COOPERATIVE INTERSECTION COLLISION AVOIDANCE SYSTEM FOR VIOLATIONS (CICAS-V) FOR AVOIDANCE OF VIOLATION-BASED INTERSECTION CRASHES

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ABSTRACT

Intersection crashes account for 1.72 million crashes per year in the United States. In 2004 stop-sign and traffic signal violations accounted for approximately 302,000 crashes resulting in 163,000 functional life-years lost and $7.9 billion of economic loss [1]. The objective of the Cooperative Intersection Collision Avoidance System for Violations (CICAS-V) project was to design, develop, and test a prototype system to prevent crashes by predicting stop-sign and signal-controlled intersection violations and warning the violating driver. The intersection portion of the system consists of a signal controller capable of exporting signal phase and timing information, a local global positioning system (GPS), and Roadside Equipment (RSE) that includes computing, memory, and Dedicated Short Range Communication (DSRC) radio. The vehicle portion of the system includes on-board equipment for computing and 5.9 GHz DSRC radio connected to the vehicle controller area network (CAN), positioning, and the Driver-Vehicle Interface (DVI). The intersection sends the signal phase and timing, positioning corrections, and a small map (< 1 kb) to the vehicle. The vehicle receives this information and, based on speed and distance to the stop location, predicts whether or not the driver will violate. If a violation is predicted, the driver is warned via a visual/auditory/haptic brake pulse DVI. The system was installed in the vehicles of five Original Equipment Manufacturers (OEMs): Daimler, Ford, General Motors, Honda, and Toyota. Intersections were equipped in California, Michigan, and Virginia. Tests of the system included both on-road and test-track evaluations. System performance was excellent and recommendations were made for continuing with a large field operational test (FOT). The system can be installed at any intersection with sufficient positioning coverage and in any vehicle with an electronic stability system. This system constitutes the first FOT-ready Vehicle Infrastructure Integration safety application

INTRODUCTION

Intersection crashes account for 1.72 million crashes per year in the United States. In 2004 stop sign and traffic signal violations accounted for approximately 302,000 crashes resulting in 163,000 functional life years lost and $7.9 billion of economic loss (National Highway Traffic Safety Administration, 2006). The objective of the Cooperative Intersection Collision Avoidance System for Violations (CICAS-V) project was to design, develop, and test a prototype system to prevent crashes by predicting stop-sign and signal-controlled intersection violations and warning the violating driver.

The developed system includes both intersection and vehicle equipment communicating via 5.9 GHz Dedicated Short Range Communication (DSRC). The intersection equipment consists of Road-Side Equipment (RSE), containing a computing system, DSRC radio and a global positioning system (GPS) unit. In signalized intersections, the RSE is connected to the traffic signal controller from which it obtains signal phase and timing information in real-time. The vehicle equipment includes On-Board Equipment (OBE), containing a computing system and a DSRC radio, as well as a GPS unit and a driver-vehicle interface (DVI) to present a timely and salient warning to the driver for whom a violation of a Traffic Control Device (TCD) is predicted.

The system was installed in the vehicles of five Original Equipment Manufacturers (OEMs): Daimler, Ford, General Motors, Honda, and Toyota. The system installed in the GM vehicle contained the full prototype, including the haptic brake pulse in the Driver Vehicle Interface (DVI). The vehicles of the other OEMs had the CICAS-V without the brake pulse. Several intersections in California, Michigan and Virginia, managed through signal controllers from different manufacturers, were instrumented with the CICAS-V equipment and used for testing

throughout project execution. The full prototype, i.e. including the full DVI, supported the pilot Field Operational Test (FOT) that concluded phase 1 of the project. Based on the very positive results from this pilot FOT, recommendations were made for continuing with a large scale FOT. The CICAS-V project is a joint effort of the U.S. Department of Transportation (USDOT) and the Vehicle Safety Communications II (VSC-2) Consortium at the Crash Avoidance Metrics Partnership (CAMP).

CONCEPT OF OPERATIONS

The Concept of Operations (ConOps) formed the basis of the system engineering activities and system development. For a signalized intersection, the basic concept of CICAS-V is illustrated at a high level in **Figure 1**. It shows a CICAS-V equipped vehicle approaching a CICAS-V equipped intersection and receiving an over-the-air messages from the local RSE. The information carried in such a message includes:

- Signal Phase and Timing (SPaT) – real-time information of traffic light status
- Geometric Intersection Description (GID) – a digital map of the intersection
- GPS differential corrections (if accurate positioning information is required)
- GIDs of stop-controlled intersections in the vicinity of the RSE (optional)

The driver is issued a warning if the equipment in the vehicle determines that, given current operating conditions, the driver is predicted to violate the signal in a manner which is likely to result in the vehicle entering the intersection. This warning will raise the driver's attention, so that the driver can determine the safest course of action, possibly bringing the vehicle to a safe stop before it enters the intersection crash box. While the system may not prevent all crashes through such warnings, it is expected that, with an effective warning, the number of traffic control device violations will decrease, and result in a significant decrease in the number and severity of crashes at controlled intersections.

The vehicle OBE determines the probability of a violation by continuously reassessing the current distance from the stop bar for the actual lane of travel, the speed of the vehicle, and the current signal phase. If the phase is amber, then the vehicle OBE determines from the time left in phase whether it will pass the stop bar before the onset of the red phase. If the vehicle will cross the stop bar after the light has turned red, given the dynamic conditions of the vehicle, an alert is issued to the driver.

