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Feasibility of Modeling Lane-Change Performance

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ABSTRACT

This paper examines the feasibility of using four driving states (low risk, conflict, near crash, and crash imminent) to characterize lane-change driving performance. Data are analyzed from a test track study to estimate the boundaries between the states and to show that performance maps can be created for lane-change events in two simple scenarios. The map structure is further investigated using naturalistic on-road data and the agreement between the test track and on-road data models is discussed. Implications for crash counter-measure development and evaluation are discussed.

INTRODUCTION

As part of the Intelligent Vehicle Initiative of the United States Department of Transportation (USDOT), the National Highway Traffic Safety Administration (NHTSA) is defining the safety problem and crash avoidance mitigation concepts for several collision types. Lane-change crashes represent approximately 10% of the 6.3 million crashes that occur annually (1999 GES). In addition, lane-change events are closely related to rear-end crashes, which account for approximately 25% of the total crash population each year. Research into lane-change maneuvers can thus help identify opportunities for crash avoidance countermeasures and can also provide a framework in which crash countermeasures should be evaluated.

This paper builds upon several previous papers that mapped driver performance in car-following situations (1, 2). Here we investigate the use of a similar approach to map lane-change performance and answer three feasibility questions:

What metrics should be used to characterize lane-change performance?

Does a similar performance map exist for lane change as that for car following?

Is there consistency between test track and on-road lane change performance data?

This paper presents an incremental approach to understand the performance factors involved in lane-change events. This incremental approach starts with a study of a simple lane-change scenario performed on the test track involving only two vehicles, where the subject vehicle changes lanes with only a slower lead vehicle present. This scenario was selected because it flows logically from the car-following scenarios referenced above and also because test track experimental data was available for this particular scenario. The paper continues with preliminary analyses of lane-change scenarios involving three vehicles. The paper concludes with a discussion of future work needed.

BACKGROUND

This section provides background information on the basic concepts needed to map driving performance and the two driving trials that produced the lane-change data discussed in this paper.

FOUR DRIVING STATES

Four driving states have been identified to form the foundation of a driver performance map (1). These have been termed “low risk”, “conflict”, “near crash”, and “crash imminent”. See Figure 1 for an illustration of these driving states and their associations with crash countermeasures. Note that this figure also shows and labels the transitions into and out of each of the states. Knowledge of driver performance in terms of these four states is very helpful to the design and evaluation of crash avoidance systems because they correspond to advisory, crash imminent warning, automatic vehicle control, and crash injury mitigation concepts.

The boundaries between these driving states must be unambiguously and quantifiably defined in order to standardize these definitions. Once standardized, the boundaries can provide a framework for accumulating data from various experimental media (test track, on-road, simulator, etc.) and will provide a lexicon for further discussion where the descriptive terms (conflict, near crash, and crash imminent) all have specific quantified meanings for comparative purposes.

As discussed above, we begin this effort by estimating the lane-change state boundaries using data collected from controlled test track studies.

TEST TRACK DATA

The Crash Avoidance Metrics Partnership (CAMP, a partnership between General Motors and Ford) collected data sets from test track studies to develop a fundamental understanding of drivers' last-second braking and steering so that drivers' perceptions could be properly mapped for collision warning system crash alert timing purposes (2, 3).

Subject drivers were recruited to drive an instrumented vehicle. For some cases the driver approached a lead vehicle that was stopped, and in other cases the subject drivers were instructed to follow a confederate lead vehicle at a specified distance and speed. In one set of trials (designated as "normal" steering intensity), the drivers were instructed to veer aside to pass the lead vehicle at the "last second they normally would to go around the target". In a subsequent set of trials (designated as "hard" steering intensity), the drivers were instructed to veer aside to pass the lead vehicle at the "last second they possibly could to avoid colliding with the target". The primary measure recorded for each trial was the distance and range rate at which the driver began to veer aside (i.e. perform a lane-change maneuver).

The authors of this paper hypothesized that the best way to measure conflict was to determine the "last-second" point at which the drivers took action to avoid a collision, either by braking or steering. Thus, the driver's last-second *normal* steering data was associated with the onset of lane-change conflict, and last-second *hard* steering data was associated with the onset of lane-change near-crash conditions. The controlled environment of a test track was thought to offer the clearest data on driver judgment. However, it was also important to compare these results to on-road data to assess real-world applicability.

TRW DATA

In 1998-2000, TRW, Inc. performed a test of an advanced lane-change warning system, in which 12 drivers drove an instrumented vehicle around a prescribed route on freeways and arterials in the Los Angeles area (4). Each driver took eight trips, each trip lasting approximately 1.25 hours. In some of the trips drivers were alerted by the warning system and in others they were not. The on-board system provided situational decision aids to the driver for those cases when a vehicle in the adjacent right lane was in close proximity or was quickly approaching from the rear. Range data came from a 360-degree scanning laser mounted on the right rear bumper. Data were collected into 1000 azimuth bins per rotational scan, at a rate of 0.1 seconds per rotation.

The present study re-used the TRW archived data and processing routines, but treated the instrumented vehicle as a sensor platform to look rearward at a naturalistic lane-change driving environment where the drivers do not know they are being studied. Thus, in most cases, the lead vehicle in the present study was the TRW laser-equipped vehicle. The advantages of this approach were (a) any visible vehicle within sensor range that changed lanes could be counted, resulting in more lane changes for study, and (b) the observed lane changes were naturalistic, since they were not influenced by the experience of being observed and driving an instrumented vehicle with an on-board warning system or experimental observer in the rear seat. The disadvantages were (a) speed, braking, and steering data could not be obtained directly from the subject vehicle but had to be inferred, (b) range limits and the effect of one vehicle "masking" another from detection limited the ability to detect other vehicles, and (c) lane-change behavior of following vehicles could not be determined when the instrumented vehicle itself changed lanes or went around a curve.

TRW's data analysis programs were modified to read the laser rangefinder data, to determine the edges of vehicles near the instrumented vehicle, and to cluster the data into vehicle kinematic time history files called "tracks". Additional routines were modified and developed to:

- Track all visible vehicles in lanes adjacent to the instrumented vehicle
- Supplement tracked vehicle location information by monitoring left and right vehicle edges
- Detect lane changes made by vehicles behind the instrumented vehicle, either into or out of its lane, using presumed locations of lane stripes relative to the instrumented vehicle
- Attempt to filter out "false" lane changes consisting of instrumented vehicle lane changes, turns, vehicle drift, curves, and stationary vehicles/objects
- Store rolling history of vehicle locations (up to six seconds of previous vehicle track history) for later processing when a lane change is detected
- Using the track history, smooth the vehicle position data using a Butterworth filter and generate new vehicle velocity profiles based on best-linear-fit slope of position data
- Upon detection of a lane change, analyze the history of vehicle locations to identify vehicles in front of the subject (lane-changing) vehicle, and vehicles to the side and rear in adjacent target lane

LANE-CHANGE TERMINOLOGY AND SCENARIOS

TERMINOLOGY

This section provides definitions of the terms used in the paper and provides some comments about their applicability.

The **Subject Vehicle (SV)** is the vehicle that performs the lane change. In the CAMP trials, it is the instrumented vehicle driven by the recruited driver. In the TRW data, the SV must be located within 46 m (150 feet - the approximate laser sensor range) behind the instrumented vehicle.

