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Deployment Path Analysis for Cooperative ITS Systems

Task 3 Report on
Development and Evaluation of Selected Mobility Applications for VII
FHWA Exploratory Advanced Research Program

Steven E. Shladover

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Abstract

Although the performance advantages of cooperative ITS systems are generally appreciated, the deployment challenges that they pose represent a significant impediment. This report begins with a summary of the types of deployment challenges faced by cooperative information systems and cooperative vehicle-highway automation systems (CVHAS), both of which require coordination of deployment of vehicle and infrastructure-based elements. The institutional challenges are discussed first, followed by the technological challenges. In each case, current progress in overcoming these challenges is reviewed and the additional needed steps are suggested. Considerable attention is devoted to showing the range of enabling technologies that are already available on passenger cars in the U.S.

Key Words: vehicle-infrastructure integration, VII, cooperative vehicle-highway automation systems (CVHAS), progressive deployment strategies, enabling technologies for vehicle automation

Executive Summary

It has long been recognized that cooperative ITS systems (based on vehicle-vehicle and/or vehicle-infrastructure cooperation) have significant performance advantages over autonomous systems. However, they also face substantially more serious deployment challenges because of their institutional complexity and the need for well-defined technical standards to ensure interoperability. The advent of the Vehicle-Infrastructure Integration (VII) initiative has provided a large boost to cooperative systems by stimulating intensive collaborative efforts by the vehicle industry and transportation infrastructure agencies to address both of these types of deployment challenges. This provides a good foundation for re-opening consideration of a range of cooperative system concepts that can contribute to improving mobility as well as safety.

Cooperative vehicle-highway automation systems (CVHAS) make use of vehicle-vehicle and vehicle-infrastructure cooperation to support automated driving functionality. These face an additional set of deployment challenges associated with the change in driver roles and the assumption by the system of full responsibility for driving. Both sets of deployment challenges are considered, divided into institutional and technological categories.

Deployment of vehicle-infrastructure cooperative systems faces some inherent challenges because of the division of responsibility for vehicles and infrastructure in most of the U.S. road transportation system. When the applications extend beyond information systems and services to include CVHAS, additional institutional challenges arise, including concerns about liability, the need for dedicated lanes and uncertainties about user acceptance.

The VII initiative is successfully addressing the primary technological challenges to deployment of cooperative information systems, based on development of DSRC standards and development and testing of the DSRC communication hardware and software under a range of operating conditions. This technology is expected to serve both V2V and V2I2V communication needs. Adding CVHAS capabilities introduces an additional set of technological challenges that have not been entirely met yet.

The VII initiative has stimulated closer interactions between the automotive industry and public-sector transportation agencies than virtually any previous activities. Some progress has been made on breaking down the barriers between the public and private sector stakeholders, and communication and mutual understanding have improved, particularly with regard to the issues associated with communication of information between vehicles and the infrastructure. Thorny issues such as data ownership and business models for supporting deployment, operation and maintenance costs remain to be resolved.

The VII initiative has not been addressing the additional issues associated with CVHAS deployment, but there has been continuing progress on these through other channels, in areas such as:

- operation of automatically steered buses
- consideration of dedicated truck lanes, where automation could be applied
- renewed interest in thinking about automation of private cars.

The U.S. DOT and its partners in the VII initiative have been investing substantial resources in recent years to develop and test DSRC for V2V and V2I2V communications. This has led to significant progress on the wireless technology and the protocols for implementing it at several levels, exemplified in the IEEE 802.11p, IEEE 1609.x and SAE J2735 standards. As these standards mature and radios that conform to them are built and tested by a variety of suppliers, the foundation for high-performance cooperative information systems will become well established. In addition, as the VII initiative has broadened its scope to encompass communication technologies other than DSRC and applications beyond automotive OEM systems (aftermarket and retrofit automotive systems, as well as systems for transit buses and trucks), cooperative vehicle information system capabilities should be expected to advance on a wider front.

The wireless communication requirements for CVHAS are more demanding in terms of latency and reliability than for other ITS services. However, DSRC should be able to satisfy these requirements if it performs according to expectations. One of the main anticipated outcomes of the current research project is verification of the ability of DSRC to support close-formation automated platoon control of vehicles. If that is accomplished successfully, it will be a large step towards removing wireless communications from the list of enabling technologies that need to be improved in order to support CVHAS.

Other enabling technologies for CVHAS have advanced significantly in the ten years since the NAHSC Demo '97, leaving a much smaller gap between current state of the art vehicles and AHS vehicles than we saw at that time. The capabilities of the automobiles currently on the market in the U.S. have been reviewed, based on the information on the vehicle manufacturers' web sites in the spring of 2008, to give an indication of the current market availability of the following enabling technologies:

- brake actuation (and related braking systems such as ABS and yaw stability control systems)
- electronic throttle control
- electronic steering actuation
- electronic transmission shifting
- blind spot/lane change warning systems
- lane departure warning and lane keeping assistance
- automatic steering for parallel parking
- adaptive cruise control (ACC) and enhancements (full speed range ACC, forward collision warning).

Although modern high-end cars already include most of the enabling technologies needed for CVHAS, they do not include all of them. The key technologies that are still not commercially available are:

- highly accurate and reliable absolute positioning
- highly accurate and reliable lane position referencing and lane detection
- detection, warning and avoidance of hazardous obstacles (other than vehicles)
- comprehensive fault detection, identification and management.

Our previous exploration of strategies for overcoming the "chicken and egg" deployment problem for CVHAS was in the period of 1999-2000, when we identified the importance of starting with transit buses and heavy trucks. That work led to the creation of the "Demo 2003" project, in which we actually implemented automated driving of buses and trucks to learn about the technical challenges involved and to solve them. All of that work preceded the current VII initiative, as well as most of the technological improvements that are now becoming available on passenger cars, so it was revisited and updated based on more recent developments. This led to consideration of the following deployment staging sequence:

1. Conduct site-specific deployment case studies to identify the range of locales that could achieve significant benefits from CVHAS technologies, providing the market scale knowledge needed to motivate investments in commercialization.

2. Apply automatic steering and precision docking to BRT buses operating on dedicated busways, with possible addition of platooning where capacity is needed.
3. Apply platooning to heavy trucks on dedicated truck lanes, with particular emphasis on its energy saving potential through drag reduction.
4. Address the extension to light duty vehicles through hybrid propulsion vehicles (which already have most of the needed electronic actuation capabilities) applied to vanpool services in managed lanes.
5. Capitalize on continuing advances in advanced driver assistance systems and the cost reductions that are likely as their market penetration advances (along with hybrid propulsion).

1. Introduction – Deployment Challenges for Cooperative Systems (and Cooperative Vehicle-Highway Automation Systems in Particular)

It has long been recognized that cooperative ITS systems (based on vehicle-vehicle and/or vehicle-infrastructure cooperation) have significant performance advantages over autonomous systems. However, they also face substantially more serious deployment challenges because of their institutional complexity and the need for well-defined technical standards to ensure interoperability. The advent of the Vehicle-Infrastructure Integration (VII) initiative has provided a large boost to cooperative systems by stimulating intensive collaborative efforts by the vehicle industry and transportation infrastructure agencies to address both of these types of deployment challenges. This provides a good foundation for re-opening consideration of a range of cooperative system concepts that can contribute to improving mobility as well as safety.

Cooperative vehicle-highway automation systems (CVHAS) make use of vehicle-vehicle and vehicle-infrastructure cooperation to support automated driving functionality. These face an additional set of deployment challenges associated with the change in driver roles and the assumption by the system of full responsibility for driving. Both sets of deployment challenges are discussed here, divided into institutional and technological categories.