For stop-controlled intersections the vehicle only needs to assess the distance from the stop bar, based on the current vehicle and stop bar locations, and the vehicle operating conditions.

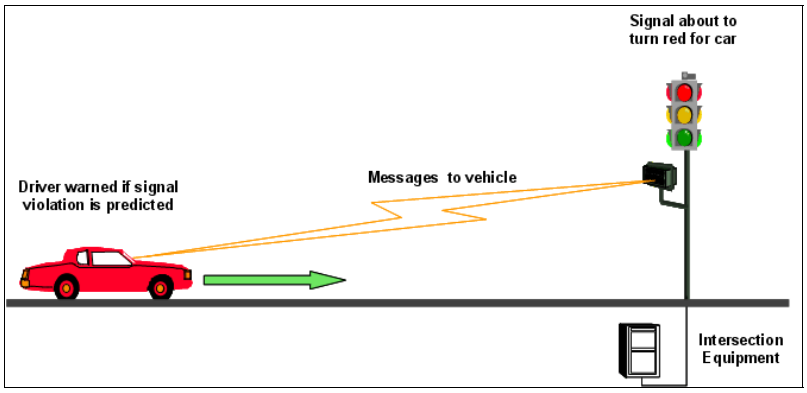

Figure 1: Basic concept of the CICAS-V system at a signalized intersection.

REQUIRED POSITIONING ACCURACY

For the CICAS-V ConOps to work, it is necessary for the vehicle to position itself with sufficient accuracy along the approach to the intersection. Researchers commonly refer to two levels of positioning accuracy: WhichRoad and WhichLane.

WhichRoad accuracy requires that the combined error of GID and positioning does not exceed 5 m. This level of accuracy is required for CICAS-V at most stop-sign controlled intersections and at signalized intersections with no dedicated turn lanes with their own movement independent of the signal indication of the through movement.

WhichLane accuracy requires that the combined error of GID and positioning does not exceed 1.5 m

(approx ½ lane width) and is necessary for CICAS-V at (mainly signalized) intersections with protected left or right turns where the turn phase differs from the phase for the straight crossing direction.

Throughout the project, it was assumed that, by using GPS differential corrections, it would be possible to achieve a positioning accuracy better than 1 m. To contain the combined GID and positioning error within the required limit, it was thus determined that the accuracy of the GID had to be better then 0.5 m.

GEOMETRIC INTERSECTION DESCRIPTION

The vehicle OBE needs to have a map of the intersection with the necessary accuracy determined by the intersection type. Throughout project execution, no distinctions were made with regard to the GID accuracy for the intersections and all GIDs had the same lane-level accuracy.

The GID has to have the following properties:

- Sufficiently accurate (30 cm for WhichLane) road/lane geometry for all lanes/approach roads;
- Intersection identification, including whether the intersection is stop-sign controlled or signalized;
- Stop bar locations for all lanes;
- An intersection reference point;
- Lane widths for all the lanes;
- Correspondence between lane and traffic signal applying to the lane.

The ConOps did not assume that the vehicle would already have an intersection map stored onboard, thus the requirement that such a map be transmitted from RSE at the intersection to the vehicle through 5.9 GHz DSRC. This imposed a constraint on the size of the GID to be transmitted over the air. The ConOps did not determine how GIDs for stop sign intersections are distributed to the vehicle. An alternative is that they are distributed by nearby RSE.

In order to increase reception probability, the GID needed to fit within a single DSRC Wave Short Message (WSM) packet. The WSM maximum packet size is 1.4 Kbytes as specified in the IEEE 802.11p proposed standard [2,3]. Furthermore, about 400 bytes of this packet are assumed to be used for security payload and are not available for the actual message content. Those constraints led to the design of a small map of about 1 Kbyte to store the GID. The GID specifications developed by the CICAS-V project have been entered in the Society of Automotive Engineers (SAE) J2735 standards process to become a future automotive standard.

In order to minimize the size of the GID, the following design choices were made:

- All geometry points are Cartesian offsets from an intersection reference point that is given in (Latitude, Longitude, and Altitude) coordinates in the WGS 84 system. This means that all the points that are used to describe the geometry are described as distance in decimeters from the intersection reference point (x [decimeters], y [decimeters], z [decimeters]);
- All roads/lanes are described as an ordered set of geometry points together with the lane width at each point;
- The lane geometry is described by specifying the centerline of the lane;
- The stop bar location for each lane is the first geometry point for the lane;
- Lane geometries are represented out to a distance of 300 m from the intersection reference point for approaching lanes (note that GIDs might overlap in some cases);
- Outgoing lanes are optional but can be included, if necessary.

