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ABSTRACT

This paper describes the results of simulation studies to determine how effectively left-turning drivers can be alerted to imminent conflicts with opposing traffic under difficult operating conditions and with limited detector capabilities. These conditions include approaching vehicles changing speed in locations that are not covered by detectors and detectors that may only be able to detect vehicle presence, but not speed. In cases without direct speed detection, one may try to rely on historical speed statistics to estimate the speed of approaching traffic, but unless the approach speeds are confined to a very narrow range the system is vulnerable to both false positive and false negative alerts in the respective cases of the real vehicle speeds being less than and greater than the assumed historical value.

INTRODUCTION

Intersections are typically the most complicated elements in the driving environment, posing the greatest challenges of perception and judgment for drivers. They are also the locations with the greatest need for safety improvements. The Intersection Decision Support (IDS) Project of the IVI Infrastructure Consortium *(1)* has been investigating how ITS technologies of sensing, communications, computations and driver interfaces can be used to support drivers, enhancing their safety as they traverse intersections.

At last year's Transportation Research Board (TRB) Annual Meeting, we presented the initial design for an IDS alert system to support drivers making left turns during permissive green signals in the face of approaching traffic *(2)*. This type of IDS is intended to help drivers better judge whether gaps in the approaching traffic will allow sufficient time to safely complete their left turns. Drivers who accurately judge the time available during a gap are more likely to avoid conflicts with oncoming vehicles during their left turns. Such conflicts, designated as "Left Turn Across Path/Opposite Direction" (LTAP/OD), currently represent 27% of crossing-path crashes at intersections in the United States *(3)*.

In our study using simulations of traffic in intersections *(2)*, we demonstrated that providing useful alerts to left-turning drivers about potential conflicts required early identification of vehicle movements, based on information about the speeds of oncoming vehicles, particularly when speeds changed (such as accelerating to beat a red signal). However, we did not cover the full range of issues associated with knowing the speeds of the approaching vehicles.

This paper expands upon our previous work by identifying some of the difficult challenges to providing early and useful alerts to left-turning drivers, such as capturing unanticipated speed changes of the turning and oncoming vehicles *(2)*. Another challenge is to determine whether generation of alerts based on historic distributions of vehicle speeds approaching the intersection, as proposed in *(4)*, could be a viable low-cost alternative to directly measuring speeds of vehicles at the intersection

Ideally, to predict potential conflicts, one would have complete information about the motions of all vehicles approaching an intersection. This would include measurements of each vehicle's location, speed and acceleration, with high accuracy and minimal latency (100 ms or less). Using such information, the current and future motions of the vehicles could be projected and the conflicts identified with reasonable accuracy. However, the cost and technical performance limitations of detector systems weigh against this ideal situation. In reality, the number of detectors that can be installed at any given intersection will be limited, their coverage areas will be incomplete, they may include vehicle presence but not speed, and their outputs may have more latency than the desirable minimum.

It is difficult and expensive to obtain complete information about the motions of the vehicles approaching an intersection; yet, to encourage widespread deployment, the IDS system would need to be as affordable as possible. Implementation of the IDS with a minimal sensor suite would minimize the cost and difficulty of deployment However, it is important to understand what capabilities of the IDS system would have to be traded away in order to reduce the number and sophistication of its sensors. It is also important to understand the range of driving conditions under which useful alerts can be generated. Since it would be very costly to test all combinations of system design and performance at full scale, this type of evaluation is well suited to computer simulation.

We previously described the logic for determining the conditions under which drivers should be alerted to an insufficient gap for making a left turn *(2)*. The parameter values used to define the alert threshold conditions must be adjusted to conform to the geometric and operating characteristics of individual intersections, such as number of lanes in each direction, presence of left-turn pockets, width of median, visibility of opposing traffic, density of vehicular and pedestrian traffic in each direction, posted speed limits and prevailing speed distribution, length of signal phases, etc. Current research includes collecting data about drivers' turning behavior at a variety of intersections under normal driving conditions and in specific staged experimental conditions in order to support refined estimates of these parameter values *(5-7)*. Based on our ongoing research, the general approach to defining alert threshold conditions described previously *(2)* continues to apply regardless of the specific parameter values that are chosen.

The more important uncertainty that needs to be resolved is the sensitivity of drivers to variability in the parameter values and in the measured data used to determine whether to issue alerts. If drivers are tolerant of variability in the alerts, it should be possible to implement an effective alert system even with considerable measurement gaps and uncertainties. On the other hand, if drivers perceive variability to be an indication that the IDS system is untrustworthy (subject to excessive false alarms and missed detections) or unpredictable, the system performance requirements will be considerably more demanding.

In this paper, we show the effects on alert triggering that can be produced by changes in the speed of approaching vehicles (even when vehicle speed is being measured), and by the unavailability of vehicle speed data. Using simulations for a variety of conditions, we determine the extent to which changes in speed or the lack of vehicle speed data for approaching vehicles will alter the alert status compared to "ideal" conditions.

