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### Title

Cooperative Adaptive Cruise Control -Improving Traffic Flow and Driving

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# Intellimotion

## Keeping up with California PATH Research in Intelligent Transportation Systems

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*California PATH—Partners for Advanced Transportation Technology—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  
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## Augmented Speed Enforcement Project at PATH Minimizing Hazards in Work Zones in Rural Areas

The Partners for Advanced Transportation Technology (PATH) developed, implemented, and field-tested an Augmented Speed Enforcement (aSE) system that will help enforce reduced speed limits in construction zones and thereby protect personnel working in the roadway. The work was conducted under a project sponsored by the United States Department of Transportation (USDOT) with collaboration from California Department of Transportation (Caltrans), California Highway Patrol (CHP), and Western Transportation Institute (WTI) of Montana State University. The project was carried out with the goal of evaluating the effect of reducing traffic speed and minimizing hazards in a work zone in the rural environment.

There are approximately 42 percent more fatal collisions in rural areas, compared to urban areas in the US even though traffic volume is lower in the rural environment [1]. More aggressive and relatively higher speed driving are primary factors that lead to more frequent injury and fatality collisions in the rural area [2]. Moreover, studies have shown higher collision rates at specific settings, such as work zones that temporarily set lower speed limits and work zones on rural two-way highways [3, 4].

The main function of this aSE system is to communicate relevant speed violation, and hazard information to the stakeholders in the work zone, these stakeholders include vehicle operators, CHP officers, and workers. The system consists of two component systems, one provided by PATH and the other WTI. Each component system was deployed and tested

individually and then integrated and tested as single system.

aSE utilizes a speed camera in conjunction with dedicated short-range communication (DSRC) and cellular communication for a driver alert and traffic

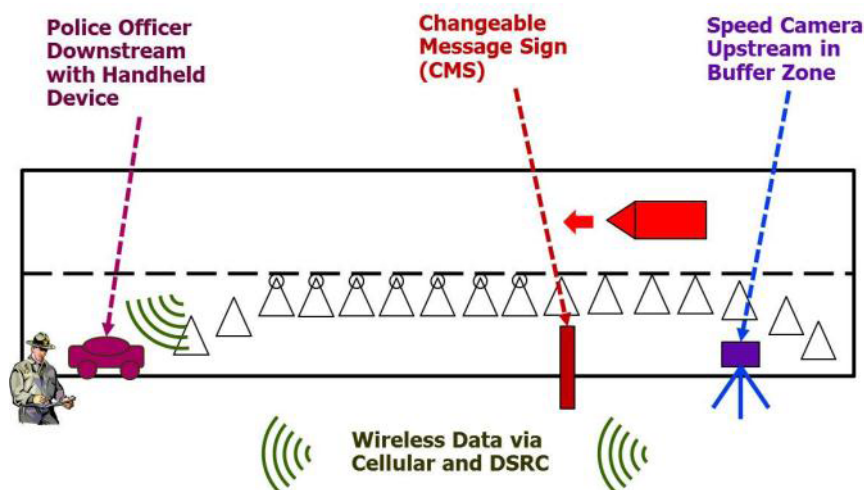


Figure 1: Interaction with Drivers and CHP in Augmented Speed Enforcement System

enforcement system to realize safety benefits. Figure 1 illustrates the functional components that provide the interface among the involved parties with the utilization of wireless communication.

aSE performs in the following sequence:

- 1) The speed camera system detects a travelling vehicle and determines if it is violating the speed limit. It photographs and performs automatic recognition of license plate numbers for vehicles that are violators.
- 2) The measured speed and license plate number are then transmitted to and displayed on a downstream Changeable Message Sign (CMS), located a distance of 200-300 meters from the camera. With the aid of this enhanced feedback, drivers are advised to observe the lower speed limit while passing through

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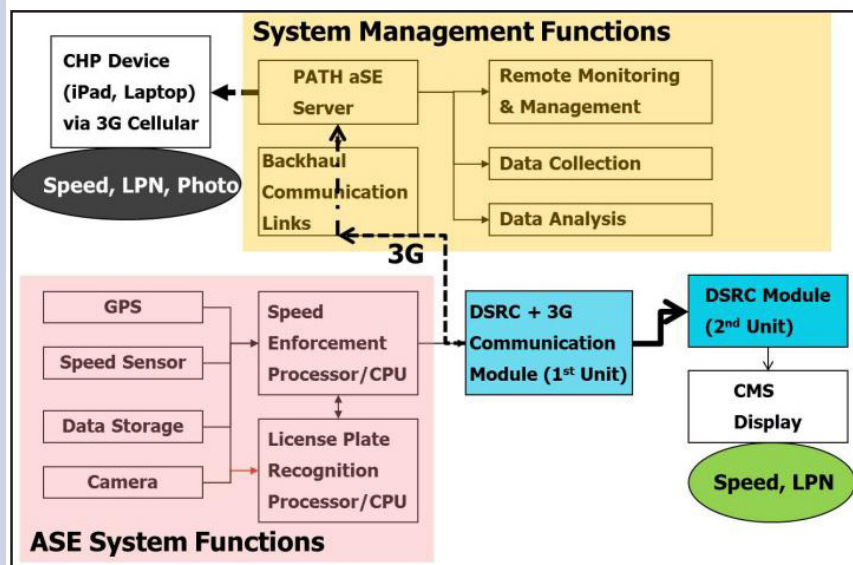


Figure 2: PATH aSE System Functional Diagram

the work zone.

