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Joint Program Office

Cooperative Intersection Collision Avoidance System Limited to Stop Sign and Traffic Signal Violations (CICAS-V)

System Design Specification - Infrastructure

Final Phase I Release v4.01

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16. Abstract The purpose of this document is to provide a set of infrastructure design specifications for the Cooperative Intersection Collision Avoidance System (CICAS) for Violations (CICAS-V), a system that involves both infrastructure and in-vehicle elements, working together, to reduce the number of crashes at controlled intersections within the United States.		
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Table of Contents

List of Figures

List of Tables

1 Introduction

The Cooperative Intersection Collision Avoidance System Limited to Traffic Signal and Stop Sign Violations (CICAS-V) is intended to provide a cooperative vehicle and infrastructure system that assists drivers in avoiding crashes at intersections by warning the vehicle driver that a violation, at an intersection controlled by a stop sign or by traffic signal, is predicted to occur. A more complete description of the anticipated CICAS-V system and its expected benefits is provided in the Concept of Operations document.

This document describes performance specifications needed to implement a CICAS-V system that meets the High-Level Requirements. Several performance metrics are defined that assess how accurately the system distinguishes between valid and invalid warning situations as well as the precision in terms of time or location of the warning delivery. Because the CICAS-V system is designed around a few enabler technologies such as Global Positioning System (GPS) and 802.11p Dedicated Short Range Communications (DSRC) wireless communications, the CICAS-V team has defined several subsystem performance metrics that ensure the critical elements of the overall system are working at least well enough to meet design assumptions.

To provide a common set of concepts, terms and mathematical expressions, Section 2 presents a mathematical treatment of intersection approach kinematics, violation prediction, violation warning performance classification, and a critical event timing model. Section 3 defines specific performance specifications for the system that should be assessed by objective testing in later phases of system development and validation before the full Field Operational Test (FOT) of CICAS-V. Section 4 is a cross-referenced traceability matrix of the performance specifications to corresponding functional requirements. Not every functional requirement has a corresponding performance specification. Many functional requirements are defined such that inspection or functional demonstration observations will be the most appropriate methods of verification and validation. Sections 5 and 6 provide a terminology, glossary, and acronym dictionary respectively. Section 7 provides a list and explanation of the variables used in the equations from Section 2.

The planned master schedule for CICAS-V includes provisions to update these performance specifications based on the results of objective testing and the FOT. The results of these test phases will be collected and analyzed then applied to the performance specifications to make CICAS-V a more viable technology for widespread deployment.

1.1 Scope

This document defines the system performance for the CICAS-V system. The following performance specifications apply directly to CICAS-V systems development under Task 8 and Task 10. The performance specifications in this document are based on the Concept of Operations, High Level Requirements Specifications, System Requirements Specifications, the results of the human factor studies, and the Pilot FOT. Both stop sign violation warning and traffic signal violation warning scenarios are considered in developing the performance specifications.

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2 Introductory Concepts and Definitions

2.1 Kinematics and Stop Maneuver Definitions

This document is specific to vehicles equipped with the CICAS-V system. Vehicle velocity will be considered positive in the forward direction of travel, and for the basic warning scenario, the direction shall represent a trajectory toward a CICAS-V intersection and then proceeding through the intersection, possibly performing a turning maneuver. The basic maneuver for consideration is a vehicle initially approaching from beyond the area described by the intersection's CICAS-V Geometric Intersection Description (GID) information. The vehicle is approaching at a constant initial speed (designated v_i) along a single lane. At some time t_b, the vehicle begins braking for a stopping maneuver such that the vehicle stops at the stop line location at a later time t_s as illustrated in Figure 1.

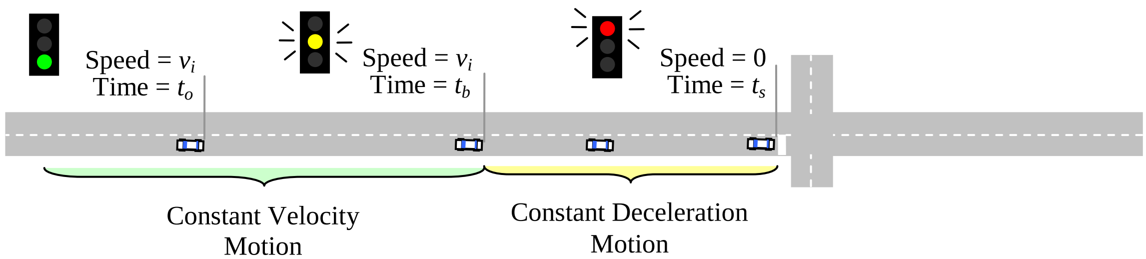

Figure 1 – Basic Stopping Maneuver

At each point in time in a vehicle maneuver, there is a rate of constant deceleration that brings the vehicle to a stop before a critical event. Some researchers have designated this rate the "*required deceleration parameter*" (*RDP*) for the maneuver. For CICAS-V, the RDP defines the constant deceleration required to stop the vehicle before it crosses a stop line and moves into potential cross-traffic, whenever such a crossing would be in violation of the traffic control signal or sign. Of course, real maneuvers are never accomplished with perfectly constant rates of deceleration, but as long as the average rate of deceleration is the same or greater than the RDP from the point of time the stopping maneuver begins until it reaches zero speed, the stopping maneuver is likely to be successful and avoid a violation. If the average rate is less than the RDP, however, the maneuver is not likely to be successful and the driver is likely to violate the traffic control sign or signal.

Figure 2 shows the RDP graphically. Constant deceleration in a velocity plot appears as a straight line from a higher speed to a lower one, or in the case of the stopping maneuver, as a straight line that slopes down to the horizontal axis. The slope of the curve represents the deceleration rate. The distance covered is the integral of $v \cdot t$, which is represented by the area under a velocity curve. If this area represents exactly the remaining distance to the stop line, the slope of the line represents the RDP. Figure 2 also shows two cases of the basic stopping maneuver. In Case 1, the vehicle has initial speed v_1, while in Case 2 the initial speed is v_2. At time t_b in both cases, the vehicle begins braking. Based on the initial velocities and the requirement that the vehicle must stop at the same distance traveled in both cases, the results show that the vehicle stops at two different times, which are designated t_{s1} for Case 1 and an earlier time t_{s2} for Case 2. The differing stopping times make the areas under each curve equal, because the vehicle is at the same distance at time t_0.

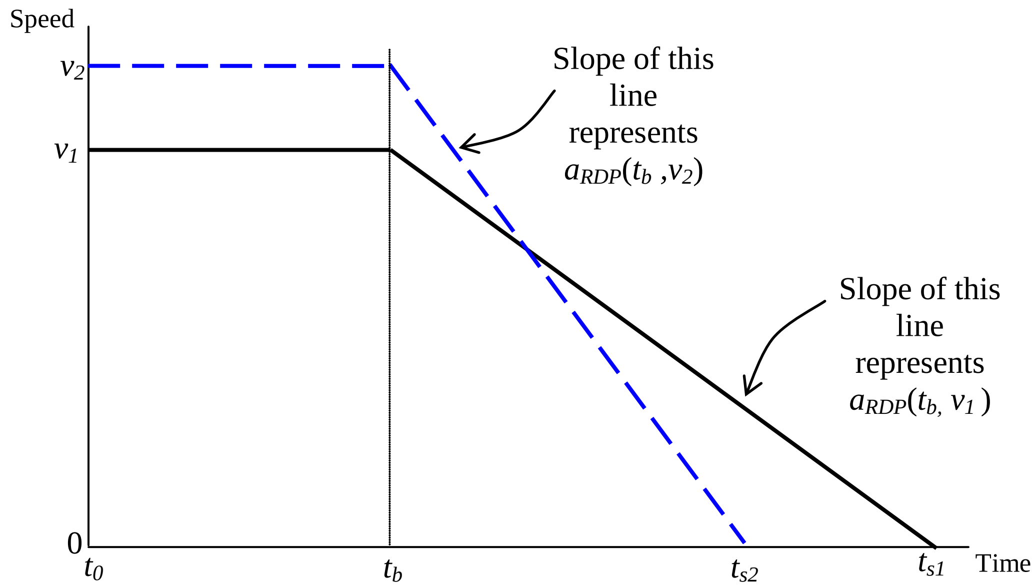

Figure 2 – a_{RDP} for Differing Initial Velocities

The general definition for acceleration (and deceleration) is:

$$a = \frac{\Delta v}{\Delta t}$$

Equation 1

For a particular case, the time origin t_s can be defined to be zero, and the final velocity set to zero. The RDP rate a_{RDP} as a function of braking time can be simplified to:

$$a_{RDP}(t_b) = \frac{v_i - 0}{0 - t_b} = -\frac{v_i}{t_b}$$

Equation 2

The quantity v_i is any particular initial velocity (v_1 or v_2 in the example plot). The higher the initial velocity, the higher the RDP deceleration, which appears as a steeper velocity curve for the deceleration phase. The negative sign in Equation 2 is necessary if the equation is to represent acceleration and velocity in general, but for simplicity, the negative sign is often omitted with the implication that the acceleration direction is normally backwards for a stopping maneuver (i.e. deceleration). In cases where the velocity before braking is not constant, the a_{RDP} quantity is not as simple to compute, but for the majority of situations for which CICAS-V is designed, such as distracted drivers or drivers having difficulty clearly seeing the traffic signal or sign, the pre-braking velocity is likely to be nearly constant.

