**A Word from Karl Hedrick**

Serving as the Director of PATH for the past six years has been a very rewarding experience for me. I took over immediately after DEMO’97 from Professor Pravin Varaiya who had led PATH during the years of the NAHSC (National Automated Highway Systems Consortia). We faced some very difficult times after the demise of the NAHSC but were able to maintain our position as the leading international research institute in vehicle automation while greatly expanding our role in traffic management and information. Pat Conroy and later Hamed Benouar led this initiative and worked closely with Caltrans to apply ITS to the states transportation problems.

I am very happy to turn over the reigns of PATH to Professor Samer Madanat. He has had a very successful career as transportation academic in our Civil and Environmental Engineering’s Transportation group. After obtaining his PhD from MIT in 1988 he joined the faculty at Purdue University and finally joined the Berkeley faculty in 1996. His area of research is in transportation systems analysis and infrastructure management. He has worked closely with both the US Department of Transportation and Caltrans. He has an exciting vision for PATH and the energy and enthusiasm to make it happen. I look forward to continue working with Samer and to help him in any way I can to make his vision come true.

**A Word from Samer Madanat**

The New PATH: Moving Research into Field Operational Tests

Since its conception, PATH has played an important role in the development of both the state and the national Intelligent Transportation System programs, participated in the founding of the Intelligent Transportation Society of America and conducted research under a number of state and federally sponsored ITS research programs.

PATH gained international reputation in the area of Advanced Vehicle Control and Safety Systems (AVCSS). In the early 90s, PATH made contributions to the National ITS Architecture. From 1994 to 1998, PATH was a key member of the National Automated Highway System Consortium. Since 1998, PATH has participated in Federal DOT’s Intelligent Vehicle Initiative Programs. Throughout, PATH researchers made fundamental advances in the application of control and systems engineering methods to collision warning and avoidance for cars, buses and trucks.

PATH researchers have also contributed significantly to research in the areas of Advanced Traffic Management and Information Systems (ATMIS). The list of accomplishments in this area includes the development of state-of-the-art Traffic Surveillance technologies, algorithms continued on page 15
California PATH staff demonstrated the results of three current research projects at the National Intelligent Vehicle Initiative (IVI) Meeting held in Washington, DC from June 24-26, 2003. The technically successful demonstrations, held at the Turner-Fairbanks Federal Highway Administration (FHWA) Research Center, in McLean, Virginia, won high praise and contributed significantly to the IVI meeting. They illustrated the professionalism and technical capabilities of PATH teams, and promoted awareness of PATH among peers and transportation organizations around the world.

**Intersection Decision Support**

One demonstration introduced an intelligent intersection, the product of the Intersection Decision Support (IDS) project sponsored by the FHWA and Caltrans. PATH demonstrated a promising, near-term deployable IDS system that warns drivers when it is unsafe to make a permitted left turn in the face of an oncoming vehicle. Using multiple detection and sensing devices (including Lidar, radar, inductive loop detectors and in-vehicle GPS), the system can identify and track vehicles approaching the intersection in real time. A central processing unit (CPU) fuses the vehicle motion data from the sensors with the signal timing and phasing data sent from the intersection’s traffic controller to run a decision making algorithm. When conditions for making a left turn are unsafe, the system triggers a large flashing “No Left Turn” road sign to warn drivers of a hazard. The circle/slash under the “No Left Turn” arrow not only flashes, but grows 50 percent in size and thickness. This apparent “looming” motion affects the fastest and most sensitive pathways in the visual nervous system and makes the sign especially visible. The sign is placed just above eye level at the opposite corner of the intersection. IEEE 802.11a wireless communication is also incorporated in the system, to allow direct communication between the CPU and approaching vehicles, which could provide information directly to in-vehicle devices.

**Frontal Collision Warning System**

PATH’s second demonstration featured Frontal Collision Warning Systems on a San Mateo Transit bus, a project sponsored by the Federal Transit Administration (FTA). The demo showed how bus drivers can benefit from a warning system that uses radar, lidar, and computers to “watch” the operating environment and a driver-vehicle interface to warn the driver of a possible frontal collision. For several years, PATH has conducted research to understand the causes and consequences of transit frontal collisions. The knowledge gained has led to the development of a prototype collision warning system that provides the driver with an effective warning when the system determines that a potential collision may occur. Based on a well established data fusion model, a preliminary detection algorithm was developed that can track different obstacles within the sensor field of view and can decouple the bus motion from the sensor mea-
measurements. A warning algorithm was also developed to incorporate a warning threshold synthesized from the drivers’ normal braking behavior. When the system determines that the distance to a vehicle or obstacle in front of the bus is closing too rapidly, it lights up two orange LED lightbars mounted on each side of the windshield. The LED elements are illuminated sequentially, giving the illusion of a moving bar of light. The more imminent the collision, the longer and faster the bar moves. This prototype has been put into regular transit service for field testing, to verify if the performance requirements developed under this project are within a reasonable and reachable range.

PATH human factors researchers worked closely with SamTrans drivers to understand their needs and expectations and their operational environment, and to define system boundaries. Drivers’ inputs and their active involvement in brainstorming different design options greatly contributed to the design of the prototype Driver Vehicle Interface (DVI). Through extensive field tests and close interaction with bus drivers, the system is being improved, and is now being integrated with side collision warning system through a joint effort by a California and Pennsylvania partnership to provide an integrated solution for transit collisions.

