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Final Report

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Executive Summary

The Vehicle Safety Communications (VSC) project was established to evaluate vehicle safety applications enabled or enhanced by communications. This project determined initial communication requirements for each application, performed some Dedicated Short-Range Communications (DSRC) vehicle testing, and helped to develop the DSRC standards so that the requirements of the safety applications were considered. In 2002, seven automotive manufacturers—BMW, DaimlerChrysler, Ford, GM, Nissan, Toyota, and VW—formed the VSC Consortium (VSCC) to participate in this project with the U.S. Department of Transportation (USDOT).

The goals of the VSC project were to:

- evaluate the potential safety benefits of communication-based vehicle safety applications in terms of reductions in vehicle crashes and functional productive years saved;
- define and evaluate the communications requirements of selected vehicle safety applications;
- work with standards development organizations to ensure that proposed DSRC communications protocols meet the needs of vehicle safety applications; and
- investigate specific technical issues that may affect the ability of DSRC to support deployment of vehicle safety applications, estimate the deployment feasibility of communications-based vehicle safety applications, and assess the ability of proposed DSRC communications protocols to meet the needs of safety applications.

Safety Applications

Initially, the VSCC complied and evaluated a comprehensive list of potential vehicle safety application scenarios. From this list, 34 vehicle safety application scenarios enabled or enhanced by wireless communications were identified. The VSCC estimated potential safety benefits for the identified vehicle safety application scenarios using available crash statistics, as well as assumptions regarding deployment, market penetration, and cooperation with infrastructure or other vehicles. These potential safety benefits appear to be significant for a number of the application scenarios.

From the 34 application scenarios, the VSCC identified 8 scenarios as high-priority and selected for further research based on the estimated potential safety benefits. Of these 8 application scenarios, 4 involve vehicle-to-vehicle communications and 4 involve communications between vehicles and the infrastructure. Three of the vehicle-infrastructure communication applications involve intersections.

Communications Requirements

The VSCC determined preliminary communications requirements for the 8 high-priority vehicle safety application scenarios. Most of these application scenarios required periodic transmission of one-way, point-to-multipoint broadcast messages. The message packet size was 200 to 500 bytes with a communications range of 50 to 300 meters. The VSC project team evaluated communications requirements through both field and simulation testing.

For field testing, the VSC project team developed and conducted evaluations on a test system based on the lower-layer DSRC standard. During the testing, the team implemented a preliminary, common safety-message set developed by the Society of Automotive Engineers (SAE) for vehicle-to-vehicle safety applications. The SAE's DSRC safety-message set includes vehicle size, position, speed and acceleration data, and braking, steering and throttle information. Actual vehicle bus data in a standard format was exchanged between vehicles from different manufacturers. The field testing confirmed the functionality of DSRC communications at real intersection locations under typical traffic conditions and demonstrated the technical feasibility of the current DSRC technology.

Through simulation, the VSC project team studied the effect of large-scale deployment of DSRC-equipped vehicles and roadside units on communications capacity. Based on the simulation testing, the VSC project team suggested the need for a high-availability, low-latency channel for latency-critical safety applications. The simulation testing also showed that emergency message prioritization consistently improved the reception probability over routine messages by 5 percent to 40 percent, and reduced the communications latency across a wide-range of simulation scenarios. The simulation results further illustrated that channel capacity is an issue that will need to be addressed for large-scale deployment in stressed traffic environments.

Standards Development

As active participants in the DSRC standards development process, the VSCC evaluated existing and proposed DSRC standards. VSCC identified specific technical issues, presented vehicle safety requirements and a proposed security solution, and secured necessary revisions in eight major areas of the standards. To ensure message authentication, the proposed security architecture requires that all vehicle and roadside units be issued certificates and that safety-relevant messages be digitally signed. In addition, compromised units need to be revoked through a certificate revocation list that is distributed to all units. The SAE developed a common vehicle-to-vehicle DSRC safety message set that includes vehicle size, position, speed, and acceleration data, and braking, steering, and throttle information.

The vehicle safety communications requirements and proposed security solution are currently being considered in the development of upper-layer and security standards in Institute of Electrical and Electronic Engineers (IEEE) committees. The preliminary vehicle safety communications requirements appear to be supported by the FCC Report and Order, and the current lower-layer DSRC standards mandated by the FCC. However,

the high-availability, low-latency DSRC channel required for particular vehicle safety applications was not designated in the FCC Report and Order.

DSRC Deployment Issues

The VSC project evaluated proposed DSRC standards, identified specific technical issues, and presented vehicle safety requirements. A test system based on the current lower-layer DSRC standard was developed and field-tested. As a result of the testing, the functionality of DSRC communications for vehicle safety application scenarios at real intersections was confirmed. In addition, the project successfully demonstrated the exchange of messages for vehicle-to-vehicle safety applications, identified channel capacity in high-penetration traffic environments as a deployment issue, and determined that 5.9 GHz DSRC wireless technology appears to be able to support the communications requirements of the majority of vehicle safety applications.

Potential Next Steps

Based on the VSC project accomplishments, and the remaining needs that have been identified, VSCC envisions that the following steps be undertaken:

- Develop prototype cooperative intersection collision avoidance safety applications.
- Develop prototype communication-based vehicle-to-vehicle safety applications.
- Develop adaptive DSRC protocols to improve communication reliability in stressful traffic environments.
- Continue to influence and contribute to DSRC standards development from a vehicle safety communication requirements standpoint.
- Implement and test upper-layer and communications protocol, when available.

1 Introduction

1.1 Background

The Vehicle Safety Communications (VSC) project was established to evaluate vehicle safety applications enabled or enhanced by communications. This project determined initial communication requirements associated with each application and promoted their accommodation in developing communications standards. The VSC project consists of a set of tasks and subtasks. A summary of the project goals and tasks has been included in Appendix A.

The VSC Consortium (VSCC) was formed to participate in this project with the U.S. Department of Transportation (USDOT). The VSCC consists of participants from seven automotive manufacturers—BMW, DaimlerChrysler, Ford, GM, Nissan, Toyota, and VW. Since May 2002, VSCC has identified and evaluated vehicle safety applications enhanced or enabled by external communications, determined their respective communications requirements, and worked with standards development organizations to ensure that the proposed 5.9 GHz Dedicated Short Range Communications (DSRC) protocols support vehicle safety applications.

1.2 Focus and Organization of the VSC Project

The VSC project goals were to:

- estimate the potential opportunity for safety benefits of communication-based vehicle safety applications in terms of reductions in vehicle crashes and functional productive years saved;
- clearly define the communications requirements of selected vehicle safety applications;
- work with standards development organizations to ensure that proposed DSRC communications protocols meet the needs of vehicle safety applications;
- investigate specific technical issues that may affect the ability of DSRC (as defined by the standards) to support deployment of vehicle safety applications;
- estimate the deployment feasibility of communications-based vehicle safety applications; and
- assess the ability of proposed DSRC communications protocols to meet the needs of safety applications.

The following questions illustrate the focus and organization of the VSC project research, analysis, testing, and evaluation carried out to achieve the project goals. Discussions related to the questions are included in the chapters listed.

- What vehicle safety applications have the potential to be improved or made possible with external vehicle communications? (Chapter 2)
- Are there significant potential safety benefits for communication-based vehicle safety applications? (Chapter 3)
- What are the communication requirements for communications-based vehicle safety applications? (Chapter 4)
- Will the proposed DSRC communications protocols (as defined by the standards) meet the needs of vehicle safety applications? (Chapter 5)
- What is the preliminary estimate of technical feasibility for deployment of communications-based vehicle applications? (Chapter 6)

The report concludes with a summary of the VSC project accomplishments, findings, and suggestions for potential next steps (Chapter 7).