The value of a_{RDP} will also vary based on the length of time over which the maneuver is performed. The later the braking for deceleration begins, the more severe the required rate of deceleration. Two different times of braking onset are represented in Figure 3 below, with the two corresponding a_{RDP} values represented as slopes with different steepness. The vehicle in Case 3 begins braking at a time t_{b3}, and stops after covering the distance to the stop line at time t_{s3}. In Case 4 however, the vehicle starts braking at a later time t_{b4}, and stops at an earlier time t_{s4}. The vehicle in Case 3 is performing a more *conservative* maneuver, while in Case 4, it is performing a more *aggressive* maneuver.

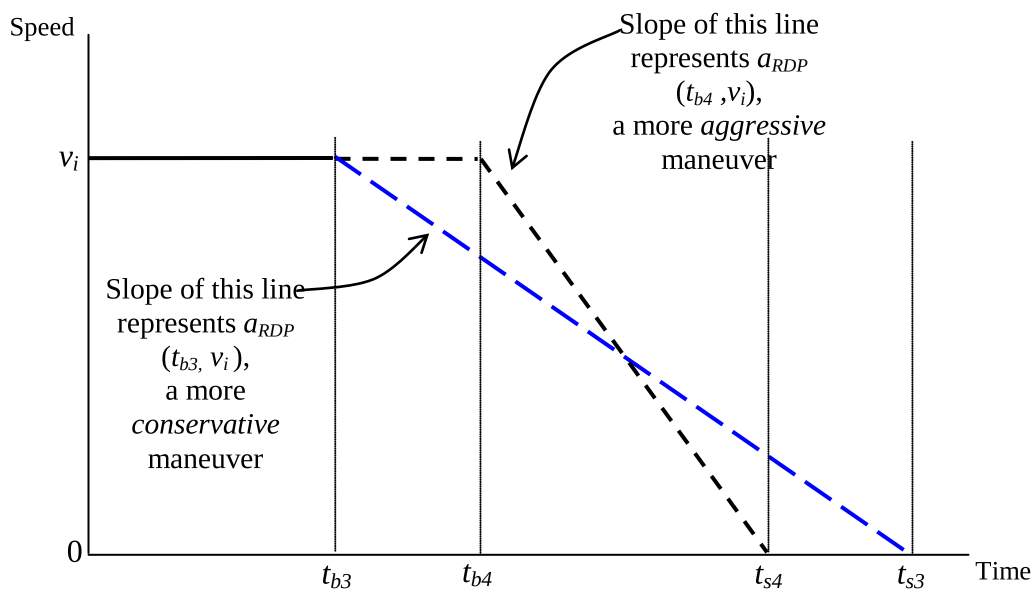

Figure 3 – a_{RDP} for Differing Braking Onset Times

From the above plots, it is easy to see that the RDP value will generally change moment to moment and from approach to approach. If the vehicle is approaching the intersection at a constant or increasing speed, the RDP value will eventually reach a level that the driver will find uncomfortable or even physically incapable of performing. Similarly, the RDP can reach a value that the vehicle itself is not capable achieving. Therefore, if a CICAS-V warning system is to be effective, any warnings that it issues must be done at a point of time where the RDP value is still reasonable for most drivers and vehicles. On the other hand, if the system warns when the RDP is still quite low, perhaps several seconds before an alert driver wishes to begin his or her stopping maneuver, that driver is likely to get annoyed with the system and find it unacceptable. Therefore, for overall system effectiveness, it is important to select and accurately implement warning trigger criteria that provide legitimate warnings that reduce intersection crashes without issuing many “nuisance alerts.”

Studies of sample populations of drivers have been done to determine the *maximum acceptable deceleration rate* most drivers are willing to attempt and able to achieve in a variety of sudden stopping situations. These findings are being used by the CICAS-V team to select appropriate warning criteria. The symbol a_{lim} is used to designate this maximum acceptable deceleration rate in this document. Figure 4 shows the result of superimposing a maximum deceleration limit on the previous velocity plot.

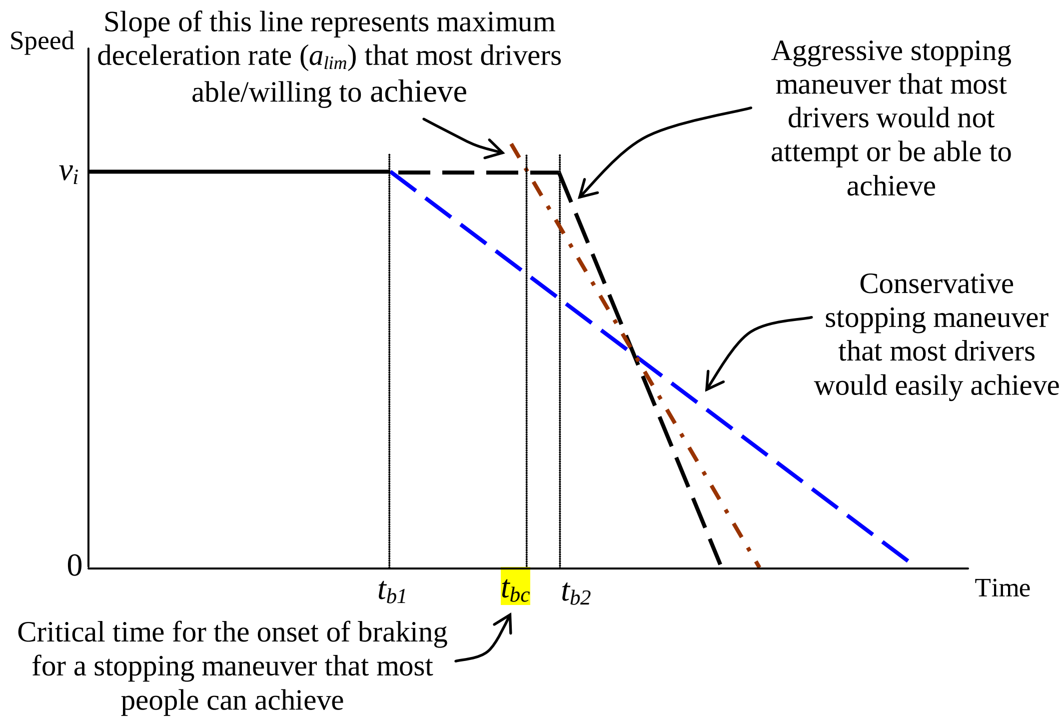

Figure 4 – Maximum Acceptable Deceleration Limit

The a_{lim} provides a limit on the timing of a violation warning. Equation 2 and the acceptable deceleration limit a_{lim}, can be used to obtain the *critical time of braking* t_{bc}:

$$t_{bc} = \frac{v_i}{a_{\text{lim}}}$$

Equation 3

If the warning comes later than t_{bc} for a given initial speed, most drivers will either not be able to perform the maneuver or not be willing to comply.

The previous plot shows the maximum acceptable deceleration rate as a constant slope; however, research has shown the limit is somewhat dependant on initial speed, and acceptability limit is generally larger at slower speeds, so the a_{lim} curve as a function of initial speed (v_i) shows a trend similar to the following plot:

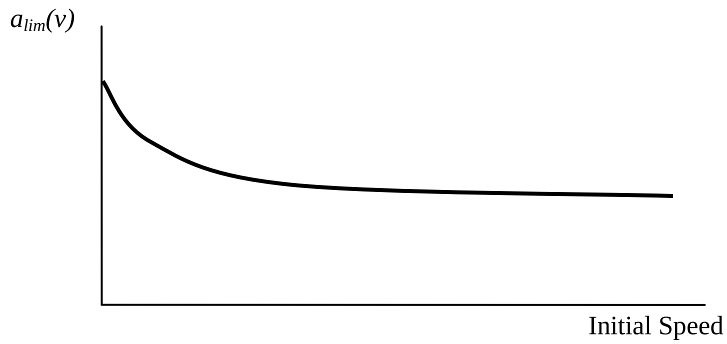

Figure 5 – a_{lim} as a Function of Initial Velocities

The $a_{lim}(v_i)$ can be used at different approach speeds to find the critical time for braking onset as shown below in Figure 6 – Time of Critical Braking Considering Speed-Dependent *alim*

