Development and Assessment of Selected Mobility Applications for VII: Principal Findings

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Abstract:

This project has shown how connected vehicle systems, based on vehicle-vehicle and vehicle-infrastructure communication and coordination, can support the development of mobility-enhancing applications with the potential to transform the performance of the road transportation system. Three separate mobility-enhancing applications were developed, simulated, and tested, and their expected mobility benefits were estimated using simulations. Cooperative adaptive cruise control was shown to have a high potential for user acceptance, and when applied at the gap settings chosen by representative drivers from the general public, it could double the capacity of a highway lane at full market penetration. Variable speed limits were shown to have the potential to reduce the adverse impacts of highway bottlenecks by increasing the traffic flow capacity of those bottlenecks if they can be implemented with smooth transitions in the speed limit settings. Automated truck platoon control was shown to be technically feasible using DSRC for vehicle-vehicle coordination, with the potential for significant fuel savings from aerodynamic drag reductions.

1. Introduction

This project was conceived and proposed in early 2007 in order to explore the opportunities that the DSRC wireless communication technology could afford to improve mobility through implementation of several advanced transportation applications. At the time, the U.S. DOT's ITS Joint Program Office was investing heavily in the Vehicle-Infrastructure Integration (VII) initiative to apply DSRC technology to safety applications, but mobility was receiving scant attention. This project aimed to open up some new directions in use of DSRC (and potentially other wireless technologies for vehicle-vehicle (V2V) and vehicle-infrastructure (V2I) coordination) to support mobility improvements.

The measures of effectiveness by which the mobility improvements could be evaluated for highway applications are assumed to include:
   - Traffic flow capacity of the highway
   - Smoothness or stability of traffic flow on the highway (reduction of shock waves)
   - Reduction of travel delays (increase of effective average speed)
   - Reduction of energy consumption (and CO_2 emissions)
   - Reduction of category pollutant emissions.

Subsequent to the start of this project, VII was renamed and broadened to become IntelliDrive, and that name was then discarded in favor of the current general term "connected vehicles". At the most fundamental level, however, the underlying concept is still based on vehicles communicating with each other and with the roadside infrastructure at frequent update intervals (100 ms) so that they can operate as a well-integrated system. The current thinking embraces a wider range of communication technologies than DSRC, and indeed one of the three applications addressed in this project could be implemented just as effectively by use of 3G data modems (although the other two are expected to need DSRC).

This project began as three distinct concept papers, but FHWA encouraged the authors of those papers to integrate them into a single project and proposal. In the course of that integration, we found good synergy between two of the three concepts, such that they could be combined into an integrated system for enhanced benefits and effectiveness. The Concepts of Operations for these systems were described in a previous technical report (1). The three concepts are:

(1) cooperative adaptive cruise control (CACC), in which a conventional adaptive cruise control is combined with V2V communication via DSRC to enable the following vehicle to obtain improved and faster data about the motions of the leading vehicle. With this enhanced data, the CACC can provide more responsive vehicle-following control, which enables drivers to use it at shorter time gap settings. These performance advantages lead to quantifiable benefits in increased highway capacity and reduced traffic flow instability.

(2) variable speed limits/advisories (VSL/VSA), in which drivers and/or their vehicles can be informed about the speed that they should travel in order to maximize the throughput and minimize the delays through a downstream bottleneck. This application can use the vehicles as traffic data probes to provide real-time information about actual speeds all along a highway (V2I data), and after the infrastructure-based intelligence at the transportation management center determines the desirable speed profile, the target set speed for each section of highway can be communicated to the vehicles (I2V data) or displayed on roadside VSL signs.

(3) automated truck platooning, in which heavy-duty trucks are enabled to follow each other automatically at very short gaps by combining V2V status information with the information they collect using forward range sensors. When all the trucks in sequence in a platoon can receive and use the information about the motions of the first truck as their reference, they are able to maintain safe vehicle-following performance at short enough gaps that their aerodynamic drag can be reduced significantly.

The first and third application are expected to need the very low latency and very high availability of the DSRC wireless technology in order to achieve their required performance and reliability, but the middle application has less stringent wireless requirements and could easily be implemented using 3G or 4G cellular data modems.