1.3 Report Organization

This report identifies the vehicle safety application scenarios evaluated for potential safety benefits and describes the preliminary communications requirements necessary to support a selected set of representative application scenarios. Included in this report is an assessment of the applicability of available wireless technologies to the preliminary requirements of the selected application scenarios. The capabilities of DSRC wireless technology were evaluated in field tests (test tracks and public roadways) and in model simulation tests. This report describes the results of those tests. Further, the report outlines DSRC security requirements and a proposed security architecture, and discusses VSCC's activities working with the SDOs to ensure that developed standards adequately support the anticipated safety applications.

This report consists of the introduction and the following chapters:

- **Chapter 2, Vehicle Safety Application Scenarios**
  Describes the vehicle safety application scenarios that may be improved by or made possible with external vehicle communications. More than 75 applications were identified in the preliminary analysis and 45 applications were selected for further review.
- **Chapter 3, Potential Safety Benefits**
  Discusses the estimated near-, mid-, and long-term benefits that might be realized by implementing wireless communications systems enabling vehicle-to/from-infrastructure and vehicle-to-vehicle transfer of vehicle safety information.
- **Chapter 4, Communications Requirements and Technologies**
  Presents the operational characteristics and preliminary communications requirements of eight representative potential near- and mid-term vehicle

safety application scenarios. Compares the wireless communication technologies available to address the preliminary requirements of vehicle safety application scenarios.

- **Chapter 5, Field and Simulation Testing**
  Describes the field-testing program carried out on test track facilities and public roadways to evaluate vehicle safety communications, including vehicle-to-vehicle and vehicle-to/from infrastructure transmissions. Discusses the simulation model testing of vehicle safety communications in scaled environments based on proposed DSRC systems.
- **Chapter 6, DSRC Communication and Security Standards**
  Discusses the work of the VSCC to ensure that the proposed DSRC communications protocols, as defined in standards, meet the needs of vehicle safety applications. Describes the progress achieved in resolving specific technical issues that may have affected the ability of DSRC to support deployment of vehicle safety applications. Presents the DSRC security requirements for vehicle safety applications that need to be addressed in the DSRC standards. Describes the security threat model, and outlines a potential design for a comprehensive security architecture and protocol.
- **Chapter 7, Conclusions**
  Provides a summary of the accomplishments of the VSC project. Sumarizes the key findings of the project, and describes the remaining vehicle safety communications needs that have not yet been met. Identifies potential next steps that might be undertaken to build on the knowledge gained from the VSC project and address the remaining needs.

2 Vehicle Safety Application Scenarios

2.1 Preliminary Analysis

An initial goal of the VSC project was to identify safety application scenarios that might be improved or made possible by external vehicle communications. The vehicle safety applications were initially compiled by reviewing existing literature under Task 1 as a starting point. The initial list of vehicle safety applications and the review of existing literature is presented in the VSC project *Task 1 & 2 Final Report.*[1]

In Task 3 of the VSC project, a comprehensive list of communications-based vehicle safety and non-safety application scenarios was compiled. The VSCC participants identified safety applications that may benefit or be enabled by wireless communications (either vehicle-vehicle or vehicle-infrastructure). In addition, brainstorming sessions between all members of the VSCC were organized to expand the list of potential safety applications, and group the safety applications with respect to complexity and when they may become commercially feasible for light vehicles. This list represents the best efforts of the participants at the time of publication. It may not contain all vehicle safety applications (due to similarity) but does contain, at a minimum, examples and brief descriptions of representative safety applications. More than 75 application scenarios were identified and analyzed resulting in 34 safety and 11 non-safety application scenario descriptions. Details of this study are presented in the VSC project *Task 3 Final Report.*[2]

The VSCC grouped the vehicle safety application scenarios by level of complexity. A time estimate of when applications might be commercially available in light vehicles, based upon deployment assumptions relevant in 2002, was developed. More than 75 potential application scenarios were identified and classified in two groups: safety-related and non-safety-related application categories.

2.1.1 Safety-Related Application Categories

- **Intersection Collision Avoidance (ICA)**
  Uses infrastructure-to-vehicle communication to warn the driver of potentially unsafe situations occurring at intersections, including traffic signal violations, left-turn assistance, blind-merge warnings, and imminent-collision warnings.
- **Public Safety**
  Improves general public safety by providing the driver with warnings related to current or up-coming traffic situations such as approaching emergency vehicles, disabled vehicles in traffic lanes, and emergency message transmissions.

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[1] *Task 1 & 2 Final Report* - Literature Review and Analysis of DSRC Standards Process, Public Document, Vehicle Safety Communications Project, Crash Avoidance Metrics Partnership, 2003.

[2] *Task 3 Final Report - Identify Intelligent Vehicle Safety Applications Enabled by DSRC*, Public Document, Vehicle Safety Communications Project, Crash Avoidance Metrics Partnership, 2004.

- **Sign Extension**
  Warns the driver of road signs, road curves, structures, work zones, wrong-way vehicles, and amber alerts.
- **Vehicle Diagnostics and Maintenance**
  Uses infrastructure-to-vehicle communication to improve safe vehicle operation through distributed safety recall information and interaction with service and maintenance providers.
- **Information From Other Vehicles**
  Uses vehicle-to-vehicle communications to determine and warn the driver of hazardous conditions such as other vehicles braking for emergency stops, merging traffic, vehicles in a driver's blind spot, and an imminent collision.

2.1.2 Non-Safety Application Categories

- **Traffic Management**
  Uses vehicle-to-vehicle communication to improve traffic flow.
- **Free-Flow Tolling**
  Uses infrastructure-to/from-vehicle communication to reduce congestion and improve traffic flow of toll roads by toll collection without the need for toll plazas along the roadway.
- **Information From Other Vehicles**
  Uses infrastructure-to-vehicle and vehicle-to-vehicle communication to improve driver navigation and enhance safe vehicle operation.

2.2 Secondary Analysis

From the comprehensive list of scenarios, additional analysis resulted in the identification of 45 vehicle safety application scenarios for further study (Task 3). Of these 45 scenarios, 34 were judged to be safety-related. Table 2-1 and Table 2-2 list the scenarios in each category that were selected for further review.

See Appendix B for a descriptive overview of these scenarios. See the VSC project Task 3 Final Report[3] for additional descriptions and details of the vehicle safety applications summarized in Table 2-1 and Table 2-2.

[3] *Task 3 Final Report - Identify Intelligent Vehicle Safety Applications Enabled by DSRC*, Public Document, Vehicle Safety Communications Project, Crash Avoidance Metrics Partnership, 2004.