SIMULATION MODELS

The simulations that are used to evaluate the IDS alternatives are based on simple kinematic models of the motions of the vehicles approaching an intersection, and the vehicle trajectories are pre-specified for each simulation run. These include the trajectories of the subject vehicle (SV) that is preparing to make a left turn and of the principal other vehicles (POVs) approaching from the opposite direction, representing the potential threats to the SV. These approach trajectories can be defined to be constant speeds or combinations of constant speed and accelerations and decelerations, at the user's option. The user can also specify the relative arrival times (lags) for the SV and POV at their respective stop bars, so that a range of relative arrival time scenarios can be tested. The scenarios of most interest, which require alerting the SV driver of a potential conflict, generally represent a narrow range of relative arrival times. Particular attention is focused on the "borderline" cases of relative arrival times, when the alert criterion is barely satisfied or barely missed, because these will be the most vulnerable to disturbance under challenging operating conditions and with imperfect or missing detector data.

A complete set of diagnostic plots can be generated for each simulation case, but in most cases only a single alert status summary plot is needed. The more complete set of plots is used to verify that the simulation is indeed representing the intended scenario, by showing the following:

(1) Speed versus time for both SV and POV, including true speed of both vehicles and speed as measured by the specified detectors (including noise, latency and sampling imperfections);

(2) Predicted time to intersection (T2I) versus time for both SV and POV, so that it is possible to see how close and how fast the vehicles are approaching, particularly since the nominal alert criterion is based on a threshold value of difference between the T2I values for these vehicles. This plot includes both T2I values predicted based on perfect sensor data and T2I values estimated from the measured data, so that the effects of measurement limitations can be seen directly. However, the T2I predictions can only be based on forecasts assuming that the vehicle motion kinematics will not change in the future. If the vehicle motions do change, the T2I predictions will be erroneous.

(3) Distance to intersection (D2I) versus time for both SV and POV, so that the physical separation between the vehicles can be seen at all times. This plot includes both true D2I values and D2I values estimated from the real-time measured data, so that the effects of measurement limitations can be seen directly.

The preceding plots are typically needed only for debugging simulation scenarios or to directly show the effects of detector limitations. For most simulation cases, only the alert status summary plot is shown. This includes a variety of measures plotted as a function of time:

(a) binary indication of SV passing through a detector coverage zone, so we can see when the SV is detected and when it is not;

(b) binary indication of POV passing through a detector coverage zone, so we can see when the POV is detected and when it is not;

(c) predicted "trailing buffer time", representing the difference between the time that the rear of the SV is predicted to clear the zone of conflict with the POV and the time that the front of the approaching POV is predicted to enter the zone of conflict. This is the primary measure of threat severity, so that if this predicted buffer time goes below a specified threshold value (nominally 3 seconds, based on previous field data observations *(6)*), the IDS conflict alert should be issued;

(d) estimated trailing buffer time, based on the available detector data being used to estimate vehicle trajectories;

(e) alert status, based on predicted trailing buffer (with perfect sensing) crossing the specified threshold;

(f) estimated alert status, based on estimated trailing buffer (with sensor imperfections) crossing the specified threshold;

(g) braking rate that the SV driver would need to apply to stop by its stop bar, assuming one second perception-reaction delay before application of brakes;

(h) braking rate that the SV driver would need to apply to stop before entering the conflict zone, assuming one second perception-reaction delay before application of brakes. This is a vital measure for determining whether the alert has been issued early enough for the driver to be able to respond safely.

PROVIDING IDS ALERTS WITH VEHICLES ACCELERATING AND DECELERATING

It is more difficult to generate IDS alerts when the interacting vehicles engage in more aggressive maneuvers. The scenarios that were described in our previous work *(2)* included a substantial acceleration by the approaching POV, representing an attempt to beat the red signal. It is even more difficult to generate an appropriate alert when the SV is decelerating moderately aggressively (at 0.2 g), as shown by the simulation results of Figure 1. This alert status summary plot shows that even with "perfect" sensing of the location and speed of the approaching vehicles, by the time the alert threshold trailing buffer value of 3 seconds is reached, it is necessary for the SV to decelerate to a stop at 0.29 g (fairly hard braking) in order to avoid a crash with the POV. This leaves very little margin for sensing imperfections (e.g., latency or noise) to further delay the identification of that threshold in real-time implementations. Fortunately, since the SV is already decelerating at 0.2 g in this case, it does not require initiation of a new braking maneuver.

Figure 1 also shows the difficulties in predicting buffer times and conflicts by use of single loop detectors or other sensors that only provide vehicle presence information, but not speed. The jagged lines toward the bottom of the plot show when the SV and POV were detected by loop detectors located at 50 m and 100 m from the stop bar, as well as the final four loops right at the stop bar. The speed of the POV could not be identified until it had passed the second of those final four loops, when the time difference between its passage over those loops could be used to estimate its speed. That time, around t = 13 seconds on the plot, was the first opportunity to estimate the trailing buffer so that it could be compared to the threshold value. By then, the buffer value was already less than 0.5 seconds, versus the threshold value of 3 seconds, and it was much too late (about 5 seconds after the alert based on perfect measurements) to issue a useful alert to the SV driver.