Throughout this report, the shorthand terminology V2V is used to represent vehicle-vehicle cooperation, and V2I, I2V or V2I2V to represent a range of vehicle-infrastructure cooperation concepts.

1.1 Institutional Challenges

Deployment of vehicle-infrastructure cooperative systems faces some inherent challenges because of the division of responsibility for vehicles and infrastructure in most of the U.S. road transportation system:

- public sector infrastructure operators and private sector vehicle developers have not worked together much and do not understand each other's perspectives very well
  - different priorities (public good and private profit)
  - different decision processes and time scales
  - different perceptions of risks
  - different attitudes towards applications of technology
- federal government (USDOT) does not have direct decision making responsibility for infrastructure deployment and operations
  - road transportation infrastructure responsibilities are divided among three levels of government (state, county and municipal), with substantially differing perspectives and capabilities

    - different regions, with different socio-economic status, have significantly different propensities to adopt new transportation infrastructure technologies
- business models do not yet exist to support the deployment, operation and maintenance of roadside cooperative infrastructure
- public infrastructure systems are designed for functional lifetimes of decades, while vehicles are designed to last for years and modern information technology systems only for months before they are deemed obsolescent
- privacy advocates express concerns about potential misuse of data communicated from private vehicles
- liability could be allocated among many stakeholders, in uncertain combinations, when something bad happens
- there is no political consensus about the appropriateness of law enforcement applications of the data that are generated and communicated.

When the applications extend beyond information systems and services to include CVHAS, additional institutional challenges arise:

- liability concerns are amplified when the driver no longer has responsibility for control of the vehicle motions
- dedicated lanes are needed to ensure safety, raising additional issues about construction costs, availability of right of way, and environmental impacts
- user acceptance uncertainties arise, considering the diversity of public opinions about transferring control from the driver to an automated system
- although passenger car applications will have the largest impact on the transportation system as a whole, they are likely to be slower and more difficult to implement than applications for transit buses and heavy trucks.

The current progress on these issues and the trends toward future progress will be addressed in Section 2 of this report.

1.2 Technological Challenges

The VII initiative is successfully addressing the primary technological challenges to deployment of cooperative information systems, based on development of DSRC standards and development and testing of the DSRC communication hardware and software under a range of operating conditions. This technology is expected to serve both V2V and V2I2V communication needs.

Adding CVHAS capabilities introduces an additional set of technological challenges that have not been entirely met yet:

- electronic actuation of driving functions (steering, engine, transmission, brake)
- sensors to accurately and reliably detect range and closing rate to other vehicles and to lane boundaries

- robust vehicle absolute positioning technologies and high accuracy digital maps
- obstacle detection, warning and avoidance
- robust information processing systems, including fault detection, identification and accommodation
- safety critical software systems
- systems to manage the transitions between automated and manual driving (check-in and check-out).

The current progress on these issues and the trends toward future progress will be addressed in Section 3 of this report.

2. Institutional Issues – Current Progress and Projected Trends

For Cooperative Information Systems

The VII initiative has stimulated closer interactions between the automotive industry and public-sector transportation agencies than virtually any previous activities. The U.S. DOT, ten state DOTs (under the auspices of AASHTO) and a couple of regional agencies have been working together with the automotive OEMs on guiding VII. Some progress has been made on breaking down the barriers between the public and private sector stakeholders, and communication and mutual understanding have improved, particularly with regard to the issues associated with communication of information between vehicles and the infrastructure.

Not all of the problems associated with cooperative information transfer have been resolved. Thorny issues such as data ownership and business models for supporting deployment, operation and maintenance costs remain to be resolved. Assuming that there will be continuing support for the VII concept among the relevant stakeholders and there will be a reasonable level of federal commitment of resources to continue the development work (both technical and institutional) there is good reason to expect continuing progress on these remaining issues. Ultimately, there will have to be a political decision about who pays how much and under what conditions, but this will not be addressed until a new Congress and Administration are in place in Washington DC.

The general U.S. hostility to public sector expenditures makes it more difficult to develop cooperative infrastructure in the U.S. than in other countries that have stronger support for infrastructure investments. U.S. taxpayers tend to view infrastructure investments as expenses rather than as investments in the future, and the political system accordingly seeks to minimize the amount of money spent on that. In contrast, military equipment is generally viewed as more of an investment, and the economic stimulus value of money spent on military equipment procurements and facilities helps to provide more robust political support for those types of public investments. In Japan, on the other hand, transportation infrastructure and other public works are viewed as economic investments, and therefore they receive stronger political support. Although it is difficult to make direct comparisons, it appears that the annual investments in construction, operations and maintenance per mile of roadway infrastructure in Japan by all levels of government are between 300% and 500% of the analogous investments by all levels of government in the U.S. This difference makes it possible for Japan to develop cooperative systems with much more costly infrastructure elements than the U.S. could consider. In addition, Japanese government ministries in Tokyo can make decisions about nationwide deployment of a technology, which the U.S. DOT cannot do because of the distributed decision making in the U.S. form of government.

<u>For Cooperative Vehicle-Highway Automation Systems</u>

The VII initiative has not been addressing the additional issues associated with CVHAS deployment, but there has been continuing progress on these through other channels, as discussed in the balance of this section.

2.2.1 Operation of automatically steered buses

Automatically steered transit buses are likely to be one of the earliest precursors to CVHAS for a variety of technical, institutional and financial reasons [1]. Buses are generally the costliest vehicles on the road, with the highest hourly operating costs and most intensive utilization. This means that technologies or strategies that can improve their operational efficiency can be very attractive economically. For purposes of cooperative system deployment, they have the added advantage that a single organization (the transit agency) is often responsible for both vehicle and infrastructure ownership and operation, so they can make the deployment decision themselves. Since urban transit buses repeatedly drive the same routes on a relatively limited fraction of the total road network, large benefits can be gained by equipping only that small fraction of the roadway infrastructure. The nature of the transit industry is such that a few key “opinion leader” agencies could be the pioneers to implement a new system, and the rest of the industry would then follow their lead (assuming they have a favorable outcome). It is likely to be easier and faster to implement CVHAS technologies on transit buses than on other categories of road vehicles because they already have electronic engine controls and in-vehicle data buses and they are custom-built to buyers’ specifications rather than being mass produced. Finally, they have professional driving and maintenance staff who can be trained to deal with any idiosyncracies of a new system before it is fully mature.

There is a strong synergy between this technological innovation and the growing interest in Bus Rapid Transit (BRT) throughout much of the world. BRT enables buses to provide a quality of transit service that is normally only possible with much more expensive rail transit systems, by operating the buses in a more rail-like manner. This typically involves some separation of the bus running way from the rest of the vehicular traffic, longer separations between stations, pre-payment of fares before boarding, signal priority to reduce delays at traffic signals, and real-time information for passengers and system operators. Additional BRT features enabled by CVHAS include precision docking at bus stations for enhanced ease and speed of boarding and alighting, automatic steering control to enable operations in narrower rights of way, and automatic speed and spacing control to enable higher throughput, better schedule coordination and adherence, smoother ride quality and reduced energy use and emissions.

