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Comparison of Driver Braking Responses in a High Fidelity Driving Simulator and on a Test Track

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16 Abstract
The purpose of this study was to compare the braking responses of drivers in the Iowa Driving Simulator (IDS) to the braking responses of drivers in a similar study conducted on a test track The test track study from the Collision Avoidance Metrics Program (CAMP) examined the braking profile of drivers in last-minute braking situations in which drivers were instructed to brake either "normally" or "hard " Comparing these data to braking data collected with a very similar protocol in the simulator showed that the two data sets do not match exactly The most prominent differences between the simulator and the test track were that drivers in the simulator were less affected by the braking instructions, decelerated more abruptly, and maintained a larger safety margin Possible reasons for these differences include limited visual and vestibular cues in the simulator, and a combination of extended practice and a somewhat artificial lead vehicle on the test track These results show that the specific characteristics of every experimental venue must be carefully considered when evaluating driver performance Differences between venues and experimental protocols affect driver behavior; it is thus critical to assess whether these differences are large enough to be relevant for the design issues being considered

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EXECUTIVE SUMMARY

The purpose of this study was to compare the braking responses of drivers in the Iowa Driving Simulator (IDS) to the braking responses of drivers in a similar study conducted on a test track. The test track study examined the braking profile of drivers in last-minute braking situations in which drivers were instructed to brake either "normally" or "hard." Comparing these data to braking data collected with a very similar protocol in the simulator showed that the two data sets do not match exactly. The most prominent differences between the simulator and the test track were that drivers in the simulator were less affected by the braking instructions, decelerated more abruptly, and maintained a larger safety margin. Possible reasons for these differences include limited visual and vestibular cues in the simulator, and a combination of extended practice and a somewhat artificial lead vehicle on the test track. These results show that the specific characteristics of every experimental venue must be carefully considered when evaluating driver performance. Differences between venues and experimental protocols affect driver behavior; it is thus critical to assess whether these differences are large enough to be relevant for the design issues being considered.

INTRODUCTION

Validating data from driving simulator studies is important to any research program that intends to generate design recommendations based on the data collected. Direct validation is often difficult, as driving simulators are frequently used to put drivers in conditions too dangerous to test on the road. This is particularly true for crash avoidance research. Although numerous crash avoidance studies have been conducted using simulators, test tracks, and field experiments (Lerner, 1993; McGehee & Brown, 1998), few crash avoidance simulator studies have been designed to include a specific validation study on a test track or on public roads (McGehee, Mazzae, & Baldwin, 2000). This paper compares data collected in the Iowa Driving Simulator (IDS) to test track data collected by the Collision Avoidance Metrics Partnership (CAMP). CAMP is a partnership established by Ford and General Motors to accelerate the implementation of automotive crash avoidance countermeasures and to define pre-competitive enabling elements (Kiefer et al., 1999). This study was designed to closely duplicate a series of test track experiments that were part of the CAMP program. Comparisons were made between braking responses across simulator and test track studies.

Rear-end collisions account for over 28% of all collisions and cause approximately 157 million vehicle-hours of delay annually, which is approximately one-third of all crash-caused delays (*5*). Driver inattention has been identified as a contributing factor in over 60% of these crashes (*6*). Because inattention is such a powerful contributor to rear-end collisions, rear-end collision avoidance systems (RECAS) offer a promising approach to mitigate this problem. The goal of all of these systems is to alert the driver to a potential collision situation, return the driver's attention to the roadway, and promote a braking response that will enable the driver to avoid the collision. The promise of increased driving safety through RECAS has generated a substantial research effort (An & Harris, 1996; Hirst & Graham, 1997; Knipling et al., 1993). With simulators, dangerous situations can be evaluated without endangering the lives of drivers. The ability to investigate rear-end collisions safely is essential to the development of effective RECAS systems. However, it is necessary to ensure that the results from simulator studies are applicable to drivers operating on public roads. To understand how simulator characteristics influence the evaluation of RECAS effectiveness, this study compared braking in the Iowa Driving Simulator (IDS) to braking on a test track.

METHOD

To generate data for a direct comparison, this study was based on a CAMP test track experiment (Kiefer et al., 1999). The protocol for the simulator study mimicked the protocol of the CAMP study and the same dependent variables were collected.

CAMP PROTOCOL

The CAMP experiment was conducted on a 1-mile long, 2-lane wide, straight, smooth road at the General Motors Milford Proving Ground in Milford, Michigan. Drivers followed a lead vehicle, which towed a three-dimensional mock-up of the rear end of a 1997 Mercury Sable. The mock-up was attached to the lead vehicle by means of a collapsible beam (approximately 40 feet long) that could collapse up to 9 feet in order to prevent injury to the drivers and experimenters in the event of a collision. The mock-up, shown in Figure 1, was constructed of a PVC frame with a polyurethane material covering, and had working rear lights and reflectors (for sensing purposes).

FIGURE 1. Side view of lead vehicle, surrogate lead vehicle, and subject vehicle (CAMP Figures 3-1 and 3-2).