**Precision Docking**

The third demo showcased precision docking, an essential element of Bus Rapid Transit (BRT) operations. The PATH system involves a variety of BRT technologies implemented on a 40-ft compressed natural gas (CNG) bus, made possible by a FTA lane-assist project and a Caltrans BRT development project.

In the precision docking demonstration, the bus steered itself along a demonstration course representing the path a bus would take to approach a curb-side bus stop. The bus was completely computer-controlled, automatically following a series of magnets that defined the course, and using a smooth speed profile for its acceleration and braking.

A 90-meter-long path of magnetic markers was placed on the roadway surface, 1.2 meters apart, to form a reference trajectory. Using PATH’s magnetic guidance system and highly sophisticated signal processing techniques, an onboard computer directs a steering input to an actuator on the steering column, which steers the bus precisely along a desired trajectory, with a tolerance of approximately one centimeter. The bus is also equipped with throttle and brake control systems that allow it to stop within ten centimeters of a designated location. With these capabilities, buses can be automated to dock precisely at bus stops, thus providing easy access and enhancing passenger safety. When combined with a boarding platform that is at the same level as the floor of the bus, precision docking eliminates the need for stepping up into the bus, which can be difficult for elderly or persons with mobility impairments. It also eliminates the need for wheelchair lifts or similar costly devices.

The PATH precision-docking bus provides highly reliable and accurate performance. Several LED lights on the dashboard inform the driver about the status and readiness of the bus and the docking systems. The driver can easily select between full and partial automation, and make the transition smoothly.

Because the guidance system eliminates driver variation and driver error in steering, a guided vehicle is capable of precise lane-keeping. The result can be a significant reduction in accidents involving side collisions to transit buses, collisions at bus stops, and passenger injuries during boarding, alighting, bus starting, bus stopping and bus turning. Guided pathways could also reduce scrapes at narrow toll booths and at the bus wash.

PATH’s technical staff has considerable experience and expertise in vehicle guidance systems and safety applications. PATH was instrumental in developing and deploying technology for the National AHS Consortium 1997 Demonstration, and many other international technology demonstrations. In recent years, PATH technologies have been deployed on snow removal equipment (snowplow and snowblower) under the sponsorship of Caltrans.
On-ramp metering has been used to manage freeway traffic congestion for decades. By restricting inflows from on-ramps, meters can improve travel conditions on the freeway itself. But a metering scheme whereby commuter delay is merely transferred from the freeway to its on-ramps and surface streets can be counter-productive. After all, it is the freeway that has more space for storing delayed vehicles and queue storage space is a commodity that should not be squandered.

A scheme that actually reduces delay would seem worthwhile. But much of the literature on how metering might achieve these reductions is not correct.

In this article simple analogies to freeway systems are used to clarify some key facts about ramp metering and delay savings. The analogies reveal why delay reductions are not realized merely by metering to increase travel speeds and flows on freeway links within a system. Rather, the analogies show that delay is diminished by metering in ways that increase outflows from a freeway system. The analogies are also used to explain why a metering logic that increases outflows at one freeway site can be very different from the logic needed at another site. This point is emphasized by showing how certain metering algorithms can actually reduce outflows (and therefore increase delay) when the freeway is plagued by a diverge bottleneck, like those that occur at congested off-ramps. Other considerations important for managing traffic on real-world freeway systems are also discussed in this article.

Simple Analogies

We now consider issues of metering and delay in the context of some very simple and hypothetical queuing systems. These systems serve people exiting a sports stadium. Their geometries, however, are similar to those of freeways. Key points arising from the stadium analogies will be used in later sections to direct our discussion concerning real-world freeway on-ramp metering schemes.

Figure 1(a) illustrates two links that merge to a common stream close to the exit of our sports stadium. Customers in the common stream are served in a first-in, first-out fashion. The figure thus illustrates a queuing system that is clearly similar to a simple freeway system. Link A and the common stream are analogous to a freeway stretch and Link B to the freeway's on-ramp. (The dashed lines labeled “off-ramp” in the figure can be ignored for now).

Let us suppose that during the rush to leave the stadium after a game, customer arrival rates to Links A and B exceed $\mu$, the capacity of the stadium exit. (Analogously, $\mu$ can be viewed as the capacity of the freeway link just downstream of a merge). Left unattended, the short stretch of common stream upstream of the stadium exit soon becomes completely queued: the flow in this queue is $\mu$. The combined rate at which customers from Links A and B advance to the common stream is then $\mu$ as well. We can assume that queues propagate backward on both these links.

The resulting customer delay in this system is given by a queuing diagram like the one in Figure 1(b). This diagram is a means of displaying data that might have actually been measured. The
Since customers from A now exit the stadium at higher rates, they incur lower delay. But this metering does not change the total delay. Figure 1(b) plainly shows that if the V- and D-curves are unaltered, total delay is conserved: at best, delay is merely re-distributed, with more now going to customers from B. (We assume for now that metering does not affect the demand for travel displayed by the V-curve).