There is a potential synergy between the first two applications when we expend the definition of the CACC concept to include I2V cooperation as well as V2V cooperation. In this integrated concept, the VSL value selected to maximize bottleneck capacity could be defined as the set speed for the ACC vehicles and communicated to them over the I2V link, and they could then be commanded to follow that speed unless they are forced to go even slower by a slower preceding vehicle.

The results that we obtained for each of the three applications are explained in the subsequent sections of the report, followed by a description of next steps that are already in progress or recommended in order to advance these applications toward deployment.

2. Cooperative Adaptive Cruise Control (CACC)

Detailed descriptions of the design and testing of the CACC system were previously provided in comprehensive technical reports (2, 3) and are not repeated here.   The results of the simulation study of the effects that CACC could have on traffic flow are reported in a separate technical report (4).

The important findings from the CACC design, testing and evaluation work are:

(a) Drivers recruited from the general public as test subjects were previously unaware of the existence of ACC, but after they had the chance to drive the ACC and CACC systems they were very enthusiastic about both systems.

(b) The CACC system using DSRC to augment the data about the lead vehicle from the forward-looking lidar system on the test vehicle was able to provide accurate but also reasonably smooth control of vehicle following.   Although some of the drivers complained about roughness in the car following performance early in the experiment, after the control parameters were adjusted to increase smoothness at the midpoint there were no further complaints about roughness and drivers' use of the system was statistically indistinguishable from before.

(c) When drivers used the standard ACC system on the test vehicle, the time gaps that they selected were fairly similar to the time gaps that they chose when driving manually (without any ACC assistance). The mean time gap chosen with ACC was 1.55 seconds, and when the distribution of time gaps chosen by all the drivers in the experiment was applied in the traffic simulation, the highway lane capacity was virtually indistinguishable from the nominal current highway lane capacity. Throughout the range of ACC market penetrations in the simulation (10% to 100%), the achievable highway lane capacity estimates remained between 2026 and 2093 vehicles per lane per hour.

(d) There was a relatively quick learning process for drivers accustoming themselves to the ACC and CACC systems.   On their first trip, they typically experimented with multiple gap settings, with a tendency toward the longer gaps, but typically by the third trip they settled on the gap selection that they used for the duration of the experiment.

(e) The distribution of the drivers' gap choices while in a car-following mode of driving was as shown in Figure 1. The preference for the short gap settings in CACC is striking, particularly with the male drivers tending to prefer the shortest gap setting of 0.6 s for 77% of the time. The gender distinction was somewhat surprising, but was consistent with the measured difference in car following preferences when driving unaided.

(f) On average, when the drivers were using the CACC system their mean time gap selections were 0.64 or 0.78 seconds (males and females respectively), compared to 1.43 and 1.68 seconds when using the ACC. These both represent 45% of the mean ACC car-following gap settings.
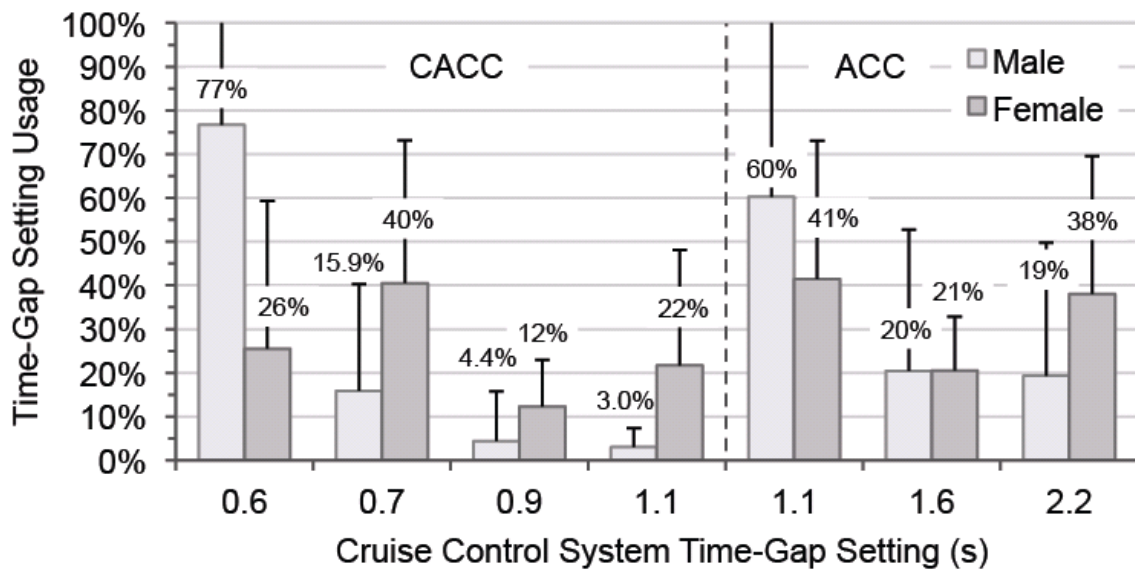