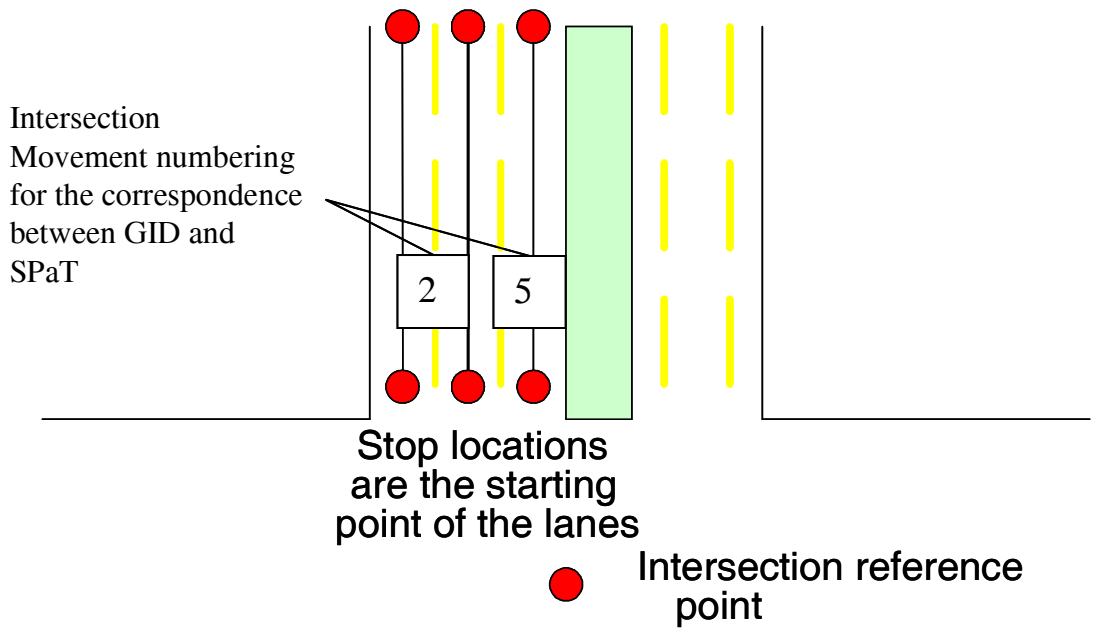

Figure 2: GID elements

The basic element of the GID (**Figure 2**) is a point or "node." Two types of GID nodes are defined: (a) the Intersection Reference Point (IRP), expressed as Latitude, Longitude, and Altitude; and (b) the Nodes that describe the lanes, given as offsets in Cartesian coordinates from the IRP. The set of nodes that describe a lane are collected in the "Node List."

Two kinds of lanes are defined:

- Reference Lane
- Computed Lane

A reference lane is a lane that is fully specified by a list of points. A computed lane is a lane that can be derived from a reference lane by a simple parallel shift of the reference lane. This method reduces the size of the GID message for cases in which several parallel lanes can be grouped into one approach. An approach is defined as all lanes of traffic governed by a single, independent signal phase cycle, moving towards an intersection from one direction. This corresponds to the term "Movement" used by Traffic Engineers.

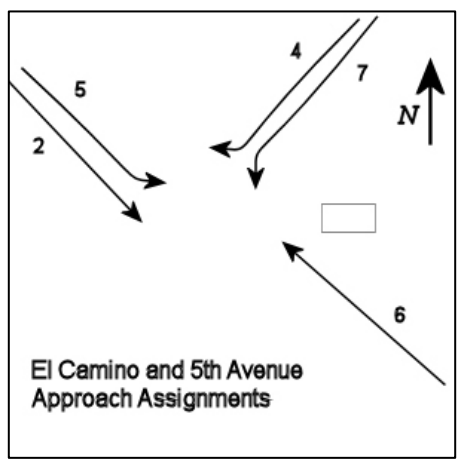

Figure 3: Approaches for the intersection at 5th Ave. and El Camino Real in Atherton, California.

Figure 3 shows the seven approaches to the intersection of 5th Ave. and El Camino Real in Atherton, California. Approach 6 consists of three lanes for which the rightmost lane is wider than the other two due to parking possibilities. Approach 2 contains three lanes and approach 5 contains two lanes. For approach 2 the GID specifies the leftmost through lane as a reference lane and the other two lanes in the approach are represented as computed

lanes. The same is true for approach 6 for which the leftmost lane is again specified through a node list and the other two lanes can be specified by the offset from the reference lane.

It should be noted that the computed lane is not a mandatory feature of the GID but a device to minimize the size. In the GID, all lanes can be specified through node lists (as reference lanes) if the size of the GID permits.

The resulting GID is a very compact map of the intersection. For instance, the size of the GID for 5th Ave. and El Camino Real is 352 bytes, while the size of the GID for the most complicated intersection in the project, Franklin and Peppers Ferry in Christiansburg, VA, is 869 bytes.

No commercial maps available today can describe the intersection geometry to the required accuracy level, and some of the required GID attributes such as stop location are similarly missing, therefore, the CICAS-V project had to generate the GIDs.

After looking at several alternatives, aerial surveying was selected as the method to map the intersections. The company chosen to map the intersections was HJW GeoSpatial, Inc. (HJW) in Oakland, California. The CICAS-V project developed specifications for the GID that were transmitted to HJW and HJW then took a high-resolution aerial photograph of the intersections. The resulting image had to be ortho-rectified. Also for this purpose a number of points on the picture were mapped by a surveyor on site. The company took the lane markings on the image to determine the location of the centerline for each lane and delivered the geometry of the lanes as a set of points, as specified. Those points were subsequently converted into the GID message, using a compiler that was specifically developed for CICAS-V.

Figure 4: Aerial view of the Intersection at 5th Ave. and El Camino Real in Atherton, California.

In mapping the intersection, work was conducted to specify the "North" direction accurately as the Geographic North in the WGS 84 Coordinate System. Using the "North" direction in the State Plane Coordinate System or the UTM Coordinate System, which are both used widely to specify geography, will lead to a rotation of the GID with respect to the Ground Truth by an angle that is location dependent. The farther the location of the intersection is away from the central meridian, the larger the angle between UTM north and geographic north. For the mapping of the intersection, this can amount to several meters of discrepancy between the position on the GID and the GPS position that the vehicle receives from the positioning system.

