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

System Design Specification - Vehicle

Final Phase I Release v4.00

(Appendix E-1)

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16. Abstract

The purpose of this document is to provide a set of vehicle system performance 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.

This document defines the system performance for the CICAS-V system. The performance specifications in this document are based on the Concept of Operations, system Functional Requirements, initial results of the human factor studies, and the preliminary Driver-Vehicle Interface (DVI) concepts. Both stop sign violation warning and traffic signal violation warning scenarios are considered in developing the performance specifications. The lessons learned in the execution of earlier CICAS-V tasks will be incorporated into future versions of this document.

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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. 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.

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 9 as well as the planned FOT of the CICAS-V system. The performance specifications in this document are based on the Concept of Operations, High-Level Requirements, initial results of the human factor studies (unpublished early results of CICAS-V Task 3), and the preliminary Driver-Vehicle Interface (DVI) concepts. Both stop sign violation warning and traffic signal violation warning scenarios are considered in developing the performance specifications. The lessons learned in the execution of Phase I and Phase II CICAS-V tasks will be incorporated into future versions of this document.

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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 use cases, 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.

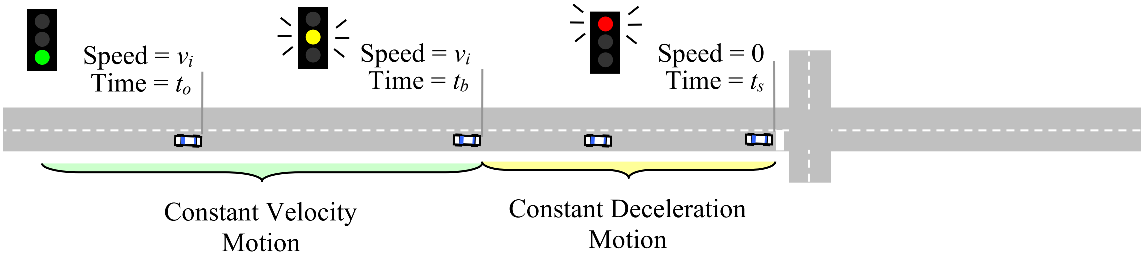


Figure 1 – Basic Stopping Maneuver

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 the CICAS-V use cases, 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 $v \bullet dt$, 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.

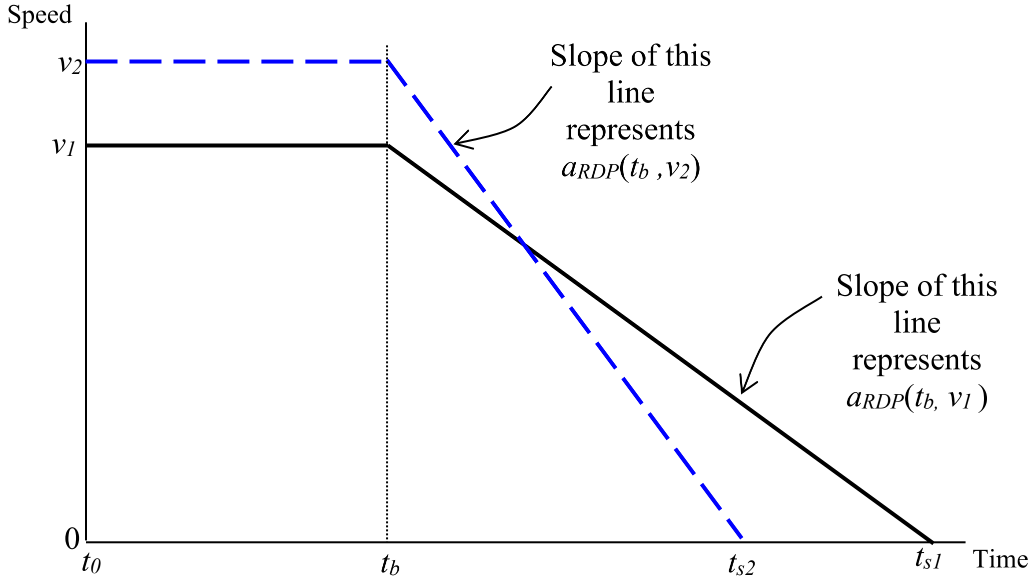


Figure 2 – a_{RDP} for Differing Initial Velocities

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 use cases 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.