3) Data about speed violators, including speed, license plate number, and photograph, are transmitted, stored and archived at a system server. This server allows remote monitoring and diagnosis of the operational status of the system as well as maintaining archives of captured and transmitted data.

4) Data can be accessed via any typical web browser by any authorized user who may be at a downstream location, at a range of 1,500 meters or greater distance from the active work zone. The information can be displayed to police officers, for example, on a handheld device such as a tablet computer or an iPad.

The overall architecture of aSE and its data flows are depicted in Figure 2 with functional blocks identified. The camera system is connected to a communication module (first unit), which allows data communication via two channels; dedicated short-range communication (DSRC) and cellular. The changeable message sign (CMS) is reached via DSRC. The DSRC radio transmits vehicle speed and license plate number for display on

the CMS. The cellular link facilitates the transmission of vehicle speed, license number and photographs to the secured server, which in return delivers this in farther to cellular-enabled portable device.

The PATH aSE system was field tested in the summer of 2012. The test site was on a section State Route 152 east of the town area of Los Banos. The actual work zone, excluding the leading taper and buffer zones, stretched for approximately one mile. See Figure 3(a) for an overall layout of the work zone. The PATH speed camera and CMS are located in the buffer zone, highlighted in pink in the middle of the diagram. As shown in Figure 3(b), The speed camera trailer was placed at the beginning of the buffer zone, facing the traffic. A changeable message sign (CMS) was located downstream from the camera

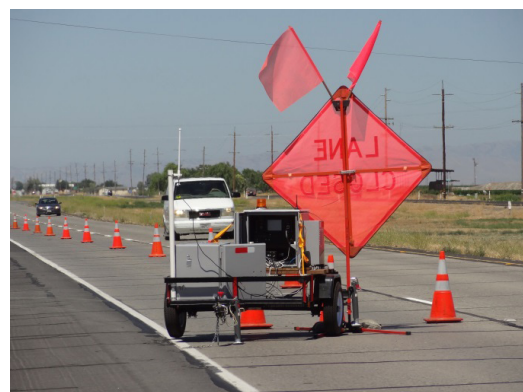


Figure 3 (b): Speed Camera on Trailer Facing the Approaching Traffic

in the buffer zone, as shown in Figure 3(c). In the default mode, the message read "WORK ZONE; SPEED; 55 MPH." In the case of a speed violation, "LICENSE; ABC123; XXMPH" is displayed.

The field testing and data collection schedule spanned the months of May, June and July of 2012. Testing periods were broken down into four different scenarios: baseline data collection with standard work zone setup,



Figure 3 (c): Display of Messages on Changeable Message Sign



WTI cones/warning lights/pager system only, PATH radar/camera/CMS system only, and a combination of both WTI and PATH systems. The four scenarios were tested for one week each at a time, and the whole cycle of four scenarios was repeated twice for a total of eight weeks of testing in the field.

### Data Collection and Evaluation

Different types of data were collected during field testing for evaluation:

- The collected measured speed of passing vehicles detected by the speed sensor were aggregated into a daily inventory of speed distribution.
- The recognized license plate numbers and the associated photographs of speeding vehicles are archived and evaluated for their accuracy.
- The vehicle speed was measured and collected by a radar sensor installed at the CMS location, which tracked the vehicles as they approached the CMS.
- The information transmission between communication modules and backed server were logged to estimate the transmission time lags.
- The average speed of traffic at several locations along the work zone were measured by iCones.

### Speed Data Measured by EVT-300 Radar at CMS Location

In addition to other speed measurement devices, we also installed a radar sensor at CMS locations to capture traffic movement. This monitoring is especially meaningful when drivers are approaching the CMS and witness the CMS displays. One sample set of 30-minute data is shown in Figure 4 with two subplots given:

1) Range rate versus range (speed plotted against distance), as shown in Figure 4(a). The used radar is EVT-300, which can track 7 targets at any instant with a sampling rate of 16 Hz. The data are plotted with the radar position at the origin, i.e. at distance zero, as the horizontal axis indicating the distance of the target away from the radar. The radar can detect target from a distance of 450 feet, so a target will be moving with the distance decreasing toward zero, from right to left in the

chart. Each color line in the plot indicates the trace of a target approaching the radar. The range rate (speed), as indicated in the vertical axis, is shown as a negative number, because the target is closing the range to the radar. As can be seen in the bottom half of the chart, two distinct targets are moving toward the radar with decreasing speeds.

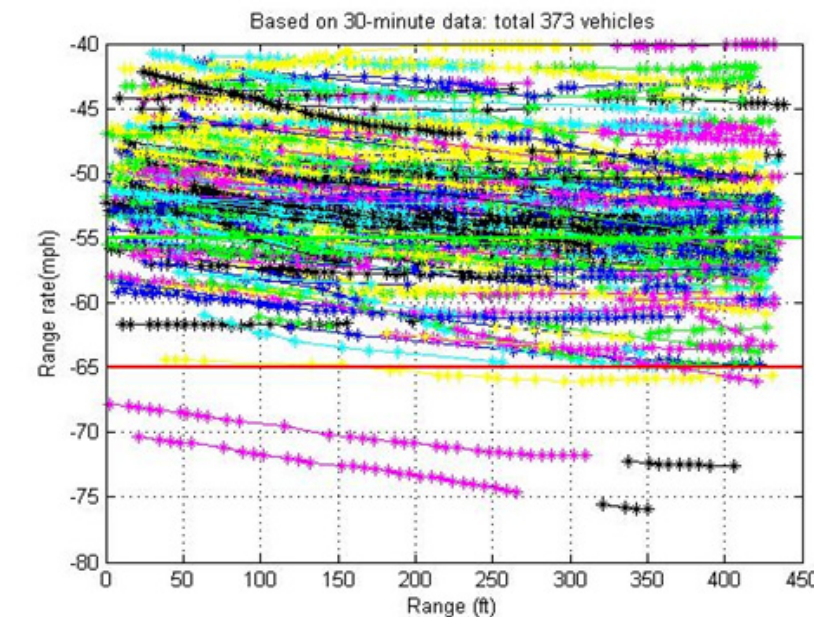


Figure 4 (a): Range rate vs. Range (Speed vs. Distance) of Vehicles Approaching CMS