With limited detector coverage, even a relatively modest coast-down deceleration by the POV (0.07 g) can introduce a risk of false alarms when the intersection encounter is not actually close enough to warrant an alert. This is shown in Figure 2, for a case with double loop detectors at 100 m and 50 m from the intersection, in addition to the more typical cluster of four loops right behind the stop bar. In the lower right quadrant of this figure, it can be seen how the estimate of time to intersection for the POV became "stale" because it was not updated between 100 m and 50 m, during which period the POV was actually decelerating. The estimated value of the POV's arrival time at the intersection was about one second too early, giving the misleading impression that the encounter between the vehicles would be closer than it really was. As a consequence, the trailing buffer estimate, based on the (now obsolete) speed of the POV measured at the 100 m distance, decreased below the 3 second threshold value for a period of about one second, generating a false positive alert at around t = 8 seconds in Figure 2.

A variety of other cases has been studied but are not plotted here in order to save space. These analyses lead to the following conclusions about the generation of timely, accurate LTAP/OD alerts:

- In order to understand the richness and complexity of the interactions between an SV and a POV, it is necessary to simulate many cases, with differences in the vehicle arrival times at the intersections. The most important cases to evaluate are the borderline cases in which the alert threshold is barely crossed or barely missed, because these best demonstrate the sensitivity of the alert system to imperfections. These can also provide a basis for deciding whether the probability of encountering these cases and generating inappropriate responses is sufficiently high to jeopardize the viability of the intersection alert system.
- In the challenging cases, the final four inductive loops at the intersection have been shown to be valuable for providing vehicle presence and speed information, especially for the slow-moving SV during the seconds immediately preceding its turning maneuver. These loops should be used in consecutive pairs as "virtual double loops" in order to estimate vehicle speed information.
- Vehicle speed information accuracy appears to be at least as important as vehicle location information accuracy in predicting potential conflicts.
- Changes in SV speed close to the intersection make the alert generation more difficult than changes in POV speed, so particular attention needs to be devoted to ensuring that accurate SV speed information is available with frequent updates.
- Aggressive decelerations by an SV approaching a left turn (in the range of 0.2 g, rather than just a 0.07 g coast-down) are difficult to address, because they leave little time available for updating estimates of LTAP/OD threat severity. In contrast, hard decelerations of POVs to stop or accelerations of POVs to beat signal phase changes are less difficult because the POV accelerations occur too late to create hazardous encounters (unless the SV will be turning so late that it is also violating the red signal), while the decelerations can be detected early enough to be accommodated within the threat assessments. These findings indicate that higher priority should be given to detecting SV motions than POV motions close to the intersection.
- If detector coverage on the intersection approach is too sparse, gradual decelerations of POVs can lead to false alerts.

ATTEMPTING TO PROVIDE LTAP/OD ALERTS BASED ONLY ON DETECTION OF VEHICLE PRESENCE

Particular attention has been devoted to the special case in which data on the presence of approaching vehicles are available, but their velocities are not. A potential low-cost IDS strategy has been suggested that includes single-loop detectors to detect the presence of approaching vehicles, with speed estimates for each based on local aggregate traffic data (such as the 85th percentile of speeds at the intersection*(4)*).

This strategy has been studied in simulation to determine how vulnerable it could be to *false positives* or *false negatives*. The example is based on the Shattuck/Hearst intersection in the City of Berkeley, California, for which we have collected substantial data *(6,7)*. At that intersection, the approach speeds are typically in the range of 20 to 30 mph (32 to 48 km/h), which is high compared to the posted speed limit of 25 mph, or 40 km/h. We set the estimated (default) speed equal to the 85th percentile approach speed of 28 mph (45 km/h) for purposes of generating the IDS alert. In the absence of detailed data on the latency, accuracy and reliability of loop detectors, we assumed perfect performance in all these dimensions for single loop detectors located at 100 m and 50 m from the stop bar, together with the final four loops clustered at the stop bar.

For the first simulation case, we studied a POV approaching the intersection with a speed set at 20 mph (32 km/h). When modeled, the situation did not produce a close enough encounter to merit an alert to the SV. However, when the POV speed was set to the estimated speed of 28 mph (at the 85th %ile), it led to an extended *false positive* (i.e., an unnecessary alert of about 5 seconds duration), as shown in Figure 3. The estimates of T2I for the POV were seriously distorted by the error in this estimate of POV speed, and even though the use of the final loops in pairs made it possible to give an accurate update of the SV speed, the POV speed estimate was seriously wrong. Note that the true predicted trailing buffer value for a POV speed of 20 mph was above 4 seconds for the entire period, but the erroneous estimated speed led to estimated trailing buffer values between 1 and 2.5 seconds, all well below the alert threshold of 3 seconds. The magnitude of the discrepancy here indicates that using estimates of vehicle approach speeds based on aggregate data rather than on real-time observed speeds for POVs is likely to be a problem for a wide range of operating conditions, and not just for the “borderline” cases.

In the opposite case, we set the speed of the approaching POV at 30 mph (48 km/h) for comparison with the 85%ile speed of 28 mph (45 km/h), and we encountered the opposite problem of a *false negative* (missed detection), as shown in Figure 4. In this case, the true predicted trailing buffer (for 30 mph) was below the 3 second alert threshold for an extended period (almost 4 seconds), but the low estimated speed of 28 mph led to an assumption of a higher buffer value throughout that time, preventing the alert from being generated. Even the small speed discrepancy of 2 mph (3 km/h) produced this extended false negative (nearly 4 seconds) because the actual buffer value was so close to the alert threshold.