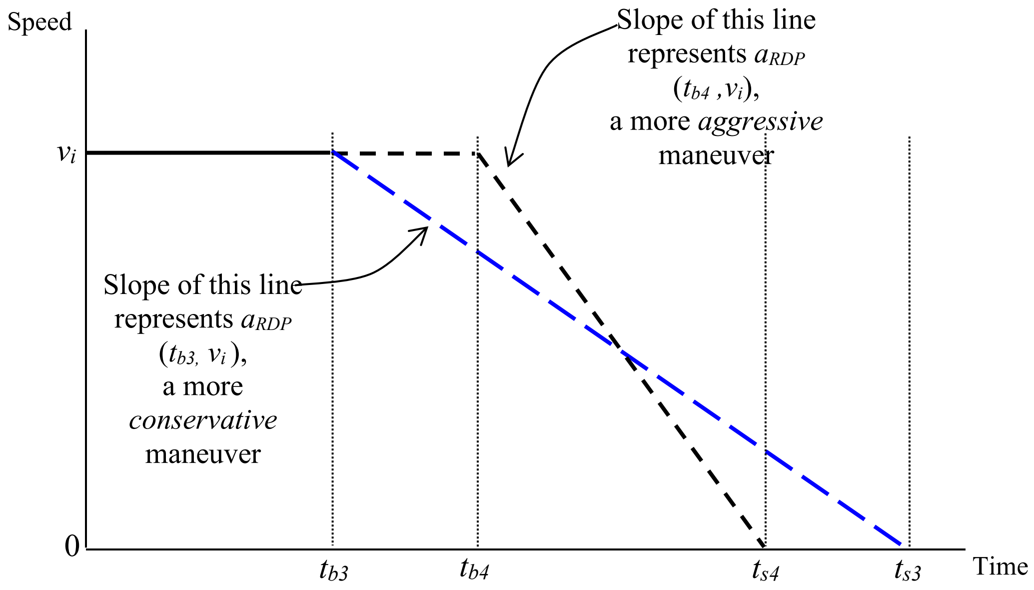


Figure 3 – a_{RDP} for Differing Braking Onset Times

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.

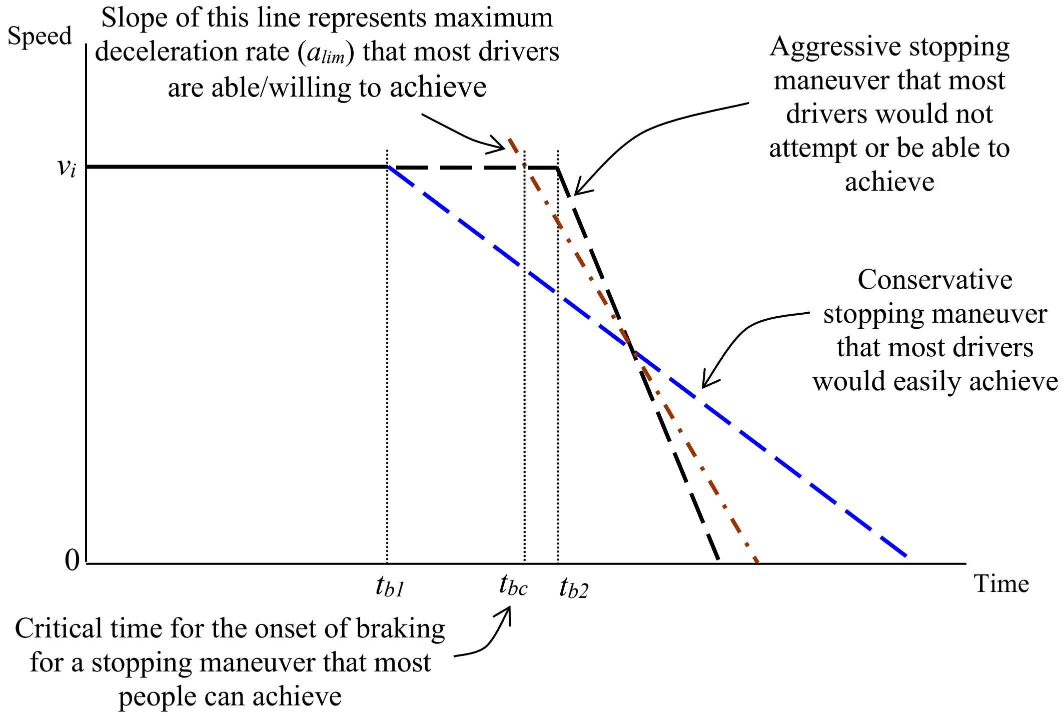


Figure 4 – Maximum Acceptable Deceleration Limit

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}:

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

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:

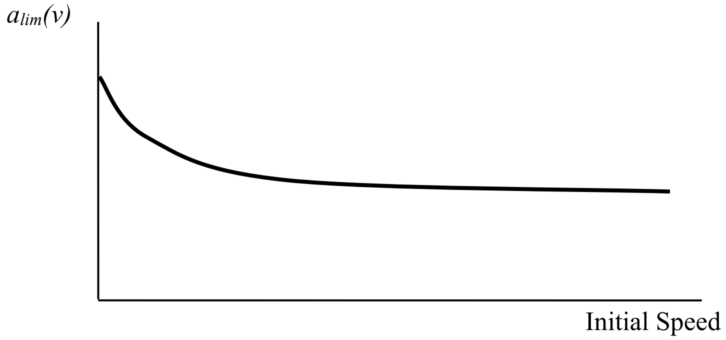


Figure 5 – a_{lim} as a Function of Initial Velocities

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.

