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Analysis of Braking and Steering Performance in Car-Following Scenarios

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ABSTRACT

This paper presents recent results of on-going research to build new maps of driver performance in car-following situations. The novel performance map is comprised of four driving states: low risk, conflict, near crash, and crash imminent – which correspond to advisory warning, crash imminent warning, and crash mitigation countermeasures. The paper addresses two questions dealing with the approach to quantify the boundaries between the driving states: (1) Do the quantified boundaries strongly depend on the dynamic scenario encountered in the driving environment? and (2) Do the quantified boundaries vary between steering and braking driver responses? Specifically, braking and steering driver performances are examined in two car-following scenarios: lead vehicle stopped and lead vehicle moving at lower constant speed. The analysis was conducted on experimental data collected from test track studies to develop a fundamental understanding of drivers' last-second braking and steering performance. The results of last-second braking performance analysis showed that the quantified boundaries depend on the dynamic scenario. On the other hand, the quantified boundaries were independent of the specific dynamic scenario based on the analysis of last-second steering performance. Finally, the quantified boundaries varied between braking and steering responses since drivers initiated last-second braking maneuvers at generally longer distances than last-second steering maneuvers.

INTRODUCTION

The Intelligent Vehicle Initiative of the United States Department of Transportation has sponsored a number of research projects that support the development and deployment of various crash avoidance systems. This research has created many databases on driver performance in such varied media as test tracks, simulators, naturalistic on-road experiments, and field operational tests. A driver performance map has been proposed to fit these disparate data sources together into a single database in order to broadly characterize driver performance [1]. Four driving states – low risk, conflict, near crash, and crash imminent – form the structure of such a map as shown in Figure 1. This structure will support the development of safety-effective crash countermeasure systems that assist drivers via advisory, crash imminent warning, automatic vehicle control, and crash injury mitigation functions.

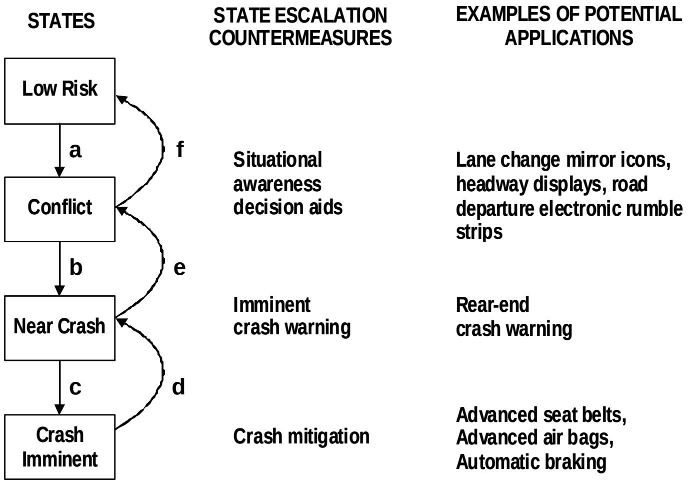


Figure 1. Driving States and Corresponding Crash Countermeasures.

Our approach to implement this performance map is to use data from controlled experiments on test tracks to quantify the transitions between the low risk driving state and the conflict state, and between the conflict state and the near crash state. The boundary between the near crash state and the crash imminent state comes from driving simulator data. The power of this approach rests in its ability to quantitatively match driver expectations with performance for the four driving states, which can then be used to evaluate proposed crash countermeasures, develop insights for new countermeasures, easily identify performance data gaps, and guide experimental design in any media so that results from disparate media and databases will fit together.

In past studies, traffic and highway engineers did not make a clear distinction between a traffic conflict and a near crash event in their application of traffic conflict techniques. The quantification of conflicts or near crashes was based on either the intensity of the evasive maneuver taken by the driver or some time-based measures [2]. A popular time-based measure has been the time-to-collision (TTC) defined as "the time required for two vehicles to collide if they continue at their present speed and on the same path" [3]. Most previous traffic conflict studies were limited to very few sites (high-conflict intersections), where roadside observers judged the driving conflict or near crash. This is contrasted with the present work, where the levels of driving states are based on the drivers' opinions as expressed in their braking or steering performance, albeit with the authors' interpretations.