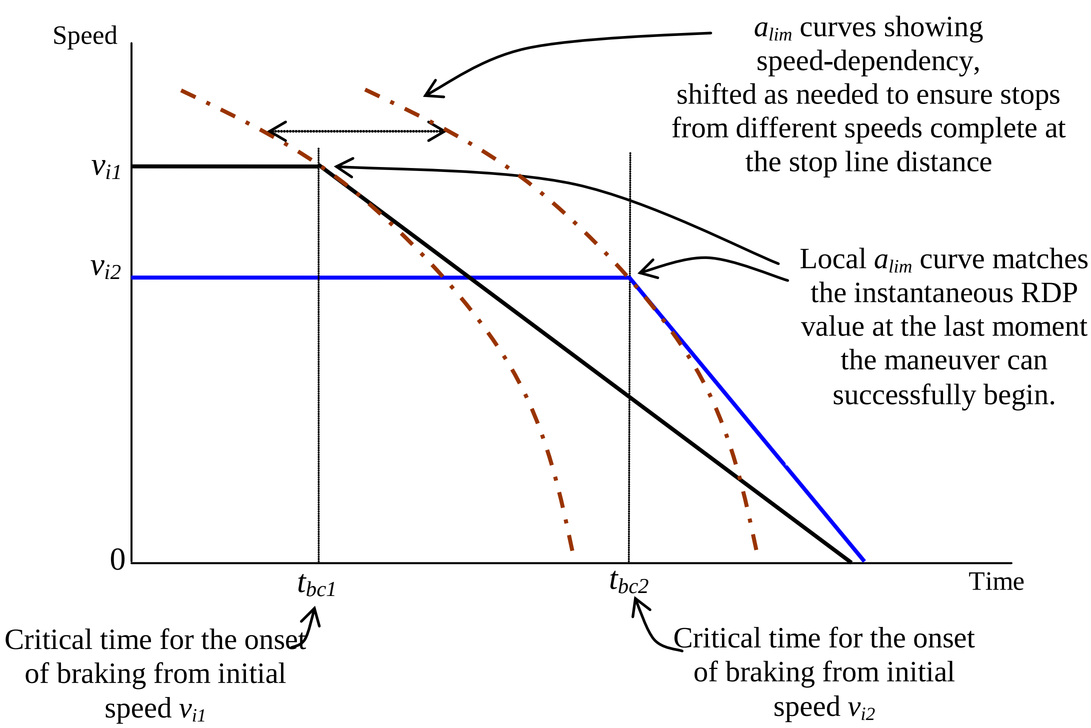

Figure 6 – Time of Critical Braking Considering Speed-Dependent a_{lim}

Working in the time domain is complicated by the fact that the absolute time the vehicle crosses or stops at the stop line depends on the whether or not the vehicle speed changes. So instead of specifying the appropriate time of violation warning based on the relative braking onset time t_{bc} as above, the CICAS-V team has decided to define a *critical warning threshold distance*, $d_{crit}(v_i)$ from the stop line, which is a function of current vehicle speed. This threshold distance may be pre-computed for a wide range of speeds by finding the distance for which the instantaneous required deceleration rate a_{RDP} matches the acceptable deceleration limit a_{lim} at that speed. As a starting point, the CICAS-V team has decided to compute the warning threshold distance values based on the kind of simple kinematics model described above, which includes an initial constant speed followed by a constant deceleration. The time it takes to safely and successfully begin the most aggressive braking maneuver most people can complete is given by the critical braking time in Equation 3 above. Over this period of time, the vehicle will cover a distance of:

$$d_{bc} = v_{ave} \cdot t_{bc} = \frac{(v_i - 0)}{2} \cdot t_{bc} = \frac{v_i}{2} \cdot \frac{v_i}{a_{\lim}} = \frac{v_i^{\ 2}}{2 \cdot a_{\lim}}$$

Equation 4

In other words, d_{bc} is the distance covered when the braking begins at the critical last moment that the braking maneuver will not surpass the deceleration limit a_{lim}. Since a_{lim} may be a function of v_i, the more general description of d_{bc} is:

$$d_{bc}(v_i) = \frac{v_i^{\ 2}}{2 \cdot a_{\lim}(v_i)}$$

Equation 5

Depending on the experimental methods, the function $a_{lim}(v_i)$ observed by human factors research may or may not be defined in a way that includes human reaction time. In order to treat reaction time separately, the warning threshold distance definition needs to include the additional distance covered during the driver's reaction period. This distance will include distances traveled during the following activities:

- Time to perceive an alert and recognize its meaning (perception time)
- Time to decide to perform braking maneuver
- Time to orient the body to brake, including placing the foot on the brake pedal in case it is elsewhere
- Time to move the brake pedal enough to deliver significant deceleration

The driver's reaction time will be highly variable depending on the level of distraction or impairment, physical capabilities, and to some degree the vehicle configuration. Certain DVI modalities have been shown in CICAS-V Task 3 research to invoke a rapid and appropriate driver reaction, so this reaction time will be minimized as much as practical. The currently conceived CICAS-V system does not attempt to dynamically estimate the driver's human reaction time because it has no direct sensing of the driver's state of attention and very indirect and limited sensing of the driver's body (basically limited to brake and accelerator pedal positions and steering wheel angle), so the driver reaction time will only be modeled as a fixed value t_{react} that is determined analyzing distributions of reaction times for a representative driver population. The distance d_{react} covered by the vehicle during the *human reaction time* t_{react}, while still in constant-speed motion, is given by:

$$d_{react} = v_i \cdot t_{react}$$

Equation 6

The critical warning threshold distance d_{crit} can now be defined as a function of initial velocity v_i:

$$d_{crit}(v_i) = d_{react} + d_{bc} = (v_i \cdot t_{react}) + (\frac{v_i^{\;2}}{2 \cdot a_{\lim}(v_i)})$$

Equation 7

The performance of the implemented system will be limited by certain practical constraints, including at least the following:

- Sampling period of vehicle speed, t_{vs}
- Sampling period of vehicle location estimate (e.g. as from GPS), t_{ls}
- Uncertainty in vehicle speed, δ_v
- Uncertainty in vehicle location, δ_l
- Processing latency due to processing throughput or periodicity of processing, t_{proc}

The total *distance uncertainty* will be a combination of at least all these factors, which in the worst case is estimated by:

$$d_u = \delta_l + (v_i + \delta_v) \cdot \max(t_{vs}, t_{ls}, t_{proc})$$

Equation 8

The performance limitations should not be so severe that the vehicle is likely to fail to stop before entering potential cross-traffic past the stop line. Therefore, the distance uncertainty should be less than the *distance from a stop line to potential cross-traffic,* which is designated as d_{ct}:

$$d_u \leq d_{ct}$$

Equation 9

The d_{ct} criterion is based on the geometry of traffic intersections. The current version of this performance specification uses a fixed value of 2.0 meters.

Combining the previous criteria, an optimal warning must be delivered no closer than d_{crit} and no further than d_{crit} + d_u. This results in the following correctness criteria for the location of the vehicle when a warning was issued, d_{warn}:

$$d_{crit} + d_{ct} \geq d_{warn} \geq d_{crit}$$

Equation 10

2.2 Violation Prediction

2.2.1 Determination of the Need to Stop

The CICAS-V system is conceived to provide violation warnings in a variety of traffic control situations, including stop sign and traffic light intersections, with many possible configurations. The CICAS-V system must be able to distinguish between situations in which the driver is mandated to stop and those where the driver has permission to proceed through an intersection (and perhaps perform a turning maneuver) at his or her discretion. In the case of traffic light-controlled intersections, the mandate to stop is time-varying, based on a sequence of traffic light phases (green, yellow, red, etc.) for each controlled approach lane. The CICAS-V system must not warn a driver if that driver has unambiguous permission to proceed, as in the case of a green traffic control light, and must attempt to warn the driver if he or she appears likely (based on the criteria describe above) to violate the signal.

To help clarify the design of the portion of the CICAS-V system that determines the need to stop, the CICAS-V team has adopted a more specialized meaning for the term *approach*. For CICAS-V, an approach is a set of one or more lanes which proceed in a particular direction and for which there is a distinct traffic control state. Once the CICAS-V system has located the vehicle position sufficiently well to determine a likely lane position, the system will look up lane attributes (which provide or constrain the traffic control state), and in the case of signalized intersections, will look up which approach the lane is grouped into. From this information, CICAS-V will be able to determine the control state for its current approach that will be in effect when the vehicle is estimated to reach the stop line, assuming it proceeds with constant speed all the way to the stop line. Note that the permitted lane attributes of “no stop” and “yield” should override other control state information, and so should be only used when truly appropriate.

In the simple case of two two-lane roads at a four-way stop sign intersection, the CICAS-V system will recognize four approaches of one lane each, and each of them has a static “stop then proceed at driver’s discretion” status. For this intersection, in all approach scenarios from all directions, the CICAS-V system should recognize the need to stop. If, however, the intersection is a two-way stop at the point a minor road crosses a thoroughfare, the CICAS-V system should recognize the situation that the vehicle does not need to stop when the vehicle is in the thoroughfare lanes, but does for the minor road. Note that the thoroughfare lanes represent an appropriate use of the “no stop” lane attribute.

For *signalized* intersections controlled by a stop light, the need to stop is dynamic. Given the current signal phase, the time remaining to the next phases, lane attributes, and the current vehicle speed and position, the CICAS-V system must determine if the driver needs to stop when his or her vehicle reaches the stop line. CICAS-V may make the determination by comparing the amount of time required to travel the remaining distance to the stop line to the time remaining before the signal phase turns red. If the signal phase is currently red, the “time to red” may be considered zero. When signalized intersections have one or more approaches where the signal phase change timing is modified by “actuation” signals such as “ground loop” or pressure-based traffic sensors, the actual time to the next red phase is not always known. This situation is indicated in the Signal Phase and Timing message with an arbitrary number with no confidence. This causes the vehicle to disregard the time to red until an accurate time can be obtained. During the period in which no time to red is available, the CICAS-V in the vehicle will continue receiving intersection messages, determine its distance from the stop bar and lane of travel, but not warn the driver. .

Multi-lane signalized intersections often have lanes dedicated to making turns, and these lanes commonly have distinct traffic control states. For example, an intersection may have two straight-through lanes in a particular direction and two short turn lanes, one dedicated to left turns and one to right turns. The traffic signal controller may present three sets of lights to the drivers in these four lanes:

- Left turn lane: Left green arrow, left yellow arrow, and red signal
- Straight through (shared by the two straight-through lanes): Green signal, yellow signal, and red signal
- Right turn lane: Right green arrow, right yellow arrow, and red signal (with perhaps the permission to turn "right on red")

In this case CICAS-V will recognize three approaches in this direction of travel, with the left and right turn approaches having one lane each and the straight-through approach having two lanes. Once the CICAS-V system has located the vehicle position sufficiently well to determine a likely lane position, the system will look up which approach the lane is grouped into and the current traffic control state for that approach. The "time to red" value will likely be different for each of the turn approaches compared to the straight-through approach.