Drivers completed several forms, including an informed consent form, before being administered instructions. They were given a description of the surrogate lead vehicle regarding impacts at low speeds. The protocol for the CAMP study was described as follows:

Each driver experienced three blocks of trials, each corresponding to a different braking instruction condition. The first block of trials was always conducted under the normal-braking instruction, whereas the second and third block of trials were conducted under comfortable-hard and hard-braking instructions (with the order of these two braking instructions counterbalanced across drivers). The first block of trials served to get drivers comfortable with braking the vehicle under more normal conditions, and with the "last-second" braking instruction. Trials in which the passenger-experimenter intervened with braking were immediately repeated.

Within each block of trials, drivers experienced 15 trials. During trials 1–3, drivers braked in response to a series of three horizontally aligned traffic cones (placed perpendicular to the vehicle's path of travel). These trials served to get drivers comfortable braking with the vehicle under the last-second braking instruction relevant to the block of trials. During trials 4–6, drivers experienced three Stationary Trials, with the order of the three target approach speeds (30, 45, or 60 mph) (48.3 kph, 72.4 kph, 96.5 kpm) counterbalanced within a driver's testing session (across the three braking instruction conditions), as well as across drivers. During trials 7-15, drivers experienced nine Moving Trials, formed by crossing the three target speeds (30, 45, or 60 mph) (48.3 kph, 72.4 kph, 96.5 kph) with the three POV (lead vehicle) braking profile levels (-0.15, -0.28, -0.39 gs). During these nine trials, drivers experienced three successive trials at each target speed (each with a different POV braking profile). The order of the three target speeds and the three POV braking profile levels were appropriately counterbalanced within a driver's testing session (across the three braking instruction conditions), as well as across drivers (Kiefer et al., 1999, pp. 3–23).

In the stationary trials, drivers approached a series of three horizontally aligned traffic cones at the three different target speeds, and stopped according to the three different braking instructions. After completing the test trials, drivers were escorted from the track, debriefed on the purpose of the study, and compensated for their time.

IDS PROTOCOL

This experiment collected data using a high-fidelity motion-base driving simulator and a protocol that closely matched the one used in the CAMP study. Although very similar to the CAMP study, the simulator protocol differed slightly to accommodate the capabilities and limitations of the simulator.

Drivers were put in a situation in which they followed a full-size vehicle traveling at the same speed as the driver's vehicle. Unlike the CAMP studies, the virtual lead vehicle was not a towed mock-up. As in the CAMP study, however, drivers were instructed to brake at the last possible moment to avoid a collision. The CAMP study included three braking instructions for drivers, "normal-braking," "hard-normal," and "hard-braking"; the IDS study included only "hard" and "normal" braking. In addition, the stationary trials in the CAMP study were omitted from the IDS study. These preliminary trials may have altered drivers' braking behavior by helping them tune their braking skills to a level above that of most drivers. Including these practice trials was not feasible in the simulator because repeated braking tends to induce simulator sickness. Aside from these differences, the experimental protocol for the moving trials of the CAMP study was duplicated in the IDS at 30 and 60 mph (48.3 or 96.5 kph), with lead vehicle decelerations of 0.15 and 0.40 g.

Both NHTSA and CAMP personnel participated in this experiment to ensure the testing methods matched those used on the test track. Additionally, a CAMP researcher was present during the final setup and testing in the IDS to ensure that the IDS protocol matched the test track protocol.

PARTICIPANTS

Sixteen licensed drivers (eight males and eight females) with normal or corrected-normal vision between the ages of 25 and 55 participated in this simulator experiment. They were paid $30 for the 1/2 hour they took to complete the experiment. The participants had all driven the IDS previously as part of a collision avoidance experiment. In the previous experiment, the participants had been exposed to three severe braking situations during a 15-minute drive. Two of these situations were unexpected and had forced many drivers to brake very hard to avoid a collision. A screening questionnaire that was part of the previous study had ruled out participants prone to simulator sickness.

APPARATUS

Data were collected using the Iowa Driving Simulator (IDS), which uses sophisticated computer graphics to create a highly realistic automobile simulation. Four multi-synch projectors generate a 190-degree forward field-of-view and a 60-degree rear view. A six-degree of freedom motion base moves the simulator dome to generate motion cues. Inside the simulator dome is a fully instrumented vehicle cab. The vehicle cab used in this study was a 1993 Saturn four door sedan. However, both the vehicle dynamics and the antilock brake system were modeled after a Ford Taurus, a typical, mid-sized American car. The Ford Taurus vehicle dynamics model used in this study was developed by the National Highway Traffic Safety Administration (NHTSA) for the National Advanced Driving Simulator (NADS). Data were collected at a rate of 30 Hz.

PROCEDURE

The experimental procedure closely mimicked that used in the CAMP study. Upon arriving at the IDS simulation facility, participants completed an informed consent form and were briefed on operation of the simulator. They were then escorted to the simulator dome and briefed by the ride-along observer. Drivers were asked to adjust the seat, steering wheel, and mirrors to their preferred position, and to fasten their seat belt.