The feasibility of the performance map structure shown in Figure 1 was previously investigated for the driving problem of a lead vehicle stopped in the lane ahead [1]. That feasibility study found that the driving state transitions could be reliably quantified and used to create a useful crash avoidance database. The usefulness and reliability of these transitions were analyzed by comparing data from an on-road naturalistic driving study to data from the controlled experiments. This paper addresses the following two questions that arose from the previous research effort:

1. Do the quantified boundaries of the driving states strongly depend on the dynamic scenario encountered in the driving environment?
2. Do the quantified boundaries vary between steering and braking driver responses?

Specifically, this paper examines braking and steering driver performance in two car-following scenarios. One scenario depicts a following vehicle, traveling at constant speed, which encounters a lead vehicle stopped ahead. The other scenario portrays a following vehicle, traveling at constant speed, which approaches a lead vehicle moving at lower constant speed. These two scenarios preceded about 40% of the 1,806,000 police-reported rear-end crashes in the United States, which involved light vehicles (passenger vehicles, sports utility vehicles, vans, and pickup trucks) based on the 2000 *National Automotive Sampling System/General Estimates System* crash database [4].

Our analysis assumes that *initial* braking or steering onset indicates when drivers judge the start of the event as they followed "last-second maneuver" instructions. That is, our methodology utilizes performance data gathered from test-track controlled studies in which subjects were instructed to wait to conduct a maneuver (brake or steer) at the last possible moment in order to avoid colliding with a vehicle ahead using normal or hard intensity. Thus, drivers indicated their sense of "conflict" onset through last-second normal intensity maneuvers, and they showed their sense of "near crash" onset through last-second hard intensity maneuvers. Eventually, it will be necessary to establish standardized quantifications for the driving state boundaries, though this was determined to be beyond the scope of this current work. Instead, this paper focuses on using the existing driver performance databases to roughly estimate and assess the quantified boundaries in the two car-following scenarios based on braking and steering maneuvers.

The analysis of braking performance in the two car-following scenarios is discussed next, and is followed by the results from the examination of the steering performance. Afterwards, the paper compares the results between braking and steering maneuvers, and discusses the application of driving state boundaries to the development of crash avoidance systems. Finally, the paper concludes with a summary of overall results and future research steps to build the proposed driver performance map for rear-end crash avoidance research.

ANALYSIS OF LAST-SECOND BRAKING PERFORMANCE

DESCRIPTION OF LAST-SECOND BRAKING PERFORMANCE DATA

The GM-Ford Crash Avoidance Metrics Partnership (CAMP) collected data sets from test track studies to develop a fundamental understanding of drivers' last-second braking performance so that drivers' perceptions could be properly identified and modeled for collision warning system crash alert timing purposes [5,6]. CAMP generated data from 4,326 last-second maneuver trials conducted in two separate studies, including 3,536 last-second braking judgment trials. The first study collected braking judgment data from 2,580 trials in response to lead vehicle stopped (LVS) and lead vehicle decelerating driving scenarios [5]. The second study obtained additional data from 956 trials that involved last-second braking response to lead vehicle stopped, lead vehicle moving at lower constant speed (LVM), and lead vehicle decelerating ahead [6]. As mentioned earlier, this paper covers the analysis of data collected in response to the first two car-following scenarios.

The first braking study employed 108 subjects split evenly by gender and three different age groups (20-30, 40-51, and 60-71 years old). Test participants were asked to make last-second braking judgments to a decelerating or stopped surrogate lead vehicle that towed a 3-dimensional mock-up of the rear-end of a 1997 Mercury Sable with working brake lights shown in Figure 2. Data were gathered on a straight, level, smooth asphalt road at a test track under daytime conditions on generally dry road and in dry weather. Subjects were asked to wait to apply the brakes at the last possible moment in order to avoid colliding with the surrogate target, utilizing "normal braking" and "hard braking" instructions. Drivers were discouraged from "second-guessing" and correcting their initial braking onset judgment by releasing brake pressure, because the interest here is when drivers *perceive* the need to begin braking. During the LVS trials, subjects were asked to approach the parked vehicle at an instructed speed of 13, 20, or 27 m/s (30, 45, or 60 mph).

Figure 2. CAMP's Test Methodology Using a Surrogate Target Vehicle [5].

The second braking study recruited 72 participants from three age groups identical to the first study, split evenly by gender. All testing was conducted during dry road, daytime conditions, which involved a lead vehicle either stopped, moving at lower constant speed, or decelerating to a stop. All subjects performed last-second braking maneuvers in these three scenarios. The following vehicle was always approaching the lead vehicle at a constant speed prior to last-second maneuver. For the LVS trials, the following vehicle approached the lead vehicle at 13 or 27 m/s. For the LVM trials, the following vehicle/lead vehicle speed combinations examined were 13/9, 13/4, 27/22, 27/13, and 27/7 m/s (30/20, 30/10, 60/50, 60/30, and 60/15 mph). Drivers performed last-second braking maneuvers using "normal braking" and "hard braking" instructions.

