

Vehicle Safety Communications - Applications: System Design & Objective Testing Results

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ABSTRACT

The USDOT and the Crash Avoidance Metrics Partnership-Vehicle Safety Communications 2 (CAMP-VSC2) Consortium (Ford, GM, Honda, Mercedes, and Toyota) initiated, in December 2006, a three-year collaborative effort in the area of wireless-based safety applications under the Vehicle Safety Communications-Applications (VSC-A) Project. The VSC-A Project developed and tested communications-based vehicle safety systems to determine if Dedicated Short Range Communications (DSRC) at 5.9 GHz, in combination with vehicle positioning, would improve upon autonomous vehicle-based safety systems and/or enable new communications-based safety applications. The project addressed the following objectives:

- Assess how previously identified crash-imminent safety scenarios in autonomous systems could be addressed and improved by DSRC+Positioning systems
- Define a set of DSRC+Positioning based vehicle safety applications and application specifications including minimum system performance requirements

- Develop scalable, common vehicle safety communication architecture, protocols, and messaging framework (interfaces) necessary to achieve interoperability and cohesiveness among different vehicle manufacturers. Standardize this messaging framework and the communication protocols (including message sets) to facilitate future deployment.
- Develop requirements for accurate and affordable vehicle positioning technology needed, in conjunction with the 5.9 GHz DSRC, to support most of the safety applications with high-potential benefits
- Develop and verify a set of objective test procedures for the vehicle safety communications applications

In this paper, we summarize the work that took place in the VSC-A Project in the areas of system design and objective testing. We first introduce the VSC-A system framework. We then list the crash imminent scenarios addressed by the VSC-A Project and the safety applications selected to potentially address them. Next we describe the VSC-A test bed system development. This test bed was ultimately used to verify Vehicle-to-Vehicle (V2V) communication interoperability

between Ford, GM, Honda, Mercedes-Benz, and Toyota vehicles. Public demonstrations of V2V interoperability were held in New York City at the 2008 Intelligent Transport Systems (ITS) World Congress. The test bed also served to validate the system and minimum performance specifications that were developed as part of this project. We discuss one of the most important achievements of the project in the communication area, i.e., implementation, testing, verification, and standardization of a safety message that supports all of the VSC-A safety applications. The result is the Basic Safety Message (BSM) as defined in the SAE J2735 Message Set Dictionary standard. Details of the objective test procedures are presented next and are followed by a summary of the performed test scenarios (test descriptions, speeds, number of runs for each test, type of test, etc.) with the corresponding objective testing results. We conclude the paper with a section summarizing the accomplishments of the project and also identify potential next steps and recommendations based on the technical results and engineering experience gained throughout the execution of the VSC-A Project.

INTRODUCTION

Vehicle-to-Vehicle (V2V) safety communications can play a major role in addressing vehicle crashes where multiple vehicles are involved. According to [1], this technology can reduce, mitigate, or prevent 82 percent of crashes by unimpaired drivers. The communications technology for V2V is 5.9 GHz Dedicated Short Range Communications (DSRC). This wireless communications technology has a very low latency and is considered to be the technology of choice for the types of crash avoidance applications that were prototyped in the Vehicle Safety Communications-Applications (VSC-A) Project [2]. The major objectives of the VSC-A development activities were the:

- Selection of high-value safety applications
- Development of a test bed that allowed interoperability between different car manufacturers
- Development and standardization of a message set for vehicle safety communications
- Development of an accurate relative positioning system
- Prototyping of safety applications
- Objective testing of the safety applications

A primary goal of the VSC-A Project was to determine whether systems that utilized DSRC-based V2V communications and positioning can help overcome limitations of autonomous systems and enhance the overall performance of safety systems. One potential advantage of V2V safety communications is that it may provide significant, additional information about the driving situation and expand the awareness horizon of the vehicle well beyond

the capabilities of vehicle-autonomous sensors. Another advantage of V2V systems is that it may be possible to integrate such systems on vehicles in which the system was not original equipment, including retrofit of existing vehicles.