The **Lead Vehicle (LV)** is the vehicle ahead of the subject vehicle, in the SV's original lane. In the CAMP trials, this is the confederate vehicle. In the TRW data, this is either the instrumented vehicle (if the SV starts the lane change in the instrumented vehicle's lane) or another car if the SV starts in a lane adjacent to the instrumented vehicle.

An **Adjacent Lead Vehicle (ALV)** is a vehicle in the adjacent lane into which the lane change is performed that is ahead of the subject vehicle at the time the lane change starts. There are no adjacent vehicles in the CAMP data. In the TRW data, an ALV may be the instrumented vehicle or another vehicle, depending on whether the SV starts the lane change in the instrumented vehicle's lane or not. Either an LV or an ALV (or both) must be present in the TRW cases, since only lane changes behind the instrumented vehicle could be studied.

An **Adjacent Following Vehicle (AFV)** is a vehicle in the adjacent lane into which the lane change is performed that is behind the subject vehicle at the time the lane change starts.

An **Adjacent Overlapping Vehicle (AOV)** is a vehicle in the adjacent lane into which the lane change is performed that at the time the lane change starts partially overlaps the SV (i.e. at least some part of the AOV is directly adjacent to some part of the SV). The reason there is usually not a collision with an AOV is that the relative velocity between the SV and the AOV is such that by the time the SV reaches the adjacent lane (see the definition of crossover time below), the vehicles are no longer overlapping.

Figures 2 and 3 depict the relative positions of these five vehicle types.

x and **x-dot** are defined to be the longitudinal distance and rate of change of longitudinal distance between two vehicles. **y** and **y-dot** are defined to the lateral distance and rate of change of lateral distance between two vehicles. Of course, they are related by the formula $MeasuredRange = \sqrt{x^2 + y^2}$. In each case, the distance was measured between the nearest points of the two vehicles in question.

The **overt time** is the first instant that the lateral movement of the SV can be detected from the y-dot values derived from sensor measurements. The lane change is defined in this study to begin at this overt time, rather than some time earlier when the SV driver begins to think about changing lanes, or takes some preparatory action such as looking into a mirror, looking over a shoulder, or turning on a turn signal.

The **crossover time** is the time when the SV can be said to cross over from conflict with a lead vehicle in the original lane and/or enter into conflict with a vehicle in the new lane. At this point, the trailing side of the SV just clears the near side of the LV, so there is low danger of a collision with the LV. At the same time, the leading side of the SV is far enough into the new lane that if there were an AOV in the new lane, there could be a collision.

Figure 4 shows the relative position of the SV with respect to the LV in an example lane change. As an illustration of the overt time and crossover time, the relative positions of the SV corresponding to these points are indicated on the figure.

The term **Setting** will refer to the geometric location of the vehicles surrounding the subject vehicle at any point of time. For example, for a lane-change maneuver involving only two vehicles in a car-following situation, the setting can be described as consisting of the subject vehicle and a lead vehicle.

The term **Scenario** will refer to the dynamic motions of each of the vehicles in the setting. Building on the example presented for the setting above, the dynamic motions of each of the vehicles involved (subject and lead vehicle) would be described. Thus, one scenario (that is used in this paper) would consist of the subject vehicle traveling at an initial non-decelerating speed above 25 mph encountering a lead vehicle traveling at a slower constant speed. Another scenario (not analyzed in this paper) would be the subject vehicle traveling at constant speed encountering a lead vehicle that is decelerating. Obviously, there are many such possible combinations of these kinematics, leading to many scenarios. For the purposes of this paper, we seek to investigate the feasibility of the approach only and defer the robust definition of all possible scenarios, or even the most common types, to further work.

SETTINGS

Figure 5 presents a pie chart that provides the proportions of the different type of settings seen in the TRW database at the overt point of first steering. Note that each one of these slices in the pie could have several scenarios associated with it depending on the relative motions of the vehicles.

The first setting considered in this paper (subject and lead vehicles only) occurred in 27% of the 1,603 lane-change events extracted from the TRW database. All lane-change events in the CAMP database were of this type. The second setting considered in this paper (subject and lead vehicles present with an adjacent following vehicle or adjacent overlapping vehicle and no other vehicles) occurred in 15% of the lane-change events.

An interesting and important result in the analysis of settings was that steering was initiated approximately 10% of time with an adjacent overlapping vehicle (AOV). Since there were no crashes in the data, we interpreted this to mean that these drivers anticipated the opening of a sufficient gap to permit the lane change.

Restrictions were placed on the lane changes studied for this analysis, resulting in cleaner, less ambiguous conclusions. In order for a lane change to be included in this feasibility study, the following conditions were true:

- There was a lead vehicle present, moving slower than the subject vehicle.
- The lead vehicle was traveling at an approximately constant speed.
- The subject vehicle's speed was 25 mph or greater.
- The subject vehicle was not braking near the overt initiation of steering.

DRIVING STATE BOUNDARY DEFINITIONS FOR A TWO-VEHICLE SCENARIO

This section presents information on the boundary conditions for the dynamic lane-change scenario involving two vehicles where the subject vehicle was following the lead vehicle under the criteria discussed in the previous section.

DRIVING STATE BOUNDARY BETWEEN LOW RISK AND CONFLICT

As part of the CAMP project described above, drivers were asked to make "last-second" steering judgments while approaching a lead vehicle. For one set of trials, drivers were asked to maintain their speed and change lanes at the last second they normally would to go around the target under "normal" steering instructions. For a subsequent set of trials, they were asked to change lanes at the last second they possibly could to avoid colliding with the target vehicle under "hard" steering instructions (2). The drivers were given these instructions for three separate car-following scenarios: (lead vehicle stopped, lead moving at a constant slower speed, and lead vehicle decelerating.)

For the CAMP scenario that most closely matched the lane-change scenario under consideration in this study, (lead vehicle moving at a constant, slower speed), data for a total of 212 "normal steering" trials and 165 "hard steering" trials met our study criteria.

Figure 6 presents the CAMP "normal steering" data and a linear regression line of the 50th-percentile (median) range values. The median range values were obtained by taking the median of the individual range points within a series of x-dot bins, each 8 kph (5 mph) wide. The median range values were then assigned to the middle of the x-dot bins.

The line in Figure 6 is offered as the boundary between the low risk and conflict driving states, which appears to be consistent with the instructions provided to the drivers in the CAMP study for "normal steering". Note that this is a straight line, and so is in keeping with the trend data discovered by TRW when they performed test track investigations of driver preferences to locate a conflict line with drivers approaching from the rear in an adjacent lane (4).

In other words, the authors propose that the (x, x-dot) values which 50% of the drivers in the trial considered to be the "last second" to use normal steering to avoid a collision could be regarded as the boundary between the low-risk state and the conflict state.