But costs arise if on-ramps are metered too restrictively. Suppose Link B, and any sources feeding Link A, are metered so restrictively that customers pass through the stadium exit at a rate lower than \( \mu \). We will assume this rate is \( 0.97\mu \), to make the scheme analogous to one recently proposed for freeway on-ramps (Jia et al, 2000). Link A is completely unqueued; otherwise the exit rate would be \( \mu \). Customers on Link A now enjoy higher speeds (as compared with the unmetered case) and flows on Link A can be higher as well. Yet total delay in the system, and the duration of the rush, both increase.

continued on page 10
Fare Collection & Boarding

Two methods for reducing passenger dwell time (the time passengers spend on the bus) and passenger inconvenience are: reducing on-board fare collection time, and eliminating on-board payment. Eleven reviewed cases have adopted or plan to adopt at least one of the two strategies.

“Exact change” fare collection is inconvenient for both passengers and bus operators: lots of coins are needed, and keeping cash on board generates security issues. Prepaid fare methods, such as seasonal passes, prevalued cards, and smart cards read by electronic card readers, have been found to reduce collection time in Charlotte, Santa Clara County, Adelaide, Bogotá, Nagoya, and Curitiba.

Eliminating on-board payment reduces passenger dwell time, since it enables passengers to board and leave by all the doors. The simplest strategy is to create a free zone for short trips within a small area, (e.g., downtown Orlando’s Lymmo). Another is to build passenger-loading platforms where passengers pay at a turnstile before entering the loading area, as in Curitiba’s staffed tube. A third is the proof-of-payment collection or honor system used in Charlotte, Eugene, Hartford, Ottawa, and Adelaide. There, passengers board with a pass or validated ticket, which they show to inspectors at random checks.

Passenger Information System

One of the earmarks of a high-quality transit system is the intelligible design of its passenger information system. Integrated visual and audible displays in vehicles and along the corridor inform passengers about basic service characteristics: the system map, stop names, names and destinations for all routes serving each stop, span of service, frequency of service during peak and off-peak hours, and a map to other connections. A further advance is real-time information supported by AVL technology that can display the arrival time of the next bus at a stop.

Service Levels

The most important characteristic of BRT service is high frequency, whether on fixed or headway-based schedules. Almost all sixteen reviewed cases provide headways of less than 5 minutes during peak hours (90 seconds in Curitiba), and around 10 minutes during off-peak hours. Feeder services often run on headways of less than 15-30 minutes, timed to meet the main service with reduced-cost or free transfer. The service span basically runs from 5AM until midnight (24 hours a day in Santa Clara).

Fare Policy

A reasonable fare structure should target the average income level and consumption ability of its customers. A BRT system should consider other traffic modes’ service levels and fare structures when setting its fare policy, since it won’t be competitive unless it either provides superior service levels at the same price or equivalent service levels at lower prices. Coordinating fare policy with other local services, such as rail transit or feeder services, can benefit customers riding both systems and increase the usage of BRT systems.

Complementary land use policy

Building a BRT system usually means property acquisition and the relocation of some residents. The impact on all affected properties, whether commercial, residential or industrial, needs to be assessed. Land-use regulations in residential areas may need to be changed to establish cut-through paths linking cul-de-sacs, so bicyclists and walkers may have direct access to transit. A good site for a station will already have some commercial activity nearby and a solid base of transit ridership. For example, Ottawa has put some BRT stations in shopping malls, so that passengers reach the malls directly by transit.
Public support for continuous funding. These lands are built in areas where land is easily acquired, to get the system. Here, segments of a transit system are first divided into multiple parts, which are then planned and constructed independently. Other innovative methods to save system expenses are:

- **Quebec**: eliminating some off-peak service to support more intensive peak services
- **Hartford**: speeding-up overall construction processes by the Design-Build method
- **Ottawa**: Outside-In approach in building the system. Here, segments of a transit system are first built in areas where land is easily acquired, to get public support for continuous funding. These lands are normally in the suburbs. Then, the system can start service on the periphery while building downtown segments.

**Miami**: adoption of minibuses to reduce operating costs.

### Benefits

BRT benefits include increased total ridership in the planned corridors, reduced travel time via higher speed, reduced passenger wait time, and reduced passenger dwell time. Some BRT systems attract riders from conventional bus services that share the same markets, some get riders by enticing them from their cars (Curitiba, Ottawa, etc.), and some get new riders from surrounding neighborhoods with good feeder services. Other positive impacts of BRT may be increases in land value (Brisbane), in customer satisfaction increases (Ottawa), reduced fuel consumption (Curitiba), reduced air pollution, and reduced accident rates.

### Cost Effectiveness

Various indices can be used to assess the cost-effectiveness of BRT systems, such as total cost, cost

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**Table: Benefits**

<table>
<thead>
<tr>
<th>Case</th>
<th>Ridership</th>
<th>Travel Time</th>
<th>Travel Speed</th>
<th>Passenger Wait Time</th>
<th>Passenger Dwell Time</th>
<th>Other Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eugene, OR</td>
<td>n/a</td>
<td>Reductions by 20% in 2007 (from 27 minutes to 21 minutes)</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 20% in 2007 (from 27 minutes to 21 minutes)</td>
</tr>
<tr>
<td>Hartford, Connecticut</td>
<td>28,000 daily riders</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Santa Clara County, CA</td>
<td>60,000 daily riders</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Charlotte, NC</td>
<td>55% since startup (from 10,138 monthly in 1/99 to 17,487 in 1/2000)</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Los Angeles, CA</td>
<td>25% travel time saving and 33% reduction of delay by traffic signals</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Orlando, FL</td>
<td>Ridership doubled (1,000,000 daily passengers)</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Miami, FL</td>
<td>24 boarding per hour. Ridership in corridor increased 49% on weekends, 44% weekdays, 130% Saturday</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Pittsburgh, PA</td>
<td>Up to 55 mph</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Ottawa, Ontario</td>
<td>100,000 daily passengers</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Quebec, Canada</td>
<td>n/a</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Montreal, Canada</td>
<td>30% increase after first year</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Adelaide, Australia</td>
<td>Annual increase 10%, daily passenger 27,000</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Brisbane, Southeast Queensland, Australia</td>
<td>45,000 trips per day</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Curitiba, Brazil</td>
<td>1.3 million passengers/day (70% use BRT)</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Bogotá, Columbia</td>
<td>600,000 passengers/day</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
<tr>
<td>Nagoya</td>
<td>30,000 passengers/day</td>
<td>Reduction by 25% in 2007</td>
<td>25 mph or some grade crossings, and 30-45 mph on the exclusive grade-separated ROW through Newington, West Hartford and Hartford</td>
<td>n/a</td>
<td>n/a</td>
<td>Reductions by 25% in 2007</td>
</tr>
</tbody>
</table>