In order to gauge the feasibility of such systems, a reference system and applications to address crash imminent scenarios were implemented. This reference system ("test bed") combined communications, accurate relative positioning and security and was integrated with the vehicles from the five Original Equipment Manufacturers (OEMs) that participated in the VSC-A Project. A fundamental aspect of the project was the establishment of interoperability between different OEMs. This interoperability requirement led to the development of the V2V message set, which was standardized in SAE J2735 as the Basic Safety Message (BSM) [3]. The development of the test bed and the applications followed a systems engineering process and the resulting minimum performance requirements formed the basis for the development and the testing of the applications. To test the performance of the test bed and the applications, objective test procedures were developed together with the United States Department of Transportation (USDOT) and the testing was performed at the Transportation Research Center (TRC) in East Liberty, Ohio, with the aid of the National Highway Traffic Safety Administration's (NHTSA) Vehicle Research and Test Center (VRTC).

CRASH SCENARIOS AND APPLICATION SELECTION

To provide a foundation for the VSC-A Project, the USDOT evaluated pre-crash scenarios based on the 2004 General Estimated Systems (GES) crash database. This list served as the basis for the selection of the safety applications to be prototyped under the VSC-A Project. Each crash scenario was assigned a composite crash ranking determined by taking the average of the crash rankings by frequency, cost, and functional years lost for each scenario. The crash scenarios were then sorted based on the composite ranking and were analyzed to evaluate whether autonomous safety systems and/or vehicle safety communications would offer the best opportunity to adequately address the scenarios.

From this ranked list of crash scenarios (based on crash frequency, crash cost and functional years lost) the top seven (7) crash scenarios to be addressed by the VSC-A Project were selected. The selected crash-imminent scenarios were analyzed and potential, DSRC-based, safety application concepts capable of addressing them were developed. The crash imminent scenarios and the applications selected to be part of the VSC-A safety system are shown in [Table 1](#). The VSC-A team together with the USDOT analyzed the scenarios in [Table 1](#) and developed concepts for safety applications that could potentially address them through vehicle safety communications. This analysis resulted in the

identification of the following safety applications as part of the VSC-A system:

Emergency Electronic Brake Lights (EEBL), defined as follows

The EEBL application enables a host vehicle (HV) to broadcast a self-generated emergency brake event to surrounding remote vehicles (RVs). Upon receiving the event information, the RV determines the relevance of the event and issues a warning to the driver, if appropriate. This application is particularly useful if the drivers' line of sight is obstructed by other vehicles or bad weather conditions (e.g., fog, heavy rain)

Forward Collision Warning (FCW), defined as follows

The FCW application is intended to warn the driver of the HV of an impending rear-end collision with an RV ahead in traffic in the same lane and direction of travel. FCW is intended to help drivers in avoiding or mitigating rear-end vehicle collisions in the forward path of travel.

Blind Spot Warning+Lane Change Warning (BSW+LCW), defined as follows

The BSW+LCW application is intended to warn the driver during a lane change attempt if the blind-spot zone into which the HV intends to switch is, or will soon be, occupied by another vehicle traveling in the same direction. Moreover, the application provides advisory information that is intended to inform the driver of the HV that a vehicle in an adjacent lane is positioned in a blind-spot zone of the HV when a lane change is not being attempted.

Do Not Pass Warning (DNPW), defined as follows

The DNPW application is intended to warn the driver of the HV during a passing maneuver attempt when a slower moving vehicle, ahead and in the same lane, cannot be safely passed using a passing zone which is occupied by vehicles in the opposite direction of travel. In addition, the application provides advisory information that is intended to inform the driver of the HV that the passing zone is occupied when a vehicle is ahead and in the same lane and a passing maneuver is not being attempted.