Figure 7 presents the x and x-dot values for lane changes in the naturalistic TRW database that match the two-car test track scenario. As can be noted from the figure, the naturalistic TRW lane-change events featured much lower closing rates than the CAMP last-second lane-change events. Here, the TRW data was grouped into x-dot bins each 0.6 meters per second wide (2 feet per second); the figure shows the 95th-percentile values for each of these bins (i.e., 95% of the lane changes were initiated at ranges above the value shown by the large solid triangles for the range rate of the bin). The authors propose that because this lane-change scenario (two vehicles) represents a fairly simple maneuver, most of the lane changes were made in the low risk driving state. *We further propose that the 95th-percentile values of range for naturalistic lane-change initiation correspond to and extend the trend of the 50th-percentile boundary between low-risk and conflict driving states for test track experiments on lane-change initiation, and that the 95th-percentile can be used to estimate the conflict threshold for natural (unforced) driving.*

DRIVING STATE BOUNDARY BETWEEN CONFLICT AND NEAR CRASH

Figure 8 presents the CAMP "hard steering" data and a linear regression line of the 50th-percentile (median) range values. Here again, the median values were obtained by taking the median of the individual range points within each 8 kph (5 mph) wide x-dot bin, and assigning the median to the middle of the x-dot bin.

The dark line in Figure 8 is presented as a representation of the boundary between the conflict and near-crash driving states, which appears to be in line with the instructions provided to the drivers in the CAMP study for "hard steering". *In other words, the authors propose that the (x, x-dot) values which 50% of the drivers in the trial considered to be the "last second" to use hard steering to avoid a collision could be regarded as the boundary between the conflict and the near-crash states.* The light gray line in Figure 8 is carried over for comparison from Figure 7 as the boundary between the low risk and conflict driving states.

DRIVING STATE BOUNDARY BETWEEN NEAR CRASH AND CRASH IMMINENT

In previous attempts to establish the boundary between near-crash and crash-imminent driving states for rear-end crash scenarios, simulation data was utilized (1). For lane-change maneuvers there was no similar database. The authors hypothesized, however, that if a relationship between the CAMP "hard" braking data and the simulator braking data could be found, we could extend this relationship to steering maneuvers.

Figure 9 presents the distribution of data at the onset of braking for ten subjects responding to a stopped lead vehicle in an Iowa Driving Simulator (IDS) experiment (1). The figure shows that the drivers who initially braked above the crash boundary were able to avoid the crash. Those who initially braked below the boundary crashed, or braked first then steered to avoid a likely crash. The curved line shown in Figure 9 divides the near-crash cases from the crash-imminent cases, which resulted in a simulated crash (1). Also included in Figure 9 is the CAMP "hard" braking data. As can be seen, all the points fall close to, but above, the boundary set by the IDS line. This relationship appears to indicate that the boundary between the near-crash and crash-imminent driving states is close to the test track 100th-percentile line of all trials.

Based on this result, Figure 10 shows the boundary between near-crash and crash-imminent driving states for steering maneuvers for the two-vehicle lane-change scenario. The boundary is based on the 100th-percentile of the CAMP "hard" steering data points. *In other words, the straight line connecting the lowest (x, x-dot) values recorded in the CAMP "hard" steering trials is our best approximation for the boundary dividing near-crash from crash-imminent states.* Also, shown for comparison in Figure 10 are the other boundary conditions from Figures 7 and 8.

COMPARISON OF THE TWO-VEHICLE AND THREE-VEHICLE LANE-CHANGE SCENARIOS

PRESENCE OF AN ADJACENT "INFLUENCING" VEHICLE

The two-vehicle scenario discussed in the previous section represents a fairly benign lane-change condition. That is, the subject vehicle had only to be concerned with the lead vehicle and could execute the lane-change maneuver with no conflict in the adjacent lane. The authors hypothesized that the presence of an adjacent vehicle could complicate the lane-change maneuver, at times forcing the subject vehicle to accept a more risky lane-change relationship to the lead vehicle.

To test this hypothesis, a comparison was made using on-road data between the two-vehicle scenario (SV and LV only) and a three-vehicle scenario that included the subject vehicle, the lead vehicle, and an adjacent "influencing" vehicle (AIV) in the adjacent lane. An "influencing" vehicle was defined as a vehicle located in the adjacent lane partly or wholly within a zone extending from 30 feet in front of the subject vehicle's front bumper to 30 feet in back of the subject vehicle's rear bumper at the overt, initial steering time. The same dynamic conditions (namely, SV speed greater than 25 mph, LV traveling at constant slower speed, and SV not decelerating prior to the overt point) were in effect.

It is important to note that because of the relative velocities of the subject and adjacent vehicles, an AIV may end up either behind or in front of the subject vehicle by the time the subject has crossed into the adjacent lane. However, we focused our attention on those cases where the SV passes between the lead and adjacent vehicle.

Figure 11 shows the result of this investigation. The small hollow triangles show the x and x-dot values for the gap between the SV and the LV at the initiation of the lane change for the cases when there is no AIV. The large solid triangles indicate the median (Figure 11a) and 95th-percentile (Figure 11b) value of x for each x-dot bin. The small gray diamonds indicate the x and x-dot values for the gap between the SV and the LV at the initiation of the lane change for the cases when an adjacent influencing vehicle is present. The large diamonds indicate the median (Figure 11a) and 95th-percentile (Figure 11b) values for each x-dot bin. Note that the large diamonds are consistently lower than the large triangles for each x-dot bin. In other words, for each given x-dot value between an SV and its LV, the median and 95th-percentile x values (the longitudinal distances) are less at initial steering when an AIV is present than when there is no AIV present. This result supports the hypothesis that the presence of an AIV influences SV drivers to accept a riskier lane change with respect to the LV (approaching it closer) than they would otherwise.

RELATIONSHIP TO AN ADJACENT FOLLOWING OR OVERLAPPING VEHICLE

The previous analysis investigated whether the presence of a vehicle in the adjacent lane affects the SV's relationship to the LV at the moment the lane change begins. The next analysis looks more closely at the role of the adjacent vehicle, and the relationship of the SV to it, both at the initiation of the lane change (overt point) and the time it crosses into the adjacent lane (the crossover point).

In order to keep the analysis as clean as possible, the following conditions had to be true in order for the lane change to be included:

- There was a lead vehicle present, moving at a nearly constant speed, which was less than the speed of the subject vehicle.
- The subject vehicle was moving at 25 mph or faster at the overt point.
- The subject vehicle had not begun to decelerate at the overt point.
- In the adjacent lane at the overt point, there was either:
    - a following vehicle (AFV) or
    - an overlapping vehicle (AOV) that was moving more slowly than the subject vehicle.

Most of the AFVs and AOVs observed in the database were in fact traveling more slowly than the SV. This is not surprising, since, typically, a lane change was made by a vehicle moving faster than the surrounding traffic, including both the LV and the AOV or AFV.

Figure 12a depicts two gaps:

1. Between the SV and LV at the overt point (hollow triangles)
2. Between the SV and AFV or AOV at overt point (solid circles)

The following observations about inter-vehicle relationships at the overt point are illustrated by Figure 12a:

- The x-range from the front bumper of the SV to the tail bumper of the LV is always positive. This x-range varied from 6 meters to 38 meters.
- The x-closing rate between the SV and LV is usually negative, i.e. the SV is overtaking the LV, as expected.
- The x-range from the back bumper of the SV to the front bumper of an AFV is positive. In most cases, the SV is moving faster than the AFV (x-dot is positive). However, there were five cases where an AFV was moving faster than the SV at the overt point.
- If the x-range from the back bumper of the SV to the front bumper of an adjacent vehicle at the overt point is between 0 and -10 meters, that other vehicle is an AOV. It is not uncommon for the SV to begin a lane change when there is an AOV alongside the SV in the adjacent lane. Note that a proximity warning system would be lit in all of these cases, yet drivers routinely perform this maneuver in lane changes.