Each driver participated in a series of five trials. While the driver followed the lead vehicle (LV) at a target speed of either 30 or 60 mph (48.3 or 96.5 kph), the LV decelerated at either 0.15 g or 0.40 g. The initial time headway, controlled by the simulator, was set at 1.7 s. Each driver experienced a series of braking events in which they were instructed to respond with what they perceived to be either a "normal" braking maneuver or a "hard" braking maneuver to the lead vehicle deceleration. After experiencing all four conditions, each driver then repeated one of the four, giving each driver a total of five braking trials. The order of the two target speeds and the two LV braking profile levels were counterbalanced within a driver's testing session, as well as across drivers. Additionally, the lead vehicle deceleration was counterbalanced across participants, as was the braking instruction.

The braking instruction merits additional description. As in the CAMP study, each driver was instructed to make these last-second braking decisions under one of two different braking instruction conditions: "normal" or "hard" braking. For the first condition, drivers were asked to brake with normal braking intensity or pressure. For the second, drivers were asked to brake with hard intensity or pressure. Following the CAMP protocol, drivers were asked to follow through with their braking response once they responded instead of "second guessing," modulating, or altering their braking response. The instructions were identical to those used in the CAMP study. They were important because the goal of the study was to examine the point at which drivers perceive the need to begin braking after encountering a possible collision situation, and to determine how hard drivers brake in response to this situation. It was anticipated that a driver response to a crash alert would typically involve either maintaining or increasing brake pressure (rather than releasing brake pressure) throughout the braking maneuver.

When testing was completed, the drivers were escorted from the simulator, debriefed on the purpose of the study, and asked to complete various questionnaires. The participants were then compensated for their time.

EXPERIMENTAL DESIGN

The experimental design was a within-subject factorial design that included two levels each of speed, braking instruction, and lead vehicle deceleration. A latin square was used to balance the order of presentation across drivers. The within-subject independent variables were defined as follows:

Target Speed. The drivers were instructed to maintain a fixed speed, either 30 or 60 mph (48.3 or 96.5 kph).

LV Braking Profile. The LV decelerated at a constant rate, either 0.15 or 0.40 g.

Braking Instruction. Drivers were instructed not to modulate their braking, and to brake either "normally" or "hard."

The braking behavior observed in the IDS was compared to the braking behavior of the drivers in the CAMP study using an array of dependent variables. The dependent variables are divided into three groups according to the different aspects of the braking response. The dependent variables describe driver response as brake onset, during brake modulation, and at the completion of the braking maneuver.

Many different variables can characterize the point at which drivers begin braking. One way to describe these variables is in terms of how the higher order derivatives that define the relative state of the two vehicles. The range refers to the distance between the vehicles. The time to collision considers the range and the first derivative of range, the relative velocity. The required deceleration includes the range, the relative velocity, and the second-order derivative of range, the relative acceleration. These variables represent increasingly comprehensive descriptions of the relative states of the two vehicles. Brake modulation describes the braking profile from the initial brake onset to the time the vehicle stops and can be described by the peak and mean deceleration. The outcome of the braking event is described by a single variable; the distance to the lead vehicle. The precise definitions of these variables are included below.

Range. The distance between the subject vehicle (SV) and LV measured in meters.

Time to Collision - TTC. The time it would take for the SV and LV to collide under the prevailing speeds and given range measured in seconds.

Required Deceleration. The deceleration level required for the driver to avoid a collision at brake onset, measured in gs.

Peak Deceleration. The maximum deceleration value for the SV, measured in gs.

Mean Actual Deceleration. The deceleration level needed to yield the observed stopping distance, measured in gs.

End Range. The distance between the SV and LV when both vehicles have come to a complete stop, measured in meters.

RESULTS

The data analysis addresses the question of how closely the collision avoidance braking behavior in a high-fidelity driving simulator, such as the IDS, matches driver behavior in a similarly designed test track experiment. The results from the IDS experiment were plotted with those of the CAMP experiment. Mean values from the IDS experiment were plotted with 95 percent confidence intervals. Mean values from the CAMP experiment were extracted from figures in the CAMP report and were plotted without confidence intervals because those data were not available. Because many of the braking responses were similar, the discussion focuses on those areas where the results from the CAMP experiment were not within the 95 percent confidence intervals of the IDS data. The discussion of the results first addresses the initial conditions, then describes the onset of braking and the braking profile, and concludes with a description of the outcome of the braking response.

COMPARISON OF INITIAL CONDITIONS

When comparing simulator and test track data, it is critical to consider how closely the experimental conditions match. Precise control is possible in simulators, but not in test track studies. This is particularly important because in some instances, small variations in the initial conditions can produce substantial differences in the subsequent vehicle trajectory.