2.2.2 Violation Prediction Criteria

For use in specifying and measuring system performance, the violation prediction is true if the result of the "need to stop" assessment as discussed above is true at the time the vehicle position has reached the critical warning threshold distance $d_{crit}(v)$ at its current speed. More formally, given the distance to the stop line d_{sb}, the current speed v, the time to the stop line t_{sb} as a function of time is defined:

$$t_{sb}(t) = \frac{d_{sb}(t)}{v(t)}$$

Equation 11

The "time to red" quantity t_r as a function of time is defined:

$$t_r(t) = \left| \begin{array}{c} 0, \mathit{if\ \ approaching\ stop\ sign} \\ 0, \mathit{if\ \ signal\ \ phase\ is\ red} \\ t_{cd}(t), \mathit{if\ \ signal\ \ phase\ is\ yellow} \\ t_{cd}(t) + t_a, \mathit{if\ \ signal\ \ phase\ is\ green} \end{array} \right.$$

Equation 12

where $t_{cd}(t)$ is the countdown time remaining in the current traffic signal phase at time t and t_a is the total length of the yellow phase for the intersection, which is typically fixed for a given intersection. With these definitions, the 'Need to Stop' criterion is:

$$t_{sb} \geq t_r \Rightarrow need\_to\_stop$$

Equation 13

Since the violation prediction is made as the distance $d_s(t)$ drops below the critical warning threshold distance $d_{crit}(v(t))$, the violation prediction is defined as:

$$\exists t \ni \frac{d_{sb}(t)}{v(t)} \geq t_r \wedge d_{sb}(t) \leq d_{crit}(v(t)) \Rightarrow violation\_predicted$$

Equation 14

If the velocity of the vehicle over time does not follow the simple basic maneuver, it is possible the *violation_predicted* criteria will be met multiple times during the approach. The complex approach can be broken into shorter episodes, as shown in Figure 7.

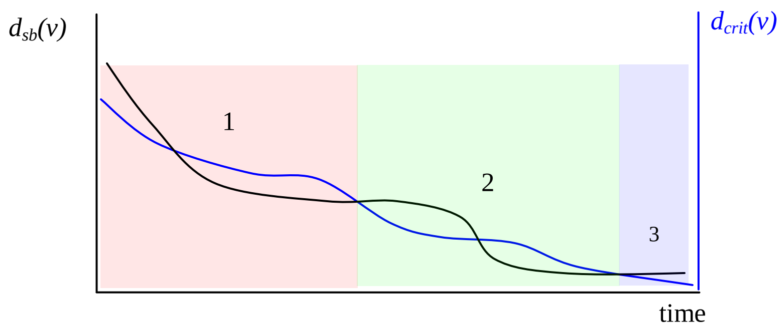

Figure 7 – Sub-Maneuvers in Multiple Warning Scenario

2.3 Event Timing Model

2.3.1 Overview

The following sequence diagram (Figure 8) shows the event sequence and the interoperation during a straightforward violation warning scenario.

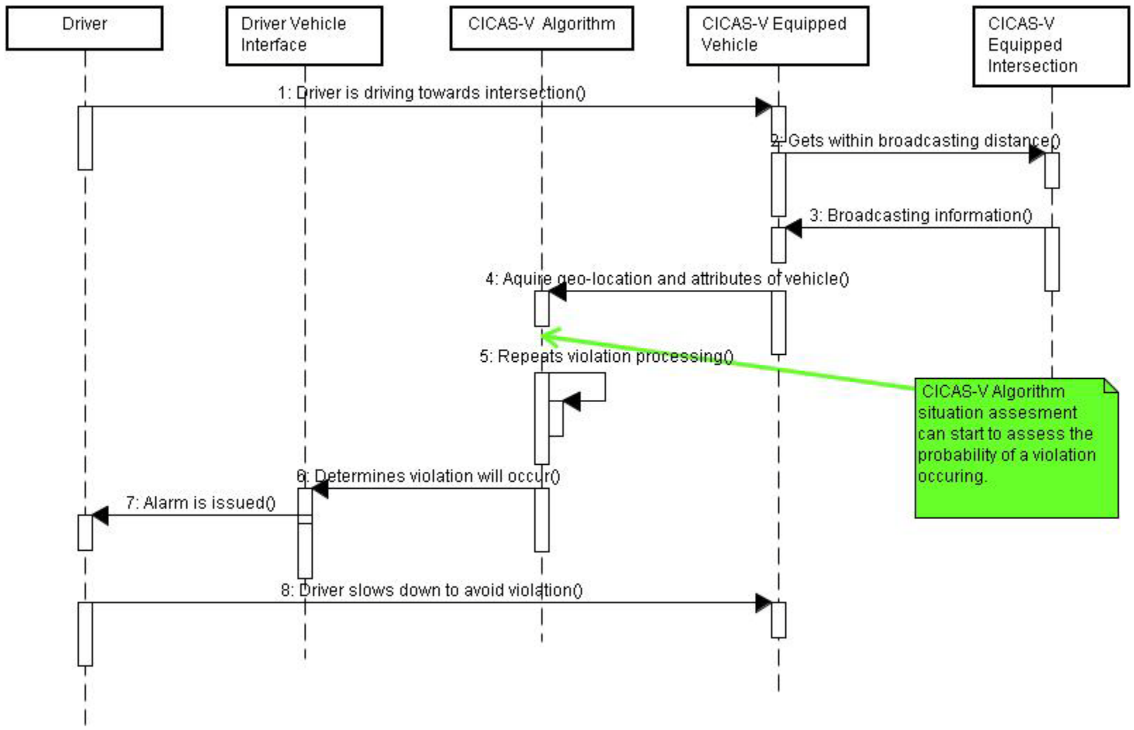

Figure 8 – CICAS-V Violation Warning Sequence Diagram

In order for this interoperation to take place, certain critical events must occur within time limits defined by the physical kinematics of the vehicle motion, vehicle maneuvering (especially braking) capability, and cognitive and physiological capabilities of drivers.

A typical sequence of events is shown in Figure 9.

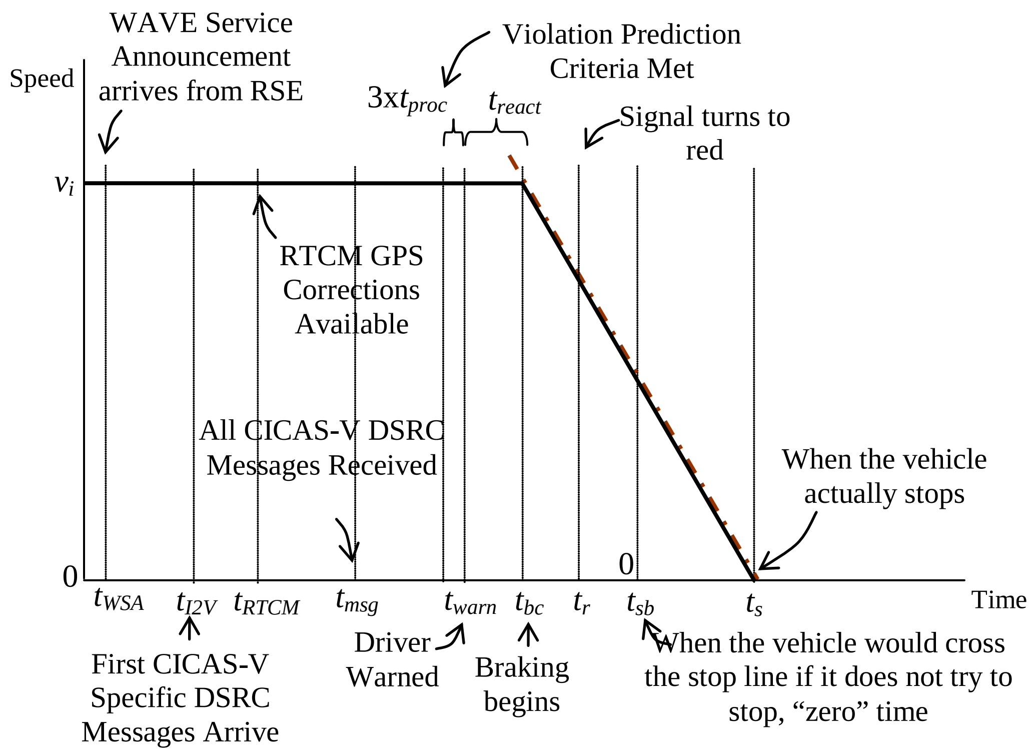

Figure 9 – Event Timing Model

Critical Events:

- When the vehicle actually stops, t_s
- Potential crossing-path collision when vehicle will pass the stop line if it does not brake, t_{sb}
- Beginning of traffic control signal red phase, t_r
- Start of successful braking maneuver, t_{bc}
- Availability of alert to driver, t_{react} before t_{bc}
- Presentation of violation warning, t_{warn}
- Availability of map-matching results and current vehicle information, t_{proc} before t_{warn}
- Completion of Infrastructure-to-Vehicle (I2V) information broadcast reception, including GID, Signal Phase and Timing (SPaT), and GPS Corrections (GPSC), t_{msg}
- Arrival of first DSRC CICAS-V messages, t_{I2V}
- First availability of CICAS-V WAVE Service Announcement (WSA) via DSRC from the intersection, t_{WSA}

2.3.2 Deadline Analysis

For a successful stopping maneuver, the time of the driver warning needs to be at least ready to activate by the time the vehicle distance reaches d_{crit}, defining a warning deadline of t_{crit} relative to the time origin designated t_{sb}.