Table 2-1: Safety-Related Application Scenarios

Category	Application Scenario
Intersection Collision Avoidance	• Traffic Signal Violation Warning • Stop Sign Violation Warning • Left Turn Assistant • Stop Sign Movement Assistant • Intersection Collision Warning • Blind Merge Warning • Pedestrian Crossing Information Warning
Public Safety	• Approaching Emergency Vehicle Warning • Emergency Vehicle Signal Preemption • SOS Services • Post-Crash Warning
Sign Extension	• In-Vehicle Signage Warning • Curve Speed Warning • Low Parking Structure Warning • Wrong Way Driver Warning • Low Bridge Warning • Work Zone Warning • In-Vehicle Amber Alert Warning
Vehicle Diagnostics and Maintenance	• Safety Recall Notice • Just-in-Time Repair Notification
Information from Other Vehicles	• Cooperative Forward Collision Warning • Road Condition Warning • Emergency Electronic Brake Lights • Lane Change Warning • Blind Spot Warning • Highway Merge Assistant • Visibility Enhancer • Cooperative Collision Warning • Cooperative Vehicle-Highway Automation System (Platoon) • Cooperative Adaptive Cruise Control • Road Condition Warning • Pre-Crash Sensing • Highway/Railroad Collision Warning • Vehicle-to-Vehicle Road Feature Notification • Cooperative Glare Reduction • Adaptive Headlamp Aiming

Table 2-2: Non-Safety-Related Application Scenarios

Category	Application Scenario
Traffic Management	• Intelligent On-Ramp Metering • Intelligent Traffic Flow Control
Tolling	• Free-Flow Tolling
Information from Other Vehicles	• Instant Messaging • Adaptive Drive-Train Management • Enhanced Route Guidance and Navigation • Point-of-Interest Notification • Map Downloads and Updates • GPS Correction

2.3 Vehicle Safety Application Summary

As part of the initial VSC project activities, a comprehensive list of potential vehicle safety application scenarios was compiled and evaluated. Of these, 34 vehicle safety application scenarios potentially enabled or enhanced by wireless communications were identified. It is likely that additional vehicle safety application scenarios enabled or enhanced by wireless communications will be identified in the future, especially as advances in wireless technology become available.

3 Potential Safety Benefits

3.1 Overview

For each vehicle safety application scenario discussed in Chapter 2, initial estimates of potential safety benefits were derived. These estimates were based on a crash statistic loss metric called "Functional Years Lost" from the General Motors 44 Crashes report.[4] In addition to this crash statistic loss metric, assumptions available in late 2002 and early 2003 regarding deployment, market penetration, and cooperation between infrastructure and/or other vehicles were used to estimate potential safety benefits. High-priority safety applications were identified for further evaluation based on estimates of potential safety benefits.

The VSCC and the USDOT jointly selected a subset of safety applications of mutual interest from the comprehensive list. Safety applications were selected based on potential safety benefit and were representative of the range of identified safety applications. Refer to the VSC project Task 3 Final Report[5] for additional descriptions and details on the process followed in the selection of vehicle safety applications based on potential safety benefit.

3.2 Analysis Ranking Attributes

The VSC project team defined a set of analysis categories by which the potential safety benefits of application scenarios could be compared. The team used a methodology for analysis and ranking that included consideration of:

- **Estimated Deployment Time Frame**
  Defines the estimated time frame before the application may be available on light duty vehicles in the United States. Estimated deployment time frame depends on technical factors such as additional sensor requirements, vehicle position plus map accuracy requirements, communication requirements, and cost. Near-term application systems were considered to be potentially deployable in the U.S. market between 2007 and 2011; mid-term applications deployable between 2012 and 2016; and long-term applications deployable beyond 2016.
- **Estimated Effectiveness**
  Defines the effectiveness of an application in terms of the reduction of three crashed-related factors: (i) direct dollar expenditures related to the damage and injury caused by a crash, (ii) functional years lost to fatal injury plus years lost of functional capacity to nonfatal injury, and (iii) number of vehicles involved in various crash types in the United States.

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[4] General Motors (1997). *44 Crashes, v.3.0.* Warren, MI: NAO Engineering, Safety & Restraints Center, Crash Avoidance Department.

[5] *Task 3 Final Report - Identify Intelligent Vehicle Safety Applications Enabled by DSRC*, Public Document, Vehicle Safety Communications Project, Crash Avoidance Metrics Partnership, 2004.

- **Estimated Market Penetration**
  Estimates the number of light-duty vehicles in the U.S. market that would be equipped with each vehicle safety application in each year after initial deployment. Also estimates the number of vehicles equipped with safety applications after the fifth year of deployment
- **Estimated Cooperation from Infrastructure and/or Other Vehicles**
  Estimates the probability of securing infrastructure cooperation and/or other vehicle cooperation in fifth year after deployment. Cooperation required by the applications is in the form of relevant safety-related data exchange using infrastructure-to/from-vehicle communication and vehicle-to-vehicle communication.

3.3 Relative Ranking

Relative ranking was done separately for near-, mid-, and long-term application scenarios. Application scenarios were evaluated based on benefits derived with respect to 44 Crashes. For each application system, the VSC team used engineering judgment in estimating the application ranking attributes. The methodology used to estimate the safety benefits and the relative ranking of the application scenarios is presented in the VSC project Task 3 Report.[6] It is important to stress that the VSC application safety benefits analysis was for the purpose of relative ranking of communications-enabled application scenarios. In the Addendum to the VSC project Task 3 Report,[7] the estimates for the evaluation attributes used for the application safety benefits analysis and application ranking are presented.

For each of the relevant crash types that benefit from an application scenario, the VSC team estimated the percent effectiveness of the application system to that particular crash type. The benefit distributions of an application system were computed based on two perspectives:

- **Benefit Opportunity**
  Estimate of the potential benefits derived by deployment of an application scenario in all new vehicles for each year after initial deployment.
- **Estimated Benefits**
  Estimate of the potential benefits derived by deployment of an application scenario using the VSC estimates for market.

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[6] *Task 3 Final Report - Identify Intelligent Vehicle Safety Applications Enabled by DSRC*, Public Document, Vehicle Safety Communications Project, Crash Avoidance Metrics Partnership, 2004.

[7] *Addendum to the Task 3 Final Report - Identify Intelligent Vehicle Safety Applications Enabled by DSRC*, Public Document, Vehicle Safety Communications Project, Crash Avoidance Metrics Partnership, 2004.

The percent effectiveness of the application scenario with respect to 44 Crashes, and the probability that a vehicle equipped with an application will get cooperative communication from other vehicles and/or the infrastructure is also based on the VSC team estimates.

3.4 Application Ranking

The following tables summarize estimated near-, mid-, and long-term safety benefits (functional years saved) for vehicle safety applications with the highest potential. The ranking is based on benefit opportunity for the fifth year after deployment.

Table 3-1: High Potential Benefit Near-term Applications

Application System	Benefit Opportunity (functional years saved)	Estimated Benefits (functional years saved)
Traffic Signal Violation Warning	17,627	364
Curve Speed Warning	11,189	116
Emergency Electronic Brake Lights	4,284	66

Table 3-2: High Potential Benefit Mid-term Applications

Application System	Benefit Opportunity (functional years saved)	Estimated Benefits (functional years saved)
Pre-Crash Sensing	34,172	523
Cooperative Forward Collision Warning	19,160	294
Left Turn Assistant	8,534	113
Lane Change Warning	7,354	113
Stop Sign Movement Assistant	7,217	95

Table 3-3: High Potential Benefit Long-term Applications

Application System	Benefit Opportunity (functional years saved)	Estimated Benefits (functional years saved)
Cooperative Collision Warning	59,336	5,453
Intersection Collision Warning	52,804	4,911

3.5 Potential Safety Benefits Summary

The potential safety benefits for identified vehicle safety application scenarios were estimated according to effectiveness toward known crash statistics, as well as assumptions regarding deployment, market penetration, and cooperation between infrastructure and/or other vehicles. These potential safety benefits appear to be significant for a number of the application scenarios, based on the deployment and other assumptions available in late 2002 and early 2003. As a result, eight application scenarios were identified as high priority for further research.

4 Communication Requirements and Technologies

4.1 Overview

Thirty-four vehicle safety application scenarios were analyzed and ranked. The result of this evaluation was a subset of eight representative near- and mid-term safety applications suitable to be used as a basis for establishing preliminary communication requirements. The requirements were described in terms of communications parameters defined in this chapter and key assumptions about the operational characteristics of the application scenarios.