2.) Distribution of speed change, grouped by starting speeds, as shown Figure 4(b) in page 4). The same set of data from Figure 4(a) are regrouped by the starting speed of a target and shown in Figure 4(b). The starting speed is the speed of a detected target when it is first tracked by the radar, i.e. the first point of a colored line in Figure 4(a). The distribution is shown in a box plot, in which the box shows the range of 25th to 75th percentile, and the end points of the line indicating the upper and lower range of data. As can be seen in Figure 4(b), a great majority of targets experience a negative speed change.

The review of data collected at the CMS radar results

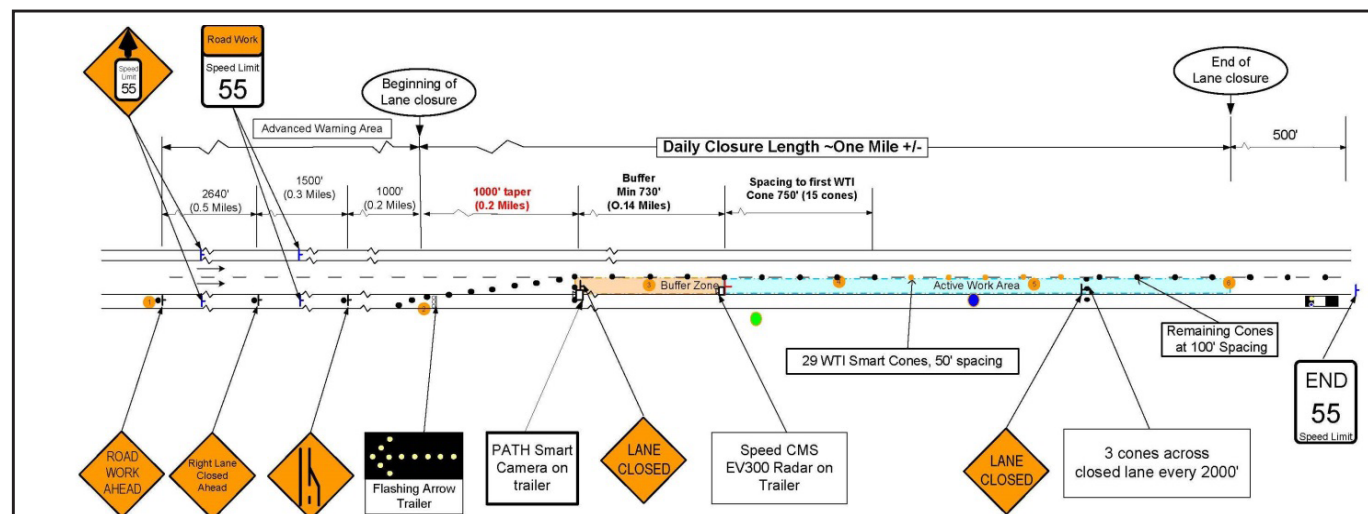


Figure 3 (a): Field Test Work Zone Layout and Placement of Speed Camera and CMS

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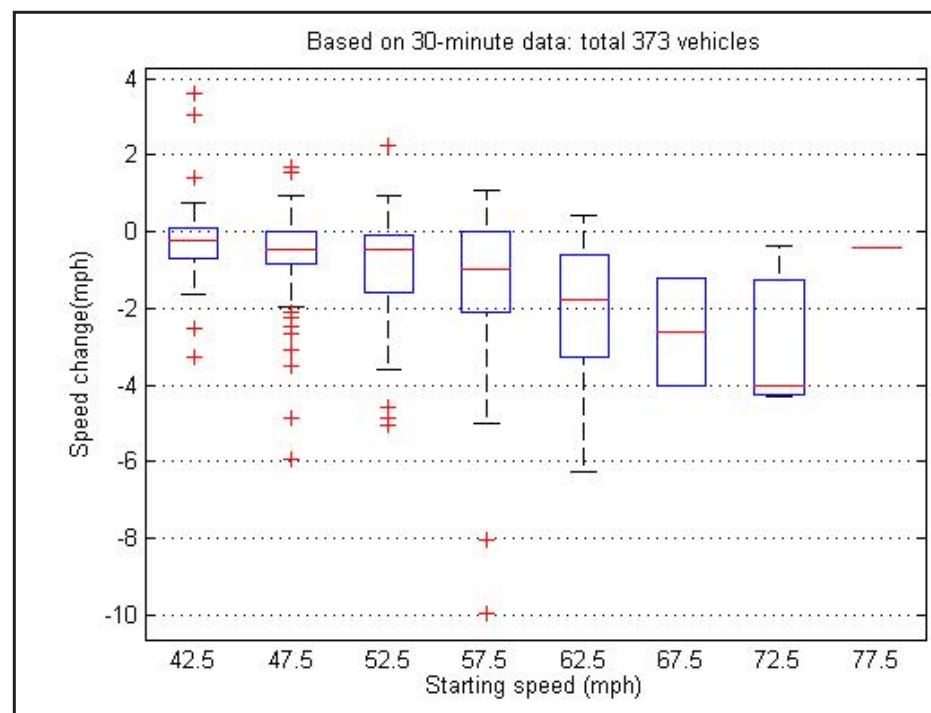