In both studies, the time headway between the two vehicles defines the relative severity of the situation at the time the lead vehicle begins to brake. Table 1 shows that the headway for drivers in the IDS was fixed at precisely 1.7 seconds. This value is quite close to the headway drivers chose in the CAMP study. In addition, it is reasonably close to the University of Michigan Transportation Research Institute (UMTRI) adaptive cruise control (ACC) field trial study (Sayer, Fancher, Ervin, & Melford, 1997), suggesting that a 1.7 second headway is representative of real driving conditions. These studies showed that as age increased, so did mean time headway. In the simulator, the headway was fixed so that all drivers could be compared with the same initial conditions. Because it was not possible to fix the headway on the test track each driver had a slightly different headway when the lead vehicle began to brake.

TABLE 1. Comparison of time headway during the IDS trials, CAMP moving trials, and UMTRI ACC field trials across age groups (CAMP data obtained from Table 3-5).

	Mean Time Headways (sec)		
Age Group	IDS at LV Braking Onset (sec)	CAMP at LV Braking Onset (sec)	UMTRI ACC Field Trials (sec)
Young (20-30)	1.7	1.3	1.2
Middle (40-51)	1.7	1.6	1.4
Old (60-710	1.7	1.6	1.5

COMPARISON OF BRAKING ONSET

Drivers were instructed to brake at the last possible moment to avoid a collision, and so the timing of the brake onset is a critical point of comparison between the simulator and test track. Several measures can define the onset of braking. The simplest is the range between the vehicles. A slightly more complex measure, the TTC, describes braking onset by normalizing the range according to the relative velocity of the vehicles. Finally, the deceleration required to avoid a collision is a measure of brake onset in terms of the requirements of the subsequent braking response. Together these measures provide a comprehensive description of the conditions at the time the driver begins braking, and can show how the simulator affects drivers' decisions to initiate braking.

Figure 2 shows that the onset of the braking in the IDS and CAMP studies coincide quite well except for test condition "normal braking at 60 mph," in which the initial range is substantially shorter in the simulator. This discrepancy could be due to the display limitations of the simulator that make it difficult to see objects clearly at a distance. Because the effect is less pronounced in the hard braking condition it may also reflect a difference in how the drivers interpret the "hard" and "normal" braking instructions.

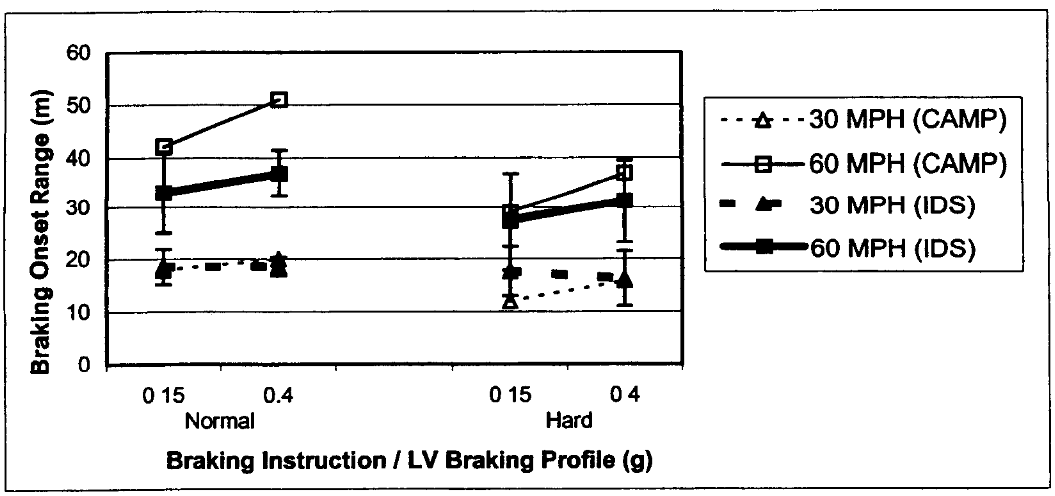

FIGURE 2. Mean range at SV braking onset as a function of braking instruction, LV braking profile, and speed condition (CAMP data obtained from Figure 3-7).

Figure 3 shows that the values for mean TTC at brake onset are quite similar for the simulator and the test track. The only difference is at the 60 mph (96.5 kph) for the normal-braking profile. In this condition, drivers on the test track began braking sooner than those in the simulator. Overall, the TTC appears to be somewhat larger for the IDS under the hard-braking instruction compared to CAMP, and smaller for the normal-braking instruction. However, the variability of the data is considerable, as indicated by the error bars, making definitive conclusions difficult. The difference between simulator and test track drivers may stem from the additional training drivers received in the CAMP study. Superior braking skills may have enabled them to narrow their safety margin in the hard braking condition.