SIGNAL PHASE AND TIMING

The intersection sends controller Signal Phase and Timing (SPaT) information to the vehicle 10 times per second and the vehicle will select the correct signal indication, based on its approach. The SPaT message contains the signal phase indication of the current phase, the time until the next signal phase change and information to correlate the signal indication with the approach for all the approaches in the GID.

As for GIDs, SPaT information is best included in a single DSRC WSM packet. This packet is generated by extracting the data in real-time from the traffic signal controller and formatting it into the SPaT message. Depending on the traffic signal controller hardware and the signal controller protocol, SPaT information is exported directly or some inference via a state machine running on the RSE is necessary to determine the correct phase.

GPS CORRECTIONS

The overarching goal of the CICAS-V positioning and GPS correction generation subsystems is to design and prototype a vehicle positioning system. The purpose is to achieve real-time sub-meter vehicle positioning near CICAS-V intersections for CICAS-V equipped vehicles at relatively low cost while using commercial off-the-shelf hardware.

The prototype design is dependent on the availability of RSE at CICAS-V signalized intersections that have a local GPS base station receiver. This receiver is configured to compute correction factors for the GPS Satellite signals that are needed to make the position result from estimation algorithms match the base station's known (surveyed) fixed location.

This locality of scope contrasts with other popular correction techniques, such as the Wide Area Augmentation System (WAAS) in the U.S, which has ground reference stations spaced approximately 500 miles apart, and, therefore, computes corrections on a regional basis. The field test results conducted to date at real intersections indicate significantly higher real-time vehicle positioning accuracy when compared to the position accuracies obtained through WAAS and Differential Global Positioning System (DGPS) corrections based vehicle positioning systems. For example, at the CICAS-V traffic intersection located in Farmington Hills, Michigan, absolute real-time vehicle positioning errors on the order of less than 0.5m are consistently achieved using the CICAS-V test vehicles.

Figure 5 shows the local DGPS correction generation and broadcast subsystem installed at a traffic point of interest, such as a controlled intersection. The GPS receiver is configured in base-station mode where it computes corrections to GPS satellite signals for other moving (vehicle-mounted) GPS receivers in its vicinity. The correction information is encoded in Radio Technical Commission for Maritime Services (RTCM)-standardized format, such as the RTCM Recommended Standards for Differential GNSS (Global Navigation Satellite Systems) service as defined by the Special Committee (SC) 104 on Differential Global Navigation Satellite Systems (DGNSS). For brevity, the corrections data message format is referred to as either RTCMv3.0 or RTCMv2.3, depending on which SC-104 release of the "Recommended Standards for Differential GNSS" is used. The RTCMv3.0 message format used in the CICAS-V system design consists of single frequency (L1) GPS information.

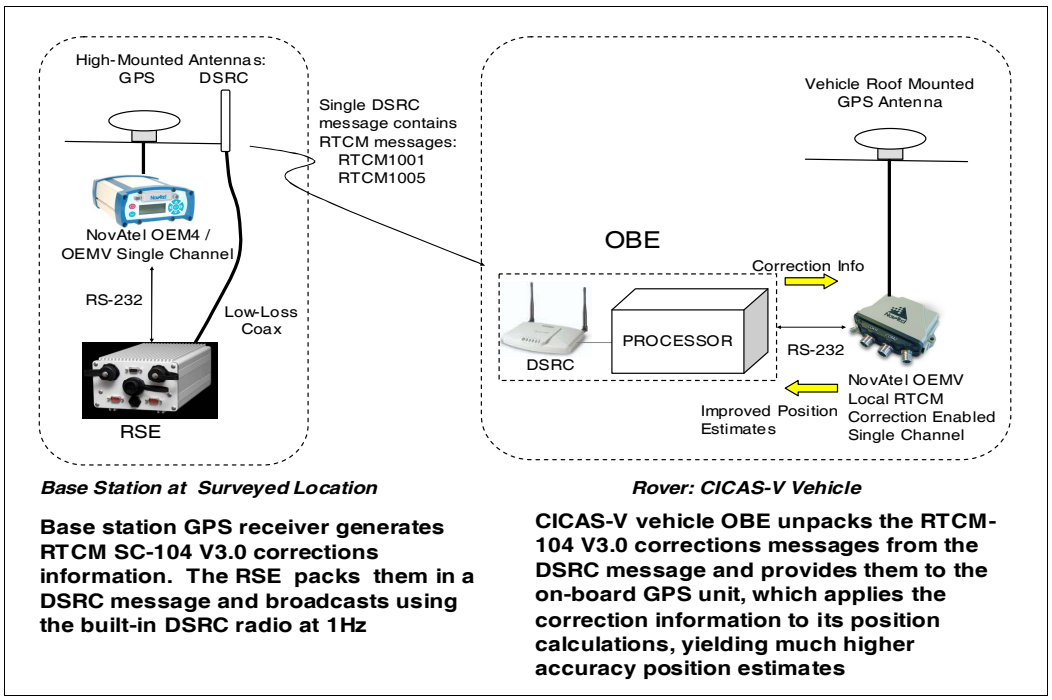

Figure 5: Aerial positioning correction equipment

The RTCM 1001 corrections provide per-satellite GPS pseudo-ranges and carrier phase measurements so the on-board (moving) GPS receiver can compute its position estimate with much higher accuracy and

reliability. The RTCM 1001 form [4] of L1-only correction information provides a good accuracy improvement with rather modest communications requirements and impact on GPS receiver workload. For example, only 101 bytes are required per RTCM 1001 binary message that includes range corrections for 12 satellites, and is often smaller according to the number of visible GPS satellites in the current constellation. The amount of correction data that has to be broadcasted in the DSRC link is dependent on the RTCM version used and on the number of visible satellites.