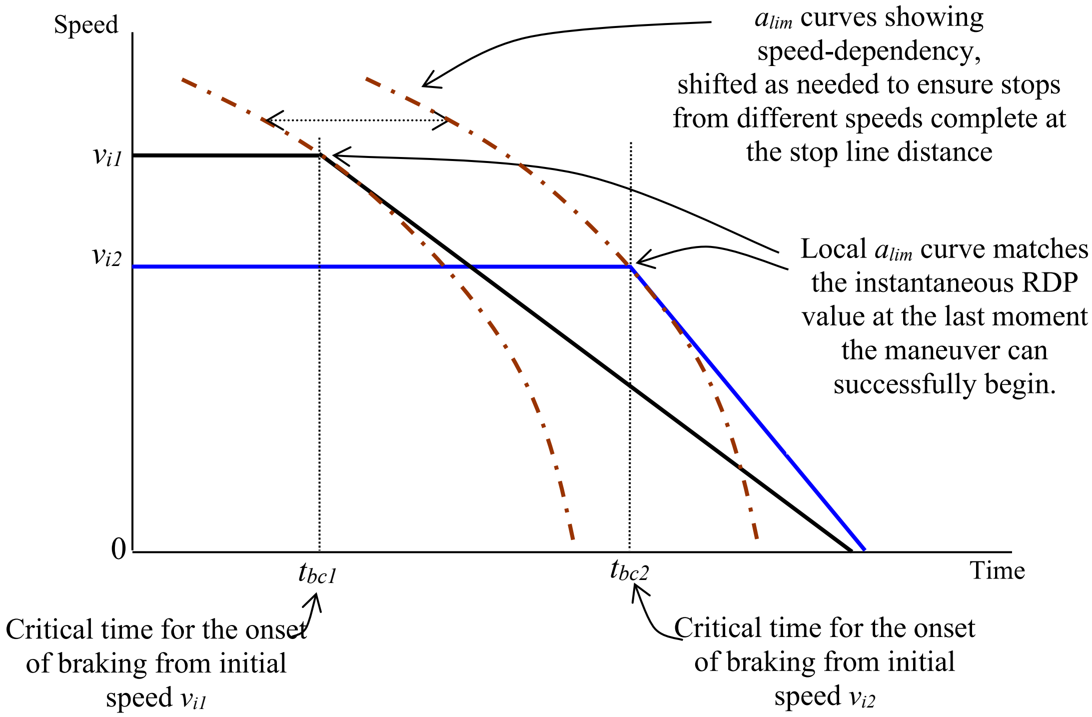


Figure 6 – Time of Critical Braking Considering Speed-Dependant a_{lim}

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 in a variety of use cases. 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}:

$$d_u \le d_{ct}$$

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}:

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

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, the 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,” camera or pressure-based traffic sensors, the actual time to the next red phase is not always defined. Therefore, the “time to red” time may need to default to a high arbitrary number which will not be used in any calculations.

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.

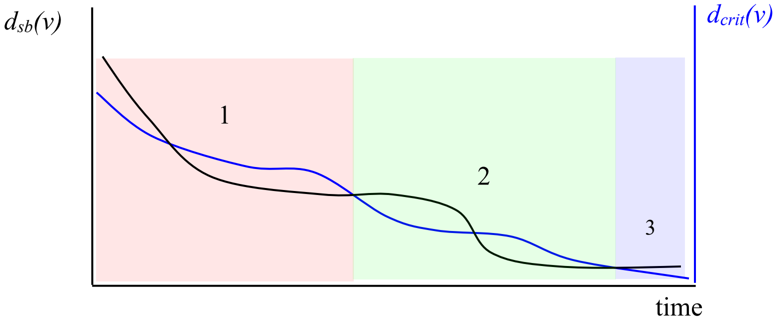
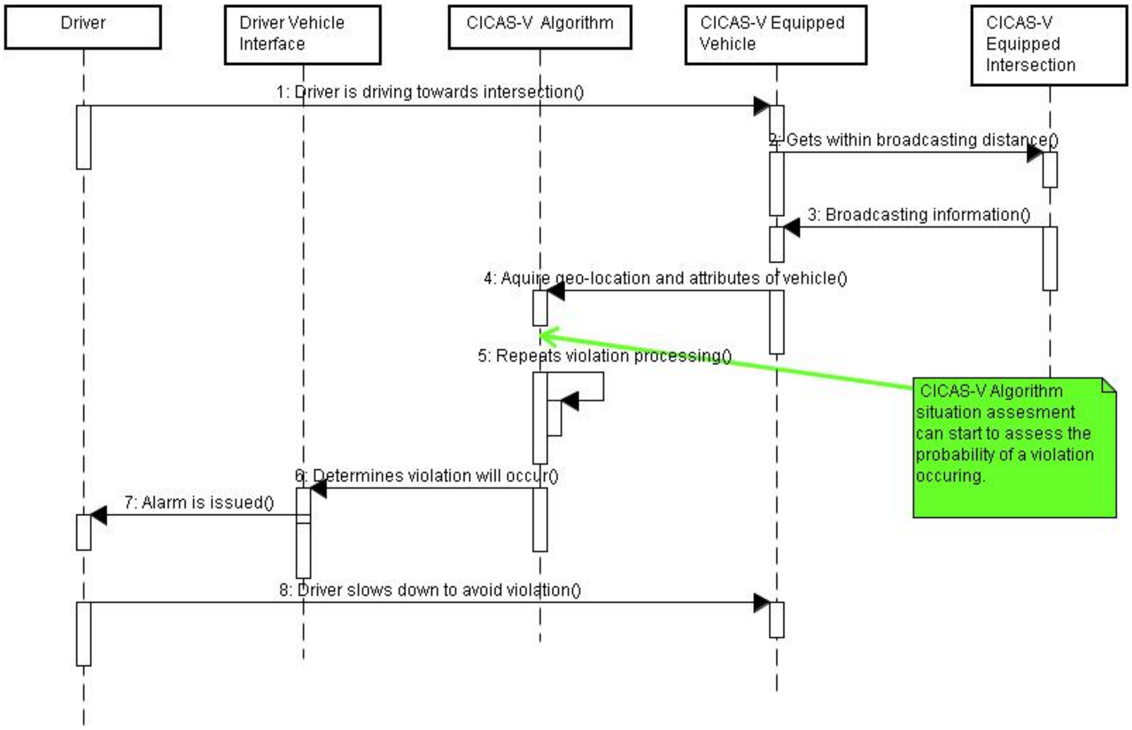


Figure 7 – Sub-Maneuvers in Multiple Warning Scenario

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.



