SCMS Manager Intersection Validation Misbehavior Management

SCMS Manager

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1 Overview

In the context of connected intersection validation, the term *misbehavior* is used to describe a situation where the movement of vehicles is inconsistent with the digitally broadcast intersection state information. For example, cars may drive a path that is not consistent with the approach lanes in the MAP data or stop when the SPaT data indicates a green phase. The proper classification and interpretation of these inconsistencies has been proposed as a core method for performing continuous monitoring of the continued performance of a validated intersection.

These types of inconsistencies can be attributed to several potential causes:

1. Careless or impaired drivers may follow a path that is erratic and inconsistent with the actual lane lines or signal status.
2. Equipment in some vehicles might be misconfigured or faulty, resulting in incorrect BSM data to be broadcast.
3. A local change may override the normal signal and lane indicators, such as a construction or emergency response situation which temporarily alters traffic flow.
4. The digital data that is broadcast may no longer be consistent with the actual lane marking and signal state.

This report considers the impact of misbehavior information provided by the Connected Intersections Message Monitoring System (CIMMS) process. This application collects data broadcast from a connected intersection (in the form of SPaT and MAP data) along with Basic Safety Message (BSM) data from vehicles that drive through the intersection. It then performs analysis to compare the movement of vehicles (as reported in the BSM data) against the intersection status (as indicated in the SPaT and MAP data). Statistical data on misbehavior events is tracked against threshold values.

2 Role of Continuous Monitoring in Intersection Validation

There are several connected vehicle (CV) use cases that depend on accurate and trustworthy broadcast data from intersections. One example application is Red Light Violation Warning (RLVW) which alerts a driver it the on-board safety system determines that they are about to enter an intersection with insufficient time to pass through the intersection before the corresponding signal turns red. Proper operation of this warning requires that the broadcast data representing the signal state and estimated time to the next state transition be timely and accurate.

Experience from early CV system deployments has shown that the level of accuracy and reliability of broadcast data from intersections is difficult to achieve. This has motivated an interest in defining a validation process that compares an intersection system's performance against a defined set of metrics. Systems that achieve the required level of performance against the defined metrics may request special status as *validated* intersections. This status entitles the intersection to broadcast a set of indications that allow vehicles to have confidence in the accuracy and timeliness of the broadcast data.

Experience with previously deployed systems has also demonstrated that intersection performance will change over time. This could be due to configuration changes or software updates to components within the intersection system, or due to physical changes such as road construction that may require changes to the physical lane markings on the ground. Ideally, any change to the intersection system would be immediately followed by changes to the digital data that is broadcast to ensure continued accuracy of the data. However, there are cases where changes may be unplanned or where operational discontinuities may result in situations where broadcast data is not updated.

For this reason, a **continuous monitoring** approach is required to be part of any validated intersection. The goal of monitoring is to quickly detect and respond to any unplanned or unexpected changes in intersection performance that result in data that is out of compliance with validation requirements.

Figure 1 is a state diagram that represents the validation status of an intersection during the operational lifetime of the system. The following sections describe the characteristics of each operating mode along with the transitions between states.

