit Corridor" intersects the north-south Guadalupe Light Rail Line.

Conclusions

Our study gleaned the insight and expertise of individuals who have experienced these BRT issues. The results should offer guidance in anticipating future problems and developing strategies to solve them. Follow-on work in this area will include in-depth site-specific case studies of BRT systems to more thoroughly probe into the institutional environment of bus rapid transit. In this way, our research should be able to offer guidance to practitioners involved with bus rapid transit systems.

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Center for Commercialization of ITS Technologies (CCIT) Opens

PATH, Caltrans, and the UC Berkeley Institute of Transportation Studies formally opened the Center for the Commercialization of ITS Technologies (CCIT) Thursday February 7, 2002. At the ribbon-cutting ceremony, CCIT Executive Director Hamed Benouar said: "CCIT will facilitate the commercial deployment of advanced transportation products and services to improve transportation safety, security and efficiency—necessary components of a vibrant and growing economy. CCIT will create strong links between the transportation industry, automobile manufacturers, University researchers, government experts, and commercial developers of advanced information technologies, in Silicon Valley and throughout California."

CCIT is structured to optimize private sector participation in the future of California's vast transportation network. The Center specializes in traveler information, transportation management, and vehicle information and control. Among the first industry participants are DaimlerChrysler Research and Technology and Siemens ITS North America.

Physically located one block from the UC Berkeley campus, CCIT offers facilities for research, development, testing, training, focus group meetings, and technology transfer, to promote commercial deployment of ITS products and services.

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