Precision docking has already been implemented in a few European applications and was attempted in Las Vegas a few years ago, but without success because of some limitations of the specific technological approach for use in that environment. Interest in the precision docking capability remains high because of its potential for facilitating boarding and alighting when a bus can approach a loading platform with no vertical gap between the bus floor and platform and a very small horizontal gap. This makes it easy and fast for passengers to board and alight the bus, especially if wheelchair passengers can be accommodated without the need to deploy a special ramp. PATH has recently tested precision docking using an experimental bus approaching bus stops along an AC Transit route in Oakland and San Leandro, CA, and expects to implement it for field operational testing on a revenue service bus (carrying passengers) in Eugene, OR under the FTA's Vehicle Assist and Automation (VAA) program in 2010.

Automatic steering of buses to enable them to use narrow lanes was implemented on a prototype basis in Eindhoven, NL and for an international exposition in Nagoya, Japan, and has been tested on test tracks by several research groups. This is attractive to transit agencies because of the possibility to provide BRT service in a dedicated busway lane that is narrower than standard lane width. Such a narrow lane could match the width of former railroad rights of way and could fit into high-density urban locations where it would not be politically, economically or environmentally feasible to acquire a wider right of way for a busway [2]. PATH will be testing this capability on revenue service buses in Eugene, OR and Oakland, CA under the VAA program during 2010.

2.2.2 Operation of heavy trucks in dedicated truck lanes

Following the buses, the next most likely precursor to full CVHAS capabilities is likely to be heavy trucks operating in close-formation automated platoons to reduce aerodynamic drag and increase lane capacity [3]. PATH experiments have already shown through direct fuel consumption measurements that operation of tractor-trailer trucks in close-formation automated platoons can produce significant fuel savings (in the range of 10% to 15% at highway speeds) [4]. In these times of unprecedented high energy costs, these savings can be a powerful motivator for adoption of truck platooning. Heavy trucks have considerable similarities to transit buses, both technically and institutionally, and share many of their attributes that are favorable for early CVHAS deployment. They are produced in much larger volumes than buses, but the large truck fleets are sufficiently influential with the truck manufacturers that they could stimulate production of trucks with new features to meet their needs.

The cooperative infrastructure issues are somewhat more difficult for trucks than for buses, however interest has been growing around the U.S. in the concept of dedicated truck-only lanes on major Interstate highways with high concentrations of truck traffic.

These highways are regularly experiencing heavy congestion because of traffic volumes exceeding capacity, and truck traffic is growing at a faster rate than passenger car traffic. Expansions to the highway infrastructure will be needed in one form or another. Accomplishing the expansion with truck-only lanes provides the added advantages of separating the trucks from the cars to improve the safety of both, reducing performance problems associated with incompatibilities of vehicle performance, and enabling pavements and structures to be optimized for construction and maintenance cost savings by designing them to serve separate classes of vehicles (either heavy vehicles or light vehicles). The Reason Foundation proposed a network of dedicated truck tollways around the country in a widely-publicized study [5] and Missouri DOT has recently studied the dedicated truck lane concept for a contemplated expansion of I-70 across the width of the state [6]. Virginia has been considering adding dedicated truck lanes for I-81, with its high percentage of truck traffic, the Trans-Texas Corridors project would include dedicated truck lanes, and Nevada DOT is starting a study of the possibilities for automation of trucks along I-80.

PATH has already done a case study of dedicated automated truck lanes within the Chicago metropolitan area [2, 7] showing how the automated platooning of trucks and the development of dedicated truck lanes on former rail rights of way complement each other to produce a more economically attractive solution when the deployment of the cooperative automation technology is scheduled at the "right" time. Caltrans also sponsored a consultant study that showed how electronic coupling of heavy trucks into platoons of three (thereby doubling the effective capacity per lane compared to operating the trucks individually) could save one lane in each direction on a proposed new truckway along the SR-60 freeway in the Los Angeles area, dramatically reducing its construction cost [8].

The CHAUFFEUR project in Europe developed and tested several concepts for truck automation, with varying levels of automation of the driving function, ranging from control assistance such as ACC or lane keeping assistance up to complete automation of two trucks following a manually-driven leader using an "electronic towbar" [9]. The electronic towbar concept was originally defined for use in mixed traffic on regular highways, and the 1999 public demonstration of a two-truck consist (automated follower behind manually-driven leader) was conducted on a public autobahn, albeit with a police escort. However, further study by the CHAUFFEUR project team led to the decision that the fully automated driving of the followers should only be done on a dedicated lane facility, segregated from normal passenger cars [10]. The traffic simulation studies indicated significant difficulties with maneuvering long truck platoons through other vehicle traffic except under the lightest volume traffic conditions.

CHAUFFEUR was succeeded by a couple of other European projects on truck automation technology, called PEIT (Powertrain Equipped with Intelligent Technologies) and SPARC (Secure Propulsion using Advanced Redundant Control), which especially advanced the technology for drive by wire actuation on trucks [11, 12]. Daimler-Benz (later DaimlerChrysler, then Daimler) corporate management eventually decided to retreat to less ambitious concepts for improving truck technology after the completion of

SPARC in 2007, declining to pursue further work in this direction. However, work on truck automation for dedicated truck lanes is continuing in both Europe and Japan. The Konvoi project, sponsored by the German ministries for research and economics, is developing and testing “convoy driving” of trucks under automatic control, including tests of driver behavior in a driving simulator and full consideration of the institutional and legal issues to be addressed in order to deploy automated truck convoys on public highways in Germany [13, 14].

A section of the new Tomei Expressway to be built in Central Japan will be the site of tests and demonstrations of truck automation before that highway is opened to public traffic. These developments are not yet documented in publicly available references, but should be presented at the 2008 ITS World Congress in New York.

2.2.3 Acceptance of Automated Driving

One of the primary uncertainties about the deployability of automated driving systems has been doubts about its acceptance by drivers (professional bus and truck drivers as well as the general public automobile drivers). Since the automotive press and industry executives tend to view the automobile as more of a plaything than a utilitarian means of transportation, they express exaggerated concerns about “loss of control” and denying drivers the “fun of driving”, representing the perspective of the specialized “automotive enthusiast” market segment. However, the experience from the NAHSC Demo ’97 demonstration of automated highway system concepts tended to contradict this perspective, although this is not generally well remembered.

During the preparations for Demo ’97, Buick scheduled a major media event to attract attention to the Demo, the NAHSC and its automotive brand. That event attracted strong participation from the automotive press and led to publication of many stories about AHS, which were virtually all strongly favorable despite the “enthusiast” proclivities of the journalists who attended. The participants in Demo ’97 who took rides in the demonstration automated vehicles were all surveyed about their attitudes toward automated driving at the end of their rides. These survey results (from one of the very rare population samples who have actually experienced automated driving) were overwhelmingly positive, as documented in [15].

Since the time of Demo ’97, automated driving has been out of fashion and has received little media attention until the recent DARPA challenges for unmanned ground vehicles. However, interest has been growing gradually within the professional community. Senior managers from General Motors have been widely quoted in statements in favor of automated driving within the past year. An international workshop on Transportation in the Year 2030 held in February 2008 with representatives from major international automotive OEMs and suppliers, in addition to academic researchers, led to a conclusion that automated driving of vehicles in dedicated lanes would be an important element of the transportation system in the industrialized world by 2030 [16]. Even more recently, a Harris Interactive survey of the vehicle technology interests of potential car buyers showed that 35% of male drivers and 27% of female drivers were interested in automated driving (only 6-7% lower than the numbers who were interested in Adaptive Cruise Control) [17]. Considering that automated driving does not yet even have a market identity or name, this is a remarkably favorable finding, which provides a good starting point for future growth and encouragement.