For example, the RTCM v2.3 format requires about 4800 bits per second (bps) to broadcast dual-frequency code and carrier-phase observations or observation corrections of 12 satellites. Similar information content can be transmitted using 1800 bps in the newer RTCM v3.0 format (i.e., for 12 visible satellites, v2.3 requires 372 bytes to transmit data, whereas RTCM v3.0 requires only 8+7.25*12 bytes).

RTCM v3.0 is primarily designed to support Real-Time Kinematic (RTK) operations that normally require broadcasting relatively large amounts of information, and generally implies highly sophisticated forms of correction analysis and error removal. However, the L1-only subset of the RTCM v3.0 format can provide good performance improvements for modest system resource requirements, and works well even with moderately-priced receivers. A minimum of two RTCM SC 104 standard messages are required from the RSE to support local differential L1 solution correction for onboard GPS receivers.

Each RTCM 1001 Message contains the satellite observations (in particular the single frequency [L1-only] GPS pseudo-range and carrier phase measurements) as derived by the base station GPS receiver by comparing the position estimate determined from current satellite pseudo-range observations with the surveyed fixed location of the base station antenna. The base station "works backwards" to compute corrections to the satellite pseudo-ranges that would yield a much more accurate position estimate. Other roving GPS receivers in the surrounding area will generally face the same set of inaccuracies in the GPS satellite pseudo-range observations, so when they apply these pseudo-range correction factors to their own observations, they too will be able to significantly reduce the errors and obtain a more accurate position estimate.

MESSAGE FRAMEWORK

The cooperative nature of the system requires the definition of the messages that are being sent from the intersection to the vehicle. The project defined the following messages as necessary for the system to function:

- Wave Service Announcement (WSA)
- Signal Phase and Timing (SPaT)
- GID Message (GID)
- GPS Correction Message

There are two messages that are to some degree optional but that were implemented. These are:

- Area GID (AGID)
- Traffic Signal Violation Warning Given (TSVWG)

It should be noted that the TSVWG message is the only vehicle-to-infrastructure message.

In order to provide a common framework for all the messages, the project created the Transportation Object Message (TOM) that is based on XML but streamlines the message for byte efficiency. Here only an overview over the basic concept will be provided.

XML is a meta-language ideally suited to dynamic data markup, which quickly became very popular in the software engineering community. XML descended from SGML and is a very expressive, flexible and powerful meta-language. The main disadvantage for XML is the low byte-efficiency, which makes it less indicated for RF transmissions.

TOM was designed after the work conducted in the W3C XML Binary Characterizations Working Group. It was created to be similar to XML but highly streamlined for byte efficiency so it could support transmitting complex application data over DSRC. While XML is well suited for describing data of arbitrary complexity, TOM has similar capability but is limited by the maximum size of an object.

A TOM frame begins each message with a Message Header and ends it with a Message Footer. The framework provides message differentiation and a basic measure of integrity. There may only be one frame per message. Ideally, that frame never exceeds 1,024 bytes to fit into a WSM packet, assuming 200-400 bytes for the security overhead and WSM frame overhead. Everything between header and footer is considered message content, expressed as a set of object tags.

The TOM framework allows all the messages that are received to be treated in the same way in their decoding, which creates efficiency in application development and improves code robustness. Also, it allows for consistent authoring of content across all the different messages. In order to develop the various messages, a TOM compiler was developed that allows the authoring of the message in XML and then converts it into a TOM message.

DSRC BROADCASTS

All the messages are sent as WSM packets according to the IEEE 1609.3 proposed standard [5, 6]. The DSRC spectrum at 5.9 GHz is partitioned into seven channels where the Control Channel (CCH) is currently envisioned as the channel where the safety-relevant messages for Infrastructure-to-Vehicle (I2V) and Vehicle-to-Vehicle (V2V) communications are broadcasted.

To optimize channel utilization, it was decided to broadcast SPaT messages on the control channel (#178) and the GID and GPS correction (GPSC) messages on one of the service channels (all other channels except #172). The control channel is used to broadcast WSA messages. These messages contain information about the intersection the vehicle currently approaches (Intersection ID), the GID version number, and the service channel used for broadcasting. The vehicle OBE can switch its DSRC radio to this service channel to receive the full GID for the intersection as well as GPSC corrections. If the vehicle determines that it has the GID already stored, it will discard the newly received GID but still receive the GPSC messages.

DRIVER-VEHICLE INTERFACE (DVI)

The warning is conveyed to the driver via the DVI. It was not a goal for the project to specify a standard DVI as it is expected that each OEM will develop proprietary solutions in the future. The DVI developed for the project included a visual icon, a speech-based warning and a brake pulse. The tests conducted within the project found this combination to be highly effective. The CICAS-V DVI is presented in more detail in [7].

SYSTEM ARCHITECTURE

The overall system architecture is shown in **Figure 6**.