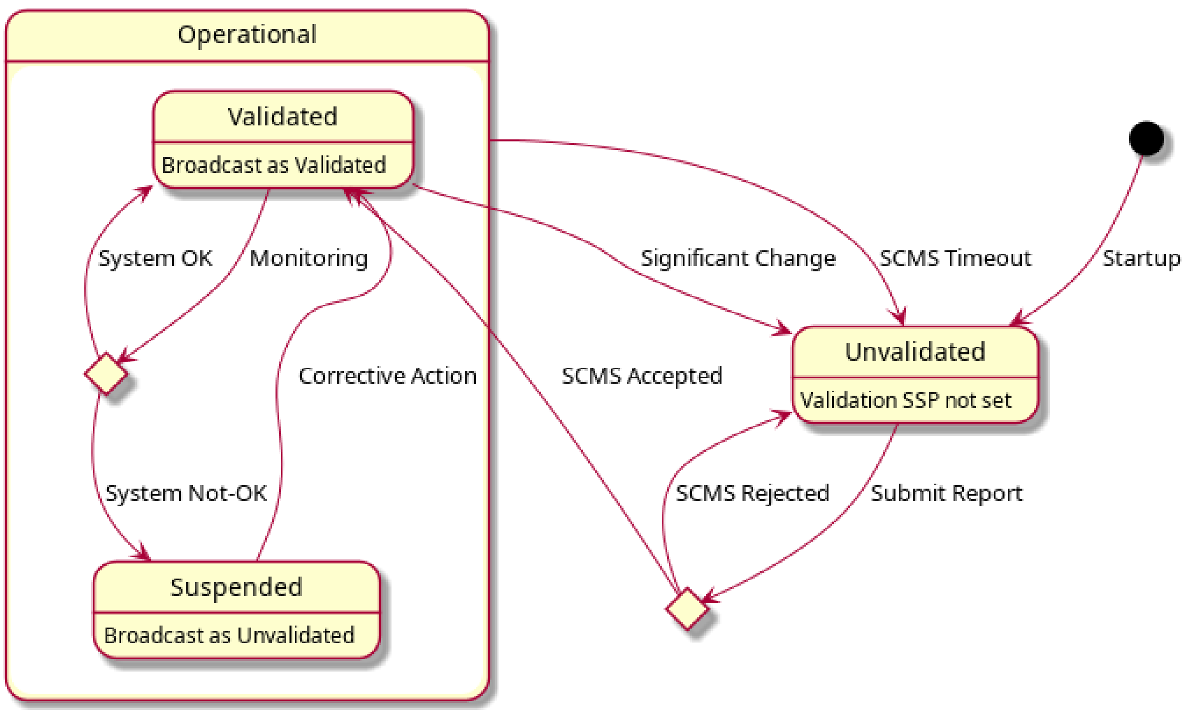

Figure 1: Validation State Diagram

2.1 Unvalidated State

On initial system startup, a newly configured CI starts in an *Unvalidated* state. In this state, the CI may be provided with a production SCMS certificate and it may broadcast signed SPaT, MAP, and RTCM data. However, while the system remains *Unvalidated*, the SCMS Provider will issue application certificates that do not include the SSP bit required to mark the CI as *Validation Enabled*. In this mode, production vehicles may receive and validate the signatures on the CI broadcast data, but vehicles will be aware that the quality of the data is unvalidated.

While in this state, an operator or an authorized contractor may collect data on the performance of the intersection using an approved data collection system. The measurement data collected must account for all operational modes of the intersection. Once data collection is complete, the operator will submit an electronic report to the corresponding SCMS Provider. This report will identify the intersection and include evaluation results for the initial validation measurements. This step is represented by the *Submit Report* transition.

The SCMS Provider will evaluate the content of the electronic validation report. In some cases, the report may be rejected as shown in the *SCMS Rejected* transition. When this happens, further data collection or corrective actions may be taken by the operator to produce a successful validation report. When the electronic report is accepted, the IC transitions to the *Validated* state via the *SCMS Accepted* transition path.

2.2 Validated State

Once in the *Validated* state, the CI will be issued application certificates that include the SSP bit required to show that the system has been validated. At this point, the continuous monitoring cycle begins. While in this state, SPaT, MAP, RTCM, and BSM data collected at the intersection will be analyzed by the CIMMS application (running locally or as a cloud-hosted service). The *Monitoring* transition shows the conditional evaluation performed by the CIMSS tool. The result of the monitoring activity may confirm that the system is operating within acceptable parameters. In this case the system follows the *System OK* transition back to the *Validated* state.

2.3 Suspended State

If the continuous monitoring detects an anomaly that exceeds a pre-defined threshold, the CI will follow the *System Not-OK* transition to the *Suspended* state. While in this state, the CI must set the application data flag to indicate that the system is not operating in a validated mode. When this bit is not set, production vehicles may receive and validate the signature on the CI data, but it will be aware that the data may not be reliable for some applications, such as RLVW.

In order to recover from the *Suspended* state, the CI operator must take some corrective action. This will require an assessment of the conditions that caused continuous monitoring to determine that the system status is not within acceptable parameters. This may be due to a temporary condition which will self-correct, or it may require minor adjustments to the CI configuration. Once appropriate corrective action has been taken, the operator may instruct the intersection to return to the *Validated* state. At this point, continuous monitoring will resume the role of monitoring the intersection operation. If the problem persists (or if a new problem emerges), then the system will once again transition to the *Suspended* state.

