The Exploratory Advanced Research Program

EXPLORATORY ADVANCED RESEARCH

Making Driving Simulators More Useful for Behavioral Research—Simulator Characteristics Comparison and Model-Based Transformation

SUMMARY REPORT

U.S. Department of Transportation
Federal Highway Administration

Cover images show simulated roadway geometry developed by the University of Iowa (left), the National Advanced Driving Simulator (center), and the Federal Highway Administration's motion-base driving simulator (right). ©The University of Iowa

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16. Abstract A central issue in making simulators useful for highway and traffic engineers concerns how well driver behavior in the simulator corresponds to driver behavior in the real world. Simulator fidelity plays a central role in matching behavior in the simulator to behavior on the road. Simulator fidelity often refers to the features and appearance of the simulator. The degree to which behavior in the simulator matches behavior on the road defines behavioral fidelity. This project characterized the physical fidelity and behavioral fidelity of four simulators. These four simulators represent a broad range of fidelity and cost. Data collected from these four simulators begin to address the question of how simulators can support highway and traffic engineers. Overall, the results show that simulators with high physical fidelity demonstrate high behavioral fidelity and are likely to provide good estimates of mean speeds in typical engineering applications such as roundabouts and roadway treatments designed to moderate drivers’ speed. A detailed analysis of both physical fidelity and behavioral fidelity suggests the need to carefully assess the match between simulator features and the properties of the roadway design issue. A model-based transformation was developed to relate data collected in the simulators to data collected on the road. Future research should examine physical fidelity in more detail and its relationship to behavioral fidelity across a broader range of driving behavior parameters.			
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

Executive Summary

Highway and traffic engineers face considerable challenges in creating designs that are consistent with drivers' capabilities and expectations; however, failing to consider driver behavior can cost lives and millions of dollars if roadways require revision after they are built. The use of driving simulators to guide designs or to evaluate design choices is a promising approach, but discrepant results across studies undermine the utility of these findings. This is particularly true when simulator results fail to match on-road data. One potential source of this mismatch is when the simulator does not have the appropriate fidelity, or realism, to address the design issue of interest. Appropriate simulator fidelity, which includes the simulator hardware and software as well as the modeling of the virtual environment, is an important component of obtaining data useful for highway design. For example, one could envision a staged approach to simulator fidelity, similar to that used in software prototyping, in which a low-fidelity desktop simulator could be used for rendering scene and roadway elements, whereas a high-fidelity simulator could be used for speed estimates. Choosing the appropriate level of simulator fidelity to address a particular design issue represents a critical challenge.

The aim of this project was to address this challenge and to help engineers identify the appropriate simulator platform for particular design questions, as well as to identify a mathematical transformation that can equate simulator data to real-world outcomes. In particular, the research team identified highway design needs and matched them to specific simulator characteristics to facilitate the appropriate choice of simulator for a particular design problem. As part of this research, the research team developed and demonstrated a proof of concept approach to characterizing simulator fidelity to allow for comparison between simulators and the real world. The research team also developed a driving environment that contained virtual recreations of two roundabouts from Maryland and Arizona, as well as a gateway from a rural road to a small town in Iowa. The researchers manipulated this virtual environment to vary the visual complexity of the driving environment and tested it on four simulator platforms, three of which were tested with and without motion. They compared driver judgment of fidelity and performance across the simulator platforms. No consistent effect of motion was found, but a moderate effect of visual complexity was apparent in the data. Performance data showed good relative and absolute matches to on-road speed data. The researchers used the data to develop linear regression and process models that could be used to transform the simulator data to match the on-road data. These models will provide the foundation for future work that will allow designers to transform results for simulator studies to make design decisions and to predict changes in driver behavior and performance on the basis of evaluations conducted on simulators. For example, these models can relate speed through a roundabout observed in a simulator to speed that is likely to be observed on the road.

Following completion of this project, additional work is necessary to improve and refine the tools developed so far. One area that requires refinement is the characterization of simulators. This is because those characteristics that matter most are not always the easiest to measure. Additional work

is needed to define the critical measures that differentiate simulator fidelity related to roadway design. Additional work is also needed to characterize what constitutes a typical vehicle and how much variability exists among vehicles on critical measures. These data could then be used to enhance the psychophysical scaling required to determine when a simulator is noticeably different from a typical vehicle and the extent to which different vehicle types influence highway design decisions. These differences must also be investigated to determine whether future studies need to include not only a range of drivers, but also a range of vehicle types.