Figure 4 (b): Distribution of Speed Change of Vehicles Approaching CMS

reveals that:

- A great majority of the vehicles show a reduction in vehicle speed while they are in the detection range of the radar.
- For the majority of the vehicles, the change in speed may be too small to be quantified as intentional speed reduction by drivers due to the CMS display. Nevertheless, there are still a meaningfully large number of speed reductions among all samples, which is consistent with data samples from other data sources.
- Anecdotally, the researchers were able to observe occasional brake lights of vehicles when they approach the CMS. This also matches the noticeable numbers of significant speed reductions in data.

#### iCone Data

We also analyzed the iCone data to identify the effectiveness of the aSE system. The field test were organized into weekly slots during which the WTI system was tested, followed by WTI-PATH joint deployment, then PATH only deployment, and finally baseline testing. This schedule was repeated twice, resulting in two sets of data, which we refer to as first set and second set. Note in the work zone diagram that iCones 1 and 2 are placed at the segment prior to entering the work zones, iCones 3 and 4 are placed at the first half of the work zone (where the PATH system is located) and iCones 5 and 6 are placed at the second half of the work zone. The iCone data are grouped into four speed ranges: 1) lower than 60mph, 2) 60-65mph, 3) 65-70mph and 4) higher than 70 mph. During the test period the system encountered approximately 4000 vehicles per day in the time it was active.

In order to measure effectiveness, we will analyze the

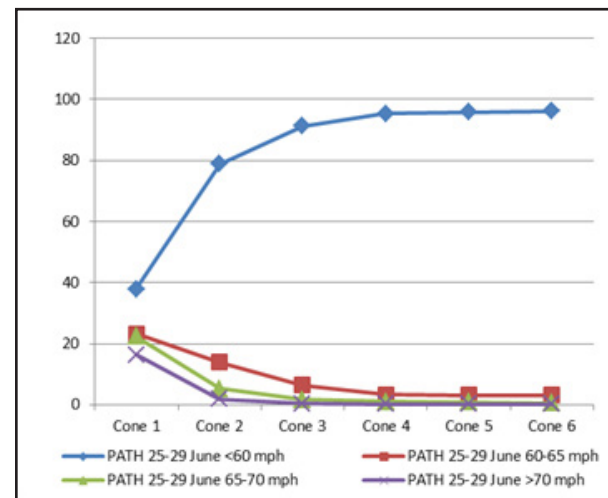


Figure 5(a): PATH aSE: Vehicle Speed Distribution, by iCone Numbers and Speed Bins

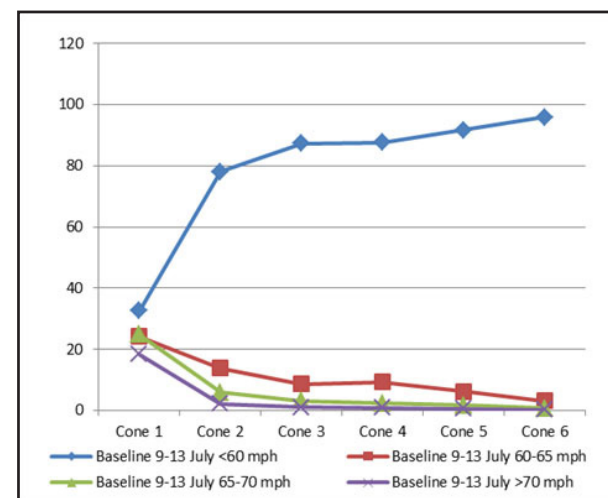


Figure 5(b): Baseline: Vehicle Speed Distribution, by iCone Numbers and Speed Bins

speed of the vehicles traveling along the work zone based on the iCone data. One important measure of effectiveness will be the observance of the reduction in number of vehicles in the higher speed bins due to the presence of the aSE system. Figure 5 shows a week of data when the PATH aSE system was deployed versus a week of baseline data when no system was deployed.

Figures 5 (a) and 5 (b) show the distribution of speed as the vehicles traverse the work zone. The numbers of vehicles in the lowest speed bin of less than 60 mph increase as the vehicles proceed from the start to the end of the work zone. This is accompanied by the decrease in the three higher speed bins as the vehicles progress through the work zone. There is a noticeable decrease of vehicles in the higher speed bins when the system is deployed.

#### CONCLUDING REMARKS

Demonstrated as a case study where the aSE system can be suitably deployed, the system was field tested on California State Route 152 near the city of Los Banos. The tests were carried out with the PATH and WTI sub-systems individually and jointly deployed to evaluate the effects of traffic movement in comparison to the baseline of a regular work zone. The four scenarios, baseline, PATH system only, WTI system only, and both systems, were tested for one week each and the cycle was repeated with a total of eight weeks of data collected. During this period, Caltrans maintenance crew performed regular maintenance work on a stretch of SR-152 on a rotating basis. Results from the field tests show that the system was indeed effective in reducing the number of speeding vehicles.