Figure 1 Drivers' Selection of Time-Gap Settings While in Car Following Mode

(g) When the distributions of driver-selected gap settings from Figure 1 were applied in a microscopic traffic simulation, the impacts of ACC and CACC on highway lane capacity could be estimated for different market penetrations of ACC, CACC and "Here I Am" (HIA) vehicles (vehicles that can broadcast their location and velocity but do not control their speed automatically). These results showed a maximum lane capacity of about 4000 vehicles per hour if all vehicles were equipped with CACC. If the vehicle population consists of CACC and HIA vehicles, meaning that all vehicles have been equipped with DSRC radios, the lane capacity increases approximately linearly from 2000 to 4000 as the percentage of CACC vehicles increases from zero to one hundred. On the other hand, if the vehicle population consists of manual and CACC vehicles, without any mandate for non-CACC vehicles to be equipped with DSRC, the increase in lane capacity follows a quadratic profile, lagging significantly behind at the intermediate market penetration values, as seen in Figure 2.
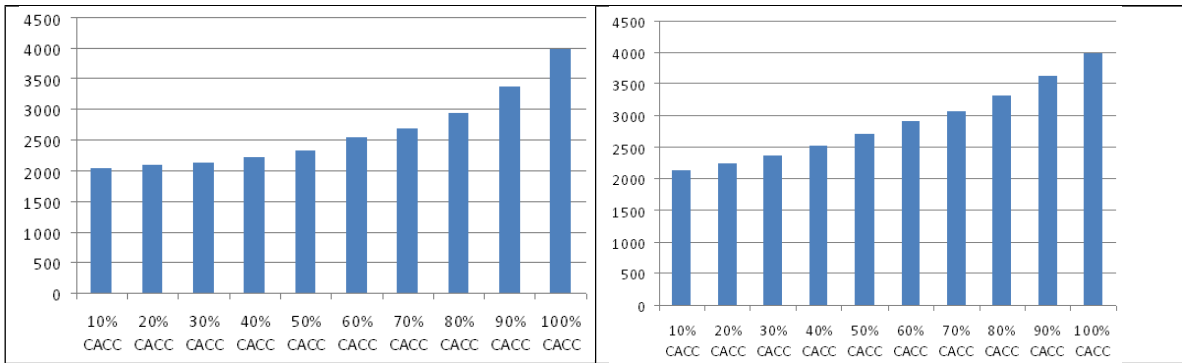
Figure 2 Highway Lane Capacity With Increasing CACC Market Penetration Relative to Manually-Driven Vehicles (Left) or HIA Vehicles (Right)