This research would also be enhanced through its application to real-world design problems to provide the opportunity for continued evaluation and refinement. For example, use of a simulator to support a State Department of Transportation project, from inception to evaluation, would enable a thorough evaluation of the utility of the simulator in all phases of the design process. Through final evaluation of the real-world design implementation, the predictions of the simulator across a broader range of performance metrics could be assessed, and model refinements could be made.

Another promising line of research would be to draw on naturalistic data to identify critical design issues and scenarios that can be further examined through simulator studies. These studies would provide additional data to improve the transformations of simulator to real-world data. A further opportunity would be to examine the minimum fidelity of simulator needed at each phase of the design process and across design problems. If lower fidelity simulators can be used to successfully address design decisions, then their use may be opened up to a broader group of highway designers who cannot necessarily afford more expensive simulation platforms.

The model-based transformations used in this study highlight the promise of driver modeling in helping to address highway design decisions. Ongoing projects continue to explore the use of driver models to enhance driver safety through a systematic evaluation of design options; however, this requires a reliable and validated model of the driver. Additional work along these lines is therefore needed, particularly as it relates to roadway geometry and visual complexity. These theory-based models can be used to accumulate an understanding of simulators and driver behavior related to a set of stimuli. A comprehensive approach that integrates a driver model with the Interactive Highway Safety Design Model would provide benefits to highway designers as an efficient way of using previous data to assess new design decisions.

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List of Acronyms and Abbreviations

EAR	Exploratory Advanced Research
FHWA	Federal Highway Administration
NADS	National Advanced Driving Simulator
WTI	Western Transportation Institute

Introduction

This report summarizes the results of a Federal Highway Administration (FHWA) Exploratory Advanced Research (EAR) Program-funded research project that explored the challenges of using driving simulators to guide roadway designs and evaluate design choices. The aim of this project was to help engineers identify the appropriate simulator platform for particular design questions, as well as to identify a mathematical transformation that can equate simulator data to real-world outcomes.

Highway and traffic engineers face considerable challenges in creating designs that are consistent with drivers' capabilities, expectations, and limits.[1] Drivers often behave in complex and counterintuitive ways, and failing to consider driver behavior can cost lives and millions of dollars if roadways require revision after they are built.[2,3] Driving simulators provide a promising approach to addressing this challenge because they make it possible to visualize new roadway designs as well as safely expose drivers to demanding situations without the expense of fully implementing the design.[4] Driving simulators also provide a means of conveying road design concepts to stakeholders through visualization and have the potential to be an important part of policy decisions and public acceptance.[5,6]

Improving Understanding

There have been many recent advances in simulation technology, which has led to a wide range of driving simulators available to researchers. These simulators all offer different levels of realism, known as *fidelity*, in addition to varying levels of complexity and usage costs. Such diversity makes it difficult for researchers to know which simulator is appropriate to address a given design question. This uncertainty is thought to be one reason why simulators have not been more widely used by highway and traffic engineers.[7]

An improved understanding of the varying characteristics of simulators and how well they might reproduce driver behavior would make driving simulators far more useful for engineers. The ideal situation would be for simulator characteristics to exactly match actual cars and roadways, but this is beyond the capabilities of even the most advanced simulators at this time. Instead, the goal is to minimize the differences between the physical characteristics of the simulator and the roadway and therefore ultimately minimize the difference between behavior observed in the simulator and out on the road.

Understanding Physical and Behavioral Fidelity

In addition to physical differences, there are several other factors known to affect driver behavior that can prove difficult or impossible to simulate, including a driver's motivation for the trip or the real-world consequences of a crash. Matching the physical features of the simulator to the roadway experience, known as *physical fidelity*, is therefore just one condition that must be replicated to ensure that driver behavior in the simulator matches behavior observed on the road.[8] Until now, the driving simulator community has mostly focused on gross measures of physical fidelity, such as "high" or "low" fidelity. The next step, and broader research goal, is to match the behavior of drivers in the simulator with behavior on the road, known as *behavioral fidelity*.[4] This requires sufficient realism of simulator controls and vehicle-handling characteristics to match actual vehicle performance.[9] The goal is for behavior in the simulator to match behavior on the road accurately enough to support design decisions.