Table 4-1: Representative Vehicle Safety Application Scenarios

Near-term	Mid-term
Traffic Signal Violation Warning	Pre-Crash Sensing
Curve Speed Warning	Cooperative Forward Collision Warning
Emergency Electronic Brake Lights	Left Turn Assistant
	Lane Change Warning
	Stop Sign Movement Assistance

- **Traffic Signal Violation Warning**
  Traffic signal violation warning uses infrastructure-to-vehicle communication to warn the driver to stop at the legally prescribed location if the traffic signal indicates a stop and it is predicted the driver will be in violation.
- **Curve Speed Warning – Rollover Warning**
  Curve speed warning aids the driver in negotiating curves at appropriate speeds.
- **Emergency Electronic Brake Lights**
  When a vehicle brakes hard, the emergency electronic brake light application sends a message to other vehicles following behind.
- **Pre-Crash Sensing**
  Pre-crash sensing prepares the driver for imminent, unavoidable collisions.
- **Cooperative Forward Collision Warning**
  Cooperative forward collision warning system aids the driver in avoiding or mitigating collisions with the rear end of vehicles in the forward path of travel through driver notification or warning of the impending collision. The application does not attempt to control the host vehicle to avoid an impending collision.

- **Left Turn Assistant**
  The left turn assistant application informs the driver about oncoming traffic to assist in making a left turn at a signalized intersection without a phasing left turn arrow.
- **Lane Change Warning**
  The lane change warning application warns the driver if an intended lane change may cause a crash with a nearby vehicle.
- **Stop Sign Movement Assistance**
  The stop sign movement application warns the driver that the vehicle is about to pass through an intersection after having stopped at a stop sign.

4.2 Assumptions

Several assumptions about operational characteristics were used to define the communication requirements of the representative safety applications, including:

- The rapid evolution of wireless technologies provides opportunities to use these technologies in support of advanced vehicle safety applications. In particular, DSRC at 5.9 GHz offers the potential to effectively support wireless data communications between vehicles and between vehicles and infrastructure.
- A standardized DSRC message set and data dictionary would be established for safety applications that use vehicle-to-vehicle and/or vehicle-to-infrastructure communications. The message set would require agreement by all public and private sector organizations involved in this aspect of DSRC.
- Some applications would require periodic broadcasts (e.g., every 100 msec.) from vehicles in order to identify the roadway position. The transmitted data would need to be based on a location-referencing standard accepted by DSRC stakeholders.
- Many of the preliminary communication requirements call for an on-board unit with a communication range between 100 to 1,000 meters. The practicality of these requirements in light of transmission characteristics such as multipath and interference with other DSRC applications should be studied before such requirements are finalized.
- Many of the applications require communications in multiple directions from the vehicle. Conceptually, this could be achieved through an on-board unit using an omnidirectional antenna, although transmission characteristics should be considered when evaluating the performance of such a system. The use of a directional antenna (especially for roadside units) should be considered for those applications in which data need only be transmitted or received in a specific direction.

- Security is an open issue for all of the applications. Potential security measures could include a method for assuring that packet/data was generated by a trusted source and that the packet/data was not tampered with or altered after it was generated. Any application that involves a financial transaction (such as tolling) requires the capability to perform a secure transaction.

4.3 Communication Parameters

The application scenarios require cooperation from the infrastructure, other vehicles, or both in the form of relevant safety-related data exchange using infrastructure-to/from-vehicle communication and/or vehicle-to-vehicle communication. The proposed operational characteristics and preliminary communication requirements for the eight vehicle safety applications are described in terms of the following parameters:

- **Type of Communication**
  Considers the (a) source-destination of the transmission (infrastructure-to-vehicle, vehicle-to-infrastructure, or vehicle-to-vehicle communications), (b) direction of the transmission (one-way or two-way), and DSRC communication, and (c) source reception of the communication (point-to-point or point-to-multipoint).
- **Transmission Mode**
  Describes whether the transmission is triggered by an event (event-driven) or sent automatically at regular intervals (periodic).
- **Minimum Frequency**
  Defines the minimum rate at which a transmission should be repeated (e.g., 1 Hz).
- **Allowable Latency**
  Defines the maximum duration of time allowable between when information is available for transmission and when it is received (e.g., 100 msec).
- **Data to Be Transmitted and/or Received**
  Describes the contents of the communication (e.g., vehicle location, speed, and heading). Design considerations include whether or not vehicles make periodic broadcasts to identify their positions on the roadway and how privacy is best maintained.
- **Maximum Required Range of Communication**
  Defines the communication distance between two units that is required to effectively support a particular application (e.g., 100 m).

4.4 Comparison of Wireless Communication Technologies

Currently available wireless communications technologies that could possibly be applied to the representative vehicle safety applications identified earlier in this chapter included:

- 5.9 GHz DSRC
- 2.5-3G PCS and Digital Cellular
- Bluetooth
- Digital Television (DTV)
- High-Altitude Platforms
- IEEE 802.11 Wireless LAN
- Nationwide Differential Global Positioning System (NDGPS)
- Radar
- Remote Keyless Entry (RKE)
- Satellite Digital Audio Radio Systems (SDARS)
- Terrestrial Digital Radio
- Two-Way Satellite
- Ultra-Wideband (UWB)

Table 4-2 summarizes the capabilities of these wireless technologies. A detailed discussion is presented in the VSC Task 3 Final Report.

Table 4-2: Comparison of Wireless Technologies

Wireless Technology	5.9 GHz DSRC	2.5-3G PCS and Digital Cellular	Bluetooth	Digital Television(DTV)	High Altitude Platforms	IEEE 802.11 Wireless LAN	Nationwide Differential Global Positioning System	Radar	Remote Keyless Entry (RKE)	Satellite Digital Audio Radio Systems (SDARS)	Terrestrial Digital Radio	Two-Way Satellite	Ultrawideband (UWB)
Capabilities													
Range	1000 m	~4-6 km	10 m	~40 km	120 km	1000 m	300-400 km	2 km	30 m	US 48 States	30-50 km	N/A	15-30 m
One-Way To Vehicle	X			X	?		X	X	X	X	X		?
One-Way From Vehicle	X				?			X					?
Two-Way	X				?							X	?
Pont-To-Point	X	X	X		?	X			X			X	?
Point-To-Multipoint	X	X	X	X	?	x	X	X		X	X		?
Latency	200 µsec	1.5-3.5 sec	3-4 Sec	10-30 sec	?	3-5 sec	N/A	N/A	N/A	10-20 sec	10-20 sec	60+sec	?

4.5 Preliminary Application Communication Scenario Requirements

Wireless technologies are rapidly evolving. This evolution provides opportunities to use these technologies in support of advanced vehicle safety applications and crash avoidance countermeasures. For example, DSRC offers the potential to support low-latency wireless data communications between vehicles and between vehicles and infrastructure. Low-latency data communications within the immediate vicinity of a vehicle potentially enable a large number of vehicle safety applications including crash avoidance countermeasures.

Table 4-3 summarizes the preliminary communication requirements in terms of the previously defined parameters.