(h)   When combinations of CACC, ACC, HIA and manually driven vehicles are considered in traffic simulations, the possibilities become considerably more complicated. Looking ahead to a Connected Vehicle environment in which any vehicles equipped with ACC would also have the DSRC radio, and therefore be capable of CACC operations, we can disregard the conventional ACC population as negligible and proceed to the highway lane capacity values shown in Figure 3. On the other hand, if DSRC radios are relatively rare and only installed on vehicles to provide CACC capabilities, the lane capacity values are likely to be as shown in Figure 4.
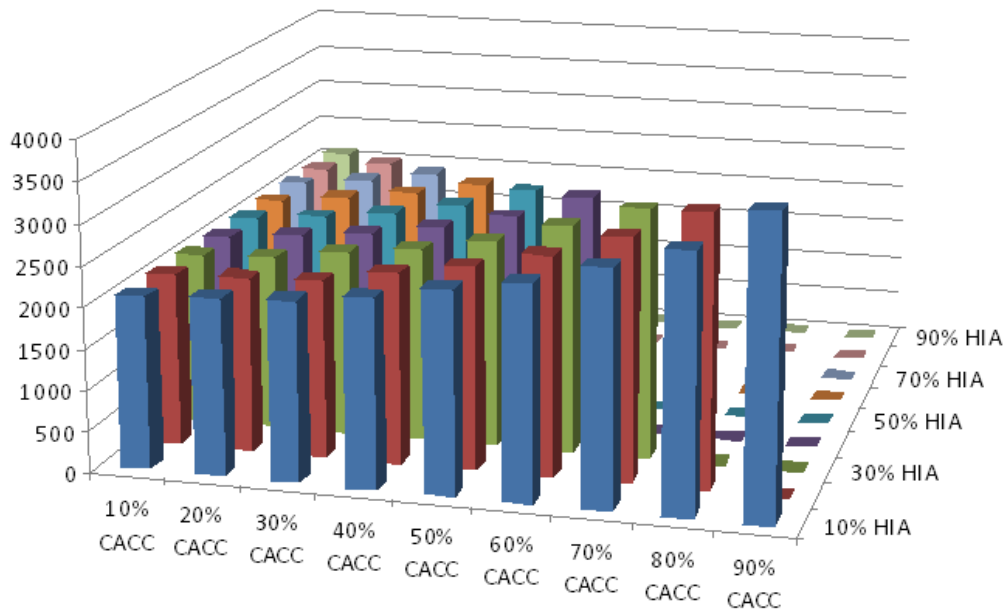

Figure 3 Highway Lane Capacity (vehicles per hour) as a Function of Market Penetration of CACC and HIA Vehicles
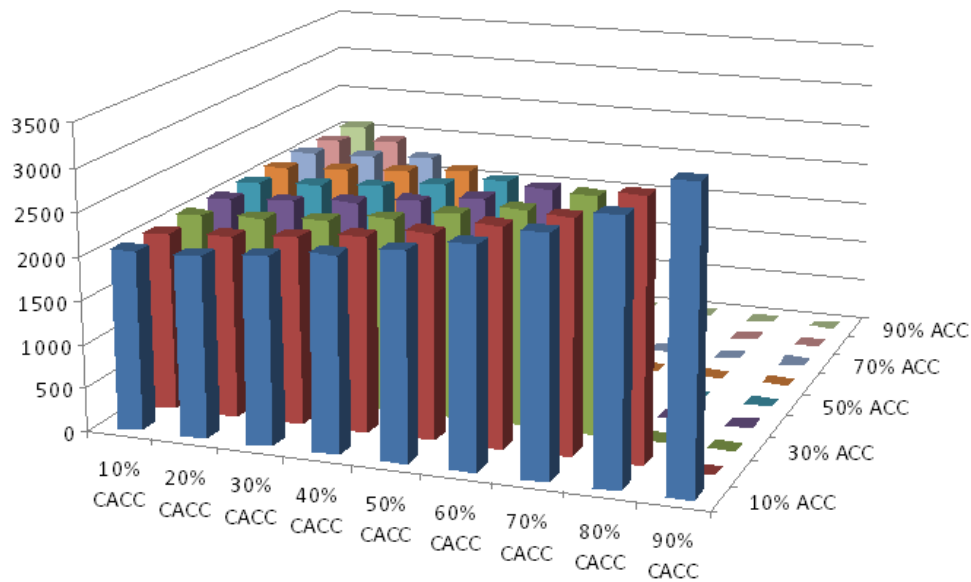
Figure 4 Highway Lane Capacity (vehicles per hour) as a Function of Market Penetration of CACC and ACC Vehicles

(i) The simulation results for highway capacity show the advantages that the introduction of HIA vehicles can have in improving the capacity achievable with CACC vehicles at intermediate levels of market penetration.

3. Variable Speed Limits and Advisories (VSL/VSA)

The basic research on algorithms for selecting variable speed limits to maximize flow through highway bottlenecks has been described in a series of technical papers and an interim report on this project (2). This research has been done using mesoscopic and microscopic traffic simulations since field testing with speed changes for an entire highway section is beyond the scope of the work proposed in this exploratory project. However, a limited-scale field test was done with a single test vehicle receiving the real-time VSL/VSA values over a wireless communication link, described in the new project report (5).