Simulator fidelity is further complicated by the fact that physical and behavioral fidelity are related to each other, in that imperfect physical fidelity will lead to imperfect behavioral fidelity.[8] Despite this, imperfect fidelity is still often sufficient to support roadway design decisions. For example, a simulator might fail to accurately replicate the cues required to guide behavior, possibly leading drivers to drive faster than they would on the actual road.[10,11] Drivers, however, rely on multiple interchangeable cues to guide behavior and can substitute one set of cues for another.[12,13] This means that two different simulators might still produce similar behavior results because drivers can adapt and use the available cues within each simulator.[14,15] Simulator fidelity is further influenced by the level of information a simulator might provide for one task compared with another. A simulator might offer a high level of realism, or fidelity, for one set of tasks but only a medium level of realism for another. For example, a simulator may offer highly accurate renderings of road signs for a sign-reading task yet would be classed as a low-fidelity simulator for driving that involves 90-degree turns because it fails to provide a preview of the road on which drivers rely during the turns.[4]

Comparing Simulators and Scenarios

During this project, the research team explored task-dependent fidelity and examined the difference between physical and behavioral fidelity. The following summary compares behavior across four simulator platforms with four different configurations of motion base and visual complexity. The simulators were used to analyze a total of six roadway scenarios among them, comprised of four roundabouts and two gateways. This summary includes a description of the different driving simulators used in the project, a description of physical fidelity in terms of the cues drivers use for vehicle control, an assessment of the behavioral fidelity of these simulators, and an overview of a model developed as part of the project to relate simulator behavioral data collected in a driving simulator to data collected on the road.

Simulators and Scenarios

Physical Fidelity

Physical fidelity relates to the degree to which the simulator replicates the physical properties of the driving situation, unlike behavioral fidelity, which is associated with the simulators' ability to replicate behavior observed in the world. This study's research team examined four simulators representing a broad range of simulation capability and fidelity and measured characteristics for each. Simulators included in the study were the National Advanced Driving Simulator (NADS), the FHWA Highway Driving Simulator, the Western Transportation Institute (WTI) Simulator, and the NADS miniSim.

Study Simulators

The following section provides a brief overview of each of the four simulators used in this study.

National Advanced Driving Simulator

The NADS used a 1998 Chevrolet Malibu cab mounted on a motion base with 13 degrees of freedom, as shown in figure 1. Accelerator and brake pedals used software-controlled electrical motors to provide feedback. The simulator has a 360-degree visual display system consisting of eight projectors that project visual imagery inside the dome, and scenery is updated at 60 Hz. The NADS features the ability to swap among several types of vehicle cabs.

Federal Highway Administration Highway Driving Simulator

The FHWA Highway Driving Simulator, shown in figure 2, is composed of a full 1998 Saturn vehicle cab mounted on a motion base with 3 degrees of freedom. The FHWA simulator has a 240-degree visual display system consisting of five projectors that project onto a cylindrical screen that is 2.7 m (9 ft) tall. All scenery is updated at 60 Hz.

Western Transportation Institute Simulator

The WTI simulator, shown in figure 3, consisted of a 2009 Chevrolet Impala sedan mounted on a motion platform with 6 degrees of freedom. The WTI simulator has a 240-degree forward-field-of-view system augmented by a 60-degree rear-view display system, consisting of five projectors and a curved screen in front of the driver and a single projector and a flat screen behind the driver. Side-view mirrors with digital screens also portrayed the scenarios for a total of eight visual channels.

National Advanced Driving Simulator miniSim Simulator

The NADS miniSim, shown in figure 4, is a portable, lower cost simulator that runs software similar to the NADS simulator. The miniSim has no motion base and, for this study, featured a quarter-cab configuration with a seat and steering wheel from an

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Figure 1. The National Advanced Driving Simulator motion-base driving simulator.

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Figure 2. The Federal Highway Administration motion-base driving simulator.

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Figure 3. The Western Transportation Institute Simulator.

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Figure 4. The National Advanced Driving Simulator miniSim Simulator.

actual vehicle. It has three flat-panel plasma displays and projects the image of a rear-view mirror on the center plasma display.

Supporting a Realistic Driving Simulator

Simulators are often characterized by a set of features that describe their hardware components, including driving controls, screens, resolution, and mirrors. The hardware configuration is critical for conveying information to the driver, such as speed and curve geometry and gas and brake pedal force; however, although hardware is a necessary condition for high behavioral fidelity, it is not sufficient on its own. For a driving simulator to accurately convey the driving environment, it must depend on hardware *and* software. In fact, software is often more important than is hardware because it is the software controlling what is presented to the driver.