$$t_{crit} = \frac{d_{crit}}{v_i} = t_{react} + \frac{v_i}{2 \cdot a_{\lim}}$$

Equation 15

In order to provide an accurate violation warning, the warning algorithm needs to have stable and accurate input quantities. A good criterion would be to budget three sample periods of the vehicle position estimation or vehicle speed sensing (whichever sampling is lower in frequency). According to the current design concept, the sampling period for both the GPS-based vehicle positioning and vehicle speed sensing provided through a vehicle Controller Area Network (CAN) network protocol converter are both 100 msec. The time to acquire accurate information t_{data} is:

$$t_{data=}t_{crit} + 3 \cdot \max(t_{sv}, t_{sl}) = t_{crit} + 300ms$$

Equation 16

In order to have highly accurate vehicle positioning, RTCM position corrections provided by the Infrastructure Roadside Equipment (RSE) via DSRC broadcast need to be available (t_{RTCM}) at least four seconds before t_{data}:

$$t_{RTCM} = t_{data} + 4000ms = t_{crit} + 4300ms$$

Equation 17

The Signal Phase and Timing (SPaT) and GID must also be available before $t_{data,}$

Although it is not expected that there will be any significant vehicle-side processing latency once the SPaT and GID DSRC messages are received, the reception of the SPaT and GID data could take several seconds, assuming the DSRC communications operates with a 30% Packet Error Rate, and GPSC rebroadcasts at 1 Hz and GID at 2 Hz. To ensure a high probability (99.6%) of receiving all the required DSRC messages, the system must allow 3.0 additional seconds (worst case) for t_{I2V} , the arrival of the first CICAS-V I2V application messages.

$$t_{I2V} = t_{RTCM} + 3000ms = t_{crit} + 7300ms$$

Equation 18

The WSA for the CICAS-V service will be broadcast on the 802.11p/WAVE Control Channel, and may be 100 msec before the application message broadcasts, which may be on a service channel. The system should allow an additional 100 msec for the arrival of the WSA:

$$t_{WSA} = t_{I2V} + 100ms = t_{crit} + 7400ms$$

Equation 19

Substituting 0.8 seconds for t_{react}, 5.0 m/s^2 for a_{lim} and an initial velocity of 20.2 m/s (~45 mph), results in a t_{crit} time of:

$$t_{crit}(20.2m/s) = 0.8s + \frac{20.2m/s}{2 \cdot 5m/s^2} = 2.82s$$

Equation 20

Plugging this value into Equation 18 results in a deadline for the initial WSA arrival:

$$t_{WSA} = t_{crit} + 7400ms = 2820ms + 7400ms = 10.22s$$

Equation 21

At the initial velocity of 20.2 m/s, this deadline imposes a DSRC reception range requirement of about 206 meters. DSRC reception during initial testing has shown good packet error rates within 200 meters, so this deadline should not be difficult to achieve at many 45 mph intersections. At 55 mph, the t_{WSA} deadline imposes a DSRC range requirement of about 263 meters, which is more difficult if the antenna does not have good gain and the vehicle-to-RSE antenna line of sight is not clear.

2.4 Performance Classification of Warning Events

As described above, the CICAS-V system must accurately distinguish between likely violation situations from non-violation situations, and for the violation situations, must provide the warning at an appropriate time to be effective. To measure the performance of the warning functionality, the presence or lack of a warning is compared to the violation prediction determined by analysis of the series of vehicle speed and position measurements. The location of a warning is compared to the warning distance threshold defined above. A warning event is analyzed at the time and location the warning algorithm status changes to a state that activates the DVI equipment. For the basic approach maneuver (constant initial speed followed by a constant deceleration at some point), the warning algorithm should only assume an active warning state once before the vehicle approaches the stop line, although for more complex approach maneuvers, it is possible for the warning state to be active multiple times. In this case, the complex maneuver may be broken into multiple basic ones, but the correctness of the secondary warning(s) must take into consideration the elapsed time since the most recent prior warning activation.

With the warning presence and location, the maneuver will be classified and tallied in one of the performance categories illustrated in the following table and described below. The tallies of each category and statistics within each category will be used to define various system performance metrics.

Table 1 – Violation Warning Event Classifications

Suppression Status	Violation Prediction when Vehicle at $d_{crit}(v_i)$	Warning Location					
		No Warning	$\boldsymbol{d_{warn}} >> d_{crit}(v_i)$	$\boldsymbol{d_{warn}} > [d_{crit}(v_i) + d_{ct}]$	$[d_{crit}(v_i) + d_{ct}] \geq \boldsymbol{d_{warn}} \geq d_{crit}(v_i)$	$d_{crit}(v_i) > \boldsymbol{d_{warn}} \geq 0$	$\boldsymbol{d_{warn}} < 0$ (past stop line)
Not Suppressed	Violation	False Negative	Premature True Positive	Premature True Positive	True Positive	Late True Positive	Late True Positive
	No Violation	True Negative	False Positive				
Suppressed	Violation	Correctly Suppressed	Unsuppressed				
	No Violation	n/a	n/a	n/a	n/a	n/a	n/a

Suppression Status

A condition where the criteria used to suppress the warning are true.

Violation Prediction

As defined in Equation 14, a violation is predicted when there is a time during the approach maneuver when the time to stop line t_{sb} is greater than "time to red" t_r while at the same time the distance to stop line d_{sb} is less than or equal to the critical warning threshold distance at the current speed $d_{crit}(v_i)$.

True Positive Warning

A warning was issued for an approach maneuver that is predicted to be a violation, and the warning was delivered within the location boundaries defined by Equation 10. In other words, the warning was delivered through the DVI at or between the distance $d_{crit}(v_i) + d_{ct}$ and $d_{crit}(v_i)$. The warning was delivered in a situation that should not be suppressed. This is one of the "correct" event warning classifications.

Premature True Positive Warning

A warning was issued for an approach maneuver that is predicted to be a violation, but the warning was delivered at a location farther than $d_{crit}(v_i) + d_{ct}$. The warning was delivered in a situation that should not be suppressed.

Late True Positive Warning

A warning was issued for an approach maneuver that is predicted to be a violation, but the warning was delivered at a location closer than $d_{crit}(v_i)$ but before the stop line. The warning was delivered in a situation that should not be suppressed.

False Positive Warning

A warning was issued for an approach maneuver that is not predicted to be a violation. The warning was delivered in a situation that should not be suppressed if the violation was predicted.

True Negative Non-Warning

A warning was not issued for an approach maneuver that is not predicted to be a violation. This is one of the "correct" event warning classifications.

False Negative Missed Warning

A warning was not issued for an approach maneuver that is predicted to be a violation. The lack of warning was not caused by warning suppression at the time the vehicle was at the $d_{crit}(v_i)$ location.

Correctly Suppressed Warning

A warning was not issued for an approach maneuver that is predicted to be a violation because the prediction occurs in a situation that should be suppressed. This is one of the "correct" event warning classifications.

Unsuppressed Warning

A warning was issued for an approach maneuver that is predicted to be a violation, but the warning was delivered in a situation that should be suppressed.

Falsely Suppressed Warning

A warning was not issued for an approach maneuver that is predicted to be a violation because the warning was suppressed at the time the vehicle was at the $d_{crit}(v_i)$ location even though the suppression criteria were not met.

"Earliness" and "Lateness" Timing Deviation Factors

While violation prediction is defined in terms of distance, it is still useful to analyze variance of warning presentation in terms of time differences. The time origin t_0 is defined to coincide with the point in time the vehicle will pass the stop line if it continues to move with constant velocity for the period after the critical warning threshold distance $d_{crit}(v_i)$. This implies that the ideal warning time t_{iw} is:

$$t_{iw} = t_r + t_{bc}$$

Equation 22

The earliest acceptable warning time t_{ew} is:

$$t_{ew} = t_r + t_{bc} + \frac{d_{ct}}{v_i}$$

Equation 23

If the actual warning time t_w is earlier than the earliest acceptable warning time, the earliness factor e_w of the premature warning event is defined as the ratio of the event timing deviation over the ideal limit magnitude:

$$e_w = \frac{t_w - t_{ew}}{t_{iw}} = \frac{t_w - t_r - t_{bc} - \frac{d_{ct}}{v_i}}{t_r + t_{bc}}$$

Equation 24

Similarly, if t_w is later than the ideal warning time, the lateness factor l_w is the ratio of the event timing deviation over the ideal limit magnitude:

$$l_w = \frac{t_w - t_{iw}}{t_{iw}} = \frac{t_r + t_{bc} - t_w}{t_r + t_{bc}}$$

Equation 25

3 Performance Specifications

3.1 Critical Sensing Subsystems Performance Specification

The CICAS-V system is designed around enabler technologies such as GPS and 802.11p DSRC wireless communications and makes several assumptions about the performance and accuracy of sensing systems that provide CICAS-V critical data inputs. The CICAS-V team has defined several sensing subsystem performance metrics that ensure the critical inputs to violation warning algorithms are working at least well enough to meet design assumptions. While many of the subsystem performance assumptions are not hard "make or break" limits, failure to achieve one or more of these assumptions is likely to compromise overall system performance, at least in certain scenarios. Most of the performance specifications for infrastructure and vehicle are the same, therefore these requirements have the same designation.

Table 2 – Critical Sensing Subsystems Metrics and Performance Specification

Performance Specification ID	Section	Metric	Definition	Ideal Performance	Acceptable Performance
PS-001	3.1.1	SPaT Absolute error	Absolute error of phase change time information	0.0 seconds	< ±0.1 seconds error,
PS-002	3.1.1	SPaT Resolution	Resolution of phase change information.	0.01 seconds resolution	0.05 seconds resolution
PS-003	3.1.1	SPaT Latency	Time from receipt of SPaT data at the RSE to broadcast of SPaT data by RSE	0.01 seconds	0.1 seconds

The critical sensing subsystems performance metrics are described below.