The data were first separated into 2.2 m/s (5 mph) bins in range-rate and the 50th percentile (50%-ile) of the range values for that data set was computed for each bin that had more than 10 data points. Bins with less than 10 data points were not used. The binning of data by range rate allows us to examine and characterize the statistical distribution (mean, median, variance, and type) of driver behavior under separate initial conditions in each driving scenario. The 50%-ile range value was attributed to the mid-bin value for range rate. The 50%-ile statistic was used in this analysis because the bin "average" or a simple fit to the cloud of data was assumed to give too much weight to the outlying range values. This approach was used on all data analyses performed for this paper.

BRAKING RESPONSE IN LEAD VEHICLE STOPPED SCENARIO

In this scenario, the following vehicle approaches a lead vehicle stopped in the lane ahead from a considerable distance, at a travel speed that remains constant until the onset of braking. The constant travel speed then characterizes the initial condition of the LVS scenario. Even though subjects were instructed to drive at three different speed conditions (13, 20, or 27 m/s), we discerned six actual travel speeds in the "normal braking" instruction and seven speeds in the "hard braking" instruction ranging from 13 to 29 m/s. Each of these speeds was maintained by at least 10 subjects until braking began. The last-second "normal braking" and "hard braking" trials contained 344 and 367 data points, respectively.

Figure 3 illustrates approximations of the 50%-ile statistics of the last-second "normal braking" and "hard braking" trials. These approximations were modeled using second order polynomial equations to fit the 50%-ile points from each bin. *Microsoft Excel* software was utilized to generate the following equations that provide rough estimates of the boundaries between the low risk and conflict driving states, and between the conflict and near crash driving states, respectively:

$$R = 0.04 \times Rdot^2 - 4.22 \times Rdot + 2 \qquad \textbf{(1a)}$$

$$R = 0.10 \times Rdot^2 - 1.35 \times Rdot + 2 \qquad \textbf{(1b)}$$

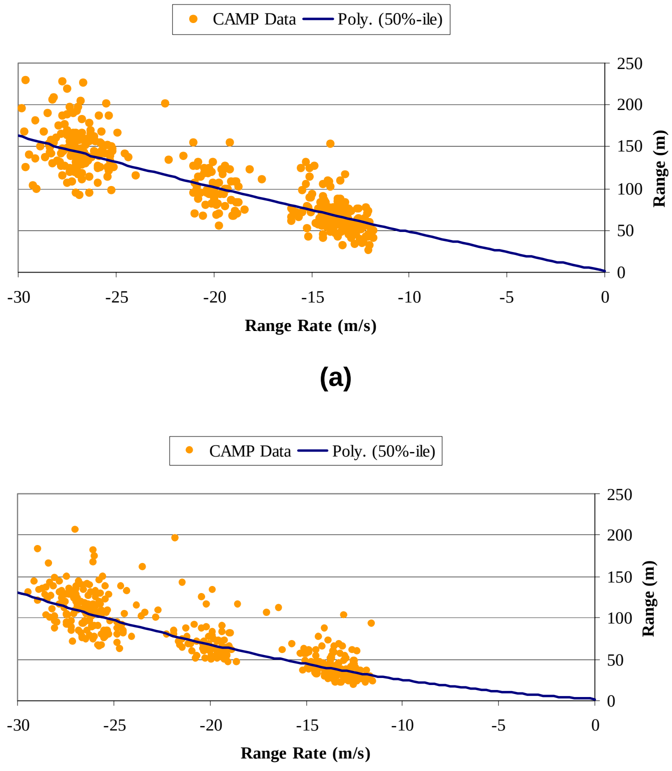
The parameter R (m) refers to the range or distance between the front of the following vehicle and the rear of the lead vehicle. The parameter Rdot (m/s) denotes the range rate or the difference between the speed of the lead vehicle and the speed of the following vehicle. Equations **(1a)** and **(1b)** extended the CAMP data to include the point R= 2 m at Rdot= 0 m/s, taking into consideration that the following vehicle comes to a stop behind a stationary vehicle at a distance equivalent to half the length of a small-size vehicle. This distance was observed from a sample of data collected in a naturalistic driving study that observed the behavior of following vehicles as they reacted to an instrumented vehicle that is either moving very slowly or is stopped [1,7]. The mapping of CAMP normal braking data to Equation (**1a**) and hard braking data to Equation (**1b**) resulted respectively in 48% and 47% of the subjects initiating their braking maneuver "over" the curve in the LVS scenario as depicted in Figure 3. By comparison, 43% of normal braking points and 40% of hard braking points were mapped "over" the curves derived from data fitting without binning.