Based on the iCones data that were placed throughout the work zone for the duration of the field tests, the percentage of vehicles traveling in excess of 65 mph was significantly reduced. For example, the summation of percentage of vehicles moving faster than 65-mph from all iCones decreased from 60.2% in the baseline scenario to 54.1% in the scenario when the PATH aSE system was in place.

PATH also carried out additional field testing activities to support the utilization of Dedicated Short-Range Communication (DSRC) for the augmented speed enforcement (aSE) project. The main objective of this DSRC experiment is to identify the effective range up to which DSRC can support the requirements of the aSE project. Secondary objectives would be to verify the benefit and necessity of specialized antenna and cables in extending the range along with the utility of using a repeater. The tests were executed in a suburban and rural setting in the city of Petaluma, CA.

The PATH aSE system developed and validated in this project have the potential to be deployed for a wide

range of highway segments, either in rural or urban areas. At locations where speeding is a concern, the augmented speed enforcement can be used to provide timely and enhanced driver feedback, achieving the primary objective of reducing traffic speeds to avoid hazards. Significantly, enforcement duties remain in the hands of officers, and the use of this system does not lead to legislative concerns in jurisdictions where automated functions are prohibited. ☼

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# Cooperative Adaptive Cruise Control - Improving Traffic Flow and Driving

Steven E. Shladover

PATH developed and field tested a prototype cooperative adaptive cruise control (CACC) system that was well liked by drivers from the general public and gave them sufficiently high confidence in its capabilities that they were comfortable driving it at head ways short enough to nearly double the capacity of a highway lane. This represents a vehicle-vehicle cooperative ITS system application that has both a potentially strong market appeal and the ability to significantly improve traffic flow conditions. It works by combining the production adaptive cruise control system with a DSRC wireless communication system that enables the

lead car to frequently update the follower car about its status, and a new vehicle-following controller to capitalize on this richer source of information about the lead car's actions. This makes it possible for the CACC system to provide more accurate control of the gap to the forward target vehicle, enabling drivers to use it at significantly shorter time gaps

The CACC system was originally developed under Caltrans sponsorship, using Infiniti FX45 vehicles loaned by Nissan. Nissan also provided generous technical support, helping us by providing full access to the vehicle data buses and supporting the early vehicle testing and debugging with the assistance of their technical staff and use of their Arizona Test Center. The field testing by 16 drivers from the general public was supported by the FHWA Exploratory Advanced Research Program, and some of the post-test data analyses were supported by Nissan Technical Center North America. These tests were so successful that Nissan Motor Company Ltd. supported the development and testing of a second generation of CACC vehicles by PATH.

The only exterior visible difference between the Infiniti FX45 test vehicles and the standard production vehicles of the same model is the extra antennas used for the 5.9 GHz vehicle-vehicle communication and for the GPS receivers used in the onboard data acquisition system. The PATH data acquisition and CACC control system are implemented on a network of three PC104 computers installed in a housing behind the rear seat of the vehicles (see Figure 1), still leaving ample cargo space

for the drivers to haul whatever they needed to. The data acquisition system records about 30 channels of technical data from the vehicle data bus, as well as the outputs of five video cameras that monitor the driver and the external driving environment (forward and rear exterior views and driver's face, hands and feet), from the locations indicated in Figure 2 (page 7).

The PATH and Nissan technical teams tested the CACC system extensively at Nissan's Arizona Test Center to verify its performance and safety before driving it on public roads or with drivers from the general public as

Figure 1: Data Acquisition System and Control Computer (enclosure open and closed)

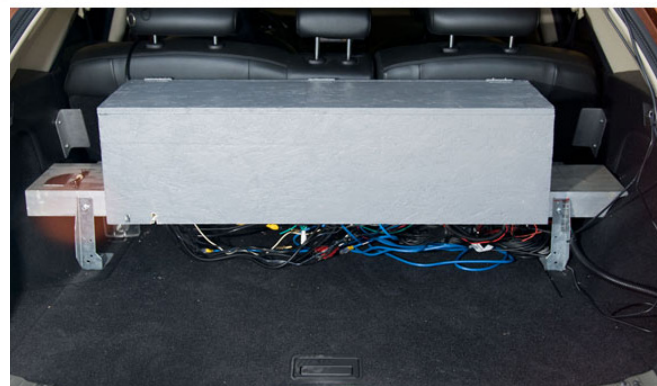
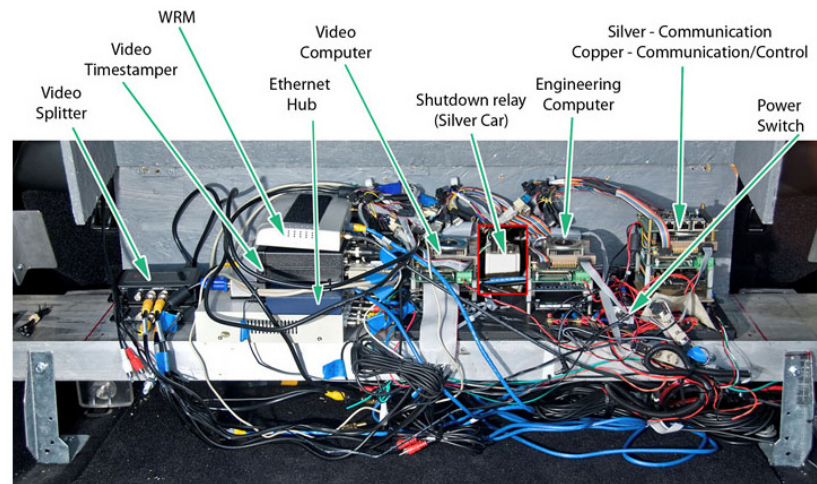


Figure 2: Vehicle interior with video camera locations shown

eral public (8 male and 8 female) who all had relatively long freeway-based daily commute trips, providing the maximum opportunity for ACC driving under similar conditions on a daily basis. These test subjects were provided with one of the test vehicles for their daily use, which they first drove under conventional manual control to establish a baseline of their normal driving behavior, and then with use of the factory-standard ACC for seven days of commute trips. For the final two days of the experimental period, they drove the CACC vehicle on their commute trips, accompanied by a PATH researcher, while another PATH staff member drove the lead car that was transmitting its performance data for use by the CACC system. We recorded many aspects of driver behavior and system performance during these tests for subsequent analysis.