The preceding two sets of results were based on the assumption that the most appropriate speed to assume for generating the alert was around the 85%ile. In order to check the sensitivity of the results to this assumption, another case was tested for an estimated speed value of 25 mph (the posted speed limit, also estimated to be the mean speed for this roadway segment). The results of this case for an actual POV approach speed of 30 mph are shown in Figure 5. It can be seen from this figure that the alert threshold value was crossed so late that the alert was delayed by more than 3 seconds, requiring the SV driver to brake at a very high rate (above 0.6 g, off the scale of the plot) in order to avoid the conflict with the POV. Since this is a very undesirable circumstance, it shows the inadvisability of choosing the mean speed value and weighs more in favor of the originally proposed 85%ile default speed estimate.

Basic conclusions from this study of generating LTAP/OD alerts without real-time measurements of approaching vehicle speeds are:

- If the estimated speed is below the actual speed of the approaching vehicles, the alerts will be issued late or will be missed entirely. Since these are unsafe outcomes, the estimated speed will have to be in the upper range of the true distribution of speeds encountered at that intersection.
- The larger the difference between the actual and estimated speeds, the more severe the consequences will be. The most likely causes of LTAP/OD crashes are driver under-estimates of the speed of fast approaching vehicles, so an alert system that is vulnerable to precisely the kinds of driver errors that we are hoping to overcome with IDS assistance would not be very effective in reducing these crashes, which also have the most severe consequences for the vehicle occupants.
- If the estimated speed is above the actual speed of the approaching vehicles, false positives (false alerts) become more likely.
- The likelihood of occurrence of these problems depends on the variability in the speed distribution of the approaching vehicles. If the approaching vehicle speeds are clustered close together, the problems are much less serious than if there is a wide variation in approaching vehicle speeds.

These results have all been based on the assumptions that the available detector data describing vehicle motions are perfectly accurate and available with no latency, which are known to be unrealistic. Recent testing of a variety of detector systems has indicated that the actual speed measurement errors are likely to be in the range of 5%, and the simplest such detectors, the inductive loops, have a latency of at least 0.5 s. If the latency is relatively consistent and unavoidable, its effects can be compensated for within the alert criterion under most cases (except when the timing is so critical that it delays the availability of critical information by so much that a timely alert cannot be issued).

CONCLUSIONS

Crossing-path crashes at intersections remain one of the most important traffic safety challenges, but also one of the most difficult to address, because of the complexity of intersection driving. ITS technologies can be applied to detect potential intersection conflicts and alert drivers to take corrective actions, but in order to provide useful alerts to drivers they need to be able to detect vehicle motions accurately and promptly. Simulations of intersection encounters have been used to help identify the effects of limitations in vehicle detection capability on the validity of the alerts that can be provided to drivers. This is important because vehicle detectors are likely to be the most costly elements of a deployed intersection decision support (IDS) system, and there are strong incentives to apply the least-costly viable detection methods so that the IDS will be economically feasible at the largest possible number of intersections.

Economizing on detectors may mean that detectors are only located at discrete locations, rather than providing continuous coverage of the intersection approaches, or that the detectors only provide vehicle presence information, but not speed. Each of these limitations means that the accuracy and timeliness of the conflict predictions will be impaired, thereby reducing the effectiveness of the alert system. Simulations of intersection turning conflicts have been used to assess the severity of these impairments, particularly with regard to increasing false positive and false negative alerts. False negatives must be minimized because these mean that alerts will not be issued for some unsafe conditions, thereby increasing the probability that a crash will not be avoided. False positives also need to be minimized because they are likely to decrease driver confidence in the alert system, making it less likely that drivers will abide by a genuine alert when it is issued.

The most important measurements for predicting imminent conflicts are the speeds of the vehicles approaching the intersection, because these have a strong influence on the probability that opposing vehicles will enter the zone of conflict at the same time. It is particularly important to have good speed measurements for the vehicle that is decelerating to make a left turn, because modest variations in its deceleration rate can make the difference between cases in which alerts are appropriate or inappropriate. At the final approach to the intersection, this speed information can be derived from the loop detectors in the immediate vicinity of the stop bar, if they are configured to be used as a sequence of “virtual double loops” (successive pairs of loops). An insufficient density of detectors upstream from the intersection is likely to lead to “stale” speed measurements for vehicles that are accelerating or decelerating after passing the previous speed detection location. An accelerating vehicle would be traveling faster than the estimated speed, making a false negative more likely, while a decelerating vehicle would have the inverse problem, making a false positive more likely.

A system concept that would rely on the historical distribution of vehicle speeds at an intersection (in place of direct speed measurements), in combination with conventional presence detectors, has also been evaluated in simulation. The viability of this concept depends on having a narrow distribution of vehicle approach speeds, so that the true vehicle speeds are not much different from the nominal value chosen based on historical data. When it was evaluated using speeds measured at an example intersection in Berkeley, California, the variability in those speeds was large enough that it produced significant false positive and false negative alerts. In this case, when the nominal historical speed was higher than the actual vehicle speed, false positives were generated, and when the nominal historical speed was below the actual speed, false negatives were generated. Additional human factors research is needed with a representative sampling of drivers to determine how sensitive they are to the boundaries between true and false positive alerts and true and false negative alerts, so that we can understand how serious the false alerts are.