The average deceleration exerted by the following vehicle, a_F (m/s^2), to come to a stop is expressed by:

$$a_F = \frac{Rdot_B^{\ 2}}{2 \times (R_B - R_f)} \qquad \textbf{(2)}$$

The parameter $Rdot_B$= -v_{F0} (m/s), where v_{F0} denotes the initial speed of the following vehicle prior to braking. R_B

(m) and R_f (m) indicate the braking onset range and the final range at the end of the braking event, respectively. The application of Equation **(2)** to Equations **(1a)** and **(1b)** shows that drivers exert higher deceleration levels when traveling at faster speeds. Moreover, the “hard braking” deceleration levels are larger than the “normal braking” levels. The 50%-ile average deceleration values vary from 0.16g to 0.3g and from 0.24g to 0.37g (g= 9.81 m/s^2) respectively in “normal braking” and “hard braking” conditions, as the travel speed increases from 13 to 29 m/s.



(a)

(b)

Figure 3. (a) Normal and (b) Hard Last-Second Braking Performance in Lead Vehicle Stopped Scenario.

BRAKING RESPONSE IN LEAD VEHICLE MOVING AT LOWER CONSTANT SPEED SCENARIO

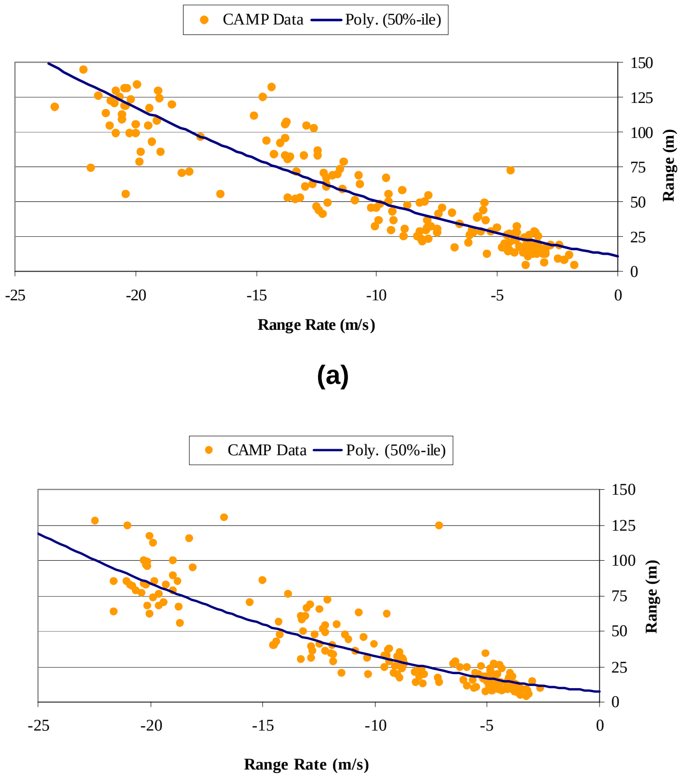
In this scenario, the following vehicle approaches the lead vehicle at a higher speed from a considerable distance, both traveling at a constant speed. The closing speed remains constant until the following vehicle begins to brake. The constant travel speeds of the following vehicle and lead vehicle (or, more simply, the constant closing speed) portray the initial conditions of this scenario. The analysis of braking performance in the LVM scenario was conducted on last-second data gathered from 164 “normal braking” trials and 151 “hard braking” trials.

Figure 4 illustrates approximations of the bin 50%-ile statistics of the last-second “normal braking” and “hard braking” LVM trials, modeled by second order polynomial equations respectively as follows:

$$R = 0.14\times Rdot^2 - 2.54\times Rdot + 11 \qquad \textbf{(3a)}$$

$$R = 0.13\times Rdot^2 - 1.21\times Rdot + 7.5 \qquad \textbf{(3b)}$$

Equations **(3a)** and **(3b)** took into account that the following vehicle slows down to the speed of the lead vehicle (Rdot= 0) at a distance of 11 m and 7.5 m, respectively, representing the 50%-ile values of all data points collected by CAMP in the “normal braking” and “hard braking” conditions. The mapping of CAMP normal braking data to Equation (**3a**) and hard braking data to Equation (**3b**) resulted respectively in 39% and 44% of the subjects initiating their braking maneuver “over” the curve in the LVM scenario as shown in Figure 4. By comparison, 40% of normal braking points and 37% of hard braking points were mapped “over” the curves derived from data fitting without binning.