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**continued on page 14**
PATH Demonstrates Automated Bus Rapid Transit Technologies

Steven E. Shladover

PATH researchers demonstrated some of the key technologies for automated bus rapid transit (A-BRT) services for invited visitors in San Diego on the weekend of August 23-24. This demonstration continued a distinguished PATH tradition of demonstrating the most advanced ITS capabilities under realistic conditions on full-scale vehicles, and true to that tradition it exceeded the expectations of the visitors.

PATH has equipped three transit buses with the sensing, actuation, communication and computation systems needed to enable them to operate under completely automatic control. At the same time, these buses were equipped with a specially-designed driver-vehicle interface (DVI) system to show how easy it is for the driver to interact with the automation systems, to transfer back and forth between normal manual driving and automation and to initiate automated maneuvers such as lane changing on the highway and precision docking at local bus stops. The emphasis of this demonstration was showing the realistic opportunities for implementation of the A-BRT technologies to improve transit service and economics. Since the demonstration buses were two standard-size (40 foot) buses powered by compressed natural gas (CNG) and one 60-foot articulated bus powered by a diesel engine, it was also possible to show how the automation technologies can harmonize the performance of these very different vehicles so that they can operate close together in an electronically-coupled “virtual train”.

The transit service functions that were demonstrated included:

- **Precision docking** of a bus at two different platforms, one representing an in-line platform at a bus terminal and the other representing a curb-side platform requiring an approach with a lane change ahead of a line of parked cars. In both cases, the bus stopped with a gap of less than an inch between the bus floor and the platform, making it easy for one of visitors to roll on and off the bus in a wheelchair. Both the steering and the stopping of the bus were controlled automatically, although initial deployments of this service would probably only use the automated steering function, leaving the full attention of the driver for watching out for pedestrians and passengers.

- **Automatic lane-keeping** (or lane assist) of the buses operating in a line-haul mode on the I-15 HOV lanes. This demonstration showed the ability of the automatic steering system to keep the bus centered accurately over the lane, while providing a smooth ride for the passengers. This is an important capability to enable buses to operate in narrow lanes where right of way is costly or unavailable. The driver was able to switch back and forth between automatic and manual steering at will, showing how a driver could override the automatic system when necessary.

- **Automatic lane-changing** while operating on the highway, initiated by the driver pressing a button on the DVI. In order for buses to be able to enter or exit from an A-BRT bus-way, or from off-line stations, it is necessary for them to be able to change lanes automatically. This part of the demonstration showed the ability to execute
this maneuver repeatedly, with a minimum of effort required by the driver.

- **Fully automated bus driving.** The buses were operated in both low speed (docking) and high speed (highway driving) conditions with fully automatic steering and speed control. Once the driver transferred control to the automated system, he did not need to do anything else until reaching the other end of the HOV lanes, where he regained control. This capability indicated the potential for future operations without requiring a driver to be on every bus operating along a dedicated, protected bus-way. However, the technology is not yet sufficiently mature and fault-tolerant to make it possible for our drivers to leave the driver's seat (except in the limited case of the low-speed precision docking maneuver).

- **Automated “virtual train” of buses.** The diesel bus was electronically “coupled” behind one of the CNG buses for a run down the length of the I-15 HOV lanes (8 miles), making use of a “WiFi” wireless data link, combined with forward-looking lidar and radar sensors to detect the gap and speed difference between the buses. The buses ran at separations of 40 m and 15 m to each other and smoothly performed the automatic transitions between these two different target separations. The operations at the 15 m separation showed the potential for automated bus trains to carry very high passenger volumes in the highest-density corridors. With that size separation between the buses in the “virtual train”, and with a long enough separation between consecutive bus trains to ensure that no failure would involve more than one bus train, a sequence of three-bus trains could provide 70,000 seats per hour in one lane, which is competitive with the highest-volume rail transit services.

The visitors who participated in this demonstration included members of the Board of Directors of ITS America and the Program Steering Committee of the Cooperative Vehicle-Highway Automation Systems (CVHAS) pooled-fund project, as well as the attendees of the TRB meeting on “Urban & Community Transit – The Role for Automated BRT”. The reactions of the visitors were very enthusiastic. For example, Neil Schuster, the President and CEO of ITS America, said,

“The San Diego demo went very well and I know our members enjoyed it; this is the fourth time I’ve seen the technology in action, and each time I’m amazed - now I can tell friends I rode in a city bus, going down a real highway at speed, too close to a bus in front of us for a human driver to attempt. For me, the expression on someone’s face the first time they comprehend they are in a moving vehicle without a driver is priceless!...what a great morning!”