The simulation that was used for this study has also been designed to be usable to evaluate other limitations in the available detector data. Future research is planned to explore the effects of measurement latency, noise and biases, to determine how adversely they affect the generation of alerts. The results of that work will lead to the definition of specifications of the limits on detector latency, noise and biases that will make them suitable for use for intersection decision support applications.

Until now, the information about vehicle motions has been assumed to come from infrastructure-based detectors. However, with the current improvements in vehicle-roadside communication by 5.9 GHz DSRC, it becomes possible for vehicles to directly communicate their locations and speeds to the intersection to provide enhanced accuracy of information. This should help significantly in overcoming the measurement problems of concern here (continuity of coverage, availability of vehicle speed as well as presence data, latency, noise and biases). Such a Cooperative Intersection Collision Avoidance System (CICAS) should be the next stage of development, growing out of the current IDS research.

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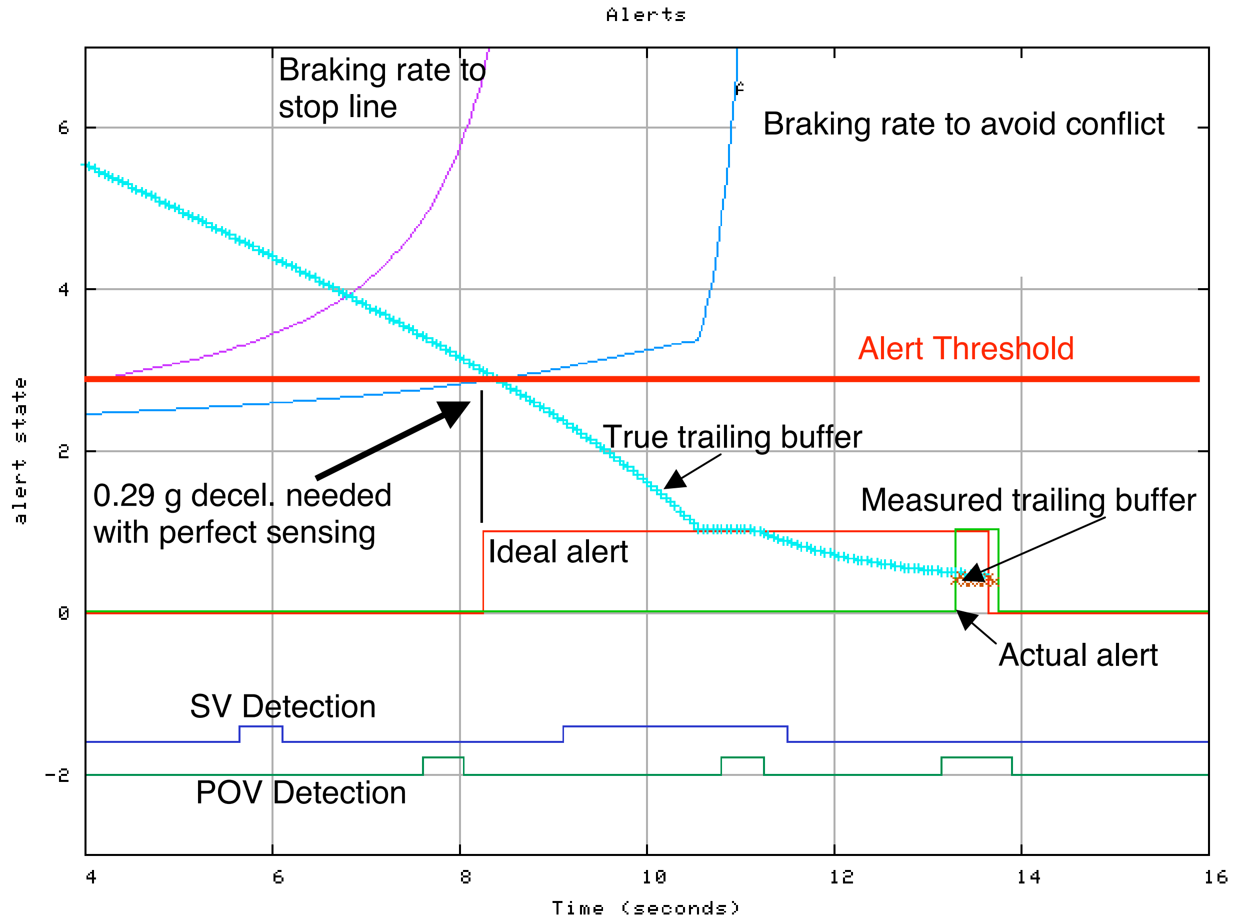