Figure 12b depicts the inter-vehicle relationships between the same pairs of vehicles at the crossover point. At the crossover point, the SV is no longer in danger of collision with the LV, but becomes in danger of a sideswipe with any adjacent vehicle. Note the following observations in comparison to Figure 12a:

- As a group, the host of hollow triangles with negative x-dot has moved downward. In other words, the x-distance from the front bumper of the SV to the tail bumper of the LV has decreased. This is to be expected, since in most cases the SV is moving faster than the LV.
- As a group, the host of solid circles with positive x-dot has moved upward. In other words, the x-distance from the rear bumper of the SV to the front bumper of the AFV has increased. This is also to be expected, since in most cases the SV is moving faster than the AFV or AOV.
- There are two solid circles below the x=0 axis; what are these? The lower point (x=-21 meters) is a case where an AFV wound up not behind the SV but in front of it. Although the AFV was behind the SV at the overt point, it was moving faster than the SV, and was ahead of the SV by the time the SV reached the crossover point. The other point (x=-2 meters) was the case of a lane change that compelled the AOV to move over another lane to avoid a collision. When the SV reached the crossover point, the AOV had already moved partway into the next lane. This explanation was determined by watching the video collected during the TRW experiment.
- With the exception of these two cases, whatever the x-range was between the SV and either the LV or the AOV at the overt point, there appears to be a minimum range at the crossover point – the point which really matters as far as avoiding a collision. This minimum range is approximately 4 meters (one car length).

The important conclusions suggested by Figure 12b are as follows:

- *There appears to be a minimum value of gap at the crossover time between the SV and the LV and between the SV and the AFV that is accepted by the drivers in this naturalistic driving database. This* *minimum gap appears to be about 4 meters and doesn't seem to depend on relative speed.*

- *The x-range between the SV and a vehicle in the adjacent lane at the initial overt steering time could be any value. Looking only at this overt point x-range is not a good method for estimating the risk or crash potential of a lane-change event. This is the case with proximity-only warning systems.*
- The relative position and velocity of the vehicles at the crossover point determine whether or not there will be a collision and we think this is what the drivers anticipate when they initiate the lane-change maneuver.

SIZE OF THE GAP BETWEEN LEAD VEHICLE AND ADJACENT FOLLOWING VEHICLE

Another way to analyze the scenario described in the previous section is to look at the size of the longitudinal gap between the LV and the adjacent vehicle (AFV or AOV), since this could also be the gap that the lane-change driver is accepting or rejecting. If this gap is closing, (the x-dot between the LV and the AFV or AOV is negative), then the SV must initiate the lane change at a time when the anticipated gap at the crossover is acceptably large, or else postpone the lane-change maneuver until a more acceptable time.

Figure 13 shows the x-range and the x-dot between the LV and the AFV or AOV for the same cases as the previous analysis (except that the two previously described special cases have not been included). The hollow squares show the x-range and the x-dot at the overt time, and the solid diamonds show the x-range and x-dot at the crossover time.

The observations from Figure 13 are as follows:

- As observed in Figure 12b, the points with negative x-dot decrease in x-range between the overt point and the crossover point, and the points with positive x-dot increase in x-range between the overt point and the crossover point.
- The x-range and x-dot points are clustered closer together at the crossover point than at the overt point, suggesting that the anticipated situation at the crossover point is used by drivers to select the initiation of a lane-change maneuver rather than the situation at the overt point.
- As observed in Figure 12b, there appears to be a minimum value of gap between the LV and the AFV or AOV. This minimum value is between 10 and 16 meters, or approximately one car length ahead of and behind the SV.

CONCLUSIONS

This paper has been concerned with the feasibility of using four driving states to map lane-change performance. Data from previous test track and on-road studies were analyzed to identify likely boundaries for these states and, in fact, consistent performance maps have been found in modeling lane-change performance as were found earlier for mapping car-following performance. This is very encouraging and suggests that a fundamental model for driving performance based on these concepts may be forthcoming.

An interesting result was that proximity-only warnings are likely to have previously unforeseen nuisance effects because drivers often start lane changes when there is another vehicle in the adjacent proximity area as they seem to anticipate longitudinal gap opening and closing.

However, a surprising result was the success of relative longitudinal measures like x (longitudinal range or longitudinal gap) to adequately map steering maneuver onset and completion for various severity levels. Our initial models assumed that lateral kinematic measures would also be needed, but we did not find this to be true so far. This result is perhaps embedded in the widely held idea that coupled lane-change and rear-end conflicts are often found in driving scenarios, and in the crash record. Moreover, this result should have some impact on how rear-end crash warning and lane-change driving aids are further developed, integrated, and evaluated.

As we found earlier in the car-following data analyses, we found here again a consistency between the test track experiments and the on-road performance analyses. Here, the 50th-percentile in test track experiments of normal last-second performance agrees well with the 95th-percentile in on-road data to define the onset of lane-change conflict.

FUTURE STUDY

The observations of the previous sections present promising possibilities for further analysis of existing data and directed acquisition of new data. Among the follow-up studies planned are:

- Determine the most common lane-change scenarios. These must be determined from the crash record and from on-road naturalistic driving studies. The former will help to inform effectiveness evaluations and the latter will help to understand nuisance warning conditions – both are important for warning systems design and evaluation.
- Perform future experiments to collect information in the scenarios of greatest interest for defining the state boundaries. The present study only examined a couple of these scenarios and likely boundaries were found in both cases. However, we found that the presence of an immediately adjacent vehicle does influence the gap acceptance of on-road drivers, so we can expect variance between the boundaries in different scenarios.

- Investigate how an automated lane-change warning or advisory should perform. The prior work by TRW considered a countermeasure that computed and analyzed the SV-AFV gap, and advised the driver only if a conflict was present, or would soon be. But the above results indicate a need to also consider the gap between the LV and the AFV, and suggest the possibility that several levels of lane-change danger need to be considered simultaneously with car-following danger. Forward and lane-change crash countermeasures should be integrated for best effectiveness.