Working together, the hardware and software generate signals for the driver and influence how they perceive the environment and control the state of the vehicle relative to the environment. There are three key requirements for supporting a realistic driving simulator: (1) perception of distances, speed, and time to reach relevant objects in the real world; (2) control of the car's speed and direction through control inputs; and (3) vehicle response to the control inputs.[12,16,17] The ability to identify and measure simulator characteristics in relation to these requirements enables researchers to define important differences between simulators, even if their hardware specifications are identical. In addition to taking a sample of measurements to quantify the physical fidelity of the driving simulators used in this study, the research team aimed to relate each simulator characteristic to what drivers experience on the road to assess how characteristics might affect behavioral fidelity.

Measuring Levels of Realism

Following data collection and assessment of simulator characteristics, the NADS and WTI simulators showed the highest level of physical fidelity; however, study results indicated that no single metric can serve as a proxy for overall simulator fidelity. In fact, the broad concept of overall level of fidelity is in fact misleading and should instead be addressed in a multidimensional manner. Several issues must be addressed before this multidimensional approach is applied more broadly. For example, cars differ substantially across most of the simulator characteristics measured. It is therefore important to identify which differences are important and which are not. Drivers were also shown to easily adapt to a wide range of vehicle characteristics, including maximum acceleration and deceleration, steering inputs, pedal feel, and visual contrast. Even though a driver might perceive differences between a simulator and the car on the road, the difference might not influence driver behavior but may still result in differences in workload and driver strategies in obtaining the same driving performance. Following analysis of various metrics of physical fidelity, further research is needed to quantify the variation of simulator characteristics, the degree to which drivers can adapt to different vehicle simulator characteristics, and the degree to which these characteristics influence behavior, driving strategies, and operator workload.

Behavioral Fidelity

Behavioral fidelity refers to the simulators' ability to replicate driver behavior observed in the real world and is considered the ultimate measure of simulator fidelity. Researchers for this project collected simulator-based data and on-road data to describe behavioral fidelity for each of the four simulators used in the study. They collected data both with and without the simulators' motion base engaged and with and without a more complex visual scene.

Data Collection

The analysis involved 167 participants ranging in age from 25 to 45 years. Forty-eight people each participated in the WTI, FHWA, and NADS simulators, and 23 people participated in the miniSim. The simulators operated on three different software platforms, but all used the same scenarios. Scenarios were used that involved two types of road segments, roundabout and gateway. The term *gateway* refers to a transition from a rural road into a town. In this study, the gateway was designed to achieve a 40-km/h (25-mi/h) speed limit on a two-lane suburban roadway in Iowa by using converging pavement markings, narrow lane markings, and speed advisories, as shown in figure 5. The roundabout scenarios were located on a rural two-lane arterial highway adjacent to the overpass of a major four-lane highway in Maryland, and a sequence of two roundabouts located on a rural two-lane roadway connected with a two-lane frontage road adjacent to an interstate highway in Arizona.[18,19]

The research team selected these roadway elements based on discussions they had with FHWA about the potential application of driving simulators to investigate design issues.[7] The researchers selected real-world examples of each road segment based on the availability of spot-speed data (i.e., the instantaneous speeds of vehicles at specific spots of the roadway) from published reports, and they based the virtual environment reproductions on the engineering schematics available for each site. The goal of these reproductions was to duplicate the road segment geometry and road features visible to the driver that were important to navigating the road segment; however, implementing identical scenarios on four different simulator platforms presented unique challenges and required a significant amount of fine tuning. A lack of established standards for road networks and dynamic element scripts was identified as a key impediment to sharing data on the driving environments across simulators as an efficient and smooth process.