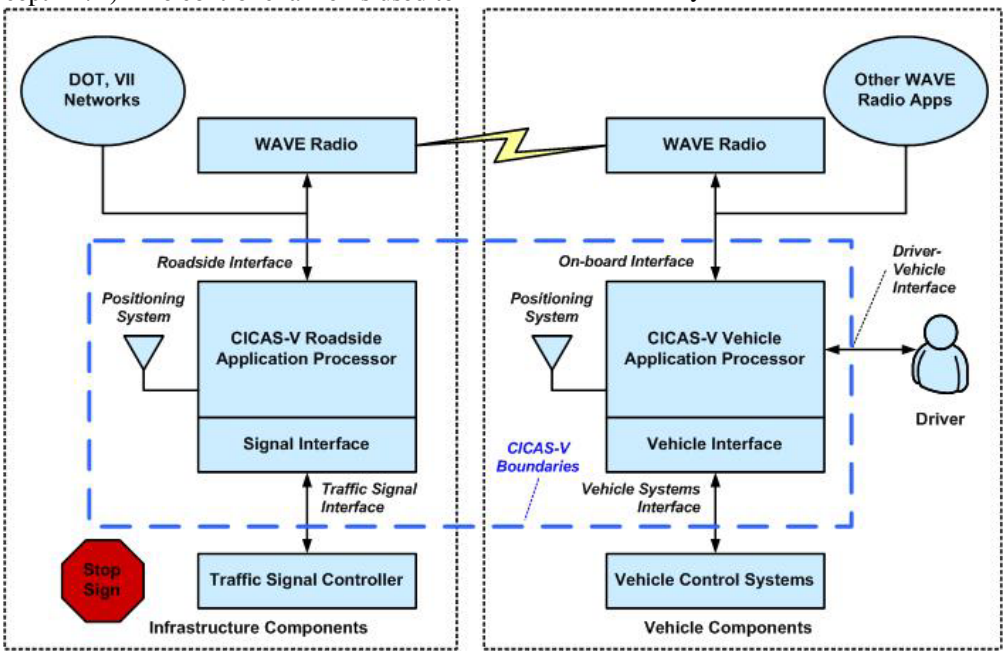

Figure 6: CICAS-V system with interfaces

As it can be seen in Figure 6, the vehicle and the infrastructure systems are very similar. In the following, the system architecture for the vehicle system will be described in greater detail.

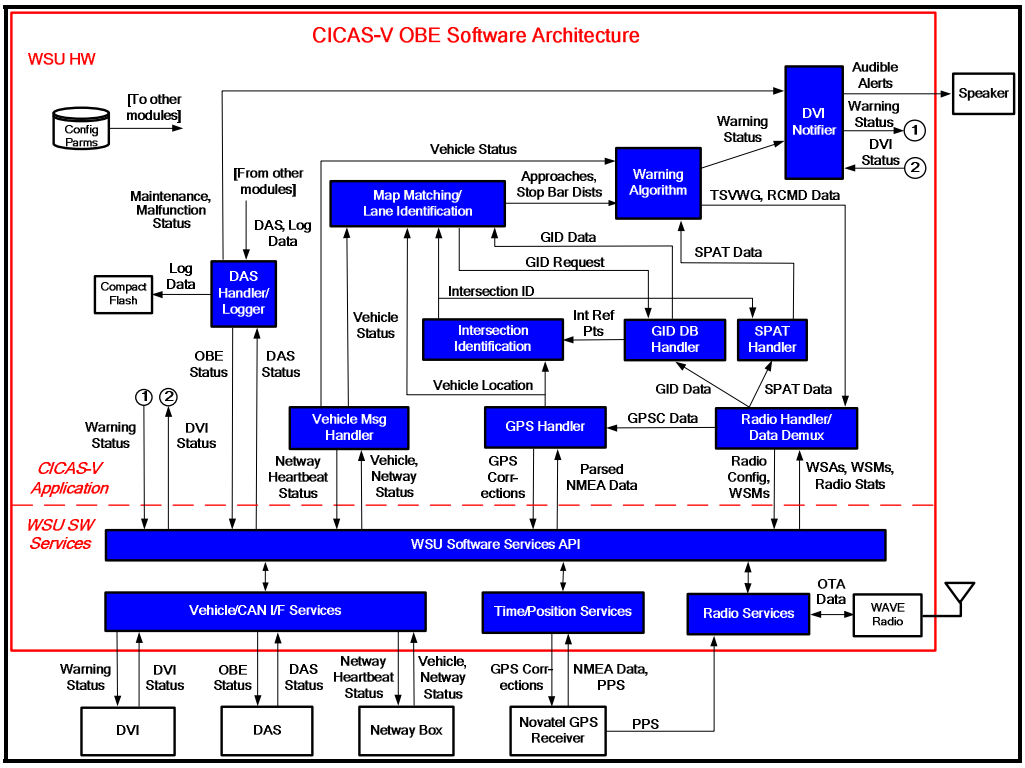

Figure 7: CICAS-V system architecture for the OBE

The software was implemented on a Linux embedded platform, the Wireless Safety Unit (WSU) by DENSO.

The software modules were divided into WSU Software Services that handled the interfaces the DSRC radio, the GPS unit and Vehicle Components, and the CICAS-V application modules.

The CICAS-V Application modules were grouped and divided into two categories:

- Interface/Message Handling Modules – Interface to external devices and/or perform message handling and parsing functions
- Violation Detection Modules – Process the latest vehicle, GPS, GID and SPaT data to determine whether an intersection violation is likely to occur

The modules assigned to each sub-category are listed in **Error! Reference source not found.** below.