Note that wile in the *Validated* state, the operator may execute a planned and managed change to the CI. If this change is deemed to be “significant”, then the operator shall inform the SCMS Provider that a *Significant Change* event has occurred. This will transition the state back to the *Unvalidated* state where it will be issued application certificate with the validation SSP bit cleared. After the planned change is complete, the operator will collect new measurement data using an approved tool and submit a revised validation report to the SCMS provider. This report may be accepted or rejected as with the initial validation report.

At all times while the intersection is in either the *Validated* or *Suspended* state, the SCMS Provider shall monitor the time interval between successive continuous monitoring reports. If the time between reports exceeds a pre-set threshold, the SCMS Provider must cease to issue new application certificates with the validation bit set. This action will force the CI to return to the *Unvalidated* state via the *SCMS Timeout* transition. This transition may happen at any time when the CI is in the *Validated* or *Suspended* sate. Recovery from an *SCMS Timeout* will require the submission of an acceptable validation report to the SCMS Provider.

2.4 System Shutdown

At any time, in any state, the system may be shutdown or caused to cease broadcasting CI data. Recovery from a system shutdown will re-start the initial validation process with the system entering the *Unvalidated* state via the *Startup* transition. The shutdown state and corresponding transitions are not shown on in Figure 1 to reduce clutter in the diagram.

3 Event Actions and Recovery

The recommended method for implementing continuous monitoring is through the use of the CIMMS application. This software can be run locally or as a hosted service, using BSM data to report on the movement of vehicles, combined with the broadcast SPaT, MAP, and RTCM messages sent from the connected intersection. The analysis software integrated into CIMMS reports *Events* which indicate anomalies within the data.

CIMMS contains 8 types of event detection algorithms:

1. SPaT/MAP Transmission Rate
2. SPaT/MAP Minimum Data Requirement
3. Signal State Conflict Monitor
4. Time Change Details Monitor
5. Stop Line Passage Event
6. Stop Line Stop Event
7. Direction of Travel
8. Connection of Travel

This set of events can be grouped into two broad categories. The first four reflect directly on the operation of the infrastructure. Events 1 and 2 are triggered if the periodicity or content of the broadcast data is out of specification. Events 3 and 4 are triggered if there is an internal inconsistency in the CI broadcast data, such as overlapping lanes simultaneously showing a green light or significant errors in the signal change time estimate.

Events 5 through 8 reflect on the CI system indirectly. They report information about the movement of vehicles through the intersection and are heavily influenced by the behavior of individual drivers, the configuration of the in-vehicle equipment, and conditions related to the physical lanes and signal head status. Proper interpretation of these events requires further analysis about the expected frequency of outliers and evidence for statistical significance showing that there may be an error in the CI itself.

Note that CIMMS does not currently provide any monitoring for RTCM. Rather than call this out in each section, this point is recognized here only. In a future version, CIMMS shall be updated to include metrics related to RTCM. Current SCMS Manager requirements for intersection validation require that RTCM be present in order for the intersection to achieve *SCMS Accepted* status.

The following sections further discuss the meaning of each event type with a discussion on potential interpretations and actions. Each section describes why an intersection may transition to the *Suspended* state in response to a specific type of event. There is also a definition of the criteria that must be met in order for an operator to attempt to transition the intersection back to the *Validated* state.

3.1 SPaT/MAP Transmission Rate

This event type is triggered when the transmission rate of SPaT or MAP messages deviate from the required 10 messages per-second over a 10 second period. Thresholds within the application put limits on how sensitive this event type is to small changes in message timing. As a direct measure of CI performance, this event type indicates that the system may be unable to maintain a consistent sequence of SPaT or MAP messages. This may be due to CPU load or clock jitter caused by active applications.

Provided that the CIMMS transmission rate filters are set appropriately, occurrences of this event type are expected to be very rare. When this event is triggered, the system shall immediately transition to the *Suspended* state and notify an operator that the system timing needs to be investigated before the CI may be brought back to the *Validated* state.

3.2 SPaT/MAP Minimum Data Requirement

This event type is triggered if the content of one or more SPaT or MAP messages are missing data elements that are marked as critical in the RSU specification. This condition is not expected to occur during normal operation provided that the CI is configured correctly. As with transmission rate, a CI should transition immediately to the *Suspended* state and notify an operator if this event is triggered. The operator shall perform an investigation into the root cause of the alert before the CI may be brought back to the *Validated* state.