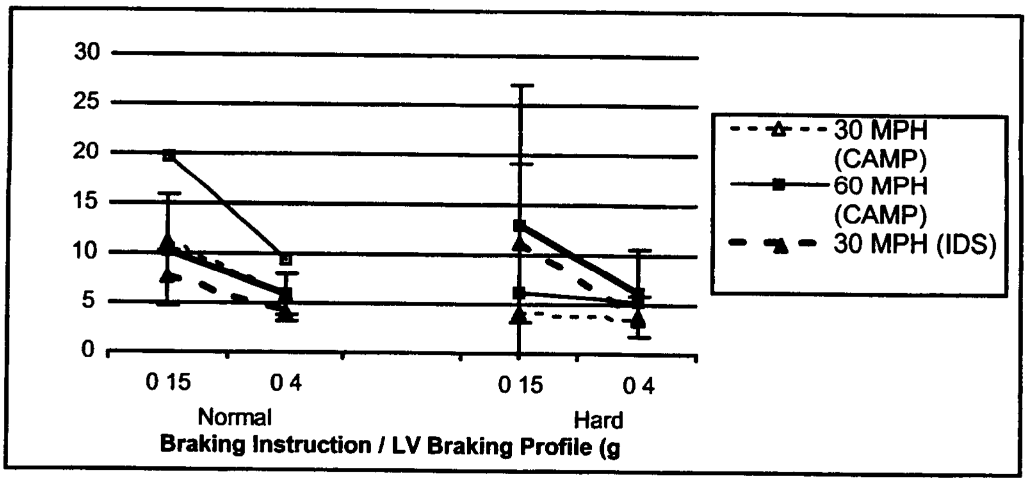

FIGURE 3. Mean TTC at SV braking onset as a function of braking instruction, LV braking profile, and speed condition (CAMP data obtained from Figure 3-21).

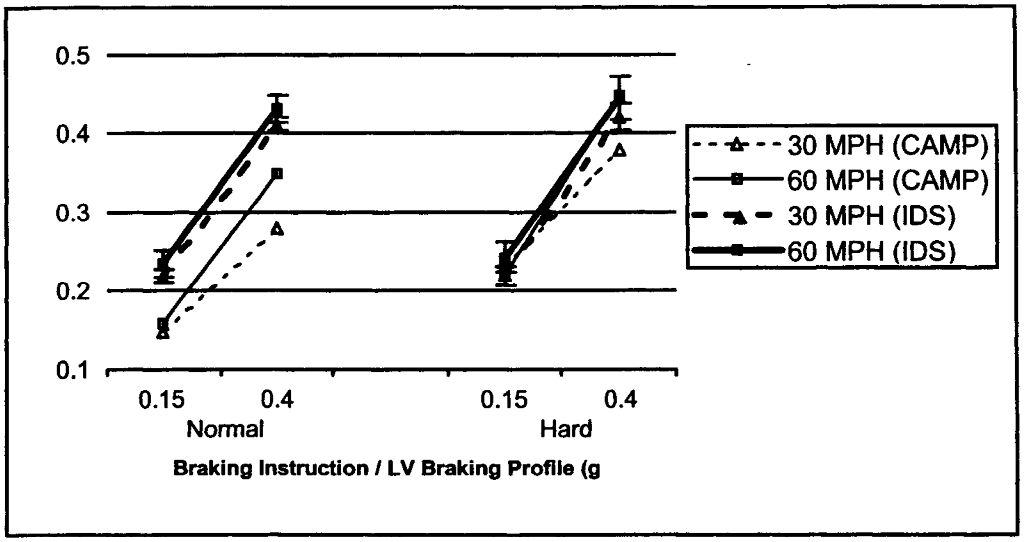

FIGURE 4. Mean "required" deceleration of SV at SV braking onset as a function of braking instruction, LV braking profile, and speed condition (CAMP data obtained from Figure 3-17).

Figure 4 shows the deceleration requirements at braking onset for the four test conditions. The figure shows, at the time the driver begins braking, the level of constant deceleration that is required to avoid collision. The IDS and CAMP data are very similar for the hard-braking instructions. For the normal-braking instructions, the drivers in the IDS responded as they had for the hard-braking instructions, but the CAMP drivers began to brake sooner, meaning that a lower deceleration was required to avoid collision. This graph clearly shows that "hard" and "normal" braking instructions affected when the test track drivers initiated their braking, but did not affect when the simulator drivers initiated their response.

Overall, the conditions when the driver in the simulator began to brake were quite similar to those on the test track. When the deceleration of the lead vehicle was greater, drivers started to brake later as measured by TTC and required deceleration. As measured by range and TTC, drivers on the test track and in the simulator also tended to brake earlier in the high-velocity conditions. Although the general pattern of responses is quite similar, and the values for many conditions match almost exactly, several important differences between driver behavior on the test track and in the simulator emerged. The drivers in the simulator began braking later than those on the test track, particularly in the high velocity situation with the "normal" braking instruction. Most interestingly, the drivers' braking onset in the simulator was not affected by the "hard" and "normal" braking instructions. The mean required deceleration at the point of brake initiation shows a clear influence of the braking instruction given to drivers on the test track, but not to drivers in the simulator.