CICAS-V Algorithm situation assesment can start to assess the probability of a violation occuring.

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.

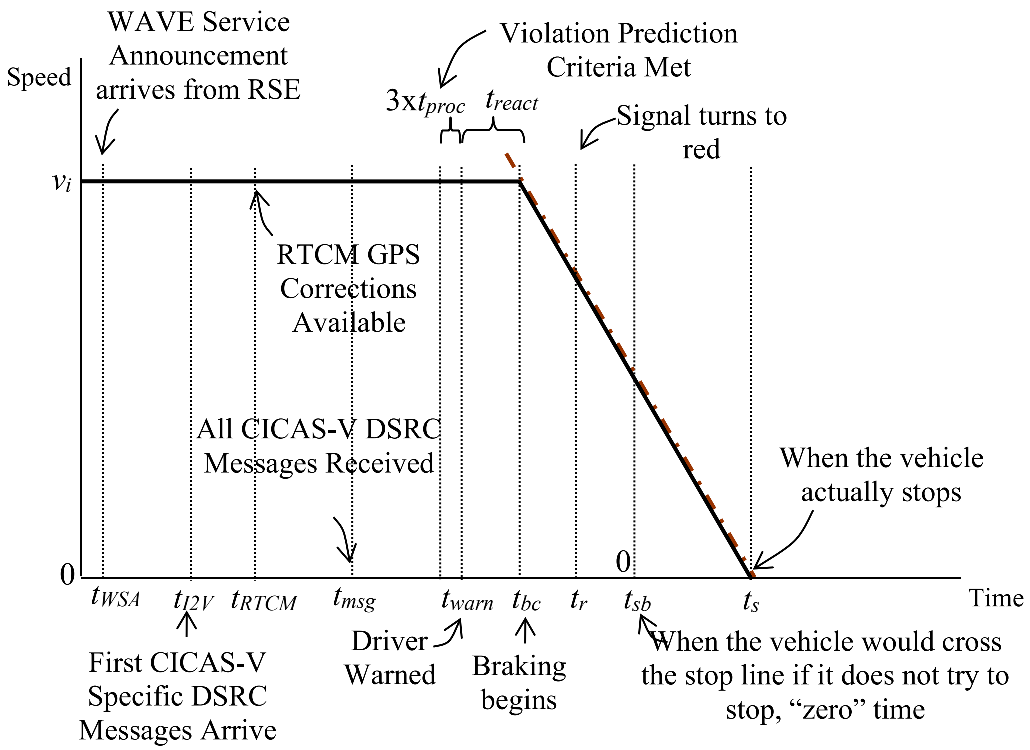


Figure 9 – Event Timing Model

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 Geometric Intersection Description (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 GPS 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 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 Infrastructure-to-Vehicle 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:

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

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 Violation Warning Metrics

The following violation warning metrics are assumed to be calculated from a large sample of intersection approach events that span a full range of driving scenarios and use cases. Each intersection approach event shall be analyzed, categorized, and tallied according to the warning event performance classifications defined in Section 2. Note that intersection approach maneuvers that do not generate a warning are still considered warning events and will be tallied into one of the "negative" tallies (e.g., "True Negative Non-Warnings"). During system performance measurement, the accuracy of the vehicle speed and location data available to the CICAS-V application shall be verified using independent measures of speed and location whenever feasible. Each intersection approach maneuver shall be analyzed with an independent implementation of the violation prediction computations. These computations should not share common source code with the CICAS-V On-board Equipment (OBE) source code.

Table 2 – Violation Warning Metrics and Performance Specification

Performance Specification ID	Section	Metric	Definition	Ideal Performance	Acceptable Performance
PS-001	3.1.1	Overall Warning Accuracy	(TruePosTally + TrueNegTally + CorrectSupprTally)/ TotalWarnEvents	100%	> 90%
PS-002	3.1.2	True Positive Warning Rate	TruePosTally/ TotalPredictedViolations _(not suppressible)	100%	> 90%
PS-003	3.1.3	True Negative Warning Rate	TrueNegTally/ TotalPredictedNonViolations	100%	> 98%
PS-004	3.1.4	Correctly Suppressed Warning Rate	CorrectSupprTally/ TotalPredictedViolations _(suppressible)	100%	> 95%
PS-005	3.1.5	False Positive Warning Rate	FalsePosTally/ TotalPredictedNonViolations	0%	< 2%
PS-006	3.1.6	False Negative Missed Warning Rate	FalseNegTally/ TotalPredictedViolations _(not suppressible)	0%	< 2%
PS-007	3.1.7	Unsuppressed Warning Rate	UnsuppressedTally/ TotalPredictedViolations _(suppressible)	0%	< 5%

Performance Specification ID	Section	Metric	Definition	Ideal Performance	Acceptable Performance
PS-008	3.1.8	Falsely Suppressed Warning Rate	FalseSuppressedTally/ TotalPredictedViolations _(not suppressible)	0%	< 1%
PS-009	3.1.9	Premature True Positive Warnings Rate	PrematureTruePosTally/ TotalPredictedViolations _(not suppressible)	0%	< 4%
PS-010	3.1.10	Average Earliness for the Premature Warnings	Average of (Earliness Factors for all Premature True Positive warning events)	0	$< 0.5t_w$
PS-011	3.1.11	Late True Positive Warnings Rate	LateTruePosTally/ TotalPredictedViolations _(not suppressible)	0%	< 3%
PS-012	3.1.12	Average Lateness of the Late Warnings	Average of (Lateness Factors for all Late True Positive warning events)	0	$< 0.1t_w$

The violation warning metrics are described below.