Perspectives about automated driving of cars have advanced to the point that it is now acceptable to discuss the possibility of updating the Vienna Convention on Road Traffic [18], which governs international harmonization of traffic laws, to accommodate vehicle automation. Article 8, Paragraph 1 states that “Every moving vehicle or combination of vehicles shall have a driver” and Paragraph 5 states that “Every driver shall at all times be able to control his vehicle or to guide his animals”. Fully automated driving could require relaxation of these restrictions, particularly for use during extended periods when the driver could not be expected to remain fully engaged in the driving process.

Passenger cars are clearly the largest and most important sector of the road vehicle population, and automated driving of passenger cars will produce much larger transportation benefits than automation of buses or trucks. However, this is also the most difficult sector to automate because of the price sensitivity of the customers, the relatively low vehicle utilization rate producing a long payback period for any incremental investment and the inapplicability of cost-benefit analysis in the purchasing decision. For all of these reasons, it will probably be necessary to achieve success with buses and trucks before it becomes possible to introduce automated driving of passenger cars.

2.2.4 Liability

It is impossible to talk about automated driving without addressing the subject of liability, and who is responsible when something goes wrong and a crash occurs. When I gave a keynote speech at the IEEE Intelligent Vehicles 2008 Symposium in Eindhoven, the Netherlands in June 2008 I asked the audience to express their opinions about several key strategic questions. One of those questions was: “What do you expect to be the primary obstacle to commercialization of automated driving systems?” and the multiple-choice answers were: 1. technological feasibility; 2. cost; 3. liability; and 4. customer acceptance/market demand. The vast majority of the audience of researchers chose liability as the primary obstacle.

The liability issue was addressed by the NAHSC in a workshop that was held with a variety of experts on the topic, including automotive industry legal staff, in Washington DC in February 1997, but unfortunately not well documented. At this workshop, it was made evident that liability is an ongoing issue for the automotive industry and is not unique to automated driving. There are well-established approaches for incorporating an estimate of liability exposure into the vehicle price so that the automotive company can protect itself. At the same time, the consumer (automobile driver) is already paying a large amount of money for liability protection in the form of automobile insurance premiums. These premiums are based on the estimated risk that the driver will be responsible for a crash (since drivers are responsible for the large majority of the crashes that occur now). The key change with AHS is that if the driver is not responsible for driving and for the crashes, but the vehicle supplier is responsible, the personal automotive insurance premiums should go down and the price of the vehicles should go up by amounts commensurate with the change in liability exposure. If the automated vehicles are indeed safer, as they should be if well designed, the amount by which the prices of the vehicles increase will be less than the amount by which the insurance premiums decrease, and everybody should be better off. They key challenge is therefore making sure that the automated system is indeed safer than today's driving.

Considering that the NAHSC workshop was ten years ago and that its findings are not widely known or understood, it will probably be necessary to engage in an analogous activity again in order to disseminate knowledge of the issue and address the liability concerns that are still prominent in people's minds.

Liability is a more acute concern in the U.S. than in most other countries because of our more litigious society, but it remains a concern everywhere. Automotive companies are much more likely to introduce new features that have safety implications in other countries before they bring them to the U.S., because the U.S. is considered to have the most hostile product liability environment based on its legal precedents.

3. Technological Issues – Current Progress and Projected Trends

Cooperative Information System Technologies

The U.S. DOT and its partners in the VII initiative have been investing substantial resources in recent years to develop and test DSRC for V2V and V2I2V communications. This has led to significant progress on the wireless technology and the protocols for implementing it at several levels, exemplified in the IEEE 802.11p, IEEE 1609.x and SAE J2735 standards. As these standards mature and radios that conform to them are built and tested by a variety of suppliers, the foundation for high-performance cooperative information systems will become well established. In addition, as the VII initiative has broadened its scope to encompass communication technologies other than DSRC and applications beyond automotive OEM systems (aftermarket and retrofit automotive systems, as well as systems for transit buses and trucks), cooperative vehicle information system capabilities should be expected to advance on a wider front.

Assuming that VII succeeds in advancing to nationwide deployment of DSRC, wireless V2V and V2I2V communications as an enabling technology for cooperative ITS should be very solidly established and no longer viewed as a high risk area. If VII also succeeds in implementing probe vehicle sampling as a means of collecting traffic condition data, it should be possible to implement a variety of new services that depend on detailed real-time knowledge of traffic conditions throughout the roadway network (on arterials, collector/distributors and rural roads, as well as expressways and freeways).

Cooperative Vehicle-Highway Automation System Technologies

The wireless communication requirements for CVHAS are more demanding in terms of latency and reliability than for other ITS services. However, DSRC should be able to satisfy these requirements if it performs according to expectations. One of the main outcomes of the current research project is to verify the ability of DSRC to support close-formation automated platoon control of vehicles. If that is accomplished successfully, it will be a large step towards removing wireless communications from the list of enabling technologies that need to be improved in order to support CVHAS.

Other enabling technologies for CVHAS have advanced significantly in the ten years since the NAHSC Demo '97, leaving a much smaller gap between current state of the art vehicles and AHS vehicles than we saw at that time. The capabilities of the automobiles currently on the market in the U.S. have been reviewed, based on the information on the vehicle manufacturers' web sites in the spring of 2008, to give an indication of the current technological infrastructure available. Vehicles on the European and Japanese markets tend to have more advanced capabilities than those in the U.S., since consumers in those markets appear to be less price-sensitive than U.S. consumers, and most of the vehicles available with the more advanced systems in the U.S. are imported rather than domestic.

The enabling technologies that have been considered in this review include key components and subsystems as well as fully-integrated collision warning and control assistance systems. Almost all of the hardware technologies needed for automated driving are already available on some vehicles, but many of these are still expensive and only available on high-end vehicles. The one exception is high-performance lateral position sensing, which is not yet commercially available on any private automobiles (the available systems that detect lateral position rely on video image processing systems that are neither sufficiently accurate nor robust for AHS use). The major gap in available technologies is on the software side, and particularly on fault management (fault detection, identification and accommodation).

The current U.S. automotive market status of the following enabling technologies has been reviewed:

- brake actuation (and related braking systems such as ABS and yaw stability control systems)
- electronic throttle control
- electronic steering actuation
- electronic transmission shifting
- blind spot/lane change warning systems
- lane departure warning and lane keeping assistance
- automatic steering for parallel parking
- adaptive cruise control (ACC) and enhancements (full speed range ACC, forward collision warning)

3.2.1 Brake actuation systems

All but the most basic cars on the market in the U.S. now have antilock braking systems (ABS), which can independently reduce the brake pressure at each wheel to avoid skidding on slippery road surfaces. The next generation braking control systems actively apply braking pressure at individual wheels, rather than backing off the pressure activated by the driver. These are traction control systems, to avoid slippage when accelerating on slippery road surfaces (the acceleration counterpart to ABS for braking) and yaw stability systems, which seek to avoid loss of directional stability when the coefficient of friction varies significantly between left and right tires.

Traction control is now standard equipment on most vehicles, but is still optional on a few of the more basic vehicles, as shown in Table 1. Yaw stability control is now standard on most high end cars and some mid-range cars, and is generally an option on other mid-range cars, as shown in Table 2. However, with the U.S. government mandating electronic stability control on all cars by the 2012 model year, it is just a matter of time before all cars sold in the U.S. have electronic brake actuation capabilities.