Intersection Movement Assist (IMA), defined as follows

The IMA application is intended to warn the driver of a HV when it is not safe to enter an intersection due to high collision probability with other RVs. Initially, IMA is intended to help drivers avoid or mitigate vehicle collisions at stop sign-controlled and uncontrolled intersections.

Control Loss Warning (CLW), defined as follows

The CLW application enables a HV to broadcast a self-generated, control-loss event to surrounding RVs. Upon receiving such event notification, the RV determines the relevance of the event and provides a warning to the driver, if appropriate.

Table 1 illustrates the mapping between the crash imminent scenarios and the safety applications defined above.

DEVELOPMENT OF THE TEST BED

Each OEM in the VSC-A Project developed a vehicle test bed to serve as a prototype platform for the V2V communications system. The OEMs jointly developed system specifications and performance requirements that served as the basis for the system and application developments. The test bed was based on a common prototype platform referred to as the On-Board Equipment (OBE). The selected OBE allowed development flexibility and was representative of current (or future) automotive grade processing power. The OBE contained a DSRC radio, a processor and various interfaces (e.g., for vehicle data, Global Positioning System (GPS) data, etc.). The test bed was an effective tool for validating safety application concepts, system test procedures and for answering critical research questions regarding V2V communications. Those issues included relative lane-level positioning, time synchronization, communications scalability and practical security and anonymity.

SOFTWARE ARCHITECTURE

In order to support the functionality of the safety applications described earlier and their development, the activities initially focused on the development of a system architecture based on various modules that could be upgraded independently from each other, if necessary. This approach allowed for fast and efficient prototyping throughout the development phase of the project. This architecture was used during the test bed design stage for the definition of the Hardware (HW) and Software (SW) architectures and required interfaces. The various modules forming the system test bed were categorized into the following major groups: Interface, Positioning & Security, Core, Safety Applications, Threat Process and Reporting, and Data Analysis. The system block diagram (Figure 1) shows the breakdown of the individual modules that make up each of the major module groupings. This provided a good framework for a comprehensive V2V safety system.

The focus of the system design activities was the core modules (Target Classification, Host Vehicle Path Prediction and Path History) and the positioning, security and safety application modules. The system design was based on the preliminary requirement specifications developed for each of the modules. Testing of the system resulted in updates to the

modules throughout the project, culminating in the final test bed implementation. In the next section the software modules are described briefly.

SOFTWARE MODULES

The VSC-A software modules are composed of support and application functions. The support functions provide the interface to any external equipment and they calculate the necessary parameters to support the application modules and the Engineering Driver-Vehicle Interface (DVI). The primary software modules are:

- Threat Arbitration (TA)
- Driver-Vehicle Interface Notifier (DVIN)
- Target Classification (TC)
- Host Vehicle Path Prediction (HVPP)
- Path History (PH)
- Data Logger (DL)
- Engineering Graphical User Interface (EGUI)
- Sensor Data Handler (SDH)
- Wireless Message Handler (WMH)

The application modules evaluate potential safety threats based on the data and inputs from the support modules. The application modules contain the warning algorithms for the safety applications shown in [Table 1](#). The SDH and WMH are basic, functional blocks necessary for parsing inputs from and submitting data to the software services of the system platform and those in use by the other support and application elements. The SDH interfaces to the vehicle Controller Area Network (CAN) gateway device to transmit and receive CAN messages and detect communication errors. It also connects to the GPS receiver to obtain National Marine Electronics Association (NMEA) data including Universal Coordinated Time (UTC) time, position, speed and heading, as well as raw GPS data. The SDH also interfaces to the external computing platform that executes the Real Time Kinematic (RTK) software to obtain accurate relative positioning of the neighboring vehicles. The WMH interfaces to the DSRC radio and to the Security Module (SM) software. It transmits and receives WAVE Safety Messages (WSM) using the SM to generate and verify message signatures. The TC categorizes the surrounding vehicles according to their position and heading relative to the HV, using the HVPP and the PH of the HV and RV. The TA arbitrates between multiple threats and chooses the one with the highest crash energy as the one to display to the driver and sends the respective request to the DVIN, which activates the corresponding alert in the EGUI.