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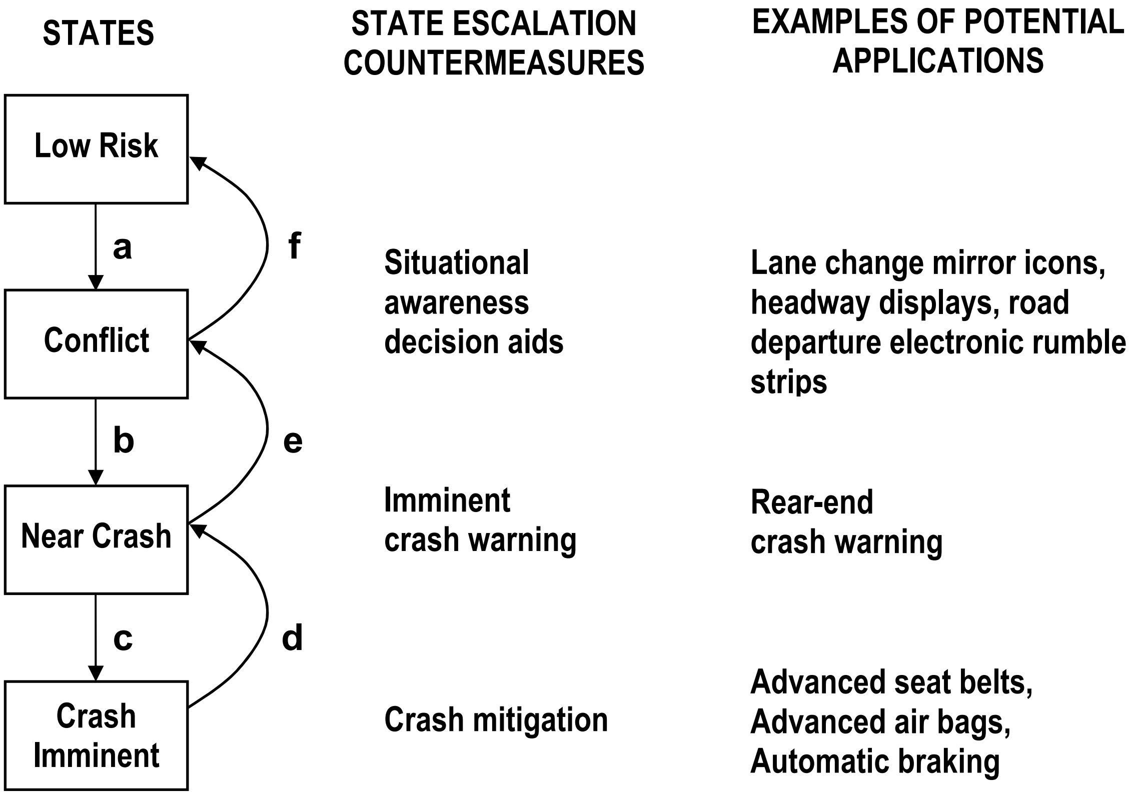


Figure 1. The Four Driving States and Their Applications

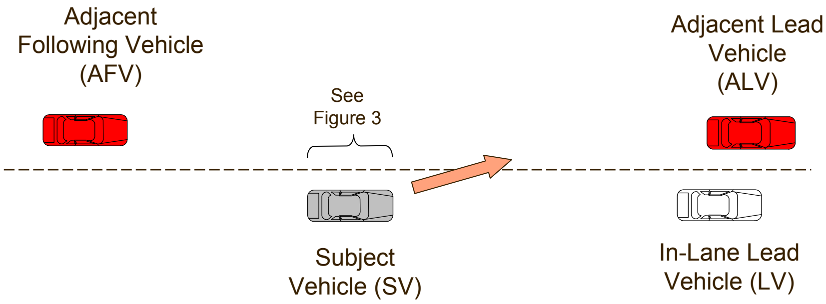


Figure 2. Lane-change Scenarios: Surrounding Vehicle Terminology

A vehicle in the adjacent lane that is overlapping the subject vehicle in longitudinal position will be called an **Adjacent Overlapping Vehicle** (**AOV**).

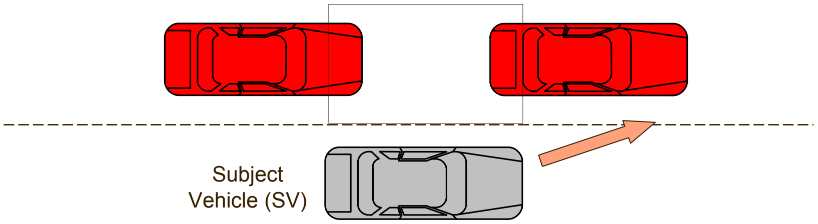


Figure 3. Adjacent Overlapping Vehicle (AOV)

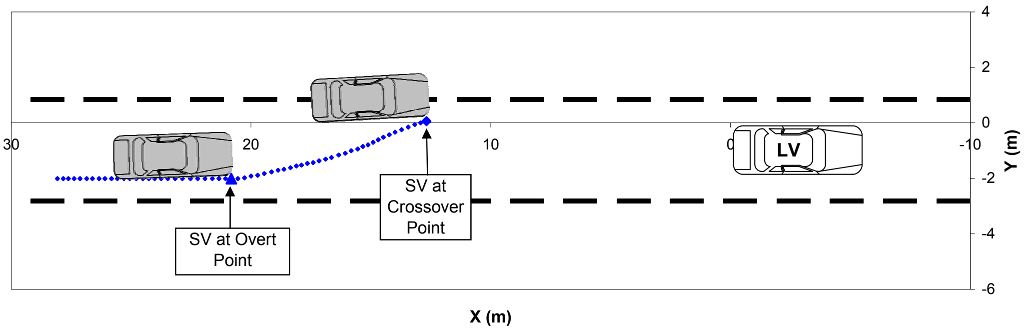


Figure 4. Example showing SV Position (with respect to LV) at Overt and Crossover Points