Table 1 – Availability of Traction Control on 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
BMW 5-7 series	$45 K +	S		
Acura RL	$46 K	S		
Nissan Maxima, Z	$28 K	S		
Nissan Altima	$20 K	S		On 3.5 liter models
Mazda 6	$20 K	S		
Mazda RX8	$27 K	S		Option on lowest model
Mazda CX9 SUV	$30 K	S		
Mitsubishi Endeavor SUV	$28 K	S		
Hyundai – most models	From $18 K	S		
Cadillac – most models	From $34 K	S		
Lincoln – all models	From $31 K	S		
Chrysler Crossfire	$36 K	S		
Buick Enclave crossover	$34 K	S		
Buick Lucerne	$37 K	S		
Saab – all models	$29 K and up	S		

Jaguar XJ	$65 K	S		
Ford Taurus	$24 K	S		
Ford Fusion	$18 K	O		On higher models
Ford Edge crossover	$26 K	S		
Chevrolet Impala	$23 K	S		
Chevrolet Malibu	$20 K	S		
Corvette	$47 K	S		
Chevy Cobalt	$15 K	O/S		Depends on model
Pontiac Grand Prix	$23 K	S		Only on top model
Pontiac Torrent crossover	$24 K	S		

Table 2 – Availability of Yaw Stability Control on 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
BMW 5 – 7 series	$45 K +	S		
Toyota Prius	$21 K	O		In package
Toyota Camry, Avalon		O		In package
Acura RL	$46 K	S		
Acura TL	$34 K	S		
Nissan Maxima	$28 K	O	$600	
Nissan Altima	$20 K	O	$900	
Mazda RX8	$27 K	S		Option on lowest model
Mazda CX9 SUV	$30 K	S		
Mitsubishi Endeavor SUV	$28 K	S		
Hyundai – most models	From $18 K	S		
Cadillac – most models	From $34 K	S		
Lincoln Town Car, Navigator	From $45 K	S		
Chrysler Crossfire	$36 K	S		
Chrysler 300	$25K	S		
Chrysler Aspen SUV	$33 K	S		
Buick Lucerne	$37 K	S		
Saab – all models	$29 K and up	S		
Jaguar XJ	$65 K	S		
Ford Taurus	$24 K	S		

Ford Edge crossover	$26 K	S		
Ford Expedition	$31 K	S		
Chevrolet Impala	$23 K	S		Only on higher models
Chevrolet Malibu	$20 K	S		On most models
Suburban	$39 K	S		
Tahoe	$35 – 50 K	S		
Chevy Express van	$24 K	S		
Chevy Cobalt	$15 K	O		Only on top model
Pontiac Grand Prix	$23 K	S		Only on top model
Pontiac Vibe van	$16 K	S		
Pontiac Torrent crossover	$24 K	S		

Full electronic brake assist or actuation is much less widely available, but is becoming available on some cars, in part because of the new emphasis on hybrid powertrains, which make electronic actuation more attractive than hydraulic actuation based on energy efficiency and cost and complexity of installation. Current electronic braking assist availability is shown in Table 3. Note that this feature is not confined to high-end vehicles, but is actually used primarily on mid-range vehicles, and Nissan has been aggressive in applying it to most of their product line.

Table 3 – Availability of Electronic Braking Assist in 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
Toyota Prius	$21 K	S		hybrid
Lexus LS	$62 K +	S		
Nissan Z	$28 K	S		
Nissan most cars	$20 – 25 K	S		
Mazda 6	$20 K	S		
Chrysler Crossfire	$36 K	S		
Chrysler 300	$25 K	O		No price on web

3.2.2 Electronic Throttle Control

Although electronic fuel injection has been widely available for many years, electronic control of the throttle has been less widespread. As with electronic brake assist, this feature is not confined to high-end vehicles, but is available on mid-range vehicles as well, and once again Nissan has been particularly aggressive in applying it throughout their product line, as shown in Table 4.

Table 4 – Availability of Electronic Throttle Control on 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
Toyota Prius	$21 K	S		hybrid
Acura RL	$46 K	S		
Acura TL	$34 K	S		
Nissan Maxima, Z	$28 K	S		
Nissan Altima	$20 K	S		
Nissan Sentra	$16 K	S		All Nissan models included
Chrysler Aspen SUV	$33 K	S		
Pontiac Grand Prix	$23 K	S		

3.2.3 Electronic Steering Actuation

Although true "by wire" actuation of steering is not available, a variety of vehicles have replaced the traditional hydraulic power steering assist systems with electrically assisted power steering (EPS). This could provide the means for easy implementation of automatic steering, by issuing electronic torque commands to the EPS. Hybrid powertrains are particularly well suited to use with this feature, since they have substantial electrical accessory power available, and EPS offers significant advantages over hydraulic in terms of energy efficiency and ease of installation. EPS availability is distributed across a wide range of vehicle classes, from high end to very basic. Table 5 shows that in addition to the hybrids, it is notable for its use on the entry-level Nissan Sentra and Chevy Cobalt, illustrating the advantages that it offers to small cars. Note that BMW has applied it as an option on some of their cars to provide a wider range of steering ratios than would otherwise be available, so that a high steering ratio can make parking easier at low speeds, while a low steering ratio at high speeds makes the car easier to control and less sensitive to small steering inputs.

Table 5 – Availability of Electrically Assisted Power Steering on 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
BMW 3 series	$33 K +	O	$1400	For more variable ratio
BMW 5 series	$45 K +	O	$1400	For more variable ratio
Lexus LS	$62 K +	S		
Acura RL	$46 K	S		
Nissan Sentra	$16 K	S		
Ford Escape hybrid		S		hybrid
Chevrolet Malibu	$20 K	S		Most models

Chevy Cobalt	$15 K	S		

3.2.4 Electronic Transmission Shift Control

The final category of actuation, after braking, engine and steering, is the transmission. Most automatic transmissions use complicated hydraulic logic to govern their shifting, but interest has grown in use of electronics to provide more flexibility, ease of programming, and less mechanical complexity. Most hybrid vehicles are supplied with continuously variable electronic transmissions to take maximum advantage of efficiency opportunities, another manifestation of the contributions that hybrids are making to raising the level of enabling technologies on today's vehicles. As Table 6 shows, the electronic transmission shifting is standard on a mix of hybrids, high-end cars and large SUVs, but is also starting to penetrate the middle and lower range General Motors vehicles.

Table 6 – Availability of Electronic Transmission Shift Control on 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
Toyota Prius	$21 K	S		hybrid
Lexus LS650 h	$100 K	S		hybrid
Lexus RX hybrid	$41 K	S		hybrid
Lexus GS hybrid	$55 K	S		hybrid
Saab 9-7X SUV	$47 K	S		
Jaguar – all	$50 K	S		
Ford Escape hybrid		S		hybrid
Chevrolet Impala	$23 K	S		
Suburban	$39 K	S		
Tahoe	$35 – 50 K	S		
Chevy Avalanche truck	$34 K	S		
Chevy Express van	$24 K	S		
Chevy Cobalt	$15 K	O		
Pontiac Grand Prix	$23 K	S		
Pontiac G5	$16 K	O		
Pontiac Vibe van	$16 K	S		4-speed only
Pontiac Torrent crossover	$24 K	S		

3.2.5 Blind Spot/Lane Change Warning Systems

Short-range sensing systems, using a variety of technologies, have been used to provide drivers with warnings of other vehicles' presence in their blind spots, or vehicles that are about to overtake them from behind in an adjacent lane. These activate warnings if the driver uses the turn signal to indicate an intended lane change in the direction where the threat vehicle has been detected. Short-range remote sensing capabilities such as this could be an element of a CVHAS neighborhood awareness sensing system. At this time, these systems are only available on a limited number of relatively expensive vehicles, and generally only as options, as shown in Table 7.