The VSC-A team decided to use the shared memory interface concept. This allows for data in memory to be accessed by

multiple modules for inter-process communication. This is advantageous, because there are many cases of one module supplying data to other functional blocks. For example, consecutive host and remote GPS time and position data points may be used by HVPP, PH, TC and the warning algorithms at the same time. The shared memory scheme used in the architecture fulfills the requirements for support of the VSC-A functionality while allowing for extensibility of the architecture.

ENGINEERING GUI

The EGUI is an “engineering-type” graphical user interface with the purpose to provide a simple engineering tool that could be used to understand, evaluate, and configure the VSC-A platform. It allows representation of visual and auditory vehicle driver warnings as a result of the application module processes. The touch-screen interface also allows the user to view and control parameters necessary for the operation of the VSC-A safety applications. [Figure 2](#) shows examples of the graphical interface as depicted on a Video Graphics Array (VGA) touch screen.

This allowed the EGUI to display the warning states of a particular threat (e.g., DNPW in [Figure 2](#)). Only one of the warning screens is visible at any particular time. In order to ensure that the most important warning was shown on the DVI screen, the TA uses the threat level, relative speed, and location of the threat from each of the application modules to assess the severity and determine the highest priority request to be used by DVIN.

IN-VEHICLE HARDWARE INTEGRATION

The in-vehicle HW integration involved the selection, purchasing, installation and integration of all the HW and SW required for completion of the test bed. [Table 2](#) identifies the model and manufacturer of the equipment installed on the VSC-A test bed vehicles.

MESSAGING STANDARDS

A major goal of the VSC-A Project was to define a single Over-the-Air (OTA) message whose contents could support all of the VSC-A safety applications as well as other safety applications that are likely to be developed in the future. That goal was achieved with the standardization of the SAE J2735 BSM [3]. An internal version of the OTA message was defined and implemented in the test bed with the objective testing verifying that this message supports all of the VSC-A applications. The BSM consists of Parts I and II. A proposal was prepared and presented for SAE to redefine both Parts I and II of the BSM. Part I consists of vehicle state data that is so critical for safety applications that it must be included in every BSM. Part II consists of data that is either required by

applications at regular intervals (potentially at a reduced frequency), required to notify applications of a given event or optional for applications. [Figure 3](#) shows the components and format of the BSM in SAE J2735.

The SAE J2735 conformant BSM uses the Distinguished Encoding Rules (DER) to encode the message for OTA transmission. In addition to the effort to develop and standardize the BSM, the VSC-A team also initiated a new SAE DSRC standards project (SAE J2945) for BSM minimum performance requirements. This standard will augment SAE J2735 to define rules necessary for effective V2V safety communications interoperability (e.g., minimum message rate, minimum data accuracy, etc.).

OBJECTIVE TESTING

OVERVIEW

The objective testing activity included the development of the Objective Test Procedures (OTPs) and test plan, conducting the objective tests, and analyzing the test results. The purpose of the objective testing was to ascertain that:

- The performance of the VSC-A system test bed was sufficient to enable the safety applications in the project
- The safety applications satisfied the minimum performance requirements developed in the system design activity of the project

The OTPs were developed for each application and were designed to include the most common scenarios that the application would encounter. The procedures included the following:

- True positive tests, where the objective is to get a warning
- False positive tests, where the objective is to suppress a warning because it is not needed

The outcomes of the objective tests were used by the Volpe National Transportation Systems Center (Volpe) to estimate the safety benefits opportunity for V2V communications based safety applications. In total, 33 test procedures were developed, 22 true positive tests and 11 false positive tests. For the benefits estimate, only the true positive tests which all had successful/unsuccessful criteria associated with them were evaluated. The OTPs were discussed with NHTSA and Volpe and agreed upon by all the participants. Following the OTP development, the test plan was written. It included the number of runs for each test, test speeds, validation criteria for each test (allowable speed ranges, etc.) and detailed setup procedures to make the OTPs as repeatable as possible. The test plan was also agreed upon by Volpe and NHTSA prior to the start of testing. The objective testing took place from June 1, 2009, to June 3, 2009, at TRC in East Liberty, Ohio.