Table 4-3: Preliminary Application Scenario Communication Requirements

	Comm Type	Trans Mode	Min. Freq (Hz)	Latency (msec)	Data to Be Transmitted and/or Received	Max. Req'd Comm Range (m)
Traffic Signal Violation Warning	• Infrastructure -to-vehicle • One-way • Point-to-multipoint	Periodic	~10	~100	• Traffic signal status • Timing • Directionality • Position of the traffic signal stopping location • Weather condition (if available) • Road surface type	~250
Curve Speed Warning	• Infrastructure -to-vehicle • One-way • Point-to-multipoint	Periodic	~1	~1000	• Curve location • Curve speed limits • Curvature • Bank • Road surface condition	~200
Emergency Electronic Brake Lights	• Vehicle-to-vehicle • One-way • Point-to-multipoint	Event-driven	~10	~100	• Position • Heading • Velocity • Deceleration	~300
Pre-Crash Sensing	• Vehicle-to-vehicle • Two-way • Point-to-point	Event-driven	~50	~20	• Vehicle type • Position • Velocity • Acceleration • Heading • Yaw-rate	~50
Cooperative Forward Collision Warning	• Vehicle-to-vehicle • One-way • Point-to-multipoint	Periodic	~10	~100	• Position • Velocity • Acceleration • Heading • Yaw-rate	~150

	Comm Type	Trans Mode	Min. Freq (Hz)	Latency (msec)	Data to Be Transmitted and/or Received	Max. Req'd Comm Range (m)
Left Turn Assistant	• Vehicle-to-infrastructure and infrastructure-to-vehicle • One-way • Point-to-multipoint	Periodic	~10	~100	• Traffic signal status • Timing • Directionality; • Road shape and intersection information; • Vehicle position • Velocity • Heading	~300
Lane Change Warning	• Vehicle-to-vehicle • One-way • Point-to-multipoint	Periodic	~10	~100	• Position • Heading • Velocity • Acceleration • Turn signal status	~150
Stop Sign Movement Assistance	• Vehicle-to-infrastructure and infrastructure-to-vehicle • One-way • Point-to-multipoint	Periodic	~10	~100	• Vehicle position • Velocity • Heading; • Warning	~300

For each high-priority application that ranked high in potential safety benefits, the VSC project team defined system level architecture and concepts of operation. The definitions included development of initial system architecture block diagrams, illustrations and information flowcharts, identification of sensors and other system needs, data message sets, and message size. Communications parameter values for the application scenarios were specified based on evaluation of the proposed system concept, engineering judgment, and industry experience. See the VSC project Task 3 Report[8] for details.

4.6 Preliminary Communications Requirements Summary

The VSC project team analyzed the eight high-priority vehicle safety applications scenarios and determined preliminary communications requirements for these scenarios, including:

- Message packet size of 200 to 500 bytes (all 8 scenarios)
- Maximum required range of communications of 50 to 300 meters (all 8 scenarios)
- One-way, point-to-multipoint broadcast messages (7 of 8 scenarios)

[8] *Task 3 Final Report - Identify Intelligent Vehicle Safety Applications Enabled by DSRC*, Public Document, Vehicle Safety Communications Project, Crash Avoidance Metrics Partnership, 2004.

- Two-way, point-to-point messages (1 of 8 scenarios)
- Periodic transmission mode (6 or 7 of 8 scenarios)
- Event-driven transmission mode (1 or 2 of 8 scenarios)
- Allowable latency of 100 milliseconds (6 of 8 scenarios)
- Allowable latency of 20 milliseconds (1 of 8 scenarios)
- Allowable latency of 1 second (1 of 8 scenarios)

If additional high-priority applications scenarios are identified, or if alternative scenarios are developed for identified vehicle safety applications, it will likely become necessary to reexamine these preliminary communications requirements.

It is expected that the communications requirements will need further refinement as prototype vehicle safety applications are developed from a safety-systems design perspective.

5 Field and Simulation Testing

5.1 Overview

VSCC tested the communications functionalities and potential technical feasibility of using DSRC to enable and enhance vehicle-safety systems and applications. Two levels of testing were performed:

- **Field Testing and Evaluation**
  Test track and public roadway evaluations to establish technical feasibility and to enable the future design and development of potential vehicle safety applications.
- **Simulation Testing and Evaluation**
  Evaluation of simulated DSRC performance in an urban intersection environment densely populated with DSRC-equipped vehicles and infrastructure.

5.2 Field Testing and Evaluation

VSCC assessed the viability of DSRC relevant to potential safety applications in real-world environments through field testing on test tracks and public roadways. This was accomplished through the testing and evaluation of communication functionalities started in Task 4 and continued in Task 10, using both vehicle-vehicle and vehicle-infrastructure wireless data transfer. Various antenna configurations also were evaluated to determine the most realistic and deployable physical structure that would meet technical requirements.

For the initial field testing, VSCC designed and developed 20 first-generation communications DSRC test kits. The kits enabled engineering testing in a number of different locations and configurations using different vehicles in test track and public roadway environments. The field testing did not require the procurement of dedicated test vehicles as individual manufacturers used their own vehicles with proprietary on-board systems.

The simulations and test results for the antenna design activity are presented in detail in Appendix D. The design details and test results for the WAVE radio modules are provided in Appendix E.

The anticipated communications parameters for two potential vehicle-safety application scenarios were tested in detail: Traffic Signal Violation Warning and Emergency Electronic Brake Lights. Testing focused on three areas:

- Collecting and analyzing data in real-world intersection environments to determine communications characteristics.
- Intersection testing using an interface with a traffic-signal controller to transmit actual traffic signal data.

- Vehicle-to-vehicle testing using test track and public roadway environments to send actual common message set data between vehicles.

5.2.1 Transmission Characteristics at Intersections

One goal of the testing was to evaluate the potential technical feasibility of deploying future intersection-based safety systems, like traffic signal violation warning. Testing focused on the capability of a DSRC on-board unit (OBU) to receive packets sent from a dedicated roadside unit (RSU) stationed near an intersection. A key issue investigated by VSCC was the degree to which a test vehicle could move through different types of intersections while maintaining communications with the RSU when variables such as buildings, terrain, roadway geometry and traffic conditions were presented.

The equipment used during initial phases of this evaluation consisted of test kits, radio modules, and 5.9 GHz antennas developed under VSC Tasks 4, 6A, and 6C. Fifteen intersection test sites were selected based on a broad range of characteristics. A comprehensive visualization approach involving aerial photos was used to illustrate how well packet reception is maintained as a test vehicle approaches, passes through, and moves away from an intersection.

The findings from tests conducted at a representative intersection demonstrated an 85 percent successful transmission ratio while the test vehicle was approaching the RSU from 250 m, and a 99 percent success ratio while approaching from 100 m. The results were derived with an inverted OBU roof-mount antenna serving as the RSU antenna (clearly not optimized for RSU conditions), and with the antenna situated at a less-than-optimal position (intersection corner, 10 feet high above the ground).

The transmission success ratios vary from intersection to intersection based on factors such as the density of traffic between the RSU and the OBU antennas, and whether or not the line-of-sight is blocked by objects alongside a curving roadway. Implementing an intersection-based safety application will need to address similar types of obstructions, but aside from these particular situations, the ability of a vehicle to receive packets from an RSU positioned at an intersection under realistic traffic conditions was proven.

5.2.2 Intersection Controller Data Exchange

In addition to testing transmission characteristics at intersections, arrangements were made to send test data from a roadside location in one, real-world intersection using a programmed traffic-signal-controller box. The objective was to work toward developing implementation requirements for interfacing with existing traffic control equipment to support potential vehicle safety applications effectively. Rather than connecting the test equipment to the traffic signal controller that actually controlled the traffic lights, the VSC team opted to connect the equipment to a second, independent controller.

The later phase field testing conducted at this location used test equipment developed in Tasks 6D and 9, consisting of WAVE radio modules (WRMs) and associated interface software. This new equipment was necessary in order to support the data connection from the traffic signal controller and the transmission of the resultant dynamic data. The test runs were similar to the intersection evaluations with an OBU-equipped test vehicle traveling through the test intersection.