(a)

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Figure 4. (a) Normal and (b) Hard Last-Second Braking Performance in Lead Vehicle Moving at Lower Constant Speed Scenario.

Equation **(2)** can be used to compute the average deceleration exerted by the following vehicle to slow down to the speed of the lead vehicle, v_L ($Rdot_B = v_L - v_{F0}$). The results show that drivers of the following vehicle exert higher deceleration levels at faster closing speeds. The 50%-ile average deceleration values range from 0.12g to 0.2g and from 0.17g to 0.27g respectively in the last-second "normal braking" and "hard braking" conditions as the closing speed climbs from 3 to 20 m/s.

DISCUSSION OF LAST-SECOND BRAKING PERFORMANCE

The analysis of braking performance revealed that drivers were generally less aggressive in the LVM scenario than in the LVS scenario as shown in Figure 5, based on measures of R_B and a_F. Perhaps, drivers prefer to initiate braking earlier to match the speed of the lead vehicle at a "comfortable" following distance. The values of R, representing the boundary between the low risk and conflict driving states, are larger in the LVM scenario than in the LVS scenario when controlling for the range rate. One-tailed t-tests conducted on the means of LVM and LVS normal braking data in the –13 m/s and –20 m/s bins produced a P-value of about 0.004 in both cases, indicating that the difference between the two scenarios is significant at lower than the 0.01 level. The boundary between the conflict and near crash driving states in the LVM scenario is also higher than the LVS scenario for all range rate values. This difference is also statistically significant based on similar t-tests. Thus, the quantified boundaries between the low risk and conflict driving states, and between the conflict and near crash states, depend on the dynamic scenario encountered in the driving environment when drivers respond by braking only.

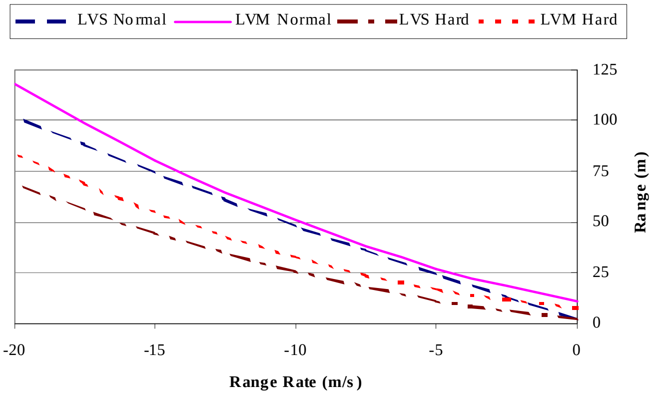


Figure 5. Comparison of Last-Second Braking Performance between Scenarios Based on 50%-ile Statistics.

ANALYSIS OF LAST-SECOND STEERING PERFORMANCE

DESCRIPTION OF LAST-SECOND STEERING PERFORMANCE DATA

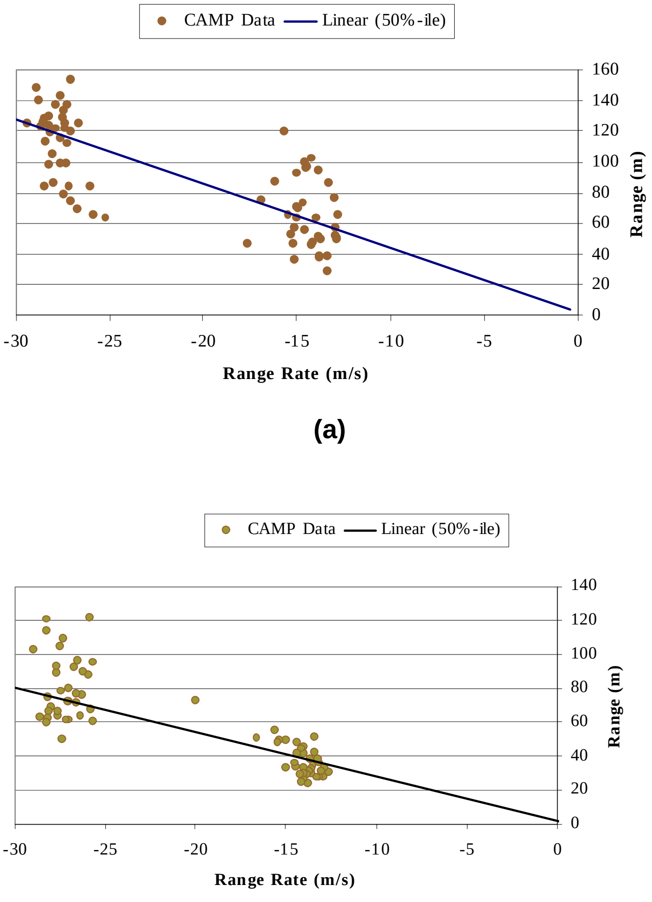
A total of 503 last-second steering judgment trials were analyzed from CAMP's original data sets that were collected during the second test track study as previously described in this paper [4]. These trials consisted of 130 LVS trials and 373 LVM trials. Similar to last-second braking instructions, 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, and change lanes at the last second they *possibly could to avoid colliding with the target* under "hard" steering instructions.