3.1.1 Overall Warning Accuracy

Overall Warning Accuracy is the ratio (expressed as a percentage) of the total number of correct warning assessments compared to the total of all warning assessments.

Overall Warning Accuracy = (True Positive Tally + True Negative Tally + Correctly Suppressed Warning Tally) / (Total Warning Event Tally)

A performance level of 100% Overall Warning Accuracy is ideal, although field operational testing shall consider an Overall Warning Accuracy of 90% or better as acceptable.

3.1.2 True Positive Warning Rate

True Positive Warning Rate is the percentage of the total predicted non-suppressible violation events that were tallied as “True Positive Warnings.” A performance level of 100% True Positive Rate is ideal, although field operational testing shall consider a True Positive Rate of 97% or higher as acceptable.

3.1.3 True Negative Warning Rate

True Negative Warning Rate is the percentage of the total predicted *non-violation* events that were tallied as “True Negative Non-Warnings.” A performance level of 100% True Negative Rate is ideal, although field operational testing shall consider a True Negative Rate of 98% or higher as acceptable.

3.1.4 Correctly Suppressed Warning Rate

Correctly Suppressed Warning Rate is the percentage of the total predicted *suppressible* violation events that were tallied as “Correctly Suppressed Warnings.” A performance level of 100% Correctly Suppressed Warning Rate is ideal, although field operational testing shall consider a Correctly Suppressed Warning Rate of 95% or higher as acceptable.

3.1.5 False Positive Warning Rate

False Positive Warning Rate is the percentage of the total predicted *non-violation* events that were tallied as “False Positive Warnings.” In other words, the False Positive Warning Rate is the percentage of the total approach events for which the CICAS-V system expressed a warning that was not needed as there is no predicted violation. A performance level of 0% False Positive Warning events is ideal, although field operational testing shall consider a False Positive Warning Rate of 2% or lower as acceptable.

3.1.6 False Negative Missed Warning Rate

False Negative Missed Warning Rate is the percentage of the total predicted non-suppressible violation events that were tallied as “False Negative Missed Warnings.” In other words, the percentage of the total approach events for which the CICAS-V system failed to express a warning when the violation was predicted, and the warning should not be suppressed. A performance level of 0% False Negative Missed Warnings is ideal, although field operational testing shall consider a False Negative Missed Warning Rate of 2% or lower as acceptable.

3.1.7 Unsuppressed Warning Rate

Unsuppressed Warning Rate is the percentage of the total predicted *suppressible* violation events that were tallied as “Unsuppressed Warnings.” In other words, the percentage of events that a warning was issued but it should have been suppressed. A performance level of 0% Unsuppressed Warning Rate is ideal, although field operational testing shall consider an Unsuppressed Warning Rate of 5% or lower as acceptable.

3.1.8 Falsely Suppressed Warning Rate

Falsely Suppressed Warning Rate is the percentage of the total predicted *non-suppressible* violation events that were tallied as “Falsely Suppressed Warnings.” In other words, it is the percentage of events that a warning was suppressed even though it should not have been suppressed. A performance level of 0% Falsely Suppressed Warning Rate is ideal, although field operational testing shall consider a Falsely Suppressed Warning Rate of 1% or lower as acceptable.

3.1.9 Premature True Positive Warnings Rate

Premature True Positive Warnings Rate is the percentage of the total predicted non-suppressible violation events that were tallied as “Premature True Positive Warnings” because the warning was issued before the earliest acceptable time. A performance level of 0% Premature True Positive Rate is ideal, although field operational testing shall consider a Premature True Positive Rate of 4% or lower as acceptable as long as the Average Earliness of the Premature Warnings is less than $0.5t_w$.

3.1.10 Average Earliness for the Premature Warnings

Average Earliness for the Premature Warnings is the average of the earliness factor e_w for all Premature True Positive warning events. An average factor of 0% is ideal, although field operational testing shall consider an Average Earliness percentage of the Premature Warnings of $0.5t_w$ or lower as acceptable. A factor of $0.5t_w$ implies an average earliness of less than 1 to 2 seconds at typical approach speeds.

3.1.11 Late True Positive Warnings Rate

Late True Positive Warnings Rate is the percentage of the total predicted non-suppressible violation events that were tallied as "Late True Positive Warnings" because the warning was issued after the latest acceptable time. A performance level of 0% Late True Positive Rate is ideal, although field operational testing shall consider a Premature True Positive Rate of 3% or lower as acceptable as long as the Average Lateness of the Late Warnings is less than $0.1t_w$.

3.1.12 Average Lateness of the Late Warnings

Average Lateness of the Late Warnings is the average of the lateness factor l_w (relative to t_w) for all Late True Positive warning events. An average lateness factor of 0 is ideal, although field operational testing shall consider an Average Lateness of the Late Warnings of $0.1t_w$ or lower as acceptable. A factor of 10% implies an average lateness of less than 200 to 400 msec for typical approach speeds.

3.2 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.