The VSC team successfully synchronized the traffic-signal controller with the installed controller at the intersection. The OBU correctly received the traffic controller data, consisting of the signal state and the time remaining. The resolution of the time remaining (1 sec) available with the test setup was deemed not adequate. To satisfy the 100 msec safety applications update rate requirement for the RSU message, the signal controller software and serial protocol would require more elaborate modifications for improving the 200 msec update rate achieved with the controller.

For a safety application such as Traffic Signal Violation Warning, no major communications issues were uncovered in Task 10 testing that conflicted with the preliminary requirements from Task 3. DSRC 5.9 GHz wireless communication at the test intersection was characterized overall with a 93 percent successful transmission ratio over the range of interest of 250 m. Power control tests were performed to verify the capability to control the maximum range of communication at a real world intersection. The test results showed that some level of maximum transmission range control could be achieved with the proper selection of transmission power. The results show that this current test equipment, which is representative of the currently approved lower layer DSRC standard, can likely support communications for application scenarios like Traffic Signal Violation Warning.

5.2.3 Vehicle Data Exchange

Vehicle-to-vehicle testing was conducted to evaluate the performance of the WRMs and associated interface software developed in Tasks 6D and 9, and to demonstrate the wireless exchange of dynamic data between different vehicle makes.

Depending upon vehicular configuration (e.g., available sensors, vehicle-specific CAN output), various amounts of information were contained in the vehicle-to-vehicle messages sent and received between vehicles. Some vehicles exchanged full sensor data based upon the proposed SAE Common Vehicle-to-Vehicle Message Set; others provided only basic information. All messages, however, contained vehicle location (i.e., GPS) information and were typically forced to 200 bytes in size.

Results showed 100 percent reception and no packet loss between two vehicles up to ranges that exceed 200 m in a vehicle following scenario, and up to ranges exceeding 600 m in both directions of travel. Reducing the transmit power from 20 dBm to 5 dBm reduced the maximum range to approximately 250 m in both directions of travel. Increasing the data rate from 6 Mbps to 27 Mbps resulted in higher packet losses and a reduction in communication range.

Testing was conducted on an interstate freeway and a State highway. Seven test vehicles formed a caravan with information shared among all. In general, the results showed that in a freeway environment, there was communication between vehicles to 180 m range with transmission power of 20 dBm. In a freeway ramp environment, there was communication between vehicles to a 100-meter range with a reduced transmit power of 16 dBm.

Based on the vehicle-to-vehicle testing, it is clear that the performance of the WRMs is adequate for future vehicle-safety application development. The field testing suggests that safety systems using DSRC communications show promise. VSCC encourages the

next stages of development be undertaken to proceed toward the timely deployment of these potential vehicle safety applications.

5.3 Simulation Testing and Evaluation

VSCC tested and evaluated simulated DSRC performance in an urban intersection environment densely populated with DSRC-equipped vehicles and infrastructure. This was done to assess simulation test scenarios of high volume, signalized intersections. A simulation test environment was configured, containing both a high traffic volume intersection with a freeway nearby. Both environments were filled with dense vehicle traffic. Great care was taken so that both the environment and the vehicle traffic patterns reflected realistic, though stressing conditions.

The results of the simulation testing in this stressing environment showed that channel capacity will need to be preserved for effective, large-scale deployment of vehicle safety applications. Adaptive protocols for scaled situations should be developed based on the potential for temporarily or intermittently reducing update rate, transmission power, or both while recognizing congested channel conditions. These adaptive protocols for congested conditions could then be incorporated into future real-world and simulation testing to ensure that the desired application performance could be realized.

5.3.1 High Priority Emergency Messages

In Tasks 4 and 6A, the proposed priority mechanism for DSRC was found to enhance a high-priority message's likelihood of successful reception. In Task 12, this same conclusion was reached for an urban environment where high-priority emergency message prioritization consistently improved reception probability over routine messages by 5 percent to 40 percent and reduced latency across a wide-range of simulation scenarios. Overall simulation test results showed that emergency message reception probability in a city environment dropped 25 percent to 50 percent when the DSRC channel was stressed with 134 to 230 cars/lane mile transmitting 200 byte routine messages every 100 msec with a 200 m range. This suggested a requirement for a high-availability, low-latency channel for latency-critical safety applications.

To further study the support of high-priority emergency messages for critical safety applications, simulated cascading emergency messages were evaluated. This was done to emulate the expected communication pattern/protocol of a class of safety applications from Task 3 that might benefit from message cascading. The simulation test results indicated that even in a saturated channel, high-priority messages cascaded through a traffic lane of 70 vehicles within one or two repetitions per node in 0.2 to 1.2 sec. However, an in-depth analysis of safety application protocol design is needed before more meaningful insights into these results can be drawn.

5.3.2 Routine Safety Messages

The reception probability rate for routine safety messages was found to be more sensitive than emergency messages to channel loading. This sensitivity was of significant interest since the channel is expected to be occupied primarily by this class of message, due to the anticipated routine transmission of the common vehicle-to-vehicle safety message.

The simulation test environment was configured to represent a high-traffic volume intersection environment with commensurately heavy communication levels due to DSRC message density. Within this simulation context, routine message latencies at particular confidence levels were insensitive to changes in routine message transmission rates from 6 to 10 Hz. These simulation results for routine safety messages further illustrate that channel capacity is an issue that will need to be addressed adequately for large-scale deployment in stressing traffic environments.

5.3.3 Intersection RSU Rebroadcast of Routine Messages

The simulation tests demonstrated that using an intersection RSU to rebroadcast routine safety messages to improve vehicle communications around a corner causes internal queue overflow in the RSU even in an otherwise moderately loaded channel. This method did, however, improve emergency message performance around a corner since these messages were far less plentiful and at higher priority than routine messages generated from all vehicles.

5.4 Field and Simulation Testing Summary

The field testing conducted under the VSC project confirmed the viability of DSRC communications for vehicle safety applications at real intersection locations under typical traffic conditions. The field testing results also demonstrated the successful exchange of the preliminary SAE common safety message set needed for vehicle-to-vehicle safety applications between vehicles from different manufacturers. These favorable field testing results demonstrated the apparent technical feasibility of the current DSRC technology, based upon the preliminary communications requirements of vehicle safety applications. This favorable evaluation enables the future development and testing of prototype vehicle safety applications.

The simulation testing completed during the VSC project implied the requirement for a high-availability, low-latency channel for latency-critical safety applications. The simulation testing also showed that emergency message prioritization consistently improved the reception probability over routine messages by 5 percent to 40 percent, and reduced the communications latency across a wide range of simulation scenarios. The simulation results further illustrated that channel capacity is an issue that will need to be adequately addressed for large-scale deployment in stressing traffic environments.

6 DSRC Communication and Security Standards

6.1 Overview

VSCC participated in the development of the DSRC standards recently underway through standards organizations such as the American Society for Testing and Materials (ASTM), the Institute of Electrical and Electronic Engineers (IEEE), and the Society of Automotive Engineers (SAE). The goal of VSCC's participation was to ensure that the communications requirements of vehicle safety applications were addressed adequately.

VSCC worked with the standards development organizations to ensure that WAVE/DSRC standard protocols meet the needs of anticipated vehicle safety applications. This work included upper-layer WAVE standards development and WAVE/DSRC security standard development through IEEE, lower-layer standards refinement and approval through IEEE 802.11, and DSRC testing and validation standard through ASTM. It also included safety message sets and data dictionary standards development in the SAE. The direct participation of the VSCC in DSRC standards development appears to be a highly efficient way to understand, analyze, and influence the development of the majority of DSRC standards.