Table 7 – Availability of Blind Spot Assistance Systems on 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
Volvo S80	$38 K	O	$700	Vision-based system
Mazda CX9 SUV	$30 K	O		On top model only
Cadillac STS-V	$80 K	S		
Cadillac STS	$44 K	O		
Buick Lucerne	$37 K	O	$400	Std in $39 K model
Jaguar XF	$50 K	O		Radar in rear bumper

3.2.6 Lane Departure Warning and Lane Keeping Assistance

One of the key functions for a CVHAS system is detecting the vehicle's position relative to the desired lane. Some current high-end vehicles are equipped with lane departure warning and lane keeping assistance systems, all of which use video image processing to estimate lane position based on recognition of the stripes between lanes. This technology only works where the lane striping is well maintained and is not obscured by water, dust, snow or ice. Although it provides sufficient accuracy for warning about an impending lane departure or for nudging a vehicle back towards the middle of the lane if it is drifting out of the lane, it is probably not accurate enough for the kind of high-accuracy steering that would enable vehicles to drive in narrower lanes. Table 8 shows the vehicles that are currently available with lane departure warning, while Table 9 shows the vehicles that combine this with lane keeping assistance. The lane keeping assistance provides steering torque through differential braking of the left and right wheels in the Infiniti models or a vibrating steering wheel to alert the driver in the Audi models.

Table 8 – Availability of Lane Departure Warning on 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
Volvo S80	$38 K	O	$1700	In package with ACC, FCW, drowsiness
Volvo V70	$32 K	O	$1700	In package with ACC, FCW, drowsiness

BMW 5 series	$45 K +	O	$500	Steering wheel vibration, requires $2400 Premium Package too
Cadillac DTS performance	$51 K	O	$300	“virtual rumble strip” audio alert on GM systems
Cadillac STS-V	$80 K	S		
Buick Lucerne	$37 K	O	$300	Std in $39 K model
Infiniti FX	$38 K	O	$4650	Package with ACC, brake assist and navigation

Table 9 – Availability of Lane Departure Warning with Lane Keeping Assistance on 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
Infiniti M class	$43 K	O	$2800	Package with FSRA, brake assist, (+$3350 nav needed)
Infiniti EX35	$35 K	O	$1950	Package with ACC, parking monitor (+$2150 nav needed)
Audi A8	$70 K	O		Vibrating steering wheel
Audi A6	$43 K	O		Vibrating steering wheel

3.2.7 Automatic Steering for Parallel Parking

One of the more sophisticated capabilities available today is the automatic parallel parking system. This uses side-looking sensor technology to evaluate the location and size of a potential parking space, and electronically assisted power steering to steer the vehicle through the parallel parking maneuver. The driver retains responsibility for controlling vehicle speed using the throttle and brake, and a display gives the driver step-by-step instructions about what he or she needs to do to use the system. Because of its complexity, this system is only available as an option on high-end cars, as shown in Table 10, but its first commercial availability was on the Toyota Prius in Japan, based on its having already been equipped with EPS.

Table 10 – Availability of Automatic Steering for Parallel Parking on 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
Mercedes S550	$87 K	O	$2850	In package with blind spot and ACC, depends on another $2860 option added
Lexus LS	$62 K +	O	$3815	Package with backup camera;

				also $700 alone on LS460L

3.2.8 Adaptive Cruise Control (ACC) and Enhancements

Adaptive Cruise Control (ACC) has been gradually entering the market, as a comfort and convenience feature on high-end cars. It may use a millimeter wave or laser radar to measure the distance to the preceding vehicle, and then adjusts the vehicle speed to maintain the desired distance based on expressed driver preferences. Most ACC systems are designed to operate at speeds of at least 25 mph, but some recent systems have added extensions to lower speeds. When the extension is fully integrated with the ACC, it is considered a “Full Speed Range ACC”, and when it operates differently it is considered a “Low Speed Following” or “Stop and Go” system. Although the first ACC systems studiously avoided being labeled as safety systems, more recently some suppliers have explicitly combined them with forward collision warning systems.

The basic ACC systems are listed in Table 11, followed by the systems that add the low-speed capability in Table 12 and the systems that add forward collision warnings in Table 13. As the table entries show, these features are generally options on high-end vehicles, indicating that they still have some time to go before they become more widely available to the public. It appears that the car buyer will have to pay at least $40 K to buy a 2008 model car with ACC.

Table 11 – Availability of Adaptive Cruise Control on 2008 Model Cars in the U.S.

Make and Model	**Base Price**	**Standard or Option**	**Additional Cost**	**Notes**
BMW 3, 5, 7 series	$33 K +	O	$2400	
Infiniti M class	$43 K	O	$2800	In package with LDP, brake assist (+$3350 nav needed)
Infiniti EX35	$35 K	O	$1950	In package with LDP, brake assist, parking monitor (+$2150 nav needed)
Infiniti QX56	$52 K	O	$1150	With front parking sonar
Toyota Avalon Limited	$35 K	O		Requires stability control option; no price on web
Audi A8	$70 K	O		
Audi A6	$43 K	O		
Audi Q7 SUV	$43 K	O		
Cadillac DTS, STS	$44 K	O	$1700	Not on all models
Cadillac XLR	$82 K	S		
Jaguar XF	$50 K	O		
Jaguar XJ	$84 K	S		Only in top models

Table 12 – Availability of "Stop and Go" ACC Capability on 2008 Model Cars in the U.S.

Make and Model	Base Price	Standard or Option	Additional Cost	Notes
Mercedes S class and related cars	$80 K +	S		
Infiniti FX	$38 K	O	$4050	In package with LDW, brake assist, nav (+$1900 hands free package to get on FX35)

Table 13 – Availability of ACC with Forward Collision Warning on 2008 Model Cars in the U.S.

Make and Model	Base Price	Standard or Option	Additional Cost	Notes
Volvo S80	$38 K	O	$1500	
Lexus LS	$62 K +	O	$2850	
Lexus ES350	$34 K	O	$2600	
Acura RL	$46 K	O		$54 K with two option packages needed to get this, including active collision mitigation braking

3.2.9 Other Automotive Technology Developments

Most of the innovations in automotive technology start in Europe or Japan and then come to the U.S. after they have been on the market in their home countries for a while. So, the international state of the art is more advanced than the preceding tabulation of vehicle availability in the U.S. indicates. Examples of automotive innovations relevant to CVHAS in other countries that have been announced within the past year include:

- Nissan's EA-2 concept car with complete "X by wire" actuation, freeing up an additional 4.5" of usable vehicle interior length
- Two-day "Steering Tech" conference in Munich in April 2008, with heavy emphasis on electronic power steering and fault management for electronic steering systems
- Continental developing an integrated vehicle safety system based on fusion of multiple sensor technologies (vision, radar) called "ContiGuard"
- Siemens VDO developing an integrated vehicle safety system based on fusion of multiple sensor technologies (vision, radar) called "CoPilot"
- Germany's national ITS project called Aktiv developing Integrated Lateral Vehicle Control, to enable vehicles to use video sensing to swerve around hazards in the road and "Roadworks Pilot" to provide traffic-responsive CACC

- European version of Honda Accord provided with “Motion Adaptive Electronic Power Steering”, adding torque to the driver’s torque commands, together with a forward vehicle collision mitigation braking system
- Volkswagen selling several models in Europe with Valeo’s Park4U product, providing steering control similar to the Toyota system now available in the U.S.
- Volkswagen demonstration of a self-parking system (with no driver in the car) at the Hannover Trade Fair in April 2008
- Hella announcing a vision-based system for Opel providing lane departure warning and recognition and in-vehicle display of roadside traffic signs
- Toyota planning a stop sign warning system for the Japan market based on digital map representation of stop sign locations, and with active braking to avoid violations
- Nissan’s Fuga model in Japan provided with a curve overspeed avoidance system using active braking matched to the curve data in the navigation system
- Volkswagen PassatCC model to be introduced in the U.S. in 2009 with ACC, Park Assist (automatic parking), Lane Assist and “Front Scan” features
- Volvo’s “City Safety” system to be introduced in Europe in 2009 using a short-range lidar (6 m range) to provide collision avoidance braking at speeds up to 15 km/h and collision mitigation braking at speeds between 15 and 30 km/h
- Opel’s Vectra model in Germany is rumored to have an option called “Traffic Assist” that uses lidar and video sensing to provide some level of driving automation.