Table 3 – Critical Sensing Subsystems Metrics and Performance Specification

Performance Specification ID	Section	Metric	Definition	Ideal Performance	Acceptable Performance
PS-013	3.2.1	Accuracy of Vehicle Position Estimation	Horizontal error in along-path and cross-path directions while vehicle is between distance 2.0x $d_{crit}(v_i)$ to 0.5x $d_{crit}(v_i)$	0.0 meters each	< 0.5 meters each

Performance Specification ID	Section	Metric	Definition	Ideal Performance	Acceptable Performance
PS-014	3.2.2	Lane Matching Accuracy	Correct lane or "no lane" identified at the critical warning threshold distance $d_{crit}(v_i)$ compared to total number of approach maneuvers	100%	> 90%
PS-015	3.2.3	Vehicle Speed Sensing	Maximum error in speed measurement while vehicle is between distance 2.0x $d_{crit}(v_i)$ to 0.5x $d_{crit}(v_i)$	0.0 m/s	< ±0.3 m/s
PS-016	3.2.4	Vehicle Acceleration and Deceleration Sensing	Maximum error in acceleration measurement while vehicle is between distance 2.0x $d_{crit}(v_i)$ to 0.5x $d_{crit}(v_i)$	0.0 m/s^2	< ±0.5 m/s^2

The critical sensing subsystems performance metrics are described below.

3.2.1 Accuracy of Vehicle Position Estimation

The OBE in each vehicle shall compute a position estimate at a rate of 10 Hz (100 milliseconds period) or faster, expressed with at least 0.05 second time resolution and at least 0.1 meter (10 cm) position resolution. The computed position shall be accurate to within 0.5 meters in the cross-path direction and 0.5 meters in the along-path direction relative to the vehicle's direction of travel. The data should include a timestamp of the GPS network time with an accuracy of 1 millisecond or higher. The OBE shall have differential GPS (DGPS) data available from the RSE through the DSRC link to increase the accuracy of its position estimate solution.

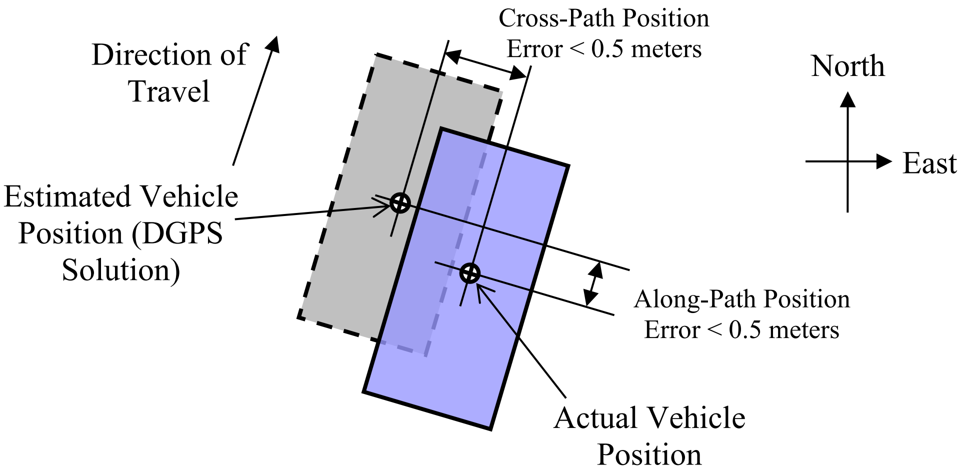


Figure 10 – Vehicle Position Estimation Accuracy, Top View

Rationale: To accurately determine the vehicle's approach lane and thereby determine which signal phase applies to it (i.e., "Does this left-turn signal apply to me right now?"), relative accuracy (with respect to intersection reference point) in the OBE positioning system of 0.5 meters (and preferably much better) is required. The 0.5 meter along-path accuracy will provide enough buffer to help a driver stop before the nose of his or her vehicle intrudes into cross-traffic. The cross-path relative positioning accuracy of 0.5m is selected based on 3.0m or wider lane widths and on a 0.3 meter accuracy of the underlying map.

3.2.2 Lane Matching Accuracy

The lane matching software module running on the OBE shall determine the correct approach lane of its vehicle for at least 90% of all transits through CICAS-V intersections where the vehicle centerline is actually within +/- 35% of the lane width of the lane centerline (see Figure 11 below). In at least 90% of the transits where the vehicle centerline is outside +/- 35% of the lane width of the lane centerline, the lane matching algorithm shall correctly return an "uncertain lane match" result, in which cases the violation assessment shall use the lane signal phase that requires the most urgent and cautious attention.