The DSRC communications system is based on well known wireless networking principles. The system relies on a carrier sense scheme to determine when the wireless channel is free, and uses a random time interval delay or "back off" to separate simultaneous users. This contention based scheme has proven effective in dynamic multi user wireless communications situations. Upper layers of the protocol rely on a combination of established Internet protocols and some new low latency short messaging schemes. For a more complete description of the underlying technologies, refer to the *Computer Networks* by A. S. Tannenbaum[9].

6.2 Communications Standards

The VSCC presented and interpreted the communications requirements of vehicle safety applications through active participation at DSRC standards meetings. As a result, the standards were modified or developed in a number of areas to better support the communications requirements of vehicle safety applications.

Specific areas that the VSCC addressed at standards meetings included:

- Broadcast-type messages
- Random Medium Access Control (MAC) addresses
- Short header for vehicle safety messages
- Antenna characteristics
- Vehicle safety messages on control channel

[9] Tannenbaum, Andrew S. *Computer Networks*, 3rd Edition, Prentice Hall, 1996.

- High-availability, low-latency channel
- Priority for vehicle safety applications
- Message set standardization
- Security

6.3 Standards Support for Vehicle Safety Requirements

The FCC DSRC Report and Order (FCC Document FCC 03-324 in regard to WT Docket No. 01-90 and ET docket No. 98-95, Final rule and Order Adopted December 17, 2003, and Released on February 10, 2004) went into effect in October 2004, and mandated the use of the ASTM E2213-03 lower-layer standard. The Report and Order contained a majority of features that were favorable to the potential deployment of vehicle safety applications. However, it did not mandate the high-availability, low-latency channel (ch172) suggested by the VSCC.

The ASTM E2213-03 standard mandated by the FCC appears to facilitate lower-layer interoperability. Test equipment based on this standard provided support for vehicle safety communications during the VSC field testing. This standard is currently undergoing a revision process within the ASTM committee. Plans are underway to replace the ASTM E2213-03 standard in the FCC mandate with the emerging IEEE 802.11p lower-layer standard, once it is completed. IEEE 802.11p is based on the anticipated revisions in ASTM E2213-03, and is expected to provide on-going synergies with IEEE 802.11a chipset designs.

The IEEE P1609 committee was tasked through the IEEE Project Authorization Request (PAR) for the development of the upper-layer DSRC standards. The upper-layer protocols are being planned as a complement to the lower-layer standard, and will depend upon lower layer standards for implementation. Through active participation in the IEEE P1609 committee the VSC team presented and promoted the communications requirements for vehicle safety applications. As of November 2004, a smaller technical drafting group was preparing updated draft standards for subsequent consideration by the IEEE P1609 committee. Although previous drafts of IEEE P1609 standards appeared to support vehicle safety communications requirements, the newly updated upper layer standards will need to be thoroughly analyzed and evaluated as soon as they are available. In addition, testing and validation of the DSRC standards is expected to begin as soon as software that implements the DSRC upper-layer standard protocols on generic host computers, and/or standards-compliant prototype equipment, becomes available. Revisions to the standards are likely to be required as a result of this testing and validation by various stakeholders.

A common vehicle-to-vehicle safety message set was developed in the SAE DSRC technical committee. A preliminary version of this message set was successfully sent and received using fields populated with actual CAN data between vehicles from two different manufacturers during VSC field testing. As of November 2004, a common intersection-to-vehicle safety message set was under development in the SAE committee.

A vehicle-to-vehicle safety message set to support pre-crash scenarios was also under development.

6.4 Security Standards

Security is an important consideration for DSRC vehicle safety applications. For the system to be secure, the applications must be able to trust that the communication has been received unaltered and from a known source. In addition, the communication must be anonymous, at least to passive listeners. It must require a low amount of computational and communications overhead and must be robust in the event of individual units being compromised.

There are unique DSRC security requirements for vehicle safety applications. Most of the vehicle safety application scenarios studied in the VSC project broadcast messages to all receivers, rather than directed to a given peer. This creates additional security challenges.

Vehicle safety requirements and potential solution suggestions have been presented and promoted by the VSC team to the IEEE P1556 standards development process. As of November 2004, a technical drafting group was integrating the requirements of other stakeholders with the vehicle safety requirements and proposed solutions. The result will be an updated draft standard for consideration by the IEEE P1556 committee.

6.4.1 Threats

The VSCC described a threat model, listed the constraints, and discussed these with the DSRC standardization groups. Four types of threats of increasing empowerment related to vehicle safety communication systems' endangerment were identified:

- Type 1: Attackers with a programmable radio transmitter/receiver
- Type 2: Attackers with access to an un-modified VSC unit
- Type 3: Attackers with access to a modified VSC unit who have obtained the keying material
- Type 4: Attackers inside manufacturing or security programming with full access

The capabilities of each attacker were evaluated and documented in Task 6B. System constraints in the categories of network characteristics, environmental characteristics, cost of goods, and management costs were estimated.

6.4.2 Defense

The threat model and constraints led to the core of the task—an architecture design that the VSCC believes may adequately address the identified threats while meeting the estimated constraints within this task.

- All on-board units and roadside units (RSUs) are issued certificates (OBUs are issued multiple certificates) in a special, compact format.

- The certificates for RSUs contain authorization information such as the area in which the unit is permitted to operate and the type of information it is allowed to broadcast.
- OBU certificates do not contain the permanent vehicle-identity information.
- All messages are digitally signed. Any units suspected of being compromised are put on a revocation list that is flooded to all other units.

Security comes at a price. Even with the currently proposed architecture, which includes many optimizations, each message transmitted would include significant overhead, and the message signatures would take time to process once they are received. Management of a public key infrastructure for RSUs would be necessary, according to the proposed scheme. In addition, there are piece costs, administrative costs, maintenance costs, and enforcement costs.

6.5 Standards and Security Summary

During the VSC project, a test system based on the lower-layer DSRC standard was developed and used to conduct extensive communication field testing. The preliminary SAE common safety message set needed for vehicle-to-vehicle safety applications was successfully implemented in VSCC field testing. This message set allowed the exchange of actual vehicle bus data in a standard format between vehicles from different manufacturers.

As a result of active participation in the DSRC standards development process, the VSCC evaluated proposed DSRC standards, identified specific technical issues, presented vehicle safety requirements and a proposed security solution, and secured necessary revisions in eight major areas. The IEEE committee is currently considering vehicle safety communications requirements and proposed security solution presented by the VSCC. Testing and validation of these emerging DSRC standards should be initiated as soon as the standards become available. As these standards become available for deployment, upper-layer DSRC standards enforcement will be necessary to ensure interoperability of vehicle safety applications.

The preliminary vehicle safety communications requirements appear to be well-supported by the FCC Report and Order, and the current lower-layer DSRC standards mandated by the FCC. However, the high-availability, low-latency DSRC channel that is likely required for particular vehicle safety applications was not mandated in the FCC Report and Order. Future technical work will be required to justify fully the need for the high-availability, low-latency channel, but it is important to reserve a DSRC channel at this time for this potential usage.