COMPARISON OF BRAKING PROFILES

Drivers in both studies were instructed to brake with one single continuous motion, without modulation. The peak and mean deceleration provide a useful description of this response, which begins with the onset of braking and ends when the vehicle stops. Figures 5 and 6 show how the drivers' braking profiles in the simulator matches those on the test track. Figure 5 shows that during normal braking, the peak deceleration was greater for the simulator than for the test track. In fact, in the simulator, the peak decelerations for the "hard" and the "normal" braking conditions did not differ substantially. It appears that the drivers given "normal" braking instructions in the simulator braked as they did when given "hard" braking instructions. This is not the case for the test track drivers; they braked quite differently with the two instructions. Figure 6 shows a similar result, with the mean deceleration following a pattern similar to the peak deceleration. These results may reflect the limited vestibular and haptic cues provided by the simulator that make it difficult for drivers to calibrate their "hard" braking and "normal" braking responses. It may also reflect the conditions when braking was initiated. The required deceleration at the onset of braking was unaffected by the braking instruction in the simulator, a pattern reflected in the subsequent braking response. Although the braking response for drivers in the simulator was not affected by instructions, the pattern of results in Figures 4, 5, and 6 show several similarities for the simulator and test track drivers. The conditions in which the lead vehicle decelerates abruptly induce to a higher level of deceleration, and conditions with a higher initial velocity induce a higher level of deceleration.

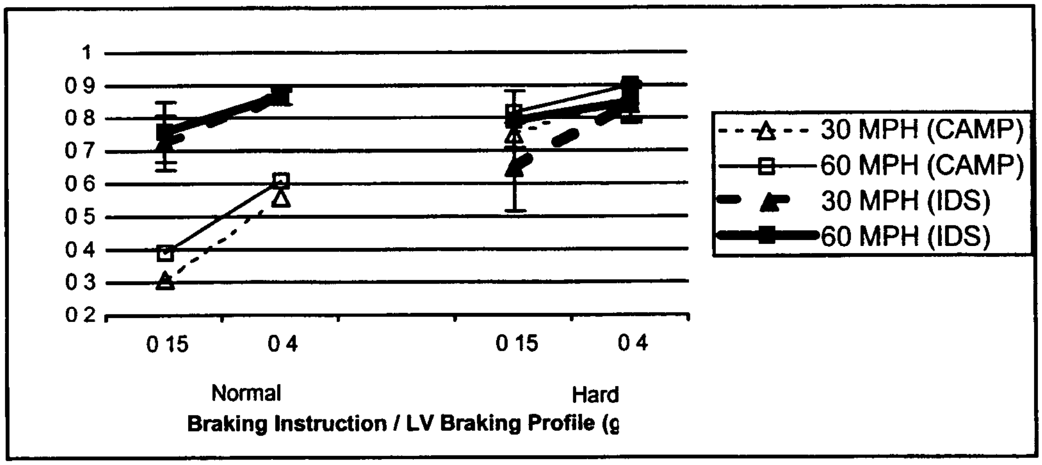

FIGURE 5. Mean peak deceleration of the SV as a function of braking instruction, LV profile, and speed condition (CAMP data obtained from Figure 3-9).

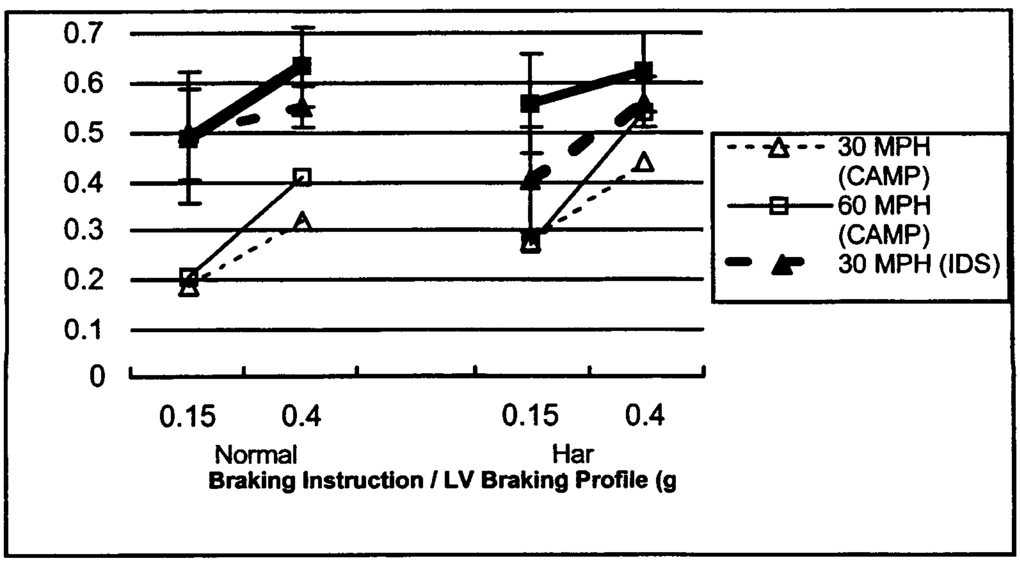

FIGURE 6. Mean "actual" deceleration of the SV as a function of braking instruction, LV braking profile, and speed condition (CAMP data obtained from Figure 3-16).