3.2.10 Missing Technological Capabilities

Although modern high-end cars already include most of the enabling technologies needed for CVHAS, they do not include all of them. The key technologies that are still not commercially available are:

- highly accurate and reliable absolute positioning
- highly accurate and reliable lane position referencing and lane detection
- detection, warning and avoidance of hazardous obstacles (other than vehicles)
- comprehensive fault detection, identification and management.

The positioning systems currently used for navigation and route guidance do not have sufficient accuracy or reliability to be used for vehicle control, which requires orders of magnitude improvements. Some of these improvements are likely to be made as positioning systems are applied to collision warning and control assistance systems. Similarly, the lane position referencing and detection systems used for lane departure warning would need to be much more robust with respect to environmental disturbances and poor-quality markings and much more reliable and accurate before they could be used for full control of vehicle steering.

General obstacle detection and the fault management functions are likely to be the most challenging technical issues for CVHAS, and are also least likely to benefit from nearer term work on collision warning and control assistance systems. Use of cooperative communication systems will help mitigate the severity of some of their technical requirements, since networks of vehicles and infrastructure intelligence could cooperate to assist vehicles that experience faults.

3.2.11 International Perspectives

The automotive market has become truly international, with complicated relationships among automotive OEMs and suppliers on different continents, but different market conditions in different conditions. Although the technologies themselves are not specific to one continent or another, the conditions that could work in favor of their adoption can vary widely from continent to continent. With the added factor of cooperative infrastructure included, it is also important to consider the significant differences in the roadway infrastructures from continent to continent.

The U.S. automotive market tends to be more price-sensitive than the European or Asian markets, with customers being less willing to spend additional money to get extra technological capabilities included on their vehicles. Americans are no longer the automotive gadget freaks that they were in the 1950s or 1960s and no longer feel much pressure to be the first in their neighborhood to show off a new automotive feature. They are also less tolerant of the performance limitations of new features that may not be fully mature. Since automotive customers in other markets are more adventurous about adopting new automotive features, the industry is introducing them in Europe or Asia before bringing them to the U.S.

Differences in government regulations can also have significant influence on the propensity toward market adoption of new automotive features. The U.S. tends to be more reluctant to impose regulations than most other industrialized countries, applying less pressure to adopt new safety technologies for example. Other regulatory differences can include tax incentives to adopt new technologies while they are still costly (used in the U.S. for some energy-related technologies such as hybrid and electric vehicles, but not for safety systems) and government type approvals for adoption of new features.

Some government regulations can have indirect influences on the adoption of CVHAS technologies, such as speed limits, minimum car-following distance rules and commercial truck driver hours of service rules. For example, in many countries trucks are limited to speeds substantially lower than light duty vehicles, often by direct mechanical means. If these limits were eased for operations on dedicated truck lanes and/or in an automated driving mode, this could be a significant incentive for CVHAS adoption. Some national regulations prohibit vehicles from following each other at time gaps below a minimum threshold value. Unless these regulations were modified, the drag-reducing and capacity-increasing benefits of close-formation vehicle following could not be gained, leaving a significant disincentive to adoption of these CVHAS capabilities. Hours of service rules for truck drivers are politically sensitive, and any changes to these rules based on application of truck platooning or related technologies are likely to be complicated and controversial because of their potentially large economic impacts.

Interest in automated driving appears to be growing in Europe, based on new support for research projects there. For example, the European Commission has recently initiated the HAVE-it (Highly Automated Vehicles for Intelligent Transportation) integrated project, with a €28 million budget (€17 million from the EC) over three years. HAVE-it is exploring automated driving for scenarios in which drivers are either overloaded or underloaded by normal manual driving functions, such as complicated merging maneuvers or tedious driving through stop-and-go conditions, with careful consideration of the human factors issues [19].

4. Deployment Strategies to Overcome the "Chicken and Egg" Problem

4.1 Background on Prior Work

Our previous exploration of strategies for overcoming the "chicken and egg" deployment problem for CVHAS was in the period of 1999-2000, when we identified the importance of starting with transit buses and heavy trucks [20, 21]. That work led to the creation of the "Demo 2003" project, in which we actually implemented automated driving of buses and trucks to learn about the technical challenges involved and to solve them [22]. All of that work preceded the current VII initiative, as well as most of the technological improvements that are now becoming available on passenger cars, as described in Section 3.2.

If the VII initiative succeeds in achieving deployment of DSRC roadside equipment throughout the country and DSRC onboard equipment on all new cars after a certain date not too far in the future, it will have made a very large step in support of all kinds of cooperative vehicle-infrastructure systems. The widespread availability of high-performance wireless access points throughout the roadway network and a large fraction of the vehicle population being able to communicate with those access points and each other is the most important single enabler of many cooperative information services. Additional research and development work will still be needed to determine how best to design and implement those services [23], but that should be possible based on investment of a small fraction of the cost of the VII deployment.

Advancing beyond cooperative information services to CVHAS automation services is more complicated and will require additional deliberate actions, which are discussed in the following sections of this chapter.

4.2 Site-Specific Deployment Case Studies

Transportation problems and opportunities are inherently local and require strategies tailored to local needs and capabilities. Implementation of new transportation alternatives such as CVHAS cannot be done in the abstract, but needs to be done at specific sites. Only a few site-specific studies have been done until now in support of CVHAS bus and truck applications [2, 7, 8], but these are not sufficient to determine whether CVHAS has wide enough applicability to justify full-scale development work. Because it will require a substantial investment of development effort to advance CVHAS to the stage that it can be applied on vehicles providing everyday transportation service, it is important to establish that a large enough market will exist to amortize that investment.

Case studies should be initiated for a wide range of BRT and truck lane applications (perhaps ten different transit operators, ten urban truckways and ten intercity truckways) to identify how broadly applicable CVHAS technologies are likely to be. These studies should consider the local needs and constraints and then compare CVHAS with other alternatives to determine whether CVHAS appears to be a viable, cost-effective alternative for meeting the transportation needs at each site. If these case studies find CVHAS to be viable in only specialized niche applications, it will probably not be worth making the full investment in system development, but if it appears to be broadly applicable, that finding should stimulate the system development investments as well as the local interest in deployment.

4.3 Transit Bus Automation for BRT Service on Busways

Most current consideration of BRT involves combinations of operational enhancements for application to buses sharing their running way with the rest of the vehicle population. However, some of the more advanced BRT concepts involve buses operating on their own dedicated bus lanes or busways, either in or adjacent to urban arterials (Eugene, OR, Cleveland, LA Metro Orange Line, new AC Transit BRT) or on freeways or HOV/HOT lanes (San Diego, Minneapolis). When the transit bus operators have responsibility for, or special access to, the running way, they can overcome the chicken/egg dilemma of vehicle vs. infrastructure interests and can make decisions about deploying cooperative technologies on both vehicles and infrastructure.