FIGURE 1 LTAP/OD alert challenges with SV decelerating at 0.2 g

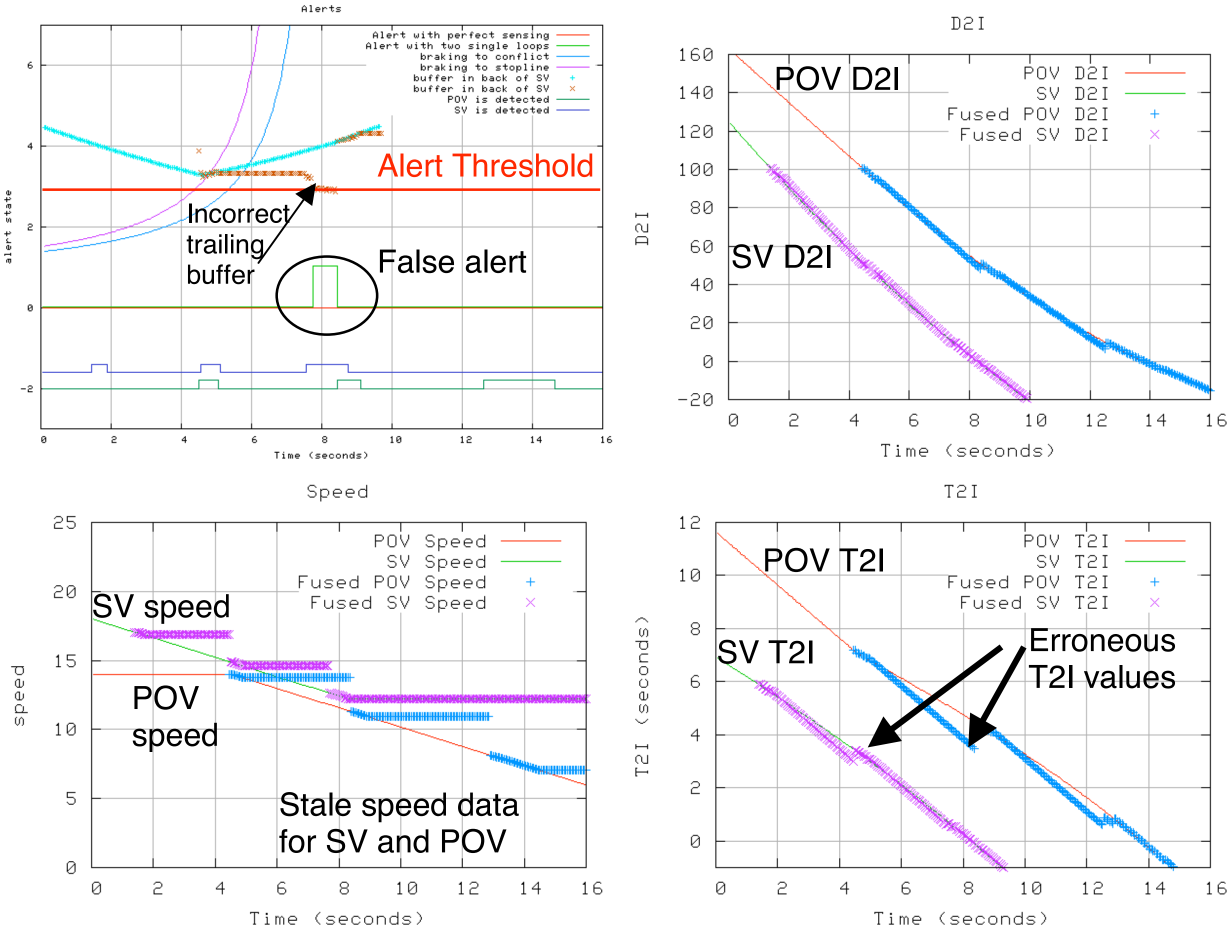

FIGURE 2 LTAP/OD false alert challenges with POV decelerating at 0.07 g

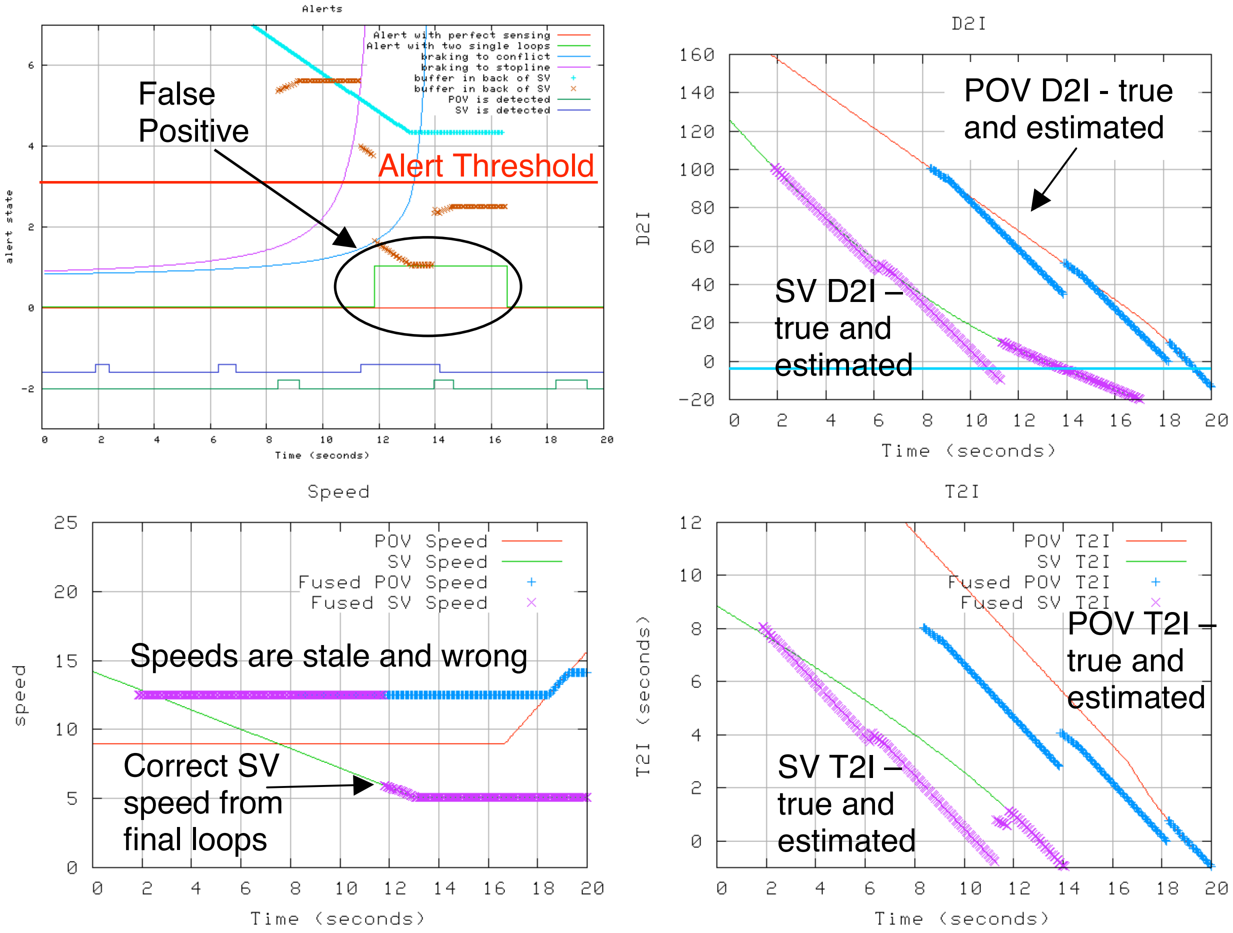

FIGURE 3 Example of false positive for POV approaching at 20 mph, but estimated at 28 mph default speed