Table 1: CICAS-V OBE Application Module Summary

Module	Description
Interface/Message Handling Modules	
Vehicle Message Handler	Interfaced to the Netway device (through the WSU Vehicle/CAN Interface Services) to receive generic CAN messages with vehicle status Transmitted and received heartbeat status information with the Netway
Radio Handler/Data Demux	Interfaced to the WAVE Radio (through the WSU Radio Services) Configured the radio, and polled the radio driver for statistics Transmitted and received WAVE Short Messages (WSMs) Processed received WAVE Service Advertisement (WSA) indications
GPS Handler	Interfaced to the Novatel OEMV GPS receiver (through the WSU Time/Position Services) Output GPS correction (GPSC) data Input GPS time and position data

Module	Description
GID Database Handler	Maintained the GID database Upon receipt of GID data, added a record to the database, or updated an existing record if the data was of a different version Deleted expired GID records Performed WAVE Basic Service Set (WBSS) selection if the GID or GPSC data was being broadcast on the Service Channel
SPaT Handler	Received and parsed the SPaT data Converted the data to a format usable by other modules
DAS Handler/Logger	Interfaced to the Data Acquisition System (DAS) (through the WSU Vehicle/CAN Interface Services) Output OBE status and input DAS status Performed hardware/software watchdog processing and determined whether a maintenance or malfunction condition exists It should be noted that the DAS Handler/Logger supports an independent system just for the collection of data to evaluate the prototype.
Violation Detection Modules	
Intersection Identification	Identified the intersection the vehicle was approaching based on the vehicle location and direction and the GID intersection reference points
Map Matching/Lane Identification	Calculated the most likely lane(s) and approach(es) of the vehicle, and the distance to the stop bar(s) based on the vehicle location and GID data
Warning Algorithm	Determined if an intersection violation was likely to occur Generated Traffic Signal Violation Warning Given (TSVWG) and Remote Command (RCMD) messages to be transmitted to the RSE
DVI Notifier	Interfaced to the Driver Vehicle Interface (DVI) (through the WSU Vehicle/CAN Interface Services) Controlled the DVI icon and flexible warning outputs Transmitted and received heartbeat status information with the visual DVI device Generated audible DVI alerts

SYSTEM INSTALLATION

The components of the intersection installation of the CICAS-V are shown in **Figure 8** and **Figure 9**. **Figure 8** shows the installation of the RSE, the GPS and a Data Acquisition System (DAS) in the intersection controller cabinet at an intersection in Blacksburg, Virginia. **Figure 9** shows the antenna installation (DSRC and GPS) at an intersection in Michigan.

Figure 8: CICAS-V cabinet with GPS, RSE, and Data Acquisition System (DAS)

Figure 9: CICAS-V antenna installation

Due to different intersection configurations, geometries and installation guidelines the installations in Blacksburg, Virginia, Oakland County, Michigan and Atherton, California differed from each other, even though the same components were used. **Figure 10** shows the installation in one of the OEM vehicles.

Figure 10: CICAS-V Vehicle Installation

Figure 10 shows the OBE (DENSO WSU), the Vehicle Interface (Netway) the GPS Receiver (Novatel OEMV) and a DAS (Virginia Tech Transportation Institue). The DAS recorded all the messages from the vehicle bus, the messages that were received from the intersections, the output of the computations from the OBE and the camera images (Forward, Driver Face, Interior of Vehicle, Rearward).

OBJECTIVE TESTING

Since the planned outcome of this project was a prototype ready for a large-scale Field-Operational Test (FOT), the system had to pass objective test procedures. Together with the USDOT a set of procedures was defined and then the system was tested using the procedures on a closed test track with an intersection (the Virginia Tech Smart Road). The test procedures are shown in Table 2.

The tests are divided into types:

- Warning Tests where the system has to give a warning
- Nuisance Tests, where the system must not give a warning
- Engineering tests where the system limits are tested

The tests covered the typical situations that would be encountered by a CICAS-V equipped vehicle approaching a CICAS-V equipped signalized or stop -sign controlled intersection. They were written such that any supplier of a CICAS-V can use them to test whether the system fulfills the performance specifications.

For a warning test to pass, the system had to alert the driver within a distance of (200 ms * vehicle speed) of the correct warning distance as defined in the warning algorithm and all the warning modalities had to come on within 200 ms of each other. The actual value that was achieved was below 100 ms. Each of the tests had criteria associated with it that determined that the test was valid, e.g., the variability of the speed had to be smaller than 2.5 mph around the nominal test speed. Each test had to have at least eight valid runs. The Various Speed Approaches tests for signalized and stop controlled intersections consisted of approaches at three speeds: 25, 35 and 55 mph, each of which needed eight valid runs.