The discussions in the TRB meeting that immediately followed the demonstration were strongly influenced by many comments indicating that the demonstration changed people’s minds about what was possible and opened their eyes to new possibilities for using vehicle automation technology to improve transit operations. That, of course, is one of the strongest reasons for investing the effort to present such a demonstration.

The efforts were considerable and involved extensive time spent away from home by a team of fifteen PATH research and development engineers, working under the leadership of Dr. Ching-Yao Chan. Their work schedule was governed by the limited availability of the I-15 HOV facility for testing in preparation for the demonstration. All of the preparatory testing needed to be conducted during the four weekends prior to the demonstration (8 am to 8 pm each day) and during the weeknights in the two weeks immediately before the demonstration (8 pm to midnight). With outstanding cooperation and support from Caltrans District 11 and Division of Research and Innovation (DRI) colleagues, extremely rapid progress was made during that final month of preparations for the demonstration.
This is made clear in Figure 1(b). Since the maximum slope of the D-curve drops to 0.97µ, as shown by one of the dashed lines, the shaded area grows. The rush, which formerly ended at time t₂, ends later. The start of the rush could occur even earlier then t₁.

Conversely, increasing the slope of the D-curve by maximizing outflows from a system decreases delay. Increasing cumulative outflow can be an important objective in any attempt to reduce commuter delay via metering. This objective is suitable not only for the simple system in Figure 1(a), but for freeway systems that include many on- and off-ramps as well.

Many engineers, unaware of the above, erroneously use higher vehicle speeds and flows on freeway links within a system as evidence that a metering scheme has decreased delay (e.g. MnDOT, 2001). The potential flaw in this reasoning is evident in the previous discussion. If we view the hypothetical system in Figure 1(a) as a freeway merge, with Link B as its metered on-ramp, our metering efforts discussed thus far have promoted higher speeds and flows on Link A because restrictions were eased there by lowering the inflows from B. But this did not diminish delay. The overly-restrictive scheme even increased delay!

Some engineers have been quick to assume that higher capacities can be sustained at an active merge bottleneck by using ramp metering (e.g. Papageorgiou and Kotsialos, 2000). Evidence of this is still preliminary however.

Now suppose that an off-ramp is located along Link A and that we continue to meter Link B with the overly-restrictive scheme. In this case, metering B to increase A’s flow could mean higher outflows from this off-ramp because customers might now get to the off-ramp with less impedance (see Daganzo, 1996). This would reduce delay if the increased off-ramp flow increased the total outflow from the system.

But suppose that the common stream has an “off-ramp” just beyond the stadium exit and that this off-ramp’s capacity is µₒ, with µₒ < µ; (see again Figure 1(a)). Suppose too that the proportion of vehicles entering the common stream that are bound for this off-ramp is αₒ. Since vehicles in the common stream are served first-in, first-out, the flow that approaches this off-ramp can never exceed µₒ/αₒ; under this (maximum) flow, vehicles use the off-ramp at its capacity, µₒ.

If the flow directed to the off-ramp exceeds the ramp’s capacity; e.g., if αₒ•0.97µ > µₒ, the off-ramp would be unable to absorb this flow. It would become an active diverge bottleneck: a queue would form in the common stream and propagate backward past the stadium exit and onto Link A. The flow leaving the stadium would become µₒ/αₒ, and this flow would be lower than 0.97µ. Delay in the system would increase; further; Figure 1(b) shows that the shaded area in the queuing diagram would grow.

The above illustration makes clear that discharge flows through the bottleneck are sensitive to αₒ. Suppose the proportion of vehicles bound for the downstream off-ramp and originating from Link A, αₒA, equaled the analogous proportion from B, αₒB. In this case, metering cannot increase flows through the diverge because changing the metering rate (for B) would not change αₒ.

However, metering can affect the diverge bottleneck (and the delay it creates) if the scheme can affect the αₒ. This can occur for αₒA ≠ αₒB. Our present metering scheme would, for example, promote lower outflows from the diverge bottleneck if αₒA > αₒB. This is because metering B would foster higher αₒ in the common stream.

Metering for Diverge Bottlenecks on Freeways
We have shown that decreased delay comes if metering increases outflows from a system, that higher travel speeds and flows within a system are not evidence of higher outflows, and that reducing αₒ can increase outflows from diverge bottlenecks. There is a key similarity between the hypothetical diverge bottleneck just described and those on actual freeways.

Freeways have multiple lanes, which afford vehicle over-taking maneuvers. So, freeway links...
upstream of diverge bottlenecks do not necessarily serve vehicles in a strictly first-in, first-out fashion. Vehicles might therefore approach a diverge bottleneck at rates greater than $\mu_0/\alpha_0$, where $\mu_0$ is again the off-ramp capacity.

Yet traffic can be impeded by diverge bottlenecks in ways that are strikingly similar to our analogy. First, non-exiting vehicles in the freeway shoulder lane can be constrained by the off-ramp’s queue. Second, this queue can spread to adjacent freeway lanes and entrap vehicles there when commuters bound for the congested off-ramp decelerate before squeezing into the shoulder lane.