3.3 Signal State Conflict Monitor

A signal state conflict is a condition where multiple lanes are in permissive mode (i.e. green or yellow) simultaneously where those lanes control traffic flows that may cause a collision. This condition should never occur during normal operation. The presence of this alert may indicate a serious failure of the signal controller (a failure that should be prevented by logic in the controller), or a significant discrepancy between the broadcast data and the actual signal head operation.

Both causes potentially present a significant risk to drivers and therefore a CI shall immediately transition to the *Suspended* state and notify an operator if this event occurs. The operator must perform an invitation into the root cause and make corrections before attempting to transition the system back to the *Validated* state.

3.4 Time Change Details Monitor

This event is triggered if there is a significant discrepancy in the predicted time for a future signal change and the timing of evidence that the actual change occurred. For example, a SPaT message may predict 3 seconds to transition from yellow to red but the broadcast may then change to red after only 1 second. This type of discrepancy may occur in rare events where a critical preemption occurs or where there is a shift in timing of messages within the CI system. Thresholds within the CIMMS application are intended to filter out false positive event indications of this type. Only after the pre-configured statistical filters are exceeded shall this event type cause the CI to transition to the *Suspended* state. An operator may attempt to transition the intersection back to the *Validated* state if there is evidence that the root cause as been eliminated.

3.5 Stop Line Passage Event

This event type is recorded every time a vehicle crosses a stop line in an MAP approach while adhering to certain parameters on speed and direction. Only if internal thresholds are crossed will this event trigger a notification indicating that there may be a timing issue.

A notification of this type indicates that multiple stop line passage events happened when the broadcast SPaT data indicated that the lane should be stopped. This may be due to a significant disparity in timing between the SPaT message broadcast and the actual signal head.

An occurrence of a notification of this type, after processing by the internal CIMMS statistical filters, shall result in the intersection transitioning to the *Suspended* state with a notification to the operator. An operator must review the collection of vehicle data that caused the notification and resolve any common cause issues prior to attempting to transition the CI back to the *Validated* state. If the operator determines that there is no significant deviation between the CI broadcast data and the actual intersection status, then it is permissible to adjust the CI thresholds to reduce the likelihood of future false positive notifications.

3.6 Stop Line Stop Event

This event type is recorded every time a vehicle is stopped at a stop line in a MAP approach lane while the SPaT data indicates that the corresponding lane should be in a permissive mode (green or yellow). The internal thresholds in the CIMMS application should filter out normal driver delays. Any resulting notification may indicate a disparity in the broadcast SPaT data and the actual signal head action.

An occurrence of a notification of this type, after processing by the internal CIMMS statistical filters, shall result in the intersection transitioning to the *Suspended* state with a notification to the operator. An operator must review the collection of vehicle data that caused the notification and resolve any common cause issues prior to attempting to transition the CI back to the *Validated* state. If the operator determines that there is no significant deviation between the CI broadcast data and the actual intersection status, then it is permissible to adjust the CI thresholds to reduce the likelihood of future false positive notifications.

3.7 Direction of Travel

This even type aggregates movement data across multiple vehicles as they pass through an intersection. Based on thresholds set in the CIMMS application, a notification of this type may be generated to indicate that a significant number of vehicles are moving in a direction that is inconsistent with the broadcast MAP data. This could indicate that the MAP data is no longer aligned with the actual lane lines, or that there is some other condition causing traffic to change route. The root cause may be related to an temporary event such as an accident, emergency vehicle activity, or a change in road conditions (such as flooding, ice, hole in the roadway, etc). However, this notification may also indicate that the MAP data that is being broadcast is no longer consistent with the normal flow of traffic. If the MAP data is systematically shifted it may cause the CIMMS system to place some cars in a different lane than the one where they are actually driving. This condition would likely result in vehicles having similar difficulty in correctly identifying their lane of travel and therefore hinder their ability issue reliable alerts to drivers.