3.1.1 SPaT Accuracy and Resolution

The reported signal timing shall specify the absolute time each signal will change phase with an absolute accuracy of +/- 0.10 seconds as defined by the GPS system, expressed with a resolution of 0.01 seconds (absolute minimum resolution is 0.05 seconds). That is, the reported timing should be accurate despite any internal RSE processing and message transmission latencies. The internal RSE latency would ideally be substantially shorter than the interval between SPaT data broadcasts, with 0.01 seconds being the ideal and 0.1 seconds being the longest acceptable latency. The accuracy and latency will be measured by the RSE using GPS time.

> **Rationale:** Using a common absolute GPS time base will allow all vehicles to make accurate signal violation assessments. At 30 m/s, a vehicle travels 1.5 meters in a 0.05 second (50 ms) period, which should be less than the setback of a stop line from the conflicting cross-traffic lane (at least the portion of the lane typically occupied by vehicles).

3.2 Operational Validation

The CICAS-V Concept of Operations and System Specification describe operational validation modes. While in this mode, the CICAS-V infrastructure will perform additional functions to verify configurations and validate performance. Requirements addressing Validation Mode functions have been deferred from the current CICAS-V system implementation. As such, Validation Mode performance specifications are included for information only and are not constituent to the current system design basis.

Table 3 – Operational Validation Metrics and Performance Specification

Performance Specification ID	Section	Metric	Definition	Ideal Performance	Acceptable Performance
PS-004	3.2.1	Coverage Assessment	Unacceptable Coverage During Approach Rate	0%	< 5%
PS-005	3.2.1		Consecutive SPaT or WSA packet errors	0	< 4
PS-006	3.2.1		Average packet error rate	0	< 30% while on a GID approach
PS-007	3.2.2	Positioning Assessment	Unacceptable Positioning During Approach Rate	0%	<5%
PS-008	3.2.2		Estimated Horizontal Error	0.0 meters	< 0.5 meters
PS-009	3.2.2		Position Dilution of Precision (PDOP)	1.0	< 5.0
PS-010	3.2.2		# Satellites	12 satellites	> 4 satellites
PS-011	3.2.2		Loss of Base station Status Period	0 seconds	<8 seconds
PS-012	3.2.2		Loss of RTCM Corrections	0 seconds	< 4 seconds
PS-013	3.2.3	GID Accuracy	Percentage of reported/recorded positions within the GID within navigable areas (inside defined lane widths)	100%	>98%
PS-014	3.2.4	SPaT Accuracy	Percentage of vehicles who perform stopping maneuver within the indicated red phases	100%	>80%

3.2.1 Intersection Validation: Coverage Assessment

While in 'Validation' or 'Operational Validation' mode, the RSE shall collect coverage assessment messages from participating vehicles (defined in the Preliminary System Interface Documentation). DSRC coverage shall be assessed throughout each approach lane as defined in the GID for the intersection, from the farthest point of the approach lane to its nearest point (see Figure 10 below). If any one vehicle approach maneuver experiences 4 consecutive frame errors for WSA or SPaT messages, or an overall packet error rate (PER) greater than 30% while within an approach lane and within the distance defined in the GID, then that vehicle's approach maneuver shall be considered unacceptable in terms of communications coverage. If more than 5% vehicle approach maneuvers are classified unacceptable in a sample of 100 approaches, the RSE may attempt to raise the transmission power of its DSRC radio by a small amount, up to the approved limit. If the frame error rate is less than 5% of all frames associated with 100 approach maneuvers, then RSE may decrease the DSRC transmission power by a small amount. To be assessed as an operationally-fit intersection, fewer than 5% of the vehicle approach maneuvers shall be classified as unacceptable at an RSE DSRC transmission power level that has been stable for at least 400 approach maneuvers distributed over all defined approach lanes.

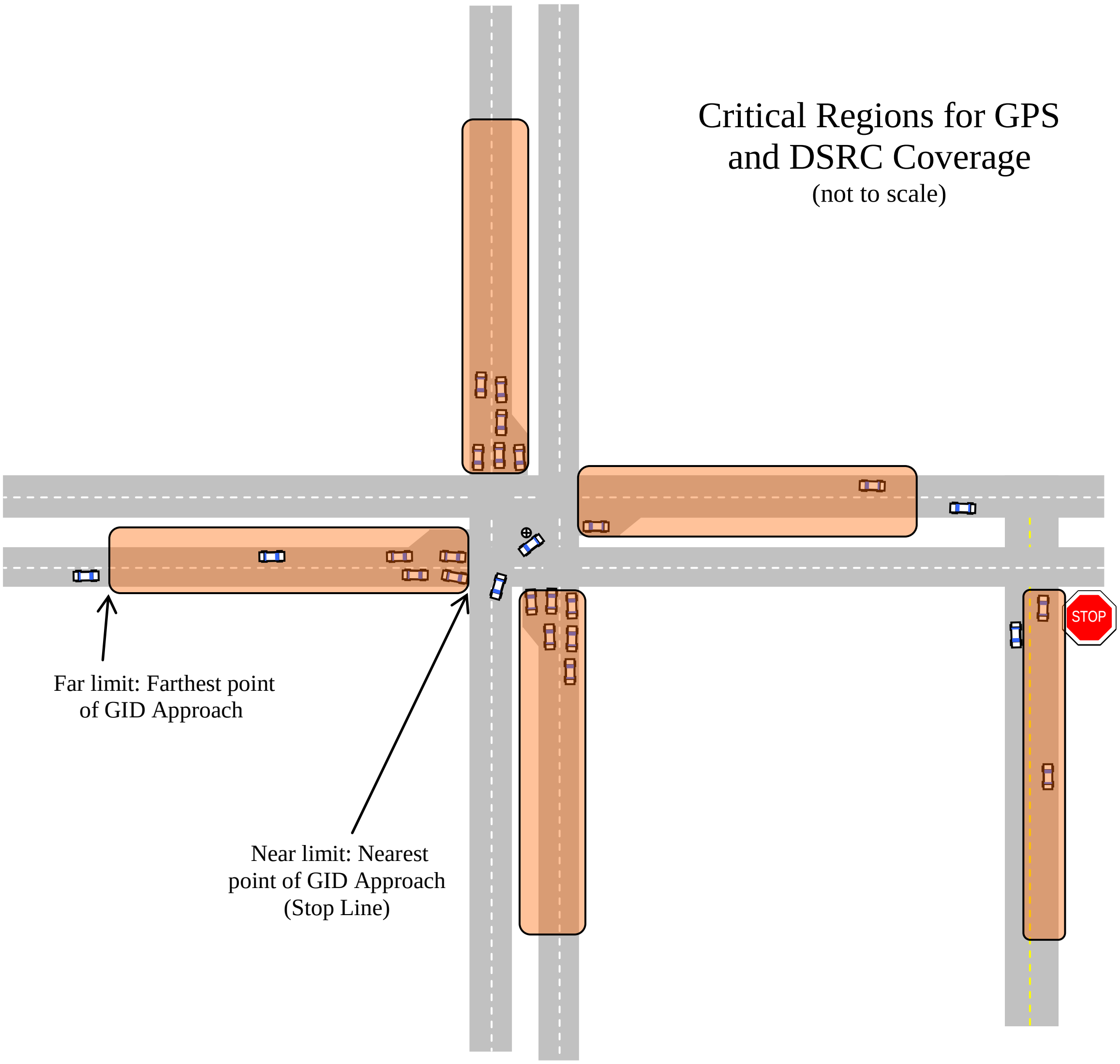

Figure 10 – Critical Regions for DSRC and GPS Reception

Rationale: The procedure described here helps to adjust the DSRC power level to a workable level and verify that most vehicles are able to receive an effective percentage of correct DSRC transmissions. The 10 Hz broadcast rate for SPaT and WSA messages guarantees 99.6% message reception reliability at 30% PER within 4 consecutive message frames (400 milliseconds). The GID defines critical regions where a CICAS-V system has sufficient time to estimate violation and warn the driver so that the vehicle can be stopped or at least significantly slowed down. The lengths of the approaches defined for a particular intersection are influenced by the curvature and grade of the lanes, posted speed limits, traffic volumes and potentially other factors. By tying the DSRC coverage area to the GID, we help ensure the vehicles will be able to get the information they need where they need to use it.

3.2.2 Intersection Validation: Positioning Assessment

While a vehicle is inside one of the "critical regions" defined above (see Figure 10), if the standard deviation of its GPS position estimate is greater than 0.5 meters in the horizontal plane, or the PDOP is greater than 5.0, or fewer than 5 satellites are used in the computations, then that GPS position estimate shall be considered unacceptable. Any reported vehicle position that is determined to be outside the intersection geometry is also considered to be unacceptable. For any particular vehicle approach maneuver, if any one of the GPS solutions is unacceptable while the vehicle is moving at a rate greater than 1.0 meters per second, that approach maneuver will be considered unacceptable. To be assessed as an operationally-fit intersection, fewer than 5% of the vehicle approach maneuvers shall be classified as unacceptable within a sample of 400 approaches by equipped maintenance vehicles.

The 'base station health' must be determined by monitoring the communications from the base station GPS and detecting the following conditions:

- Poor PDOP – GPS PDOP estimate is greater than 5.0
- Few Satellites – The count of observed satellites used in computations < 5
- Unhealthy Communications – One or more kinds of communications messages from the GPS have been absent for more than 8.0 seconds
- Unmonitored – The RTCM data has been unavailable for more than 60 seconds, which is the default timeout of the Onboard Equipment (OBE) GPS receiver

In such situations, vehicles shall be warned via the DSRC broadcasts of any of these abnormal status conditions no later than the next scheduled DGPS transmission. If any of these conditions disappears, the status condition in the DSRC broadcasts will be correspondingly reset.