The data that was collected during the testing was recorded in a data logging and visualization tool called CANape [4].

CANape is a SW tool developed by Vector CANtech, Inc. and is used for the development, calibration and diagnostics of Electronic Control Units (ECUs) as well as data acquisition and analysis. The CANape software was customized by Vector for the VSC-A Project. [Figure 4](#) shows an example of the primary screen that was used for the objective testing. The screen is divided into four quadrants as follows:

- Quadrant 1 contains a bird's-eye view, which is a graphical representation of the location of the HV, centered at (0,0) and the RVs that the HV is in communication with
- Quadrant 2 contains the camera data which will consist of a single image, as shown below, or up to four images multiplexed together
- Quadrant 3 contains the HV's sensor data and GPS data
- Quadrant 4 contains the RV track data as determined by the TC core module

OBJECTIVE TEST RESULTS

The complete list of tests, the speed for the runs, the number of runs for each test and the test outcome is shown in [Table 3](#). As can be seen from [Table 3](#), all the applications passed the objective tests.

SUMMARY/CONCLUSIONS

The major accomplishments of the project are:

- Defined a set of high-priority, potential crash scenarios that could be addressed by V2V communication
- Selected and developed a set of V2V applications to address the above set of potential crash scenarios
- Defined efficient system architecture for V2V safety system where all VSC-A safety applications are enabled at the same time
- Successfully implemented a test bed with all the safety applications on a platform running an automotive grade processor (400 MHz)
- Successfully incorporated and evaluated in the test bed two relative positioning approaches (RTK and Single Point (SP))
- Successfully incorporated in the test bed the necessary OTA communication protocol (SAE J2735) and security protocol (IEEE 1609.2 Elliptic Curve Digital Signature Algorithm (ECDSA) [5] with Verify-on-Demand (VoD) [6])
- Defined OTPs for all the VSC-A safety applications, including true positive and false positive tests
- Successfully executed and passed all objective tests for all the VSC-A safety applications

- Refined, with field data, the required OTA message set for V2V safety (BSM within SAE J2735) which led to the recently published version of the standard [3]
- Conducted a study to quantify availability and accuracy of GPS-based relative positioning by using RTK and SP methods for V2V
- Confirmed that IEEE 1609.2 ECDSA with VoD functioned properly under all test conditions for the VSC-A safety applications
- Performed and analyzed initial scalability with up to 60 radios [8] to characterize channel behavior under IEEE 1609.4 [7] and under dedicated full time use of channel 172

Another outcome of the technical work was the identification of technical questions and topics that still need to be answered for any successful deployment:

- How does the system perform with large numbers of communicating nodes?
- How can security certificates be managed and privacy preserved?
- Are the standards sufficient for interoperability?
- What are requirements for data reliability and integrity?
- What are technical solutions for acceleration of market penetration?
- How to enhance the safety applications and system design?
- How to enhance relative vehicle positioning?

Those questions and topics are being addressed under the current NHTSA V2V safety roadmap [1] which outlines the next set of activities needed to support a NHTSA decision regarding V2V safety in 2013.

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DEFINITIONS/ABBREVIATIONS

BSM

Basic Safety Message

BSW/LCW

Blind Spot Warning, Lane Change Warning

CAMP

Crash Avoidance Metrics Partnership

CAN

Controller Area Network

CLW

Control Loss Warning

DER

Distinguished Encoding Rules