7 Conclusions

7.1 Summary of Project Accomplishments

The VSC project began in May 2002. The purpose of this project was to evaluate vehicle safety applications potentially enabled or enhanced by wireless communications, identify associated communications requirements, and promote the accommodation of these requirements in developing communications standards. As a result of work on this project, VSCC has:

- Prepared a comprehensive list of thirty-four potential vehicle safety application scenarios enabled or enhanced by wireless communications.
- Developed preliminary communications requirements for the potential application scenarios.
- Estimated potential safety benefits resulting from the deployment of vehicle safety applications.
- Identified eight high-priority vehicle safety applications based on estimated potential safety benefits.
- Conducted extensive communication testing on scenarios representative of the eight high-priority applications with promising results.
- Developed the first lower-layer DSRC standard compliant test system (hardware and software) with vehicle and infrastructure interfaces to enable potential prototyping of prospective communication-based vehicle safety applications.
- Conducted extensive testing at 15 intersections and confirmed the successful functioning of DSRC communications for potential vehicle safety applications at a real intersection.
- Synchronized a traffic controller unit to an existing intersection unit to transmit actual signal timing and phase for future intersection collision avoidance applications.
- Confirmed reception of signal timing and state by on-board units.
- Implemented and demonstrated successful exchange of preliminary SAE common message set needed for vehicle-to-vehicle safety applications.
- Identified channel capacity issues in traffic density scenarios through simulations and recommended development of an adaptive DSRC protocol to improve communication reliability in stressful traffic environments.
- Determined that 5.9 GHz DSRC represents the wireless technology most likely to support the communications requirements of the majority of vehicle safety applications.

7.2 VSC Findings

7.2.1 Applications

A variety of safety applications are feasible using wireless communications between the vehicle and the roadside and between vehicles. The full safety improvement impact of these applications generally depends on the extent of penetration of the systems in the vehicle fleet and the availability of supporting infrastructure systems. Therefore, conditions required for rapid and thorough infrastructure deployment across the country, and rapid penetration in to the annual vehicle build, must be established in order to fully exploit the potential safety benefits of the assessed applications.

From the 34 application scenarios potentially enabled or enhanced by wireless communications, eight were identified as high-priority and selected for further research based on the estimated potential safety benefits.

- High Potential Benefit Near-term Applications
  - Traffic Signal Violation Warning
  - Curve Speed Warning
  - Emergency Electronic Brake Lights
- High Potential Benefit Mid-term Applications
  - Pre-Crash Sensing
  - Cooperative Forward Collision Warning
  - Left Turn Assistant
  - Lane Change Warning
  - Stop Sign Movement Assistant

7.2.2 Communications

Preliminary communications requirements were determined for the eight high-priority vehicle safety application scenarios. Most of these application scenarios required periodic transmission of one-way, point-to-multipoint broadcast messages. The message packet size was 200 to 500 bytes with a communications range of 50 to 300 meters.

Several assumptions about operational characteristics are necessary to assure the functionality of the proposed/evaluated applications:

- The rapid evolution of wireless technologies will provide opportunities to use these technologies in support of advanced vehicle safety applications.
- A standardized DSRC message set and data dictionary will be established for safety applications that use vehicle-to-vehicle and/or vehicle-to-infrastructure communications. The message set would require agreement by all public and private sector organizations involved in this aspect of DSRC.

- Some applications will require vehicles periodic broadcasts (e.g., every 100 msec.) from vehicles in order to identify the roadway position. The transmitted data would need to be based on a location-referencing standard accepted by DSRC stakeholders.
- On-board units will be capable of supporting a communication range between 100 to 1000 meters.
- Suitable technical processes and supporting administrative infrastructures will be established to support secure and authenticated transactions. This includes assumptions about certificate generation and distribution, as well as OBU lifecycle management and the secure retirement of terminal equipment.

The preliminary vehicle safety communications requirements appear to be supported by the FCC Report and Order, and the current lower-layer DSRC standards mandated by the FCC. However, the high-availability, low-latency DSRC channel required for particular vehicle safety applications was not. It is expected that the communications requirements will need further refinement as prototype vehicle safety applications are developed from a safety-systems design perspective.

- Functionality of DSRC communications for vehicle safety application scenarios at real intersections was confirmed. The findings from tests conducted at a representative intersection demonstrated an 85 percent successful transmission ratio while the test vehicle was approaching the RSU from 250 m, and a 99 percent success ratio while approaching from 100 m.
- The transmission success ratios vary from intersection to intersection. Implementing an intersection-based safety application will need to address specific structural aspects of the intersection, but the ability of a vehicle to receive packets from an RSU positioned at an intersection under realistic traffic conditions was proven
- For a safety application such as Traffic Signal Violation Warning, no major communications issues were uncovered. DSRC 5.9 GHz wireless communication at the test intersection was characterized overall with a 93 percent successful transmission ratio over the range of interest of 250 m. The results show that the current test equipment, which is representative of the currently approved lower layer DSRC standard, can likely support communications for application scenarios like Traffic Signal Violation Warning.
- Simple isotropic antennas appear to meet OBU communication needs for the studied applications.

Based on the vehicle-to-vehicle testing, it is clear that the performance of the WAVE radio modules is adequate for future vehicle-safety application development. The field testing suggests that safety systems using DSRC communications show promise. VSCC encourages the next stages of development be undertaken to proceed toward the timely deployment of these potential vehicle safety applications.

Simulation testing showed that channel capacity will be a critical issue for effective, large-scale deployment of vehicle safety applications. Adaptive protocols for scaled situations should be developed based on the potential for temporarily or intermittently reducing update rate, transmission power, or both while recognizing congested channel conditions. These adaptive protocols for congested conditions could then be incorporated into future real world and simulation testing to ensure that the desired application performance could be realized.

7.2.3 Standards

The preliminary vehicle safety communications requirements appear to be well-supported by the FCC Report and Order, and the current lower-layer DSRC standards mandated by the FCC. However, the high-availability, low-latency DSRC channel that is likely required for particular vehicle safety applications was not designated in the FCC Report and Order. Future safety application prototyping will justify fully the need for the high-availability, low-latency channel, but it is important to reserve a DSRC channel at this time for this potential usage.

Plans are underway to replace the ASTM E2213-03 standard in the FCC mandate with the emerging IEEE 802.11p lower-layer standard, once it is completed. IEEE 802.11p is based on the anticipated revisions in ASTM E2213-03, and is expected to provide on-going synergies with IEEE 802.11a chipset designs.

As of November 2004, smaller technical drafting groups were preparing updated draft standards for subsequent consideration by the IEEE P1609 and P1556 committees. Although previous drafts of IEEE P1609 standards appeared to support vehicle safety communications requirements, the newly updated upper layer standards, and the P1556 security standard will need to be thoroughly analyzed and evaluated as soon as they are available.

7.3 Remaining Needs

At the present time, there are no complete, detailed safety systems designs or detailed communications requirements for specific vehicle-safety applications. DSRC communications protocols need to be identified and tested, specifically for any proposed revisions to the lower-layer standards in ASTM or IEEE 802.11p as well as upper-layer DSRC standards under development in IEEE P1609. There is a need to actively participate in the development of DSRC standards that have not yet been completed, as well as those that are anticipated to be developed in the future.

Further, there is a need to focus on complete systems designs for specific prototypes for a number of vehicle safety applications. It is not yet certain if vehicle safety applications can be designed to effectively mitigate the effects of potential channel overloading in high-traffic environments. Communications requirements need to be refined to the detailed protocol level through the design of several representative prototypes for vehicle safety applications. There is also a need to aid in the development and testing of additional vehicle safety message sets to support infrastructure-to/from-vehicle safety applications and specific applications with potentially unique message requirements.

7.4 Potential Next Steps

Based on the VSC project accomplishments, and the remaining needs that have been identified, VSCC envisions that the following steps be undertaken:

- Develop prototype cooperative intersection collision-avoidance safety applications.
- Develop prototype communication-based vehicle-to-vehicle safety applications.
- Develop adaptive DSRC protocols to improve communication reliability in stressful traffic environments.
- Continue to influence and contribute to DSRC standards development from a vehicle safety communication requirements standpoint.
- Implement and test upper-layer and security standards, when available.

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