The most significant findings involved the drivers' selection of time gap settings on the ACC and CACC systems, which are summarized in Figures 3 and 4. These results showed diverse preferences among the available time gap settings when drivers had the standard ACC system, with some preference for the shortest setting (1.1 s), but substantial amounts of car following still occurring at the longer settings. With the CACC, the preferences shifted dramatically toward the shortest two settings, indicating how the tighter control response of the CACC gave the drivers increased confidence in the safety of the system, so that they would be comfortable driving at significantly shorter gaps. Indeed, the summary results in Figure 4 showed that both male and female drivers chose mean CACC time gap settings that were only 45% as long as the gap settings they chose

Figure 3: Time-Gap Setting Preferences During Car Following by Drivers in Field Test

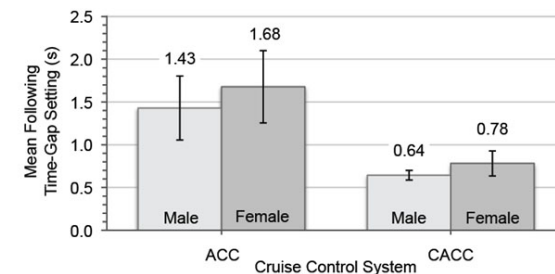
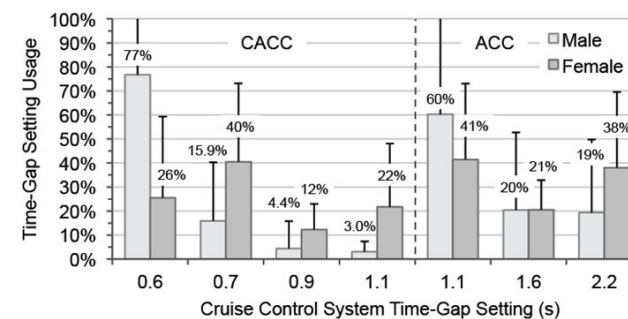


Figure 4: Mean Preferred Time Gaps During Car Following

under conventional ACC control. The implications of widespread use of CACC are very favorable for traffic flow stability and capacity. The fast response of the CACC system to speed changes by the leading car helps to reduce the car following response lag, which stabilizes traffic flow dynamics, especially when compared with the slow response of the conventional ACC. The reduced time gaps chosen by the drivers with CACC could have an even more dramatic effect on the capacity per lane. This effect was represented in a simulation of a simple freeway section with one onramp, operating at capacity. In the baseline condition, without use of any ACC, the capacity was about 2000 vehicles per hour per lane. When ACC vehicles were added to the mix, with the car-following gaps that our drivers actually selected in the field test, the capacities ranged from 2030 to 2100 vehicles per hour per lane, over market penetrations from 10% to 100%. This indicates that ACC is unlikely to have any significant benefit to traffic flow capacity.

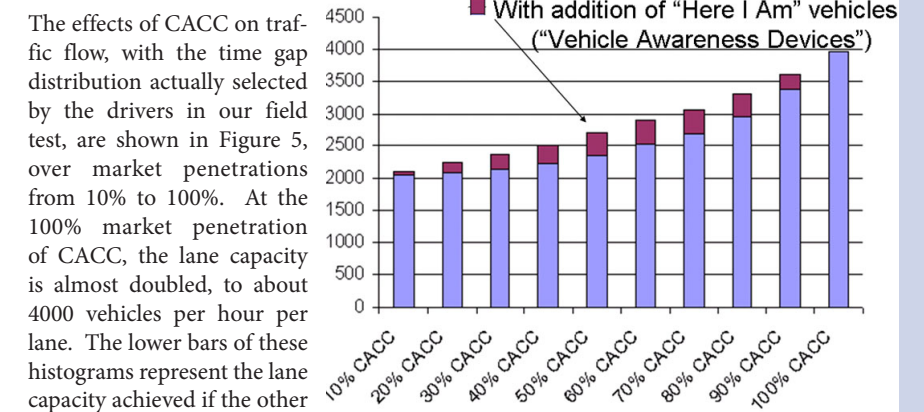


Figure 5: Lane Capacity as a Function of CACC Market Penetration

The effects of CACC on traffic flow, with the time gap distribution actually selected by the drivers in our field test, are shown in Figure 5, over market penetrations from 10% to 100%. At the 100% market penetration of CACC, the lane capacity is almost doubled, to about 4000 vehicles per hour per lane. The lower bars of these histograms represent the lane capacity achieved if the other (non-CACC) vehicles are not equipped with any communication capability, so they cannot act as lead vehicles for CACC. In these cases, the shorter CACC gaps can only be achieved when two or more CACC vehicles are driven consecutively in the lane. The upper bars of the histograms represent the lane capacity achievable if the non-CACC vehicles are equipped with DSRC "Vehicle Awareness Devices", broadcasting their vital state information so that they can serve as lead vehicles for CACC following. In this case, every CACC-capable vehicle can always drive at the reduced CACC time gap regardless of which vehicle it is following. The effect of this is a faster growth in lane capacity at the low to intermediate market penetrations of CACC.