COMPARISON OF THE OUTCOME OF THE BRAKING RESPONSE

Both in the simulator and on the test track, drivers' ultimate goal was to avoid colliding with the lead vehicle. Because the instructions required drivers to brake at the last minute and not to modulate their braking, drivers who overestimated the distance needed to stop would come to a stop well behind the lead vehicle. Drivers who underestimated the distance might be forced to increase their brake pressure as they approached the lead vehicle. Figure 7 shows a consistent pattern with test track and simulator drivers. The mean range at the end of the braking process indicates that drivers may have overestimated the distance needed to stop for the lower lead-vehicle deceleration, particularly in the high velocity conditions. Lower lead-vehicle deceleration produces a longer range at the end of the braking, as does a higher initial speed. The pattern of results is very similar for the IDS and CAMP drivers. Interestingly, the data from the CAMP and IDS studies coincide very closely at higher velocities and differ only slightly at lower velocities. The hard-braking, high-velocity condition precisely overlaps the data. Figure 7 shows that drivers in the IDS tended to stop slightly farther away from the lead vehicle. One explanation is that the simulator provides an impoverished set of cues to calibrate the drivers braking behavior and so the higher mean deceleration of the simulator drivers may have caused them to stop before the test track drivers. Also, the greater number of trials may have enabled the test track drivers to brake more precisely and accept a smaller error margin.

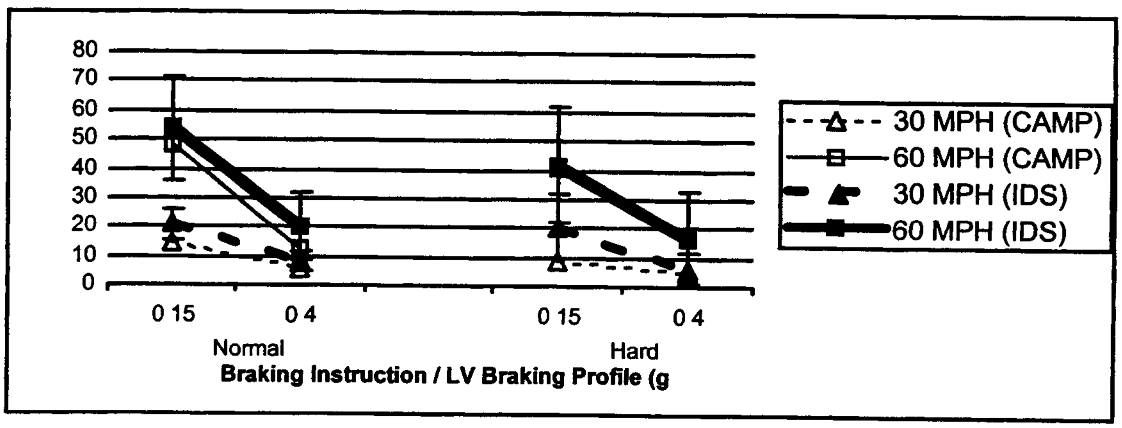

FIGURE 7. Mean end range as a function of braking instruction, LV braking profile, and speed condition (CAMP data obtained from Figure 3-13).

DISCUSSION

This study compared driver performance in a simulator to driver performance on a test track. Driver performance was narrowly defined as a last-second braking maneuver, where drivers were instructed to brake at the last moment to avoid collision. Although the motion and visual cues in the IDS are imperfect, the data agree in many respects. The general pattern of results is similar, with the initial speed and degree of lead vehicle deceleration affecting drivers on the test track and in the simulator in a generally similar way. Under several experimental conditions, the similarity of the responses went beyond the general pattern of response. The mean values were almost identical in several instances and, more frequently, were well within the confidence intervals. As an example, all but one of the eight pairs of means in the comparison of the mean end range matched very closely. Although the simulator and test track drivers performed similarly, there are differences apparent from the onset of braking, through the braking process, and in the final outcome of the braking event. In particular, the instructions regarding "normal" and "hard" braking had little influence on drivers in the simulator.

The analysis of the braking response focused on each stage of the response separately; however, a comprehensive comparison of driver performance in the simulator and on the test track must consider the interactions between these stages. Each stage affects the subsequent one, and understanding these interactions may help reconcile otherwise conflicting results. For example, the speed and positions of the vehicles at the point at which the driver begins to brake may systematically affect subsequent braking behavior. The required deceleration at brake onset shows that the "hard" and "normal" braking instructions did not affect simulator drivers. In contrast, when test track drivers began braking, their required deceleration was substantially less in the "normal" braking condition than in the "hard" braking condition. These differences between the simulator and test track behavior are important because they reflect driver response to the instructions before braking has begun, and such differences must reflect discrepancies in the visual cues and experimental protocol, not the vestibular cues. These differences might help explain why, for drivers in the simulator, the peak deceleration in the "normal" braking condition was as high as the peak deceleration in the "hard" braking condition. Specifically, drivers may have braked equally hard in the "normal" and "hard" braking condition in the simulator because the initial conditions for the braking process, in terms of required deceleration, were the same. Because the braking profile may be highly dependent on the conditions at the onset of braking it is unlikely that differences in vestibular cues during the braking process completely account for the differences between the simulator and test track data.