The important findings from the VSL/VSA research are:

(a)   Based on the simulation results, application of a suitable VSL/VSA strategy to gradually reduce speed upstream of a bottleneck should make it possible to avoid or at least delay traffic flow breakdown at the bottleneck by increasing the effective capacity of the bottleneck. The degree of improvement depends on the overall traffic demand relative to the capacity of the bottleneck.

(b) If all vehicles followed the VSL speed on the approach to the bottleneck, it should be possible to increase the capacity of the bottleneck by 5-18%, depending on the road geometry and traffic conditions. This can lead to savings of as much as 10-35% in the

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vehicle-hours of delay in the corridor that is constrained by the bottleneck, again depending on the road geometry and traffic conditions.
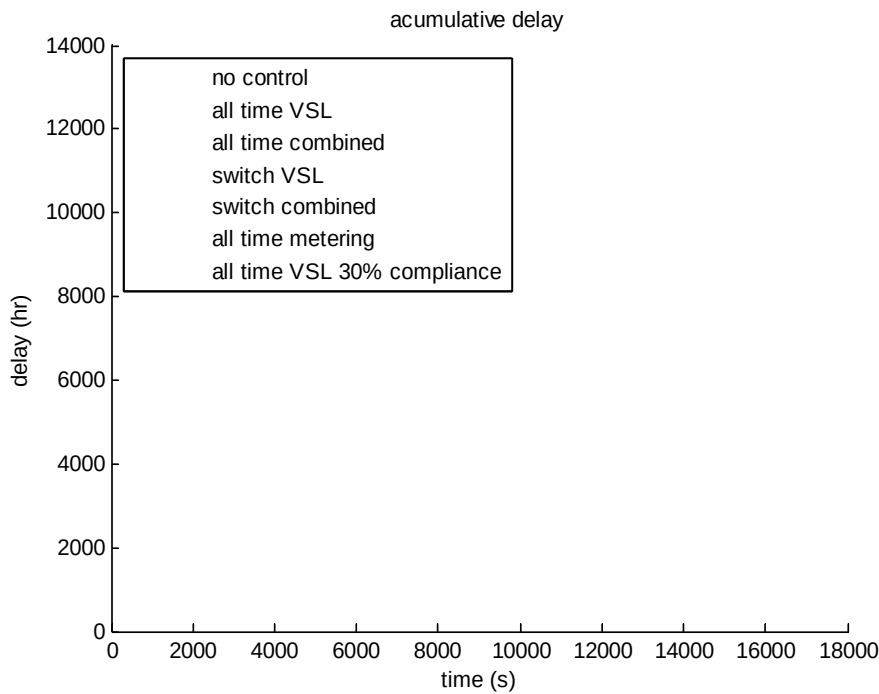

Figure 5 Cumulative Delay Over a Five Hour Period in Simulated I-80 Corridor Under Different Control Strategies

Figure 5 shows an example set of simulation results for the I-80 westbound corridor from Richmond to the Emeryville, CA bottleneck under several control strategies. The highest line on the plot (blue) shows the delay without any control actions, and the yellow line below it shows the effect of full-time ramp metering, which provides a modest reduction in delay. The other, much lower, plots show the much reduced delays associated with several different implementations of the VSL control developed in this project.

(c) Compliance with the VSL speed can be achieved if at least 30% of the vehicles follow the VSL speed. This percentage of speed limited vehicles constrains the ability of the rest of the vehicles to go any faster.

(d) VSL has been evaluated with and without coordinated ramp metering (CRM) in order to understand the relative effectiveness of these alternative strategies in mitigating congestion. On the corridor that was selected for evaluation (I-80 from Richmond to Emeryville, CA), the ramps have such small queue storage capacity that CRM can have only limited effectiveness, so VSL was found to be significantly more effective. CRM was predicted to provide delay reductions of about 23% and total travel time reductions of about 19% from the uncontrolled case, while the various VSL strategies, with and without CRM, provided delay reductions of 61% to 81% and total travel time reductions of 51% to 60% compared to the uncontrolled case.

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(e) Calculation of effective VSL values depends on use of high fidelity traffic condition data. The existing loop detector infrastructure data in the evaluation corridor has significant problems in accuracy and availability, which has necessitated significant effort in data cleaning and massaging in order to make it usable as inputs to the VSL algorithm. With general availability of connected vehicle probe data, these problems should be mitigated.