The restrictions on access to busways by “other” vehicles help to simplify the driving environment for the BRT buses, minimizing the need for interactions with other vehicles. This reduces the need for comprehensive collision avoidance functionality. Since the bus driver still needs to be on the bus to interacting with passengers and to drive it on the other parts of its route (before it enters and after it leaves the exclusive busway), the bus driver can also take responsibility for hazard awareness and response, even while an automated system is doing most of the driving. The bus driver’s responsibility would become more like that of train operators in heavily automated rail transit systems such as BART.

Automatic steering control functions for buses in busways have progressed to the stage that they are entering the FOT stage in a new FTA-sponsored project called Vehicle Assist and Automation (VAA) that PATH will be working on with Caltrans, Lane Transit District (Eugene, OR) and AC Transit. Assuming favorable results in the VAA project, automatic steering control has good prospects for being adopted by other transit properties. Because of the high value of transit buses and the economic advantages that can be gained from automatic steering control (reduced right of way and construction costs for busways and reduced travel times), an economic case can be made for investing in the addition of the automatic steering capabilities even when it is only produced in limited quantities and hence still expensive (in the range of $100 K per vehicle initially).

Automatic speed and spacing control of buses does not yet have as much urgency as automatic steering control, however recent increases in fuel costs have stimulated such significant additional demands on capacity-constrained bus systems that one has recently expressed interest in platooning of buses to increase its capacity while minimizing the impacts on cross traffic.

Because the number of new transit buses sold each year in the U.S. is so small (currently about 5000), it is not possible to obtain major economies of scale in production of CVHAS systems based on applications <u>only</u> to transit buses. With annual production volumes of hundreds of CVHAS systems, the additional costs per vehicle are likely to remain in the range of $15,000 for lateral control or $25,000 for full automation [2].

4.4 Automation of Heavy Trucks on Dedicated Truck Lanes

Heavy trucks operating in dedicated truck lanes have many similarities to transit buses in busways, in that they are high-value vehicles that can benefit from separation from the light-duty vehicle traffic. They also have professional drivers and maintenance staffs who can be trained to use and maintain the CVHAS technologies while these are still immature.

Although no dedicated truck lane facilities have been put into service yet in the U.S. (except for some short climbing lanes on steep highway sections), they are under active consideration in a variety of locations, both urban and intercity. The availability of automation technologies for heavy trucks can actually increase the attractiveness of the dedicated truck lane option, just as the availability of dedicated truck lanes can encourage the feasibility of truck automation.

It is not yet clear whether the most promising initial dedicated truck lane application would be for long-distance intercity travel in a location with few right of way restrictions, or whether it would be for an intra-urban application with a high volume of short-haul trips and severe right of way constraints. Case studies are needed for a variety of potential applications, taking account of the local physical, political and financial constraints as well as the economic advantages that could be gained. These will help determine the pioneer application sites.

Regardless of the application, it appears that the primary interest is likely to be in automated platooning of trucks rather than automatic steering control because this will produce significant energy savings and increases in the capacity of trucks per lane, so that a higher volume of trucks can be accommodated within right of way and construction cost constraints. Effective close-formation platoon control will almost certainly require automatic steering as well because when driving at the short spacings needed to reduce drag it is not possible for the driver of the following truck to see the lane markings, and it is very stressful to continuously follow the motions of the immediately preceding truck manually.

Heavy trucks are produced in much larger quantities than transit buses, so they offer a better opportunity for achieving economies of scale in production of CVHAS systems. With total annual production of a few hundred thousand trucks, it is conceivable that ten thousand to several tens of thousands per year could be equipped with CVHAS, particularly if large truck fleet operators became interested in the technology. At these volumes, the additional costs per vehicle for full automation could probably be reduced to the range of $5,000 [2].

4.5 Extension to Light Duty Vehicles Through Hybrid Vehicles in Managed Lanes

Extending applications of CVHAS from heavy vehicles (buses and trucks) to light duty passenger vehicles is challenging but worth pursuing because this is where the largest benefits are likely to be gained. The main challenges are associated with the need to keep the incremental cost of the vehicle equipment within a marketable range (order of magnitude $1000), the need to have the technology "bullet proofed" for use by naïve drivers without periodic maintenance, the lack of a clear mechanism for coordinating vehicle and infrastructure deployment decisions, and the complexities of introducing a significant innovating in driving into the automotive production, marketing and sales processes. These are compounded by environmental sensitivities about projects or technologies that would make driving easier or more attractive and could therefore potentially lead to increased private car usage.

For the foreseeable future, it is likely that automated vehicles will not be able to mix freely with manually driven vehicles but will need to be largely separated from them. The closest analogy in current highway operations is to the HOV, HOT or managed lanes on some of our urban freeways. These are therefore attractive places to consider for introduction of CVHAS capabilities, particularly because of the importance of clustering the equipped vehicles in close proximity to each other in order to take advantage of their capabilities. The most obvious initial CVHAS service to offer is cooperative ACC, which is being tested in the current research project, since it should offer significant benefits at a minor incremental cost above autonomous ACC and it could provide advantages by communicating with preceding vehicles that do not even have ACC, just as long as they have the DSRC communication capability.

In order to mitigate environmental concerns, the initial CVHAS host vehicles could be vans used by vanpools. These have the added advantage that by focusing on employer-based vanpool fleets at large employers, it would be possible to concentrate the initial CVHAS vehicles in specific corridors and at places where there is a possibility of providing some centralized preventive maintenance. As the review of current automotive technology in Section 3 of this report showed, there is an additional technological advantage in focusing on vans with hybrid powertrains because they are most likely to already have the electronic actuation systems that will be needed.

4.6 Advances in Advanced Driver Assistance Systems (ADAS)

Section 3 of this report provided a snapshot of the advanced driver assistance systems (ADAS) that are currently available to automobile buyers in the U.S. The market penetration of these systems is still at a low level and growing relatively slowly, but it has reached higher levels and rates of growth in Japan and Europe. Over the coming years, this growth should extend to the U.S. as well, providing vehicles with many of the sensing and actuation capabilities that they will need for comprehensive CVHAS. The early adopters of these systems tend to be in the other countries rather than in the U.S., but as they purchase more ADAS-equipped vehicles they help generate economies of scale in the production of these systems, eventually lowering the costs to where they become more widely acceptable in the U.S. market.

4.7 Cost Reductions

There are large up-front fixed costs in the design, development, testing and production of the components and subsystems that comprise CVHAS systems. This means that the prices that have to be paid by vehicle buyers cannot come down to moderate levels until there is a substantial production volume (unless the suppliers decide to subsidize the early adopters because they are so confident of a large return on their investment later). The dominant consideration in achieving unit cost reductions therefore has to be increasing the number of vehicles to be equipped each year. The strategies suggested here have followed that principle, beginning with the smaller volume but higher value users and then advancing step by step to higher volume users who will be able to pay successively lower prices. The key challenge is ensuring that at each step along the way, these vehicle users achieve sufficient benefits from the system to justify the price that they have to pay. As an indication of how much progress still needs to be made, *Business Week* reported in July 2008 that, “The $1,300 GM "Driver Awareness Package," offered on the Cadillac CTS and DTS and Buick Lucerne, includes lane-departure warning, blind-spot detection, and heads-up instrument-panel display. So far this year, 5% of CTS sedan buyers have opted for the package.” [24]

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