Failure to appreciate this fact can aggravate the problems of freeway diverge bottlenecks. To elaborate on this point, we first note that the overly-restrictive metering strategy in our earlier analogy is akin to so-called demand-capacity metering schemes that have been around for decades (see, for example, Wattleworth, 1964). With these schemes, each on-ramp is controlled to keep flows entering the downstream freeway link from exceeding some target flow; the target typically approaches or equals the links estimated capacity.

This kind of metering can be ill advised for a diverge bottleneck. This is because on-ramps not for upstream of the bottleneck may be metered restrictively, even though drivers entering the freeway at these locations are not likely headed for the problematic off-ramp. (Commute distances on freeways tend to be long). So, thanks to this metering, drivers who are bound for the problematic ramp and who enter the freeway many miles upstream (at on-ramps that may or may not be metered) can travel the freeway with less impedance.

By metering commuters not destined for the problematic off-ramp to favor those who are headed there, the demand-capacity scheme promotes higher $\alpha_0$ on the freeway. Consequently, the scheme may not prevent queues from forming on the freeway (just as the metering scheme in our analogy did not prevent queuing on Link A and on the common stream when our hypothetical diverge became an active bottleneck. Further the scheme can cause bottleneck outflow to diminish and commuter delay to increase.

**Further Issues in Metering for Freeway Diverge Bottlenecks**

Having seen how demand-capacity metering can be problematic for diverge bottlenecks, we next discuss other well-known metering algorithms that share this limitation. This will be followed by discussion of traffic management policies better suited to diverge bottlenecks.

The ALINEA metering algorithm (Papageorgiou and Kotsialos, 2000) can create problems at a freeway diverge or exacerbate problems that already exist there. Under ALINEA’s “traffic responsive” logic, an on-ramp’s metering rate at some time $t$ is adjusted from its previous rate based on freeway occupancy measured by detectors downstream. At each time step, the metering rate is made more (or less) restrictive than before if the measured occupancy is above (or below) some specified target. The target is typically the occupancy corresponding to capacity flow on the downstream link.

Suppose ALINEA was deployed on the freeway stretch shown in Figure 2. When the off-ramp near the downstream end becomes congested, a queue (shown with shading) forms and propagates backward past two neighboring on-ramps upstream. The detectors just downstream of each on-ramp then measure occupancies above their targets, because queued occupancies exceed those corresponding to capacity flows. Consequently, more restrictive metering rates are implemented at these on-ramps.

However, few if any vehicles entering on these nearby on-ramps are headed for the congested off-ramp, because commute distances on a freeway are usually longer than a few miles. By metering inflows from these nearby on-ramps more restrictively than from on-ramps further upstream, the scheme can promote higher $\alpha_0$ on the freeway stretch. This reduces outflows from the bottleneck and makes the freeway queue upstream even more dense. The detectors then measure even higher occupancies: a downward spiral may thus occur, marked by more restrictive metering at the nearby on-ramps that intensifies queuing and increases delay. This state of affairs might continue for some time.

Variants of ALINEA’s logic, including the algorithms known as METALINE (Papageorgiou and Kotsialos, 2000) and SWARM (NET, 1996),

![Figure 2](Hypothetical freeway site)
function with “coordinated logic,” whereby neighboring on-ramps are grouped together and each ramp’s metering rate is assigned so that the burden of moderating freeway inflows is shared by the entire group. But this can still foster higher $\alpha_o$ upstream of a diverge bottleneck. Even an entire group of on-ramps may not serve a high proportion of traffic bound for the problematic off-ramp.

Even if not subjected to metering schemes like those above, diverge bottlenecks can create huge delay (Muñoz and Daganzo, 2000; Cassidy, et al, 2002). Fortunately there are cases whereby different on-ramp metering logic can be effective in dealing with this type of bottleneck. For example, one might coordinate the metering rates at multiple on-ramps in ways that deliberately reduce $\alpha_o$. On-ramps serving many vehicles destined for the problematic off-ramp could be metered more restrictively than others (see Lovell and Daganzo 2001). Implementing such a metering scheme can be difficult, since it requires estimates of demands for freeway travel by origin and destination. In the future, it may be possible to identify vehicles bound for a problematic off-ramp and meter these vehicles differently from other on-ramp traffic (Daganzo et al 2001). However, the necessary technology has yet to be tested.

It should also be noted that a diverge bottleneck might be suitably addressed using a freeway traffic management strategy other than on-ramp metering. In many cases, the simplest solution for such a bottleneck would be to increase the rate at which vehicles can exit the off-ramp. This would commonly entail treating bottlenecks on nearby surface streets, since these are frequent causes of off-ramp queues. Other strategies for managing diverge bottlenecks and mitigating other sources of delay are offered in Daganzo et al 2001. Suitable schemes will vary from site to site. Sometimes doing nothing may be preferable to implementing an ill-suited scheme.

Conclusions

We have shown that commuter delay can be reduced by metering to promote higher freeway outflows. This can sometimes be done by limiting the $\alpha_o$ upstream of diverge bottlenecks. Greater outflows can also be realized if meters keep a freeway queue from propagating beyond an off-ramp and starving it of flow.

Sometimes delay can be reduced if metering alters travel behavior; for example if it motivates some commuters to change their routes. Those who switch routes, however, often incur more delay than the had previously: after all, they had previously viewed their new routes as inferior. Moreover, commuters who divert from a freeway may increase delay on surface streets. (Traffic subjected to these added delays could include city buses and their many passengers). So, evidence of commuter route diversion does not necessarily mean reduced delay. Unfortunately, the full effects of such diversion can be difficult to evaluate, because these effects are often spread over many neighboring surface streets.