(f) An in-vehicle display of VSL values was implemented on one of the ACC test vehicles, for use along the I-80 Westbound corridor. As the vehicle traveled along the corridor, it received the VSL values that were computed for the entire corridor, based on existing loop detector data, transmitted from the PATH server where the computations were done over a 3G cellular modem communication link. This demonstrated the technical feasibility of providing the real-time update information to a vehicle, which then decided which VSL value to display to its driver based on its GPS coordinates along the corridor (used to associate the vehicle with the correct network segment).

(g) The VSL displays were provided to 16 drivers recruited from the general public in order to determine their reactions to this new concept. The direct measurements of their reactions were recorded based on the set speeds that they chose for the ACC on the test vehicle, which were then compared with both the recommended VSL values and the prevailing local traffic speeds on the network segment where they were traveling. The drivers were also surveyed to determine their subjective reactions to the VSL information. The results showed general support for the VSL concept, but concerns about some of the limitations of the specific implementation that they experienced. The drivers were also more supportive of a VSL implementation with roadside displays that apply to drivers of all vehicles, rather than an implementation in which only a few drivers receive VSL displays in their vehicles.

(h) The experiment providing the VSL displays to drivers indicated the need to provide a variety of practical refinements to the basic VSL algorithm to make it more suitable for public use, including:
  - filtering to smooth out VSL changes and addition of hysteresis to ensure that the VSL values that any individual driver sees do not oscillate;
  - limitations on the magnitude of speed change from one time interval to the next and from one network segment to the next so that drivers can adjust their speeds relatively smoothly (in increments no larger than 10 mph per step);
  - lower limits, to ensure that drivers are not confronted with freeway speed limits below those that would be posted on major arterials;
  - limitations on the difference between the VSL value displayed to drivers in their vehicles and the prevailing speed of traffic in their section of highway, so that they are not being asked to drive too much slower than their neighbors;
  - addition of explanation for the reason for the reduced speed.

(i) The VSL value that is best for traffic flow can also be provided as the reference speed for an infrastructure-cooperative form of CACC, automatically limiting the speed of the

vehicle to the VSL value. We planned to test this on the segment of the I-80 corridor where continuous video monitoring is available, so that the interactions between the VSL-limited vehicle and its neighbors could be observed through the vehicle trajectories to check for potential problems (such as excessive lane changing by impatient drivers stuck behind the subject vehicle). It was not possible to do this experiment because the location with the continuous video monitoring turned out to be right at the bottleneck rather than upstream of the bottleneck, and in this location the traffic was either free-flowing or severely congested, with virtually no intermediate conditions when the VSL algorithm would be recommending a speed significantly different from the prevailing traffic speed. The survey of the drivers of the test vehicle equipped with the VSL display indicated more support for an operational concept based on the display than one that would automatically determine the CACC set speed.

4. Automated Truck Platoons

The automated truck platoon experiments at highway speed were conducted in September 2010 and May 2011, producing results relatively late in the project period of performance. This meant that there were no prior publications about this aspect of the project, but the results of that truck testing are described in a new technical report (6).

The important findings from the automated truck platoon work are:

(a) The DSRC communication system at 5.9 GHz, with 100 ms update intervals, has sufficient capabilities to support this most demanding of V2V communication applications. Two different generations of DSRC transceivers were used on the test trucks at different times, the Savari Onboard Units (SOBU) and the Denso Wireless Safety Units (WSU). The Denso WSUs have the advantage that they implement more of the IEEE 1609 standards, including diversity, but although they worked well for low-speed testing of the truck-tractors at the Richmond Field Station, they failed to work for high-speed highway testing with 53-ft trailers in central Nevada. This was disappointing because their diversity capability was seen as an important feature in enabling the first and third trucks to maintain line of sight contact under all road conditions, including curves and grade changes.

(b) A platoon of three tractor-trailer trucks was successfully driven under automated longitudinal platoon control, maintaining adequate tolerances on longitudinal gap variations while cruising and maneuvering. On an essentially flat section of road, the rms error in vehicle-following gap was maintained within 0.9 m and the maximum error was maintained within 1.6 m for the second truck following the first while cruising at a steady speed of 85 km/h. The analogous values for the third truck following the second were 1.2 m and 2.1 m.