> **Rationale:** The motion qualification is defined here because GPS signal may be lost due to unavoidable physical conditions around a vehicle. When the vehicle is stopped or moving very slowly, these conditions may persist longer than the time-out period. For example, the subject vehicle may be waiting for a light to change next to a large vehicle, or under a tree, or in a zone of high multi-path signal reflections, or some other situation that blocks several GPS satellites. Vehicles that are moving slowly or stopped near the intersection are not a major concern for violations, so if GPS reception is poor in relatively small areas of the overall intersection where vehicles are frequently slow or stopped, it probably does not matter. Like the DSRC, the critical zones are those that are 3 to 12 seconds before the intersection at moderate to fairly high rates of speed relative to "normal" traffic flow.
>
> The position-estimation and lane matching algorithms in the vehicle should ignore DGPS correction information from the RSE if the 'base station health' described above is abnormal. An abnormal condition exists if either the number of satellites used to produce the correction is less than five, or the PDOP number is greater than five, or the GPS communications at the RSE have been interrupted by at least eight seconds. At these times, if the vehicle OBE can obtain DGPS correction information directly from the vehicle's own GPS receiver, such as Wide-Area Augmentation System (WAAS), the OBE may use them. It should be

noted that this requirement focuses on the quality of the correction factors, which are inputs to the DGPS-aware positioning algorithm.

3.2.3 GID Accuracy

While in 'Validation' or 'Operational Validation' mode, the RSE shall analyze the collected GID accuracy messages (defined in the Preliminary System Interface Documentation) for consistency with the map geometry. To be considered operationally fit, 98% of the locations reported for assessment shall be within navigable sections of the GID once reporting vehicles are within the 300 meter range to the intersection reference position (center).

3.2.4 Intersection Validation: Signal Phase Timing Accuracy

The RSE shall log the signal phase/timing data and compare it to observed driver behavior reported by vehicles. If in a 400-vehicle sample, a significant majority (80%) of the closest (50 meters) vehicles in the presumed red-phase approach lanes does stop (velocity < 0.5 meters per second) within the red signal phase, the signal phase timing shall be considered operationally fit. The 400 vehicle sample could be obtained from maintenance vehicles or equipped vehicles from the general public.

3.3 Maintenance Functions

The CICAS-V Concept of Operations and System Specification describe maintenance functions. The following performance metrics and specifications will help to ensure the CICAS-V infrastructure is maintainable.

Table 4 – Maintenance Function Support Performance Specifications

Performance Specification ID	Section	Metric	Definition	Ideal Performance	Acceptable Performance
PS-015	3.3.1	Backend Connectivity Access Time	Latency to connect and begin a session which allows command interaction and/or data transfers	0.0 minutes	5.0 minutes
PS-016	3.3.2	Backend Connection Bandwidth	Raw data transfer rate	1.0 Gbps	2.4 Mbps
PS-017	3.3.2		Sustainable data transfer rate	1.0 Gbps.	200 Kbps

The maintenance function performance specifications are described below.

3.3.1 Backend Connectivity Access Time

A backend connection to each RSE-equipped site shall be available through a wide-area communication channel, such as cellular modem, WiFi, WiMax, broadband wired, twisted pair, or other types. The RSE shall either maintain an ongoing connection with a backend system, or shall readily accept remote connection requests and provide an active connection within five minutes of a trained user's initiation of such a process. The backend connection shall include access to logged data by traffic safety officials, such as state Departments of Transportation (DOTs), as well as authorized CICAS-V developers and researchers. Traffic safety officials shall also have control-level access to change the operational state of the RSE-equipped intersection, update signalization timing plans, and make other configuration changes.

> **Rationale:** The system shall provide access as needed for both planned and unplanned events and management needs.

Note: The connection may be designed to operate primarily in one of three modes: "always on" (information flows readily in both directions), “polled” (backend requests specific information on the backend system's schedule), or “event-driven push” (RSE decides it has something of interest to send to the backend such as a failed health check; a data archive has reached a certain size limit; a vehicle reports a serious violation, etc.).

3.3.2 Backend Connection Bandwidth

The backend connection shall provide at least 2.4 Mbps of raw data transfer bandwidth and support for a wireless connection with a sustained throughput up to 200 Kbps per RSE installation. For a wired connection, this connection shall provide 100 Mbps raw data transfer rate with 50 Mbps sustained throughput.

> **Rationale:** An evolution data optimized (EVDO) cellular modem is probably the minimally-acceptable wireless mechanism for remote access and should be capable of providing at least this level of bandwidth. For a wired connection, 10/100 base Fast Ethernet device is the minimum. This rate should support the transfer of operational validation datasets. It is expected that many installations will provide much better bandwidth than this minimal specification.

4 Traceability of Performance Specifications

The following table relates sections of this “Performance Specifications” document with corresponding requirements from the System Requirements Specification and essential requirement or specification text.

Table 5 – Traceability Matrix

Performance Specification ID	Performance Specification Section	Performance Specification	SyRS Requirement ID
PS-001	Sect 3.1.1	The reported signal timing shall specify the absolute time each signal will change phase with an absolute accuracy of +/- 0.10 seconds as defined by the GPS system time standard.	DR-100 DR-200 DR-200-001
PS-002	Sect 3.1.1	The resolution of phase change information shall be 0.01 seconds.	DR-200 DR-200-001
PS-003	Sect 3.1.1	The RSE components shall receive, process, store, and transmit all signal timing and status data within 100 milliseconds of receiving the data from the traffic controller assembly.	PR-200
PS-004	Sect. 3.2.1	The coverage assessment Unacceptable Coverage During Approach Rate shall be less than 5%.	FR-300 FR-315 FR-320 FR-325 FR-340
PS-005	Sect. 3.2.1	The coverage assessment Consecutive Frame Errors shall be less than 4.	FR-300 FR-315 FR-320 FR-325 FR-340
PS-006	Sect. 3.2.1	The coverage assessment Packet Error Rate shall be less than 30%.	FR-300 FR-315 FR-320 FR-325 FR-340
PS-007	Sect. 3.2.2	The positioning assessment Unacceptable Positioning During Approach Rate shall be less than 5%.	FR-300 FR-315 FR-320 FR-325 FR-340
PS-008	Sect. 3.2.2	The positioning assessment Estimated Horizontal Error shall be less than 0.5 meters.	FR-300 FR-315 FR-320 FR-325 FR-340
PS-009	Sect. 3.2.2	The positioning assessment PDOP shall be less than 5.0.	FR-300 FR-315 FR-320 FR-325 FR-340

Performance Specification ID	Performance Specification Section	Performance Specification	SyRS Requirement ID
PS-010	Sect. 3.2.2	The positioning assessment number of satellites shall be greater than 4.	FR-300 FR-315 FR-320 FR-325 FR-340
PS-011	Sect. 3.2.2	The positioning assessment Loss of Base Station Status Period shall be less than 8 seconds.	FR-300 FR-315 FR-320 FR-325 FR-340
PS-012	Sect. 3.2.2	The positioning assessment Loss of RTCM Corrections shall be less than 60 seconds.	FR-300 FR-315 FR-320 FR-325 FR-340
PS-013	Sect 3.2.3	The geometric intersection description accuracy metric for an intersection shall be 98% or higher for the intersection to be considered operationally fit.	FR-300 FR-315 FR-320 FR-325 FR-340
PS-014	Sect. 3.2.4	The signal phase timing accuracy metric for a signalized intersection shall be 80% or higher for the signal phase and timing to be considered operationally fit.	FR-300 FR-315 FR-320 FR-325 FR-340
PS-015	Sect. 3.3.1	The RSE shall provide an active connection through the Maintenance User Interface within five minutes of a trained user's initiation of such a connection.	FR-405
PS-016	Sect. 3.3.2	The RSE Maintenance User Interface shall provide at least 2.4 Mbps of raw data transfer bandwidth.	HR-225
PS-017	Sect. 3.3.2	The RSE Maintenance User Interface shall provide a sustainable data transfer rate of 200 Kbps or greater.	HR-225

5 Glossary

Automated Braking: Braking by control systems in the vehicle without driver initiation.

Backend System: This is the system that sends out various messages and updates to the roadside application processor. The backend system consists of the following subsystems: 1) ***Central processor*** that provides map data and signal timing plans. 2) ***Communication network*** that allows communication between the roadside equipment (RSE) and the central processor. 3) ***Geographic information system*** that maintains and coordinates the location and geometry of a stop-sign controlled intersection as well as a CICAS-V signalized intersection.

CICAS-V Intersection: The system that involves the traffic light(s). The traffic light(s) includes a traffic signal controller which can also contain a “sniffer” within it.

Dedicated Short Range Communications (DSRC): DSRC or Dedicated Short Range Communications is a short to medium range wireless protocol operating in the licensed 5.9 GHz band and specifically designed for automotive use. It offers communication between the vehicle and roadside infrastructure.

Differential Corrections: Global Positioning System (GPS) corrections generated by a single or a network of reference stations (located in precisely known locations) which can be used by user receivers in a certain geographical area to improve their positioning accuracy.

Differential Global Positioning System (DGPS): DGPS is an enhancement to Global Positioning System that uses a network of fixed ground based reference stations to generate and broadcast a correction signal for spatially correlated GPS errors (i.e. ionospheric, tropospheric and timing related errors). User GPS receivers in the area served by the DGPS can apply the broadcast corrections to improve their positioning accuracy in the position estimation process.