STEERING RESPONSE IN LEAD VEHICLE STOPPED SCENARIO

The analysis of steering performance in this scenario was conducted on data gathered from 69 "normal steering " trials and 61 "hard steering" trials. Linear approximation was the best fit for the 50%-ile values from each data bin, under "normal" and "hard" steering instructions. Figure 6 shows approximations of the last-second "normal steering" and "hard steering" trials based on 50%-ile statistics, which are expressed respectively as:

$$R = -4.21 \times Rdot + 2 \qquad \textbf{(4a)}$$

$$R = -2.62 \times Rdot + 2 \qquad \textbf{(4b)}$$



(a)

(b)

Figure 6. (a) Normal and (b) Hard Last-Second Steering Performance in Lead Vehicle Stopped Scenario.

It should be noted that these linear approximations extended the CAMP data to include the point R= 2 m at Rdot= 0 m/s. Without this extrapolation, the linear approximations would yield negative values of R (i.e., crash) at low negative values of Rdot. The mapping of CAMP normal steering data to Equation (**4a**) and hard steering data to Equation (**4b**) resulted respectively in 50% and 49% of the subjects initiating their steering maneuver "over" the curve in the LVS scenario as illustrated in Figure 6. By comparison, 56% of normal steering points and 38% of hard steering points were mapped "over" the curves derived from data fitting without binning.

STEERING RESPONSE IN LEAD VEHICLE MOVING AT LOWER CONSTANT SPEED SCENARIO

A total of 207 "normal steering " trials and 166 "hard steering" trials were examined in this scenario. Figure 7 illustrates approximations of the bin 50%-ile statistics of the last-second "normal" and "hard" steering trials, which were modeled respectively by the following linear equations:

$$R = -3.84 \times Rdot + 4.53 \quad \textbf{(5a)}$$

$$R = -2.56 \times Rdot + 2.25 \quad \textbf{(5b)}$$

Unlike the analysis of braking performance in the LVM scenario, the CAMP data were not extrapolated to the origin (Rdot= 0) because the following vehicle steered and changed lanes at negative values of Rdot. The mapping of CAMP normal steering data to Equation (**5a**) and hard steering data to Equation (**5b**) resulted respectively in 51% and 48% of the subjects initiating their steering maneuver "over" the curve in the LVM scenario as illustrated in Figure 7. By comparison, 45% of normal steering points and 37% of hard steering points were mapped "over" the curves derived from data fitting without binning.

DISCUSSION OF LAST-SECOND STEERING PERFORMANCE

Figure 8 compares the steering performance between the LVS and LVM scenarios based on 50%-ile statistics obtained from data bins. There is a slight difference between the two scenarios in the "normal steering" condition, which is equal to $|-0.37 \times Rdot - 2.53|$ m. This difference becomes larger with increasing values of $|Rdot|$. Drivers were generally a little less aggressive in the LVS than in the LVM scenario, which is quite the opposite of braking performance. A two-tailed t-test conducted on the means of LVM and LVS normal steering data in the –13 m/s bin produced a P-value of 0.5, indicating that the difference between the two scenarios at this range rate is not statistically significant at the 0.05 level. On the other hand, the near crash boundaries of the two scenarios almost overlap in Figure 8 with a negligible difference of $|-0.06 \times Rdot - 0.25|$ m. It is prudent to state that the observed difference under both steering instructions is almost negligible; and thus the steering response is independent of the two dynamic scenarios given the approximations made to fit the experimental data.