These results show how CACC can provide not only direct benefits to the individual drivers who choose to use it but also benefits the freeway traffic flow in general by significantly increasing lane capacity. These benefits justify public investment in encouraging CACC development and usage.

the test subjects. Based on these tests, we concluded that the CACC time gap settings should be 1.1, 0.9, 0.7 and 0.6 seconds, compared to 1.1, 1.6 and 2.2 seconds for the standard ACC. It was important to have one setting common to both systems (1.1 s) to provide a baseline for comparison between ACC and CACC, and 0.6 s was the shortest gap that the research team thought would be safe for driving in general public traffic conditions.

For the field test, we recruited 16 drivers from the gen-

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# New Upgrade Connected Vehicle Test Bed in Palo Alto and San Jose

For this project, PATH would upgrade a pre-existing DSRC test bed in the City of Palo Alto, CA. This work is being conducted in close coordination with the U.S. DOT's ITS Joint Program Office and is included on the list of FHWA's Affiliated Connected Vehicle Test Beds.

Recent advances in communication and sensor technologies have made a fully connected surface transportation system possible enabling a rich set of applications. In the future, vehicles will be able to communicate with each other (V-V) and with the infrastructure (V-I) in real time. Transit buses will be able to communicate their schedule and passenger loads to the signal controllers inside the intersection cabinets and request priority. Disabled pedestrians will be able to utilize a nomadic device such as smart phone to communicate to the intersection their presence and intention to cross. Then signal controllers will provide them enough time to cross and ensure that they have cleared the cross walk before changing to the next phase. A freight truck will be able to request priority directly to the infrastructure in order to minimize unnecessary stops and maximize fuel economy while reducing pollution. Cars will be able to receive en-route real-time information about the road conditions, incidents, and congested areas that may affect their trips. They will also receive alternate routes that could shorten their trips. Overall, the promise of a new era, enabled by sensors and communication devices, is a surface transportation system that is more safe, efficient, predictable, reliable, and environmentally friendly. To make this era possible, a state of art test bed, fully wired and connected is required. It will serve researchers, vehicle manufacturers, and entrepreneur to test and prove their concepts in real world settings, with real traffic and the most unpredictable part of any road network, the human drivers, present.

In 2005 and under a project called "California VII (Vehicle Infrastructure Integration)", California PATH program, with funding and support from Caltrans and Bay Area's Metropolitan Transportation Commission (MTC), designed and installed the first Connected Vehicle (VC) test bed in the U.S. This internationally recognized test bed had 14 RSEs that were placed along US 101, I-280, and SR 82 (El Camino Real). This test bed became the main venue for researchers, car manufacturers, and in-vehicle system developers to test their early devices and applications. Currently, besides our California test bed, a few other CV test beds have been installed in the U.S. and abroad.