3.8 Connection of Travel

Similar to direction of travel, this event type aggregates the movement of multiple vehicles through an intersection. A notification of this type is generated only if internal thresholds are exceeded over a defined period of time. The notification indicates that multiple vehicles have traversed lanes in a way that is not permitted in the MAP data. For example, multiple cars may be proceeding straight from a turn-only lane. A few isolated incidents of this type may be attributed to careless or distracted drivers who fail to follow the posted lane restrictions. When multiple vehicles follow a similar unauthorized path it may indicate a significant error in the MAP data, or a temporary condition that is causing traffic to move in an unexpected way through the intersection.

4 Defining Event Thresholds

Many of the event types defined in the prior section depend on internal statistical thresholds in the CIMMS system. In setting these thresholds, it is valuable to consider the factors that impact the statistical significance of several event types. This analysis supports the development of a spreadsheet model that can be used to support the bounds on thresholds that shall be used when configuring a CIMMS system. At this time, this section is intended to be informative and not declarative. Over time and with validation experience, it is expected that SCMS Manager will publish more specific guidance on threshold values.

This guidance is specifically intended for use with the indirect event types that may be triggered by CIMMS. The four indirect types include "Stop Line Passage Event", "Stop Line Stop Event", "Direction of Travel", and "Connection of Travel". Each of these events may be significantly impacted by a combination of factors that include driver behavior, vehicle system configuration, short-term disturbances, and CI configuration errors. In most cases, it is not possible to distinguish among these distinct causes based only on the BSM and CI data captured by the CIMSS system. However, with appropriate modeling, it may be possible to anticipate an acceptable rate for type 1 errors (false positives) and type 2 errors (false negatives). The following sections describe an approach that may be useful in modeling driver behavior and placing bounds on these error types. Over time, actual vehicle data may be used to define specific distribution parameters to produce actionable threshold settings.

4.1 Modeling Driver Behavior

Human drivers will never follow a perfect path or have perfect reaction times. There will always be significant variation among drivers that will impact their driving patterns including bias to one side of a lane or the other, stopping distance with respect to a stop line, and reaction times. Even a single driver will never perfectly repeat a particular driving pattern. When averaging among a large number of drivers, it is reasonable to assume that driver metrics can be modeled using a Normal distribution.

The following method can be used to estimate the expected number of violations that may be observed per-day. In the specific example, stop location violations are considered. A similar methodology can be used to estimate frequency of occurrence for other parameters.

- Assume that the number of vehicles that arrive at a specific lane at a specific intersection can be modeled using a Poisson distribution with parameter λ set to the observed mean number of vehicles per-day observed over a period of time.
- Assume that the actual location where a driver stops with respect to the stop line can be modeled using a Normal distribution with a mean μ and standard deviation σ.
- Define a *critical distance* Das a distance beyond the stop line that causes significant threat to the flow of traffic.

Based on these parameters, perform the following calculations:

- The Z-Score for the Normal distribution is calculated as $Z = \frac{D-\mu}{\sigma}$
- The probability of a violation is $p = 1 - s(Z)$ where $s()$ is the standard Cumulative Distribution Function (CDF) of the Normal distribution. This estimates the probability p that any one vehicle will exceed the *critical distance*, D.
- Estimate the number of expected daily violations as $N = \lambda * p$

A spreadsheet model is included that performs these calculations. For example, with $\lambda = 1,200$ vehicles per-day, $\lambda = -0.5$ meters, standard deviation $\sigma = 0.8$ meters, and a critical distance $D = 0.7$ meters, the expected number of violations is 81 per-day. Using this model, with actual data collected from real driver metrics and vehicle arrival rates, can provide critical guidance for thresholds used in configuring the CIMSS detection algorithms.

Note that the assumption of a Normal distribution for stop distance must be validated with a test of fit for the Normal distribution. Similarly, the use of a Poisson distribution to approximate vehicles per-day per-lane must be validated using data. It is possible that the vehicle stopping distance is biased to one side, indicating that an exponential distribution may be a better fit. Also, the arrival rate of vehicles likely changes by season, so the parameters may need to be adjusted based on season.

4.2 Extension to Other Parameters

The modeling approach described in the previous section may be extended to set expected values for other properties such as calculating the probability of classifying a vehicle in the wrong lane, resulting in a direction of travel or connection of travel violation. With sufficient data collected from actual vehicles, is will be possible to estimate the actual sensitivity of the CIMMS method can be estimated for specific measurements such as lane line accuracy, stop line accuracy, and SPaT phase timing.