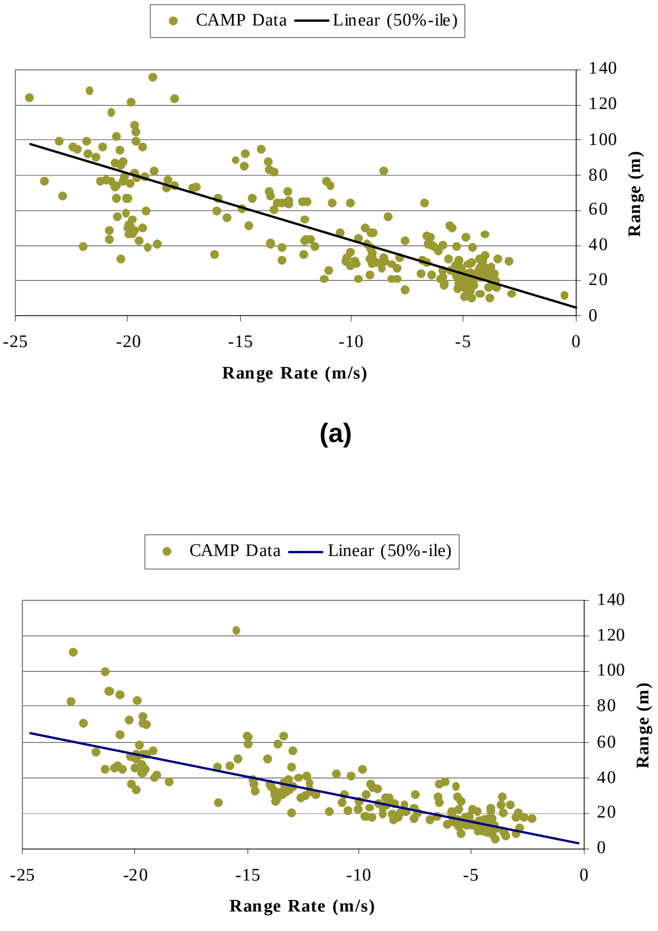


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Figure 7. (a) Normal and (b) Hard Last-Second Steering Performance in Lead Vehicle Moving at Lower Constant Speed Scenario.

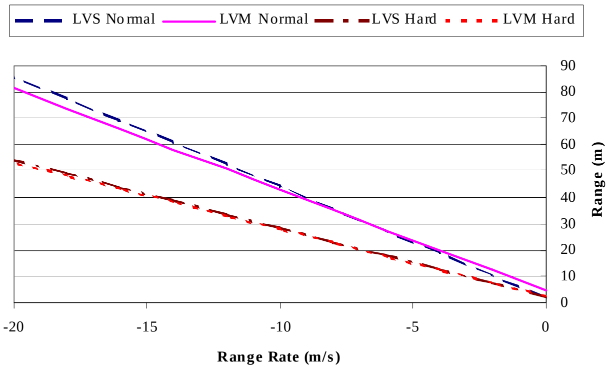

Figure 8. Comparison of Last-Second Steering Performance between Scenarios Based on 50%-ile Statistics.

DISCUSSION

Figure 9 demonstrates that drivers initiate last-second braking maneuvers at generally longer distances than last-second steering maneuvers in order to avoid a lead vehicle ahead in their lane of travel. Thus, the quantified boundaries of the driving states vary between braking and steering driver responses as observed from the CAMP trials. Consequently, distinct boundaries must be established for different driver responses to each dynamic scenario encountered in the driving environment. The results shown in Figure 9 point out the need to design crash warning algorithms that take into account various types of possible driver response. For instance, a rear-end crash warning algorithm based on braking response may issue alerts too early (i.e., nuisance alerts) for some drivers who plan on steering and changing lanes to avoid the vehicle in front of them. Projects are currently under way to collect on-road naturalistic data that characterize driver response to these different driving situations.

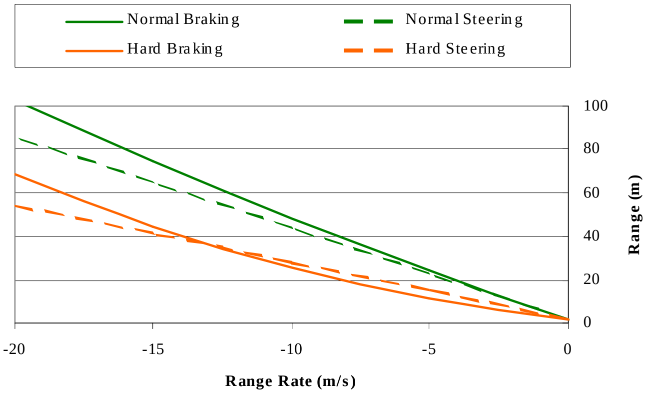

Figure 9. Comparison between Last-Second Braking and Last-Second Steering Performance in Lead Vehicle Stopped Scenario.