(c) The truck platoon was tested for a range of target inter-truck following gaps, beginning with 10 m. As the performance at each gap was verified to be satisfactory, shorter gaps were attempted, going as short as a 4 m gap by the end of the testing period.

These results show the basic technical feasibility of closely-coordinated longitudinal control of heavy trucks in a platoon, maintaining short gaps using the combination of DSRC radio communications and radar and lidar ranging sensors.

(d) The DSRC radios were also used to coordinate maneuvers among the trucks, with a particular focus on platoon joining and splitting maneuvers. These maneuvers were performed in different combinations, simultaneously and sequentially for the joins and splits between the first and second and the second and third trucks. The sequential maneuvers are to be preferred for future implementations because the simultaneous maneuvers require significantly larger speed changes by the third truck. The platoon joining from a 14 m gap to a 10 m gap required 35 seconds of transition time, and the splitting from 10 m to 14 m gap required 25 seconds of transition time.

(e) The trucks were also maneuvered through a sequence of speed profile changes to test the ability of the following trucks to follow the leader. The rate of speed changes for these maneuvers had to be limited because of the fundamental power limitations of the trucks. The speed change tests showed that the second truck followed the first with an effective lag of 0.8 seconds, and the third truck followed with an effective lag of 1.2 seconds relative to the first. The rms errors in gap and speed between the trucks throughout the speed change tests were 0.2 m and 0.01 m/s (average) and 0.57 m/s (max) between the first and second trucks and 0.25 m and 0.07 m/s (average) and 0.65 m/s (max) between the second and third trucks.

(f) One of the largest potential benefits from truck platooning is the saving of energy and CO_2 emissions based on reductions in aerodynamic drag. The direct fuel consumption of the trucks was monitored throughout the testing through their engine controllers' fuel injection systems, and the trends in fuel consumption were studied to provide initial estimates of the benefits that could be gained. These measurements are difficult to control carefully because of the strong influence of wind conditions on the drag. Although the September 2010 tests were conducted under calm winds, the May 2011 tests suffered from strong wind conditions, and the tight schedule compelled the project team to use all available time for testing, including the strong wind times, which produced noisier results than we would have preferred.

All the trucks in the platoon save fuel when they are driven at close spacing within the platoon. The lead truck saves less than the followers save, and there is some inconsistency in the results regarding the savings by the second and third trucks. Nevertheless, we should expect the first truck in a platoon at 6 m gaps to be able to save 4 to 5% of its normal fuel consumption in steady cruising on flat roads at 85 km/h, with the following trucks saving 10 to 15%. Because these results were measured at an altitude of 6000 ft. (1800 m), where the air density is only 80% of that at sea level, the relative savings at sea level should be more significant since the total aerodynamic drag should be about 25% higher than it was at the high-altitude test site (while the other losses would be unchanged).

When we consider that many long-distance trucks in the U.S. cruise at speeds around 115 km/h (71 mph) rather than the 85 km/h speed of these tests, their aerodynamic drag could be 80% higher than we measured since the drag increases with the square of the speed. Combining this effect with the altitude effect, the typical aerodynamic drag experienced by trucks operating in long-distance revenue service could be twice as high as it was in our tests. Following the rule of thumb that aerodynamic drag accounts for about half of fuel consumption of trucks at highway speed, this implies that the fuel savings that would be experienced in practice could be 50% higher than what we measured in these tests.

These results show strong enough potential fuel savings to justify significantly more attention to truck platooning in the future, as we become increasingly concerned about how to reduce consumption of petroleum-based fuels.

(g) A limited fault detection and identification system was implemented on the experimental trucks to provide visible indicators to the truck driver and the researcher observing from the passenger seat about the status of the truck control system, so that they would be made aware of potential problems as soon as possible. This was found to be particularly important and useful for faults on one truck that may not otherwise be apparent to people traveling in another truck with which it is closely coupled.

5. <u>Next Steps to Lead Toward Deployment</u>

As an Exploratory Advanced Research Project, this project was not necessarily expected to lead directly to deployment of its results, but rather to additional application refinements in further research and development efforts to point toward deployment. Some progress has already been made in developing the next generation of R&D projects to follow on from this project, but more work is needed in each of the application areas.