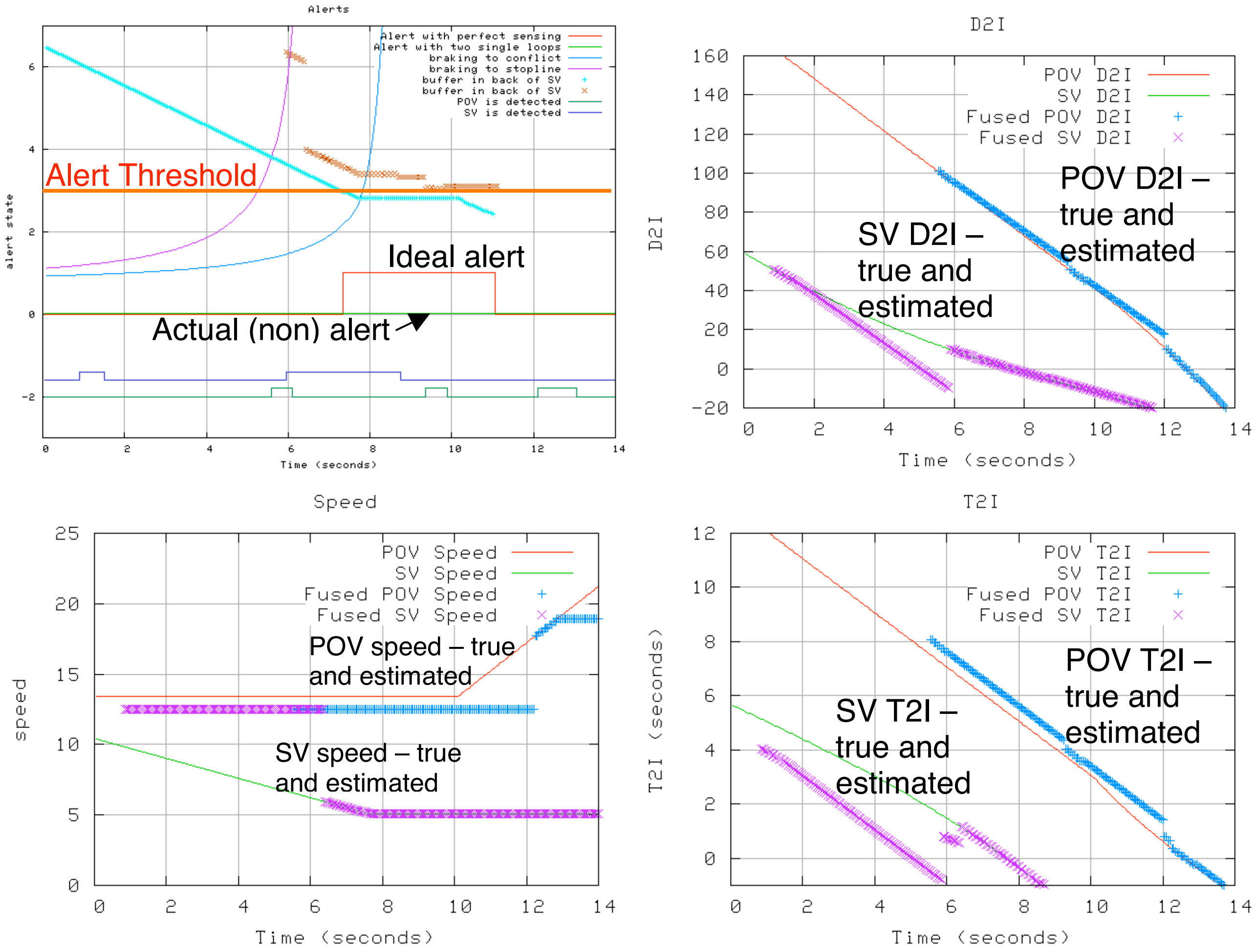

FIGURE 4 Example of false negative for POV approaching at 30 mph, but estimated to be at 28 mph default speed