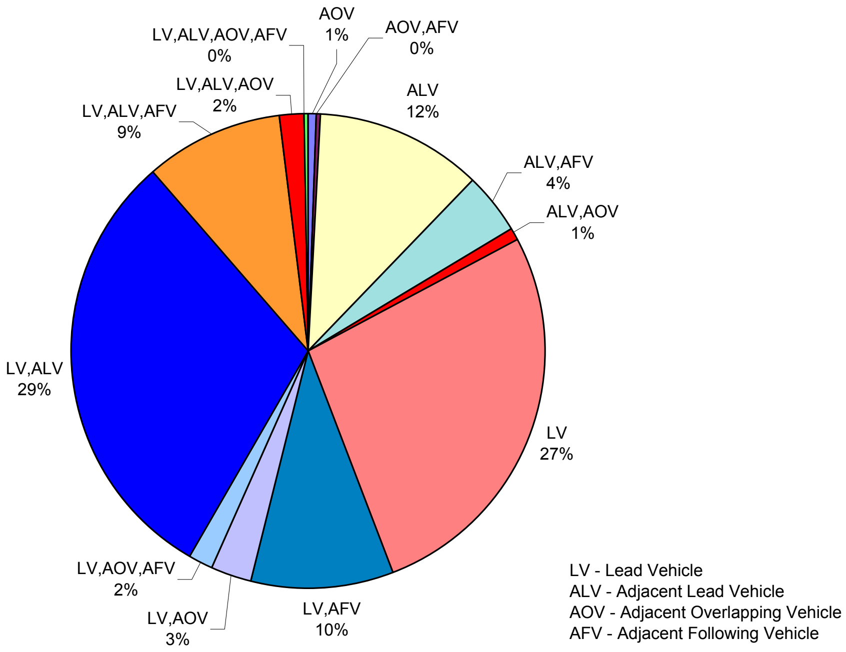


Figure 5. Settings at Overt Point – TRW Numeric Analysis

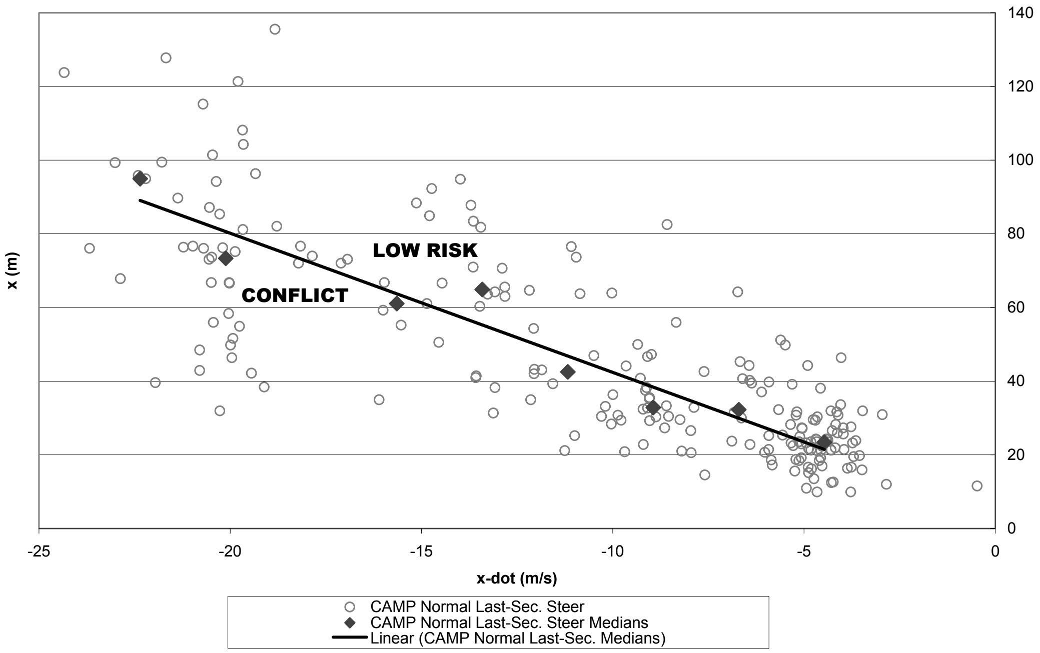


Figure 6. Low Risk and Conflict Boundary using CAMP Normal Last-Second Steer

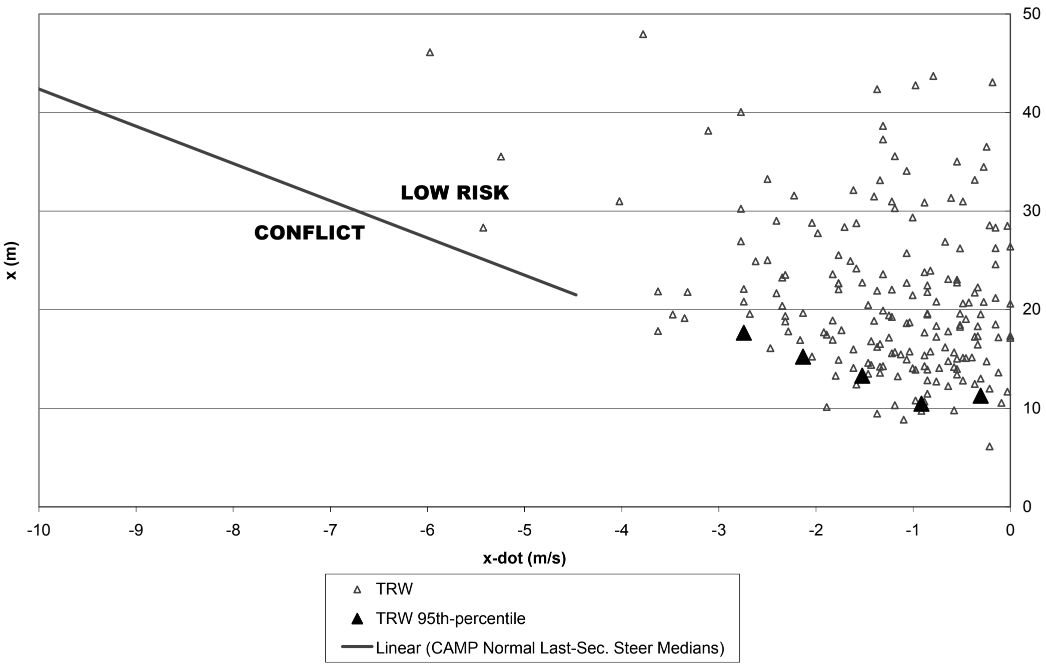


Figure 7. Comparison of Test Track and On-Road Steering Data