5.1 Cooperative Adaptive Cruise Control

During the project reported here, Nissan Motor Company Ltd. provided the test vehicles, with the original ACC system, as well as considerable engineering support to assist in the implementation of the CACC system built around the original ACC. After they had the opportunity to test drive the CACC system they became convinced of its potential for further development and initiated a company-funded project to develop a second generation CACC based on the PATH system tested in this project. Nissan has built four new test vehicles with the second-generation CACC, and have tested it together with PATH at their Arizona Test Center.

Nissan has outlined a multi-year R&D plan to refine the CACC and address the technical issues that could not be covered in the current project. These include incorporation of enhanced positioning capability so that the CACC vehicle can distinguish potential lead vehicles in its own lane from those in adjacent lanes, to make sure that it is "listening to"

the same vehicle that its forward sensor is "seeing", ensuring string stability with sequences of multiple CACC and ACC vehicles, and handling emergency stop situations at short time gaps. Nissan is also supporting simulation studies of the interactions between equipped and unequipped vehicles in various traffic scenarios, to make sure that the CACC impacts on traffic will be favorable rather than unfavorable.

Additional work will be needed, with public support, for field testing the newer generation CACC vehicles and systems with naïve drivers from the general public. The later work will also need to incorporate vehicles from multiple manufacturers, with diverse performance characteristics, in order to ensure that the traffic impacts remain favorable with different combinations of vehicle performance. This work should lead to definition of minimum performance requirements that vehicles must meet in order to be considered "CACC compatible".

It is worth noting that CACC is one of the applications chosen for inclusion in the "INFLO" (Intelligent Network Flow Optimization) project of the Dynamic Mobility Applications program under the Connected Vehicle initiative of the U.S. DOT, but this work is still at a very early stage, with the development of the Concept of Operations planned for a project that is likely to extend from mid 2011 to mid 2012.

5.2 Variable Speed Limits/Advisories

Caltrans is in the process of approving a new PATH project that will prepare the way for public field testing of VSL/VSA real-time displays on roadside portable variable message signs along a freeway corridor (to be chosen) in the San Francisco Bay Area. Because of funding resource limitations, this field testing work is being spread out over a four-year period even though it would be more logical for it to be completed within two years. The first year of work involves selection of the field test site, identification of equipment needed to implement the field test, and refinement of the VSL/VSA algorithms for implementation in a real-world setting with many practical constraints.

Because the VSL/VSA concept is new and unfamiliar in the U.S., considerable outreach work is going to be needed to build understanding among the general public and the law enforcement community. In particular, it is going to be necessary to find the most effective ways of communicating to non-specialists about the benefits that should be expected from implementation of VSL/VSA systems so that they will be more likely to accept it. There are genuine concerns about how to handle enforcement of VSL when the legal speed is changeable over time and location – how can the law enforcement officers and the drivers know with certainty what the legal speed limit is (and was) at any specific time and place?

There is interest in VSL/VSA opportunities at the federal level, with the Active Transportation and Demand Management program and its element on Active Traffic Management. Similarly, VSL is one of the components of the emerging INFLO project

under the Dynamic Mobility Applications program, but this is only starting on the definition of the Concept of Operations within the next year.

5.3 Automated Truck Platooning

This element of the project does not yet have any direct follow-on activity visible. Although there are substantial efforts on development and testing of automated truck platoons in Japan (Energy ITS Project) and Europe (SARTRE Project), this concept has not yet caught hold in the U.S. That is particularly ironic since there is active consideration of development of dedicated truck lanes at several sites around the U.S., while the overseas countries have had a much harder time conceiving how they could develop such facilities. Dedicated truck lanes are an important, and possibly essential, pre-requisite to automated truck platoon operations, so that linkage needs to be explored further.

Based on the results of this study, the energy savings from truck platooning are potentially so large that a more extensive test program is urgently needed to quantify the realistically achievable fuel savings under a variety of conditions, including a full range of truck speeds, loading conditions, and trailer configurations. The results of that test program could provide the authoritative data needed to convince the broader stakeholder community that the economic benefits from these energy savings are large enough to justify the up-front investments needed to transition automated truck platooning from a research curiosity to commercial reality.

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