Figure 10 illustrates the utility of the state boundaries to the design and effectiveness estimation of crash warning systems. The 50%-ile boundaries of the conflict and near crash states are drawn for the LVM scenario based on last-second braking performance. In addition, the warning boundary of a rear-end crash warning algorithm is plotted as a dashed line to show the application of the driving state boundaries to the design and timing selection of the algorithm. This algorithm issues a warning based on TTC of 3.5 seconds (R_W= 3.5×|Rdot|). Typically, a warning algorithm should accommodate the preference of at least 50% of the drivers on when to brake at the near crash boundary line in order to enhance their acceptance of the system. Figure 10 shows that drivers approaching a slow-moving lead vehicle at closing speeds below 5 m/s normally initiate hard braking above the line of 3.5-second TTC. Therefore, drivers could consider these alerts as “too late” for the situation. Conversely, drivers normally brake below the line of 3.5-second TTC when approaching a slow-moving lead vehicle at closing speeds over 5 m/s. In this situation, TTC-based alerts could be perceived as “too early.”

Figure 10 also illustrates the use of driving state boundaries to count the number of conflicts and eventual near crashes, which are needed to estimate the effectiveness of crash warning systems. Nine braking onset data points observed from LVM cases in a field test of an intelligent cruise control system are displayed along with the trajectories of three selected cases [8]. All nine cases were considered driving conflicts in the field test study. The trajectory of case 1 did not cross the boundary between the low risk and conflict states and thus should not be counted as a conflict based on the 50%-ile boundary from CAMP’s LVM trials. In fact, the driver of the following vehicle exerted an average deceleration of less than 0.07g to match the lead vehicle speed. On the other hand, cases 2 and 3 should be qualified as conflicts since their trajectories clearly crossed over the conflict boundary. The average deceleration applied in both cases exceeded the 0.12g level. Of these two cases, case 3 could be classified as a near crash since its trajectory dropped below the boundary between the conflict and near crash driving states.

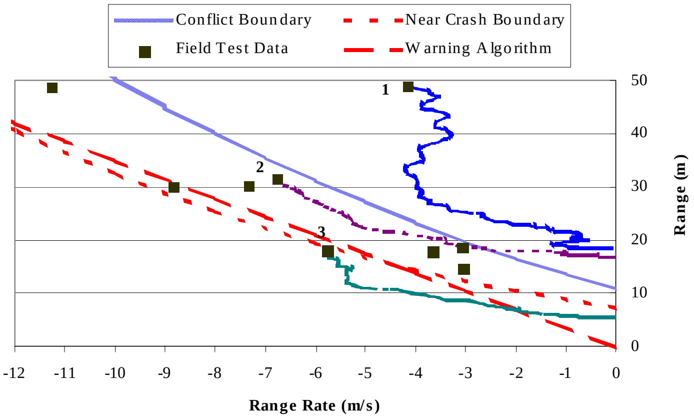

Figure 10. Utility of Driving Conflict State Boundaries in Lead Vehicle Moving at Lower Constant Speed Scenario.

CONCLUDING REMARKS

The analysis of last-second braking performance showed that the quantified boundaries of the driving states strongly depend on the dynamic scenario encountered in the driving environment. This conclusion is evident between the LVS and LVM “car-following” scenarios. On the other hand, the quantified boundaries seem independent of these two dynamically distinct scenarios based on the last-second steering performance.

Future research in this area includes a number of steps that will lead to the creation of a comprehensive driver performance map for rear-end crash avoidance research. To complete the analysis of most prevalent car-following scenarios in rear-end crashes, quantified state boundaries for the lead vehicle-decelerating scenario will be defined and estimated using test track and driving simulator data. In addition, mapping of actual data collected from on-road studies will be conducted to validate the quantified boundaries of all three scenarios. Finally, further research must address whether or not the quantified boundaries of the driving states depend on:

- Context of the driving environment (e.g., slippery versus dry road, good versus reduced visibility, or light versus heavy traffic).
- Age and gender of drivers.

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