Geometric Intersection Description (GID): A digital representation of the geometry of the intersection that enables the vehicle to match itself to the correct approach road and to the correct approach lane on that approach road. It includes such information as the location of the stop line, a lane numbering scheme, the orientation of the intersection to north, a version number and possibly other additional features.

Geospatial Database: A database with geospatial information about CICAS-V intersections. The database contains information such as the intersection IDs for all the CICAS-V intersections within a defined area, intersection type IDs (signalized, stop sign controlled) the GIDs for all CICAS-V stop sign controlled intersections in the specified area, a version ID and other information that may become important in the future.

Global Positioning System (GPS): A satellite-based navigational system allowing the determination of a unique point on the earth's surface with a high degree of accuracy and provides a highly accurate time source given a suitable GPS receiver and GPS satellite visibility. The network of satellites is owned by the US Department of Defense. It uses a Medium Earth Orbit (MEO) satellite constellation of at least 24 satellites.

Infrastructure: A high level term that is used when referring to all the different equipment that is located within an intersection to make the CICAS-V application work. (The RSE, DSRC WAVE radio, roadside GPS unit, and signal controller / sniffer are all located within the "Infrastructure").

Intersection: For CICAS-V, an intersection is a junction of two or more public roads where at least one approach to the intersection is controlled by either a stop sign or a traffic signal.

Onboard Equipment (OBE) is the system installed in each vehicle providing CICAS-V capability. The **OBE Application processor** is the "brain" of the Onboard System (OBS). The OBE is the component that gathers all the information sent to it from the RSE, decodes maps, and ultimately declares if the driver shall be warned by assessing an algorithm.

Onboard GPS: A Global Positioning System (GPS) that is constantly updating the vehicles location and also has the ability to apply external generated differential corrections for improved accuracy.

Packet Error Rate (PER): Packet Error Rate is used to measure the DSRC performance between vehicles and infrastructure devices. PER is the ratio, in percent, of the number of DSRC packets dropped or lost by the vehicle to the number of DSRC packets sent by a specific application from the infrastructure device. For CICAS-V, the PER is further constrained to be assessed while a vehicle is "on-GID," that is, while the vehicle is in an approach lane defined in a GID and at a distance between the farthest and nearest points of the approach lane's centerline as defined in the GID.

Position Dilution of Precision (PDOP): A unitless figure of merit expressing the relationship between the error in user position and error in satellite positions. Geometrically PDOP is proportional to 1 divided by the volume of the pyramid formed by lines running from the receiver to four or more satellites observed. Thus a small PDOP is associated with widely separated satellites.

Roadside Equipment (RSE): A system installed at the roadside or in the intersection that includes a WAVE radio and the software to operate that radio. The **RSE / Application processor** is the "brain" component of the Roadside System (RSS). The RSE collects data sent to it from the backend system, the roadside GPS unit, and the interface to the signal controller and broadcasts these data to the CICAS-V equipped vehicles.

Roadside GPS: A Global Positioning System (GPS) that detects positioning coverage, generates differential corrections as needed, and sends out differential corrections to the roadside application processor.

Stop Line: Demarcated location on an approach to an intersection where a vehicle needs to stop for appropriate traffic control devices. The stop line location will be included in the geometric intersection description. For intersection approaches that do not have a stop line, an appropriate stopping location will be included in the geometric intersection description.

Traffic Operations Center: A physical or virtual location where traffic control operations for a state or local DOT are managed. A traffic operations center is generally responsible for traffic operations for a specific geographic region.

Traffic Signal Related Terms:

> **Fixed Time Signal Control**: Traffic signal timing such that the signal phase durations do not change from one cycle to the next. None of the phases function on the basis of actuation. (Also known as pre-timed control.)
>
> **Traffic Actuated Signal Control**: Traffic signal timing where the initiation of a change in or an extension of some or all signal phases can be accomplished through any type of detector.
>
> **Traffic Signal Controller**: Hardware located at the intersection that is responsible for controlling the traffic signal indications displayed on the traffic signal head.
>
> **Traffic Signal Cycle**: A complete sequence of signal indications.
>
> **Traffic Signal Face**: The part of the traffic signal provided for controlling one or more traffic movements on a single approach.
>
> **Traffic Signal Head**: A housing that contains light sources, lens, and other components to be used for providing signal indications. A traffic signal head may contain one or more signal faces.
>
> **Traffic Signal Indication**: The illumination of a signal lens or equivalent device.
>
> **Traffic Signal Phase**: The green, yellow, and red clearance intervals in cycle that are assigned to an independent traffic movement or combination of movements.
>
> **Traffic Signal Timing**: The amount of time allocated for the display of a signal indication.
>
> **Traffic Signal Sniffer:** A device that senses the current on load switches or wires that control individual traffic signal indications such that the state (e.g., on/off) of each indication can be determined. A signal sniffer does not interface with a traffic signal controller. A signal sniffer may have some processing capabilities such that the yellow duration for a given timing plan can be "learned" and a sub-second countdown from yellow to red can be determined.

Vehicle Sensors: Sensors on a vehicle installed by the automobile original equipment manufacturer.

Vehicle-to-Vehicle Communication: Communication between vehicles using 5.9 GHz Dedicated Short Range Communication WAVE radios.

Wireless Access in Vehicular Environments (WAVE): WAVE standards (IEEE 1609) provide a radio communication component to support the U.S. Department of Transportation's Vehicle Infrastructure Integration Initiative and Intelligent Transportation Systems program. IEEE 1609.3 is part of a standards family to support vehicle-to-vehicle and vehicle-to-roadside communications that will allow motor vehicles to interact with each other and roadside systems to access safety and travel-related information. See DSRC.

6 Acronyms

CAN	Controller Area Network
CICAS-V	Cooperative Intersection Collision Avoidance System Limited to Traffic Signal and Stop Sign Violations
DGPS	Differential GPS
DOT	Department of Transportation
DSRC	Dedicated Short Range Communications
DVI	Driver-Vehicle Interface
EVDO	Evolution data optimized
FOT	Field Operational Test
GHz	Gigahertz
GID	Geometric Intersection Description
GPS	Global Positioning System
GPSC	GPS Corrections
I2V	Infrastructure-to-Vehicle
ms	Milliseconds
OBE	Onboard Equipment
PDOP	Position Dilution of Precision
PER	Packet Error Rate
RDP	Required deceleration parameter
RF	Radio Frequency
RSE	Roadside Equipment
RTCM	Radio Technical Commission for Maritime Services
SPaT	Signal Phase and Timing
WAAS	Wide-Area Augmentation System
WAVE	Wireless Access in Vehicular Environments
WSA	WAVE Service Announcement

7 Calculation Variables

Variable	Variable Description
a_{lim}	The maximum deceleration rate that most drivers are able/willing to achieve
$a_{lim}(v_i)$	The maximum deceleration rate as a function of the initial velocity of the vehicle
a_{RDP}	Acceleration (deceleration) rate as a function of the Required Deceleration Parameter (RDP)
$a_{RDP}(t_b, v_2)$	Acceleration (deceleration) rate as a function of the RDP, starting time $t_{b,}$ and starting velocity v_2
$a_{RDP}(t_b)$	Acceleration (deceleration) rate as a function of the RDP and starting time $t_{b,}$
d_{bc}	The distance covered when the braking begins at the critical last moment that the braking maneuver will not surpass the deceleration limit a_{lim}.
$d_{crit}(v)$	The critical warning threshold distance $d_{crit}(v)$ at the vehicle's current speed.
$d_{crit}(v_i)$	The critical warning threshold distance as a function of the initial velocity of the vehicle
d_{ct}	The distance from a stop line to potential cross-traffic
d_{react}	The distance covered by the vehicle during the *human reaction time* t_{react}, while still in constant-speed motion
d_{sb}	The distance from the vehicle to the stop line
d_u	The total distance uncertainty
d_{warn}	The distance between the vehicle and the stop line when a warning is issued.
e_w	Earliness factor, a measure of how much earlier a warning was issued before the earliest acceptable warning time
t_0	The reference starting time for an analysis
t_a	The total length of the yellow phase for the intersection
t_b	The time at which the vehicle begins braking for a stopping maneuver
t_{bc}	The critical time for the onset of braking
$t_{cd}(t)$	The countdown time remaining in the current traffic signal phase at time t
t_{crit}	The time at which the vehicle reaches d_{crit}
t_{data}	The time by which accurate information is required
t_{ew}	Earliest acceptable warning time

Variable	Variable Description
t_{I2V}	The time of arrival of the first CICAS-V I2V application message
t_{iw}	Ideal warning time
t_{ls}	Sampling period of vehicle location estimate (e.g. as from GPS)
t_{msg}	Time of completion of I2V information broadcast reception, including Geometric Intersection Description (GID), Signal Phase and Timing (SPaT), and GPS Corrections (GPSC)
t_{proc}	Processing latency due to processing throughput or periodicity of processing
t_r	The time from the present to when the signal will turn red
t_{react}	The *human reaction time*, a fixed value that is determined by analyzing distributions of reaction times for a representative driver population
t_{RTCM}	The time by which accurate vehicle positioning data needs to be available
t_s	The time at which the vehicle stops at the stop line
t_{s1}	The time at which the vehicle stops for the first of two successive stops
t_{sb}	The time of potential crossing-path collision when vehicle will pass the stop line if it does not brake
t_{vs}	The sampling time of vehicle speed
t_{warn}	The time of presentation of violation warning
t_{WSA}	Time of first availability of CICAS-V WAVE Service Announcement via DSRC from the intersection
v_{ave}	Average speed
v_i	Initial speed of vehicle
δ_l	Uncertainty in vehicle location
δ_v	Uncertainty in vehicle speed

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