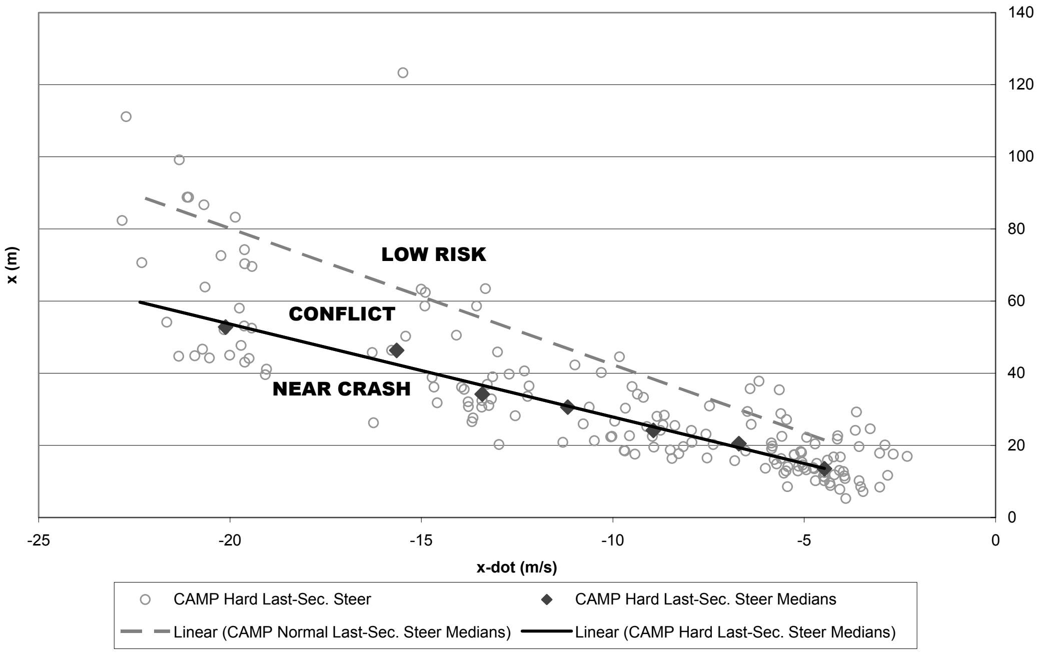


Figure 8. Conflict and Near Crash Boundary using CAMP Hard Last-Second Steer

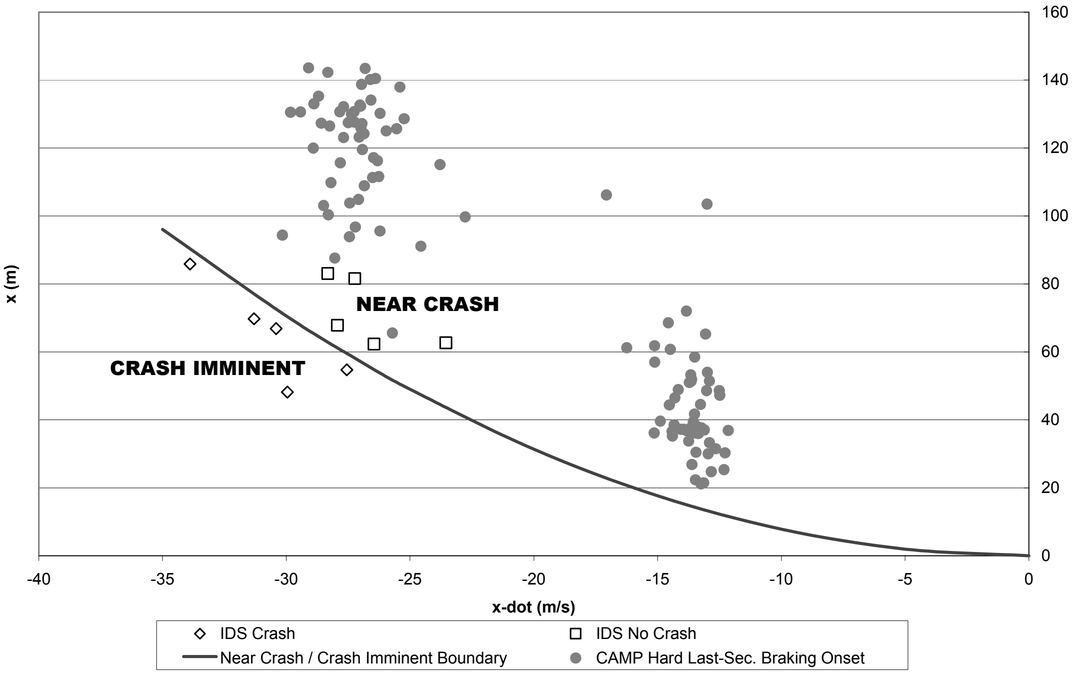


Figure 9. Comparison of IDS Crash / No-Crash Data with CAMP Hard Last-Second Braking

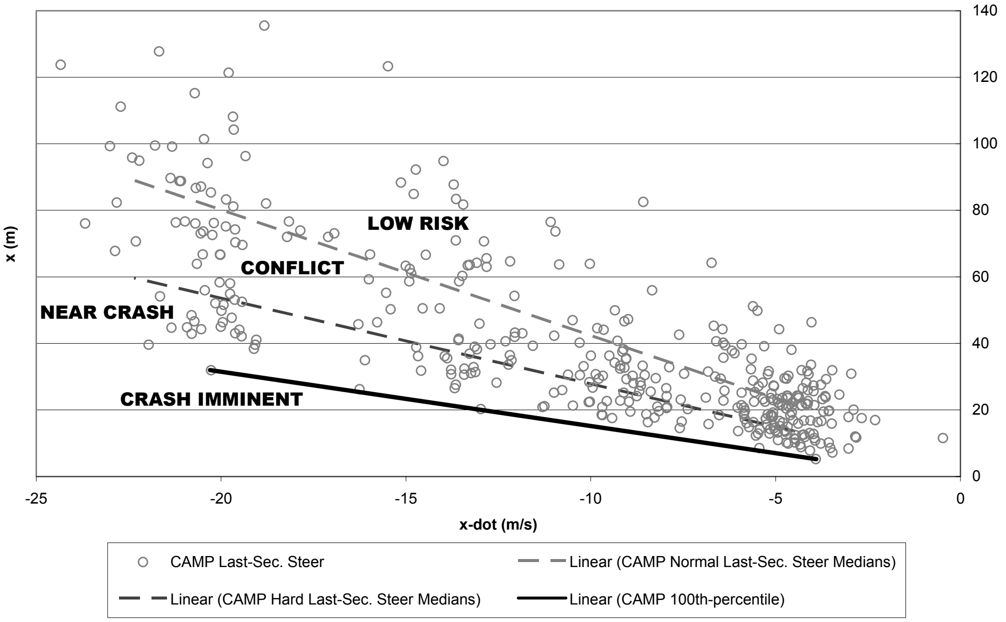
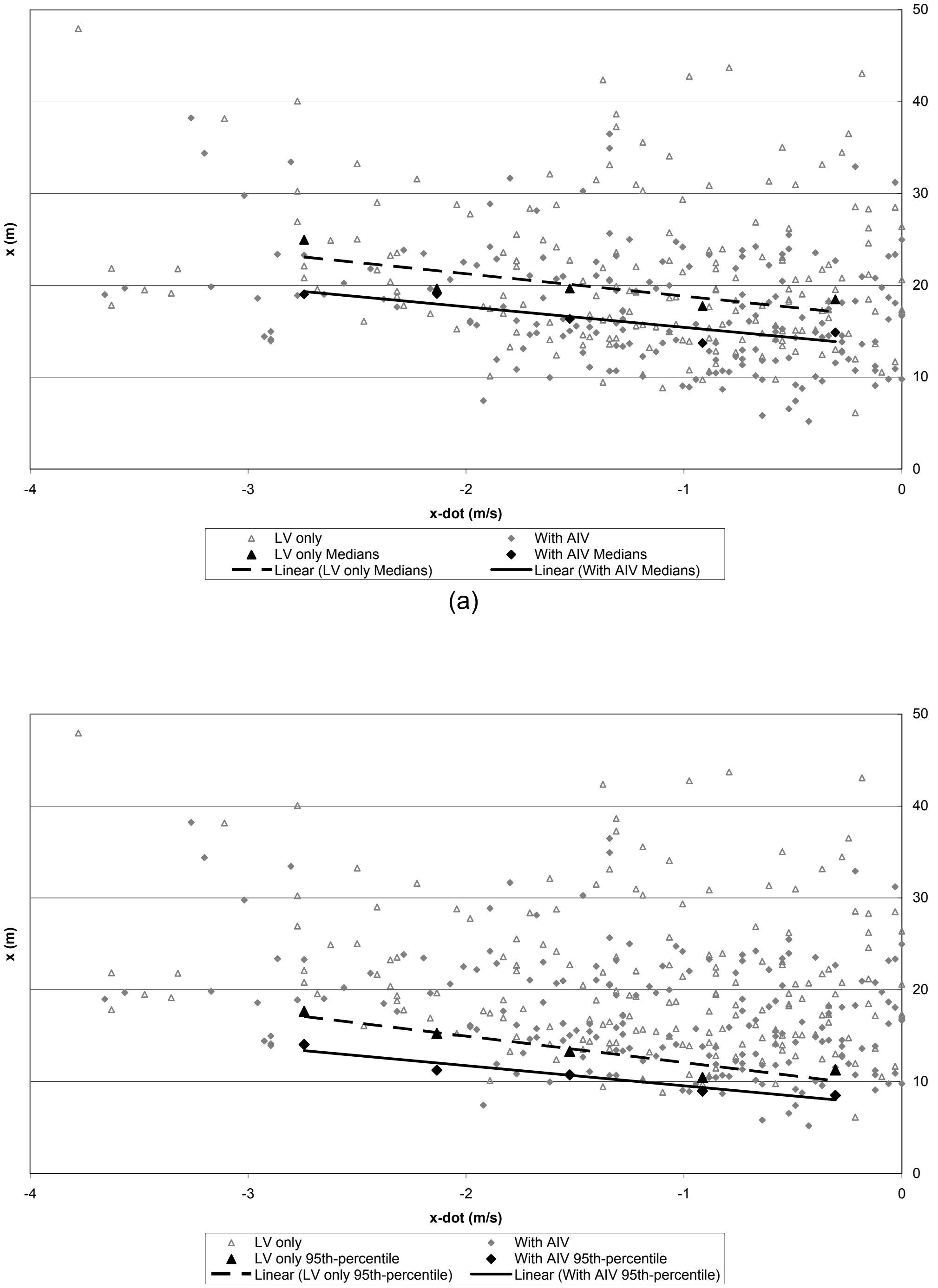