Several features of the simulator and of the experimental protocol may explain the differences between the simulator and test track data. In particular, the simulator provides a somewhat impoverished set of visual and vestibular cues, the CAMP study provided drivers with more training than the IDS study, and the IDS and CAMP studies included different elements of the driving situation. In combination, these factors account for the differences in driver response.

One important difference between the IDS and the CAMP testing environments had to do with the sensory cues available to the driver. The limited resolution of the simulator (3.5 arcmin/pixel) decreases drivers' effective visual acuity and impairs their ability to detect relative motion compared to the test track. In the IDS, the threshold of 0.003 rad/sec for detecting a change in the rate of expansion impairs relative motion detection most severely at long ranges. The uncertainty caused by the impoverished visual cues may have induced the slightly different braking strategy observed in the simulator. Care should be taken to compensate for this limitation by creating scenarios that do not require drivers to respond before they are able to detect the relative motion of the lead vehicle, as in the 60 mph (96.5 kph) condition in this study. Another potential limit of the simulator is its ability to convey the vestibular and haptic cues associated with braking; drivers do not receive the same feedback as on the road, cues that would help them realize how hard they are braking. Although the IDS motion base provides some motion cues, it does not fully replicate the actual experience. The impoverished visual, haptic, and vestibular cues help explain the poor compliance with the "normal" and "hard" braking instructions and the higher mean and peak deceleration of the drivers in the simulator.

Another contributor to differences between simulator and test track performance may be the added training received by the drivers in the field study. Drivers in the CAMP experiment completed 45 trials coinciding with three different braking scenarios, compared to five trials for IDS drivers in this experiment. In the CAMP study, drivers began by approaching a series of three horizontally aligned traffic cones at different target speeds, and stopping according to the different braking profiles. The same profiles were tested for drivers approaching a stationary lead vehicle. The drivers then completed trials with a moving lead vehicle for the various braking profiles, speeds, and lead vehicle decelerations. The extended exposure to the braking scenario may have given drivers in the CAMP study braking skills that most drivers do not have (Duncan, Williams, & Brown, 1991). These skills may have enabled them to brake more precisely and to accept a smaller margin of error. The drivers in the simulator had less training and may have been less sure of how close they were to the lead vehicle. The braking strategy observed in the simulator may have been an effort to compensate for this uncertainty, causing simulator drivers to decelerate at a greater rate and inducing them to stop further away from the lead vehicle. More practice might have calibrated the braking response of drivers in the simulator so that they could have followed the "normal" and "hard" braking instructions more precisely.

Both the simulator and test track put drivers in an artificial situation. In the CAMP study, drivers followed a surrogate lead vehicle, constructed from the rear half of a 1997 Mercury Sable and attached to a lead tow vehicle by a collapsible beam. Realism was sacrificed to provide a safe environment for participants and experimenters, and this may have altered the braking response. Moreover, the CAMP study did not include ambient traffic. The simulator scenarios had drivers follow a "real" vehicle on a "real" roadway that included ambient traffic. In this way, the simulator was able to include aspects of the actual roadway that are not possible to capture on a test track. However, the realism of these features is suspect and the drivers face no risk. Interestingly, the results suggest that these differences between the test track and the simulator had little effect on drivers' behavior because drivers in the simulator were slightly more conservative than those on the test track.

CONCLUSIONS

This comparison of test track and simulator braking performance showed surprisingly good agreement. The most systematic source of disagreement between driver performance on the test track and in the simulator was the failure of simulator drivers to comply with the instructions for “normal” and “hard” braking. For those instances where the two sets of data disagree, a detailed analysis of the response process shows that no single difference between the two experimental venues can conclusively explain the results. One obvious explanation for the disparity is the simulator’s impoverished haptic and vestibular cues. This explanation is incomplete, however, because the required deceleration before onset of braking showed that drivers in the simulator were not affected by the “hard” and “normal” braking instructions. Multiple causes and interactions across different stages of the braking response make it difficult to determine the precise reason for different behavior in the simulator and on the test track. A computational model of driver performance could help clarify

the results because the influence of particular cues could be manipulated independently. Such an approach would be particularly important in that driver responses interact with the kinematics of the driving situation to produce complex non-linear behaviors that are not easily anticipated without the aid of a computer-based model.

The comparison between driver performance on the test track and in a high-fidelity simulator shows that differences between these two evaluation venues can produce somewhat different behavior. Simulators can support studies that are too dangerous to be conducted on test tracks or in the field. The test track provides a useful bridge between the limited fidelity of the simulator and the danger and lack of experimental control of the actual roadway. Careful comparison between test track and simulator data are needed to identify how each experimental venue influences driver behavior, and how these venues can best be used to gather data to guide the design of collision avoidance systems. As simulators become more sophisticated, they may eliminate many of the differences observed in the IDS. Specifically, the National Advanced Driving Simulator (NADS) has a very high resolution display system and a motion-base that provides both high frequency vibration and sustained acceleration cues. Replicating this study on the NADS would clarify the role of vestibular cues and practice with specific braking maneuvers on the braking process.

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