Field-testing of a scheme’s effectiveness is increasing freeway outflows is a much simpler matter. Such tests need not focus on vehicle speeds and flows on freeway links. Instead, counts can be made of the vehicles exiting at each freeway egress point, that is, at each and every off-ramp in the system and at the freeway link farthest downstream. These counts should be recorded at specified times the rush, and intervals of 5 minutes or so should generally suffice. The counts for each and every egress point can then be summed together at each of these $t$, $D(t) = \sum_i D_i(t)$, and the cumulative curve of these summed $D$ can be plotted over time.

One can construct such a cumulative curve before a scheme’s deployment and determine the area under the curve bounded by the start and end times of the rush. The same kind of curve can be measured after the scheme’s installation, and the area determined for the comparable time period. The difference in these areas is an indicator of the scheme’s performance. This idea is implicit in some work regarding dynamic traffic assignment for roadway networks (Lin and Cao, 1997).

Without higher freeway outflows, and absent favorable changes in travel behavior, on-ramp metering can at best only transfer traveler delay from the freeway to on-ramps and surface streets. Although there might at times be advantages to this, the transfer can result in queue storage problems.

The literature says surprisingly little on this problem. Even less is written about the added commuter delays created by overly restrictive metering schemes, or by schemes that promote higher $\alpha_o$ upstream of diverge bottlenecks. For example, most reports promoting or critiquing demand-capacity schemes or algorithms like ALINEA make no mention of their limitations in addressing diverge bottlenecks. Perhaps this is a reason metering schemes are sometimes designed without due consideration for local freeway conditions; (see Cassidy, 2002 for an illustration of this).
In some instances, bottlenecks are relatively easy to identify from measured traffic data. In other cases, sources of delay are not so readily distinguished. Some diverge bottlenecks, for example, can be difficult to diagnose because of other geometric inhomogeneities nearby. In these cases, bottlenecks can usually be identified with the aid of high resolution methods for processing traffic measurements. Such methods might include suitably scaled curves of cumulative vehicle count vs time (Cassidy and Windover 1996). These kinds of data plots can reveal much about the sources of delay and other details of freeway traffic.

Making such diagnoses is important, since no single metering logic can suitably address all conditions that arise on different freeways. So a metering scheme, or any traffic management strategy, should be designed only after the freeway of interest has been carefully examined and its bottlenecks identified. For a freeway with a diverge bottleneck, adhering to this sequence can save commuter delay. Not adhering to this sequence can be disastrous.

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Persaud, B., Yagar, S. and Brownlee, R. (1998) Exploration of the breakdown phenomenon in freeway traffic. Transpn Res. Rec. 1634, 64-69 (see especially Figure 1).

per rider, subsidy per rider, cost per passenger mile, passenger per vehicle, passenger per vehicle hour, fare box recovery rate, benefit-cost ratio, etc. The measurement methods used in the cases reviewed varied considerably from one to another.

Other Issues
Since most reviewed cases are successful BRT implementations, some of them naturally are calling for future extensions (Curitiba, Ottawa, Adelaide, Los Angeles, Miami, Nagoya, and Bogotá). Future extensions involve many complex issues, for example, funding sources, cost-benefit analysis, technology options, operation and maintenance, public acceptance, multi-agency and multi-jurisdictional coordination over the corridor, service cuts of conventional services, potential markets, etc. Adelaide's government plans to use a mixture of a new alignment and rail alignment instead of a guided busway on a new extension because the original O-Bahn technology is no longer feasible from a cost-benefit perspective. Similarly, Nagoya’s future plan doubts the necessity for an expensive guideway system given uncertain markets and development. On the other hand, future plans for mixed traffic type BRTs like Los Angeles’ call for exclusive bus lanes on arterial segments where feasible, within limits dictated by predicted congestion and delay. Even a thriving BRT system can’t always grow using its original technology. Moreover, the multi-agency cooperation needed to ensure level of service, service coverage, and fare policy can involve very complicated issues when system extensions are planned.

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for Traffic State estimation, improved Traffic Flow theories, intelligent onramp metering control schemes, new models for traveler route choice in the presence of advanced traffic information, and other state-of-the-art developments.

Based on this solid foundation of accomplishments, the new thrust at PATH has now shifted to the validation of these research products through Field Operational Testing (FOT). This represents the logical next step in moving the results of the research toward deployment. Until now, most of the validation of PATH research has been performed through simulation or controlled experiments. While these are helpful, they cannot be a substitute for testing new technologies or strategies in the real world.

To reflect this new thrust on FOT, PATH underwent a reorganization during the summer of 2003. The previous division of PATH between AVCSS and ATMIS research was not appropriate to the new research emphasis, where experts in sensing and communication technologies, transportation science, behavioral research, economics and policy work collaboratively in the planning, design and implementation of Field Operational Tests. The objective of the new structure is to emphasize an application problem orientation, rather than a technology orientation.

The new PATH is organized along four programs:

- Traffic Operations Research
- Transit Operations Research
- Transportation Safety Research
- Policy and Behavioral Research

In the following sections, we describe the research agendas of these four programs. We place special emphasis on new research initiatives, and on the collaborative aspects of these research activities. We also highlight current or planned FOT efforts.