Table 2: CICAS Test Scenarios Overview

Name	Purpose	Kind
Signalized Various Speed Approaches Test	Test whether warning distance is as specified for signalized intersections and given vehicle speed	Objective Requirement Warning

Edge of Approach Testing for Warning	Test whether expected warning is given when vehicle is driven on edge of lane	Objective Requirement Warning
Edge of Approach Testing for Nuisance Warning	Test whether nuisance warnings are avoided when vehicle is driven on edge of lane	Objective Requirement Nuisance
Late Lane Shift Test – Warning	Test whether expected warning is given when shifting from green lane into red lane after red lane's warning distance passed	Objective Requirement Warning
Late Lane Shift Test – Nuisance Warning	Test whether nuisance warning is avoided when shifting from red lane into green lane before red lane's warning distance passed	Objective Requirement Nuisance
Multiple Intersections within 300m Radius: Warning Case	Test whether warning appropriate warning is given for approaching intersection in presence of multiple nearby intersections	Objective Requirement Warning
Multiple Intersections within 300m Radius: No Warning Case	Test whether warning is avoided when approaching intersection in presence of multiple nearby intersections	Objective Requirement Warning
Dynamic Signal Change to Yellow, Too Late to Warn	Test whether warning is avoided on signal change from green to yellow when red arrives after the stop bar	Objective Requirement Nuisance
Dynamic Signal to Red, In Time for Warning	Test whether expected warning is given on signal change from green to yellow when red occurs before vehicle passes stop bar.	Objective Requirement Warning
Dynamic Signal to Green, No Warning Case	Test whether warning is avoided when signal change from red to green before the warning distance	Objective Requirement Nuisance
Stop Sign Various Approach Speeds Test	Test whether warning distance is as specified for stop sign intersections and given vehicle speed	Objective Requirement Warning
SPaT Reflection and Reception	Tests the system performance / system limits when line of sight between intersection and vehicle is obscured by another vehicle	Engineering Test

Table 3: Results of objective testing

Test Name	Speed	Comment	Tests Conducted	Tests Successful	Success Rate	Pass / Fail
Signalized Various Speed Approaches Test	25		8	8	100%	Pass
	35		8	8	100%	Pass
	55		8	7	88%	Pass
Edge of Approach Testing for Warning	35	Right Side	8	8	100	Pass
Edge of Approach Testing for Nuisance Warning	35	Left Side	8	8	100%	Pass
Late Lane Shift Test	35	Right to Left w/Warning	8	8	100%	Pass
	35	Left to Right w/o Warning	8	8	100%	Pass
SPaT Reflection and Reception	35		8	8	100%	Pass

Multiple Intersections within 300m Radius: Warning Case	35		8	8	100%	Pass
Multiple Intersections within 300m Radius: No Warning Case	35		8	8	100%	Pass
Dynamic Signal Change to Yellow, Too Late to Warn	35		8	8	100%	Pass
Dynamic Signal to Red, In Time for Warning	35		8	8	100 %	Pass
Dynamic Signal to Green, No Warning Case	35		8	8	100%	Pass
Stop Sign Various Approach Speeds Test	25		8	8	100%	Pass
	35		8	8	100%	Pass
	55		8	8	100%	Pass
Overall						Pass

As can be seen in Table 3, the system passed all the objective tests with almost 100% of the runs passing. The only failed run happened at one intersection approach where the brake pulse failed to trigger, even though the other warning modalities warned the driver at the correct distance. The SPaT reflection and reception test did not have pass/fail criteria attached to it since it tested the system outside the performance specifications. In this test, the CICAS-V equipped vehicle followed a tractor-trailer within a distance of 4.5 m to see whether enough packages from the intersection could be received to enable the vehicle to issue a correct warning. In all the test runs the warning was issued such that the vehicle was able to come to a stop before entering the intersection crash box but in several instances the warning came more than 200 ms late. The complete description of the objective test procedures can be found in [8], the complete analysis of the objective testing can be found in [9].

DISCUSSION

The development work in the CICAS-V project resulted in a CICAS-V that was deployed in intersections in three states in the United States with different traffic signal controllers and intersection configurations. The installations varied in difficulty due to the location of the traffic signal controller cabinet relative to the antenna placements, the space available in the cabinets, and other local factors. In all cases, the intersection installation was stable and without maintenance is still working in the Michigan intersections, even after a severe winter. The intersection installation could be accomplished with a reasonable amount of effort even for complex intersection installations. The development and test of the intersection GIDs showed that the necessary maps with successive could be developed. The positioning correction methodology used proved that the required accuracy for lane level positioning is achievable and that the overall system is feasible and can be installed at intersections. A final deployment analysis would need a full FOT.

The vehicle part of the CICAS-V was improved in successive releases of the software and extensive system tests were performed to verify all functions and aspects of the system. The software release that was used for the pilot FOT [10] was improved in several subsequent releases using the results from the tests with naïve drivers. The final release of the project was used for the objective tests. The system performed well during the objective tests and was judged to be ready for a large-scale FOT. The passed tests included both Warning Tests where the correct warning had to be given and Nuisance Tests, where an incorrect warning had to be avoided.

The overall performance of the system showed that it is ready for a large scale Field Operational Test. Plans and experimental protocols have been developed as part of the project and can be used to conduct the test [11].

CONCLUSION

The CICAS-V project developed a cooperative intersection collision avoidance system that warns drivers of an impending violation of a traffic control device. The system was installed in several vehicles and intersections in California, Michigan and Virginia. To support the system, message sets, a digital map format for intersection maps, and a map matching and positioning system for accurate positioning in the vehicle were developed. For the evaluation of the system readiness for an FOT with naïve drivers, objective test procedures were developed and the system was tested using those procedures. The CICAS-V passed all the objective tests. The system was also tested with naïve drivers in a pilot FOT and was found to be ready for an FOT. This constitutes the first test of a CICAS-V in a real-world environment and the results show that such a system can function well and can be tested in a large-scale field test with naïve drivers.

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