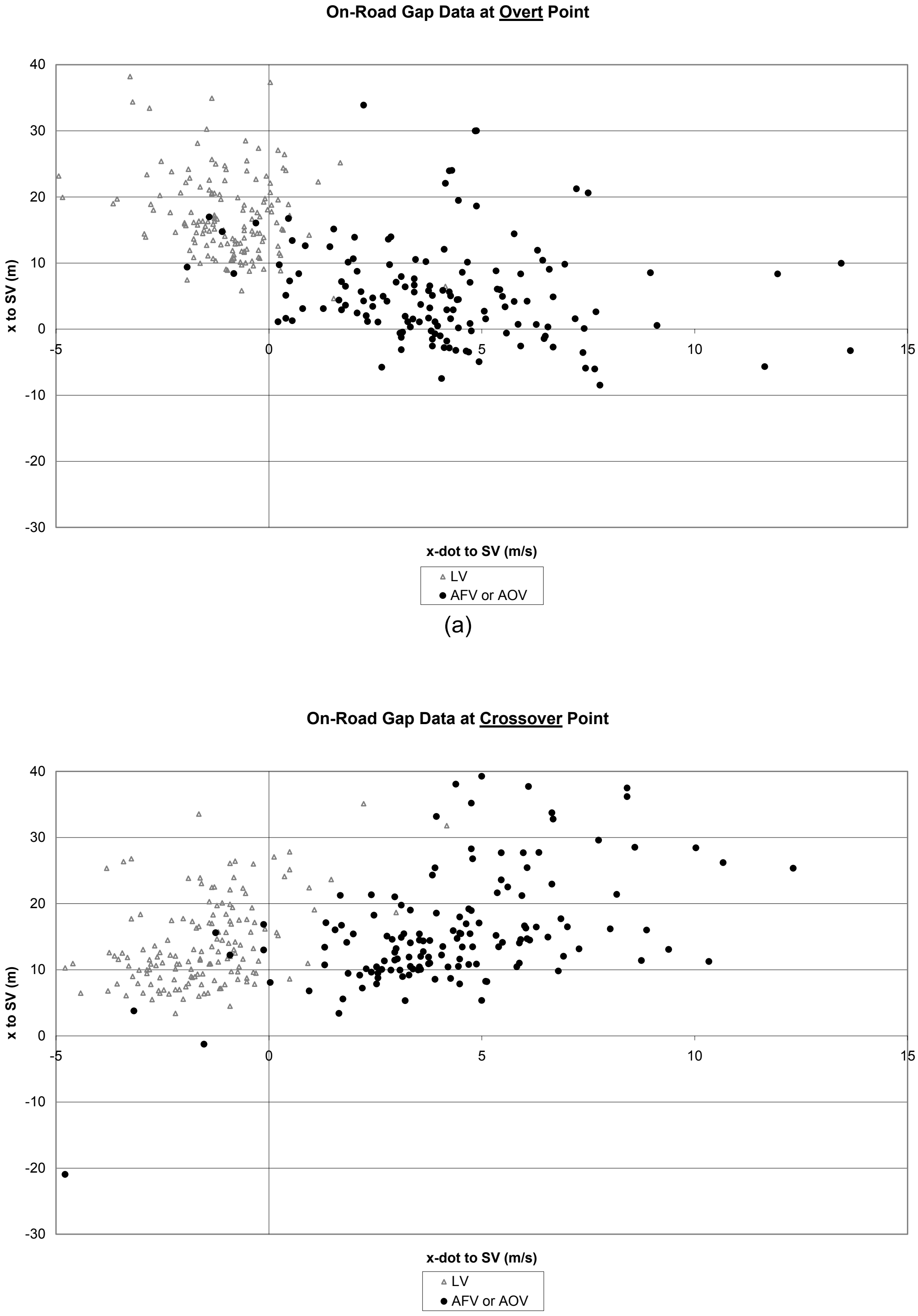
Figure 10. Near Crash and Crash Imminent Boundary using CAMP Steering 100th-percentile



(a)

(b)

Figure 11. Comparison of (a) Median and (b) 95th-percentile On-Road SV-LV Gap at Overt Point



(a)

(b)

Figure 12. TRW Cases at (a) Overt Point and (b) Crossover Point with a LV and either an AFV or a slower AOV

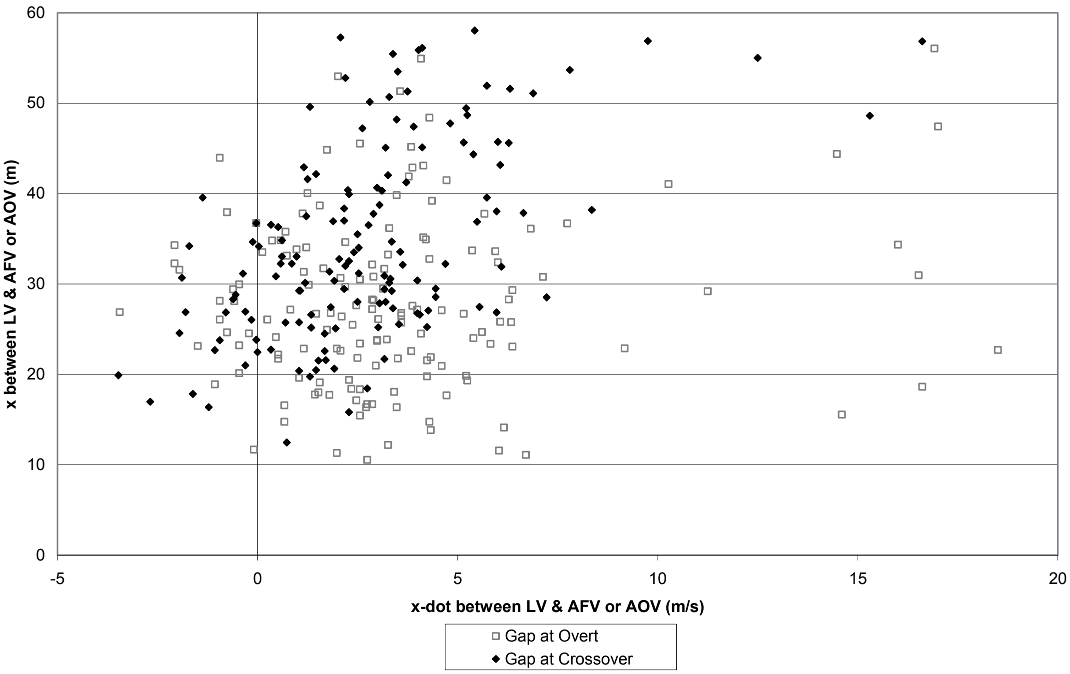


Figure 13. On-Road Gap between LV and Adjacent Vehicle