The PATH traffic operations research program focuses on advancing the state-of-the-art in traffic management and traveler information systems, while producing results that can be implemented in the field. The research is undertaken by a state-wide team of fifteen faculty and more than 40 graduate students and staff working closely with the program sponsors. Currently there are more than 25 active research efforts including development and testing of surveillance technologies, algorithms for data processing, fusion and analysis, development of analytical and simulation techniques for performance measurement, simulation and visualization tools for impact analysis and evaluation, and formulation and testing of advanced operational strategies for managing congestion and reducing commuter delays.

Examples of Traffic Operations Research Include:

The Performance Measurement System or PeMS. Development and implementation of systems to provide real-time traffic information to motorists in various forms from changeable message signs to personalized itineraries via cellular phones.

Formulation and demonstration of control strategies to alleviate bottlenecks at freeway merging areas, adaptive signal control strategies on urban arterials that also provide priority to transit vehicles, and systems that facilitate the coordination of operating agencies to minimize the response time to incidents.

In addition, unique laboratories and test beds have been created to provide the data and operating environments to study traffic flow dynamics and test improved strategies in real-world conditions. These facilities and data are being used by researchers worldwide.
Transit Operations
Program Leader: Wei-Bin Zhang

Working with a large numbers of transit agencies, built upon solid technical expertise and through fundamental research as well as Field Operational Tests, the PATH transit research program addresses real-world problems and brings in advanced, yet practical solutions. The following examples highlight the ways in which PATH is working on improving Public Transportation Systems:

Bus Rapid Transit (BRT): is a new form of transit involving innovative planning and advanced technologies that improve the efficiency of operating mass-transit bus routes. PATH’s research in BRT covers a wide range of subject areas including planning, evaluation and technology development. As an example, PATH is also working on an adaptive signal priority concept that allows busses to smoothly travel through intersections while minimizing the disturbance of the flow of cross traffic. Building on its Advanced Vehicle Control System’s research, PATH developed lane assist and precision docking systems allowing transit busses to be operated on a narrow lane and to dock at bus stops with rail-like accuracy. To demonstrate the most advanced BRT concepts, PATH developed and demonstrated an Automated BRT system on I-15 using two automatically controlled busses in San Diego in August 2003 (see article on page 8).

On-Demand Responsive Transit (DRT): and para-transit services provide critical links for transit dependant riders to gain mobility, but have currently been less cost effective for transit agencies to operate. PATH addresses factors influencing productivity and operating costs of DRT by developing approaches for improving the transit agency’s cost of operation.

Frontal Collision Warning System (FWCS): Under the Transit Intelligent Vehicles Initiative (IVI) program sponsored by Federal Transit Administration, PATH is working with transit agencies, the California Department of Transportation and a bus manufacturer to develop requirement specifications for a frontal collision warning system. As part of this study, PATH has developed prototype frontal collision warning systems that work within urban settings where the driving environment is more complex than in highway settings.
The PATH Transportation Safety Research Program’s objective is to provide products that can be tested and deployed within a short time frame using a combination of advanced technology and human factors research. PATH research has a proud heritage of vehicle-infrastructure collaboration, and its many enabling technologies and capacities make it tangible. This research ranges from implementation of wireless, sensing technologies; to human factors and driver cognition expertise to unlock the “Science of Driving”; through in-the-field hardware, software and systems application of vehicle, vehicle-highway, and driver experiments.

PATH’s aim is to develop first-class applied safety research products, developed in collaboration with its customers and aimed at near-term deployment in order to make streets and highways safer. PATH has many projects and research interests dealing with intersection safety, snow removal equipment operation, modeling of driver actions, elderly drivers, at-grade rail crossing and pedestrian safety.

One of the largest safety efforts is the intersection decision support (or IDS) project explores a promising, near-term deployable vehicle-infrastructure cooperative system to aid drivers in identifying when it is unsafe to make a permitted left turn in the face of an oncoming vehicle. Using multiple detection and sensing devices (including lidar, radar, inductive loop detectors and in-vehicle GPS), the system can identify and track vehicles approaching the intersection in real time. Combined with vehicle motion data, signal timing and phasing data sent from the traffic controller are used to run a decision-making algorithm. When conditions are unsafe for making a permitted left turn, a dynamic “no left turn” sign pulses (or “looms”) and displays a warning to the driver. In order to illustrate an alternate path to deployment, dedicated short-range wireless communication has also been incorporated to allow direct communication between our roadside and approaching vehicles, thus creating a “smart” intersection that can provide information directly to in-vehicle devices.

The Policy and Behavioral Research program focuses on understanding the role, response, and impacts of advanced transportation technologies. It brings together a variety of theories, methodologies, and disciplines in answering applied policy, planning, and implementation questions related to transportation technology use, markets, and response. Disciplines and approaches include: engineering, planning, economics, systems and policy analysis, psychology, sociology, business, and marketing. Research in this area seeks to address transportation issues related to congestion, air quality, and energy and land use.

Projects involve faculty, staff, and students from across the State. These include: smart parking management; carsharing; elderly driving behavior and attitudes; institutional approaches to inter-jurisdictional system management; measuring impacts of graduated licensing laws in California; an evaluation of California’s chassis network; shared-use, low-speed modes linked to transit, including e-bikes and Segway Human Transporters; innovative methods to improve transit access and reliability, such as intelligent bus priority lanes; and planning/evaluation of Caltrans’ Innovative Corridors Initiative.

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