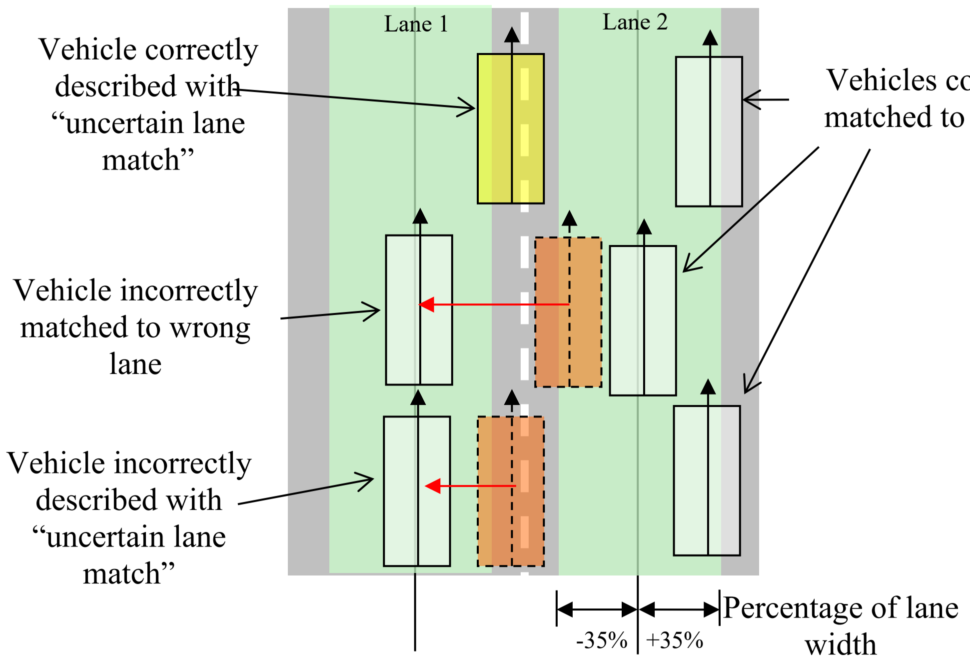


Figure 11 – Lane Matching Zones

It may be possible to increase the accuracy of the violation warning algorithm by extending the lane matching zones outwards for the inner and outer lanes, as shown below.

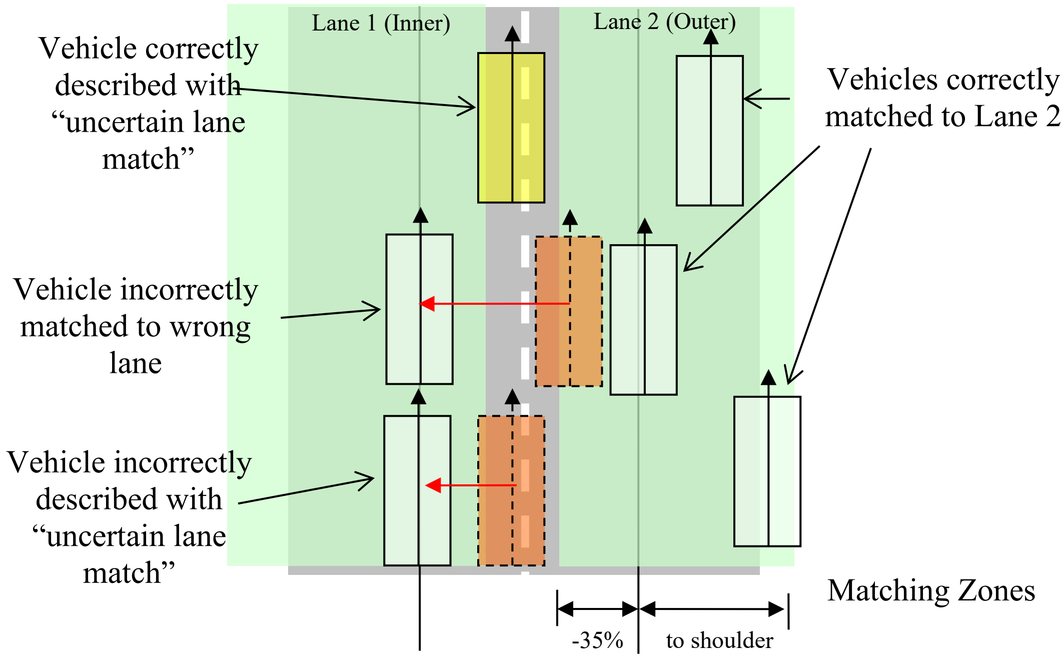


Figure 12 – Extended Lane Matching Zones

If the lane-matching algorithm produces a vector of lane-match probabilities, it may be possible to at least rule out some lanes of consideration, which may be useful if the ruledout lanes have a different signal phase sequence. For example, lane-matching may return the following probabilities: Left-Turn Lane: 5%; Left Through-Lane: 15%; Right Through-Lane: 65%; Right Turn Lane: 15%. The left-turn lane probability is so low, and the "centroid" of probability is far enough to the right that the violation algorithm can ignore a red left-turn signal indication.

3.2.3 Vehicle Speed Sensing

The system shall be able to sense the vehicle speed accurate within +/- 0.6 m/s.

3.2.4 Vehicle Acceleration and Deceleration Sensing

The system shall be able to sense the vehicle acceleration and deceleration (including braking) accurate within +/- 0.5 m/s^2 and also indicate whether the driver is applying significant brake pedal pressure, also known as a "Driver Intended Braking" level of braking.

3.3 Behavioral Performance Results Metrics

The following metrics are not used to specify performance requirements but do reflect the performance of the system relative to its overall objective to reduce traffic signal control violations.

Table 4 – Behavioral Performance Results Metrics

Performance ID	Section	Metric	Definition	Ideal Performance	Acceptable Performance
PS-017	3.3.1	Violation Warning Compliance Rate	Percentage of approaches that the driver began a braking maneuver after a warning was issued	100%	>50%
PS-018	3.3.2	Average speed reduction after warning	Percentage decrease from initial speed at the critical warning threshold distance to the speed near the stop line after a warning was issued	100%	>90%

The behavioral performance results metrics are described below.