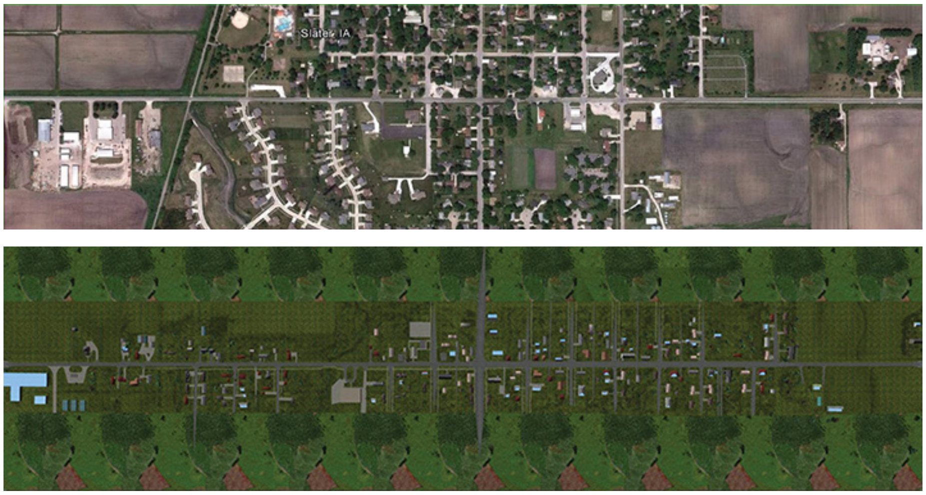

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Figure 5. Example of geometric matching of real (top) and simulated (bottom) roadway geometry of a gateway in Iowa.

The researchers used the same general procedure to govern data collection at each simulator facility, although minor variations were introduced depending on the logistical and operating requirements of each site. They used existing databases and local advertisements to recruit participants, who were initially contacted and verbally screened for eligibility and motion sickness before moving forward. Participants initially conducted a practice drive in the simulator to familiarize themselves with the operation of the simulator vehicle and experience of driving within the virtual environment, as shown in figure 6. Participants then drove the main route twice with varying levels of visual complexity and road segment orders.

Simulator Evaluation

Each participant then completed a simulator realism survey to evaluate the overall feel, braking response, and visual realism of the simulator. These components formed the three dimensions of subjective simulator fidelity, and the results showed that the simulators differ considerably over these three dimensions of simulator realism. The NADS simulator, with the advanced motion base on, had the highest reported realism of overall feel. The FHWA simulator represented the lowest realism of overall feel; however, this simulator did provide the highest perceived realism for being able to read the signs and see the road. This was attributed to the simulator being specifically developed to offer visual properties to support research for road and signage design. Drivers felt best able to brake and stop with NADS while having the motion on and with the WTI while having the motion off. This part of the study showed that no simulator configuration dominates the other in terms of perceived realism. In summary, the participants judged that the NADS is the most realistic simulator overall, the FHWA simulator best supports drivers' ability to read signs, and the WTI simulator provides the best braking feel. Moreover, the effect of the motion base was shown to be relatively small and can even have a negative impact on realism.

Influencing Driver Behavior

As part of this research project, the research team analyzed the effects of simulator, motion, and visual complexity on driver behavior. The effect of motion failed to reach statistical significance and had little impact; however, visual complexity had a substantial influence on behavior. In some cases, particularly for drivers in the miniSim in the Iowa gateway, it led to an approximately 8-km/h (5-mi/h) speed reduction. In addition, drivers of the miniSim on the Maryland roundabout were traveling almost 16-km/h (10-mi/h) faster than were drivers in the other simulators. In most other cases, the influence of visual complexity was modest, so the substantial simulator differences between the miniSim and the other simulators is thought to have contributed to this speed difference.

In general, the collected data for the mean speed of drivers in the simulators relative to the mean speed observed on the road was similar. Drivers in the WTI simulator drove closest to real-world speeds at low speeds, whereas drivers in the FHWA simulator drove substantially slower at speeds below 50 km/h (31 mi/h) but drove faster once speeds increased beyond that threshold. Results indicated that speed varies more in the simulator than on the road. One explanation for this is that the simulator provides poorer cues regarding the speed and poorer feedback regarding drivers' modulation of speed, leading to greater reliance on the speedometer, poorer speed control, and more variability in speed. This suggests that simulators can provide good estimates of the mean speed but poorer estimates of other elements of the speed distribution. Drivers drove faster and more variably in the miniSim and more slowly in the NADS relative to the speeds observed on the road, suggesting that the breadth of distribution may be more indicative of simulator fidelity than the mean speed.