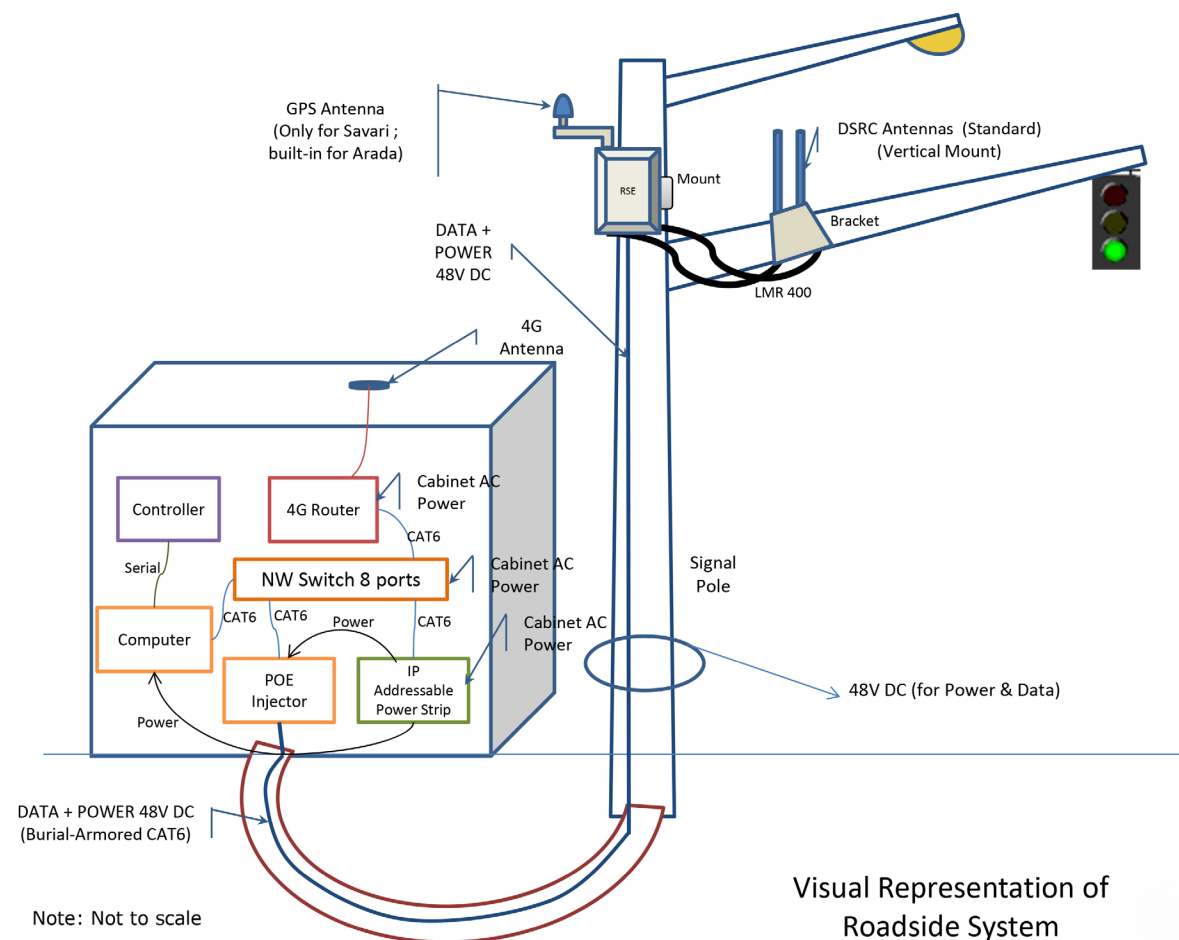
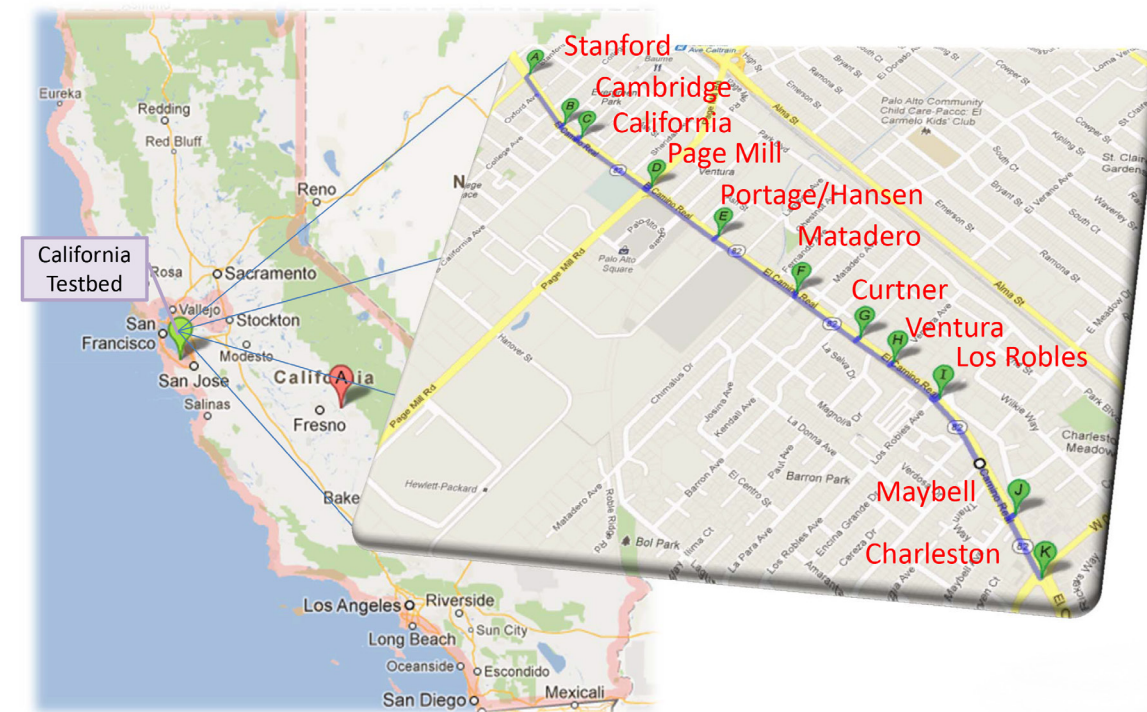
Domestically, there are test beds in Virginia, Michigan, Minnesota, Colorado, Florida, Arizona, and New York. More states are planning to have their own test beds. Internationally, there are test beds in Germany, Japan and Netherlands.

Not all of these test beds follow the same system architecture similar to what has been deployed in the U.S. but all have the goal of providing the same value for researchers, car manufacturers, and in-vehicle system developers to study the challenges of Connected Vehicle environment and measure its benefits. There are also many efforts to develop standards for communication protocols that would support the Connected Vehicle environment both domestically and internationally.

PATH will be upgrading a portion of the aforementioned test bed that is located in the city of Palo Alto. As part of this effort, PATH will install RSEs at 11 consecutive signalized intersections along SR 82. The new test bed will be 1.9 miles long starting with Charleston Road intersection on the southern end and ending with Stanford Avenue intersection on the northern end. This test bed, with consecutively equipped intersections, would enable the researchers from academia and industry to test some specific applications such as Eco-Driving or coordinated heavy vehicle movement through the corridor. In addition, there will also be two more RSEs installations at to be determined rail-road crossings in the City of San Jose. The two brands of RSEs that this test bed will utilize are the latest versions of Savari and Arada.

The proximity of the test bed to physical R&D facilities of major vehicle manufacturers as well as its location at the heart of Silicon Valley makes it a perfect test bed for the industry players to use it. PATH will coordinate and facilitate these usages. PATH will also participate and partner in some of the research experiments and evaluation processes that industry partners will perform.

# Test Bed Geography



Visual Representation of Roadside System

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Keeping up with California PATH Research in Intelligent Transportation Systems

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