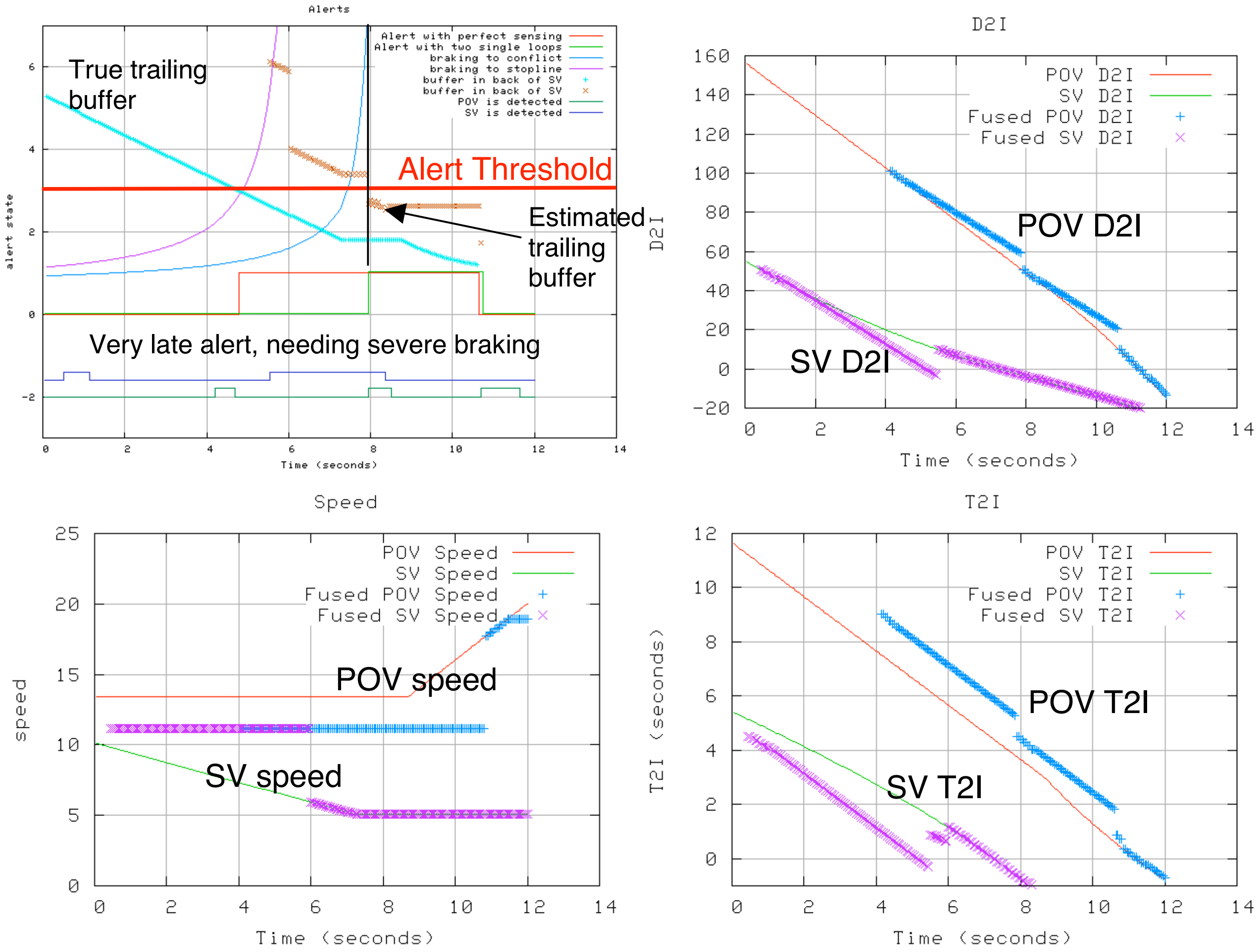

FIGURE 5 Sensitivity case for POV approaching at 30 mph, but estimated to be at 25 mph default speed