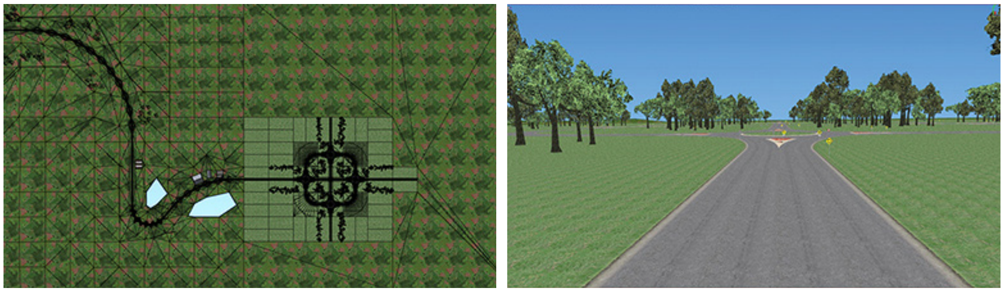

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Figure 6. An overview and screen image of the practice driving route.

Model-Based Transformation of Simulator Data

As described in the previous section, behaviors seen in the driving simulator and on the roadway in this research project are generally in agreement, but there are still some mismatches to be addressed. For example, the distribution of speeds observed in the simulator should ideally match speeds observed on the road, but this is not always the case. Simulator characteristics can explain some of the behavior differences, but there are other important characteristics that can lead to differences, including familiarity with the route and individual driver motivations.

Predicting On-Road Behavior

Although the mean speed observed on the road compared with the simulator was shown to differ slightly in absolute terms during this study, in relative terms the mean speed was similar.[8,20] To solve many design issues, it is important to match simulator and road data in absolute terms. There is a requirement to develop a method to transform simulator data to accurately predict on-road behavior. To meet this requirement, the research team focused on a computational model based on the perceptual, cognitive, and motor-control processes that govern driver speed maintenance. Unlike a regression model, this model uses a theoretical approach to explain the underlying constraints that bound the driver response and provides a way to transform the distribution of speeds observed in the simulator to those observed on the road. This approach offers promise in transforming simulator data to match roadway data and builds on existing models of driver behavior to describe how drivers perceive and respond to road characteristics.

Analyzing Models

This project also included an analysis of applicable driver models to the roundabout scenarios and integration of these models into a simple speed maintenance model. The research team used data from NADS and the miniSim to estimate the parameters of the model—these simulators were chosen because of their differing configurations. Past research efforts beyond this project to model drivers' speed choice and improve highway safety and capacity have already produced a series of models that predict drivers' speed as a function of roadway geometry.[21,22] For over 50 years, this has been an ongoing and active research topic, and yet there is still not a definitive model.[23,24] Most of these existing statistical models summarize drivers' speed choice without describing the mechanisms that guide speed selection.[25]

Process models, however, complement these statistical models and describe the drivers' perceptual, decisionmaking, and motor control processes.[10,26] Process models can describe drivers' speed selection in terms of an error-correcting mechanism that strives to minimize the deviation from a desired speed. Desired speed might reflect a driver's ability to steer the vehicle through a curve while maintaining an appropriate distance from the lane boundary, often expressed as the time-to-line crossing.[27] Though not part of this research study, one factor that influences this speed choice is traffic in the opposite lane. Without traffic, the research team noted that drivers often cross the centerline to smooth the curve, but most models assume the driver attempts to stay within the lane boundaries. Steering demand increases as the radius of the curvature and lane width decrease and speed increases. Small steering errors at high speed quickly lead a driver toward the lane boundary and forces drivers to slow down to maintain a constant time-to-line crossing. This creates an inverse relationship between lateral acceleration and curve radius and can explain why drivers often choose speeds through curves that are less than what might be expected.[12]

Analyzing Scenarios

The research team focused its analysis on four of the six road segments considered in the earlier simulator data collections. These were the two roundabout sections from Arizona and Maryland.

Two of these sections are featured in figures 7–10. This group of figures shows a bird's eye view of the route through the roundabout, with each stage of the route annotated; and below this, the curvature across the segment is shown, also with each stage annotated. The curvature data from these sections were used as the primary input to the driver model, which determines the speed maintenance behavior of the driver model.

Model-based transformations aim to directly relate driver behavior observed in the simulator to behavior on the actual roadway. A transformation is made possible by first estimating those model parameters that produce the speed trajectories observed on the road; however, the limited on-road data available for this project make such estimates difficult. The researchers estimated the model parameters for each simulator configuration based on the data collected from the simulators. The resulting parameters reflected how simulator characteristics influence driver behavior. The model can then transform the simulator and estimate roadway data by adjusting the model parameters using a scaling parameter based on the ratio of the roadway parameter to the simulator parameter. This method is subsequently able to describe differences in how drivers negotiate curves through parameters of a dynamic driver model. These parameters can provide a more diagnostic and generalizable description of how driving in the simulator differs from driving on the road. The resulting practical utility of this contribution is that it can be used to transform speed observed in the simulator to speed observed on the road.