3.3.1 Violation Warning Compliance Rate

The percentage of True Positive and Premature True Positive warning events in which the driver subsequently begins a stopping maneuver that reduces the current velocity by at least 90% from the instant of violation warning to the time the vehicle reaches the stop line. A percentage near 100% would indicate a major success for CICAS-V technology, although there are still significant benefits to society of much more modest reductions (e.g. < 50%).

3.3.2 Average Speed Reduction After Warning

The percentage difference between the initial vehicle speed at the instant of violation warning and the minimum vehicle speed within one vehicle length of the intersection stop line. A value near 100% indicates a major success for CICAS-V technology, although it might be argued that a smaller amount of speed reduction still represents a beneficial outcome.

Note: there are situations in which the speed reduction after warning may be legitimately less than 100%. For example, the violation warning algorithm predicts a violation, and the driver slows down, but because there is sufficient distance to the stop line, the vehicle may legally continue to move throughout the red phase and then accelerate before it reaches the stop line when the signal reverts to a green phase. This might happen either when the red phase is very short or when the red phase is long but nearing its end when the vehicle reached the d_{crit} distance.

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 CICAS-V system shall have an Overall Warning Accuracy metric greater than 90%.	CO-315-001 CO-320 CO-320-001 CO-320-002 FO-370 FO-375 FO-395 HO-100 IO-500 PO-200
PS-002	Sect. 3.1.2	The CICAS-V system shall have a True Positive Warning metric greater than 90%.	CO-315-001 CO-320 CO-320-001 FO-370 FO-375 FO-395 HO-100 IO-500
PS-003	Sect. 3.1.3	The CICAS-V system shall have a True Negative Warning metric greater than 98%.	CO-300
PS-004	Sect. 3.1.4	The CICAS-V system shall have a Correctly Suppressed Warning metric greater than 95%.	CO-300 CO-305 CO-310 CO-315
PS-005	Sect. 3.1.5	The CICAS-V system shall have a False Positive Warning metric less than 2%.	CO-305
PS-006	Sect. 3.1.6	The CICAS-V system shall have a False Negative Missed Warning metric less than 2%.	CO-315 CO-315-001
PS-007	Sect. 3.1.7	The CICAS-V system shall have an Unsuppressed Warning metric less than 5%.	CO-300 CO-305 CO-310 CO-315
PS-008	Sect. 3.1.8	The CICAS-V system shall have a Falsely Suppressed Warning metric less than 1%.	CO-310

Performance Specification ID	Performance Specification Section	Performance Specification	SyRS Requirement ID
PS-009	Sect. 3.1.9	The CICAS-V system shall have a Premature True Positive Warnings metric less than 4%.	CO-300 CO-305 CO-310 CO-315
PS-010	Sect. 3.1.10	The CICAS-V system shall have an Average Earliness for the Premature Warnings metric less than $0.5t_w$.	CO-300 CO-305 CO-310 CO-315
PS-011	Sect. 3.1.11	The CICAS-V system shall have a Late True Positive Warnings metric less than 3%.	CO-300 CO-305 CO-310 CO-315
PS-012	Sect. 3.1.12	The CICAS-V system shall have an Average Lateness of the Late Warnings metric less than $0.1t_w$.	CO-300 CO-305 CO-310 CO-315
PS-013	Sect. 3.2.1	The computed position shall be accurate to within 1.5 meters in the cross-path direction and 1.5 meters in the along-path direction relative to the vehicle's direction of travel.	FO-310 FO-360 FO-365 PO-110 XO-100
PS-014	Sect. 3.2.2	The lane matching software module running on the OBE shall determine the correct approach lane of its vehicle at least 90% of all transits through CICAS-V intersections.	FO-315
PS-015	Sect. 3.2.3	The system shall be able to sense the vehicle speed accurate within 0.3 m/s	FO-365 FO-375
PS-016	Sect. 3.2.4	The system shall be able to sense the vehicle acceleration and deceleration (including braking) within +/- 0.5 m/s^2.	FO-365 FO-375
PS-017	Sect. 3.3.1	When there are correct warnings, the DVI shall elicit a statistically significant (two-sigma) change in driver behavior, as seen in the Violations rate reduction after warning (VRRAW) metric.	CO-320
PS-018	Sect. 3.3.2	When there are correct warnings, the DVI shall elicit a statistically significant (two-sigma) change in driver behavior, as seen in the Violations rate reduction after warning (VRRAW) metric.	CO-320

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 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 Wireless Access in Vehicular Environments (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.

On-board Equipment (OBE) is the system installed in each vehicle providing CICAS-V capability. The **OBE Application processor** is the "brain" of the On-board System. 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.

On-board 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.

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. 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 is 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 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.

Traffic Signal Timing: The amount of time allocated for the display of a signal indication.

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 Communications 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
DSRC	Dedicated Short-Range Communications
DVI	Driver-Vehicle Interface
FOT	Field Operational Test
GHz	Gigahertz
GID	Geometric Intersection Description
GPS	Global Positioning System
GPSC	GPS Corrections
I2V	Infrastructure-to-Vehicle
OBE	On-board Equipment
RDP	Required deceleration parameter
RSE	Roadside Equipment
RTCM	Radio Technical Commission for Maritime Services
SPaT	Signal Phase and Timing
TSA	Traffic Signal Adaptation
VRRAW	Violation rate reduction after warning
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 Infrastructure-to-Vehicle 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 Infrastructure-to-Vehicle (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 in a variety of use cases
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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