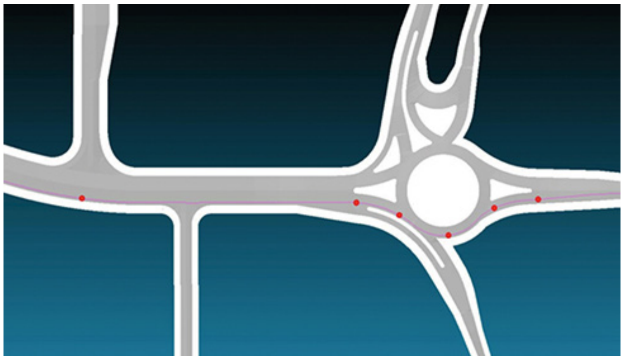
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Figure 7. Layout of the first Arizona roundabout.

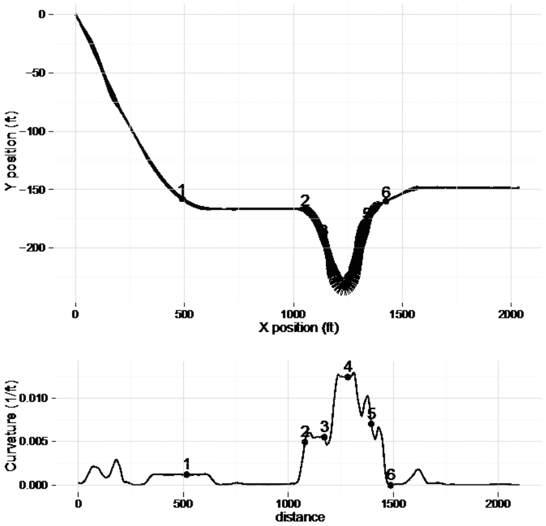

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Figure 8. Layout curvature data of the first Arizona roundabout. (The width of the line in the center graph corresponds to the radius of curvature shown in the bottom graph.)

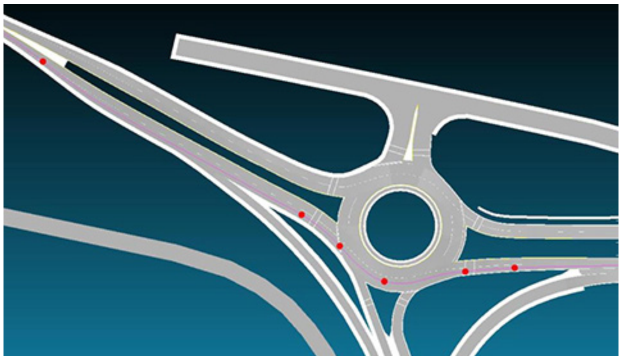
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Figure 9. Layout of the first Maryland roundabout.

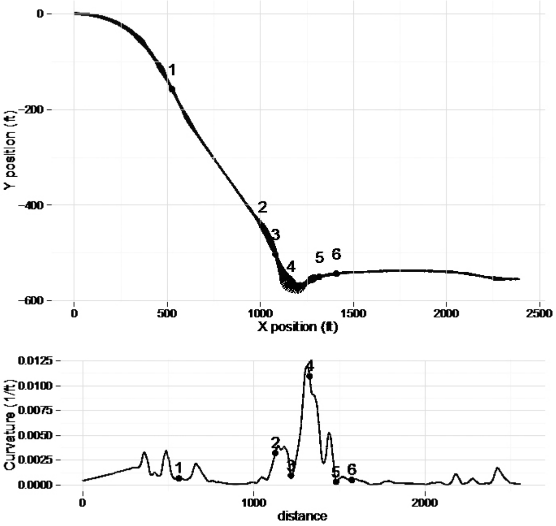

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Figure 10. Layout curvature data of the first Maryland roundabout. (The width of the line in the center graph corresponds to the radius of curvature shown in the bottom graph.).

Conclusions and Recommendations

As described in the previous section, behaviors seen in the driving simulator and on the roadway in this research project are generally in agreement, but there are still some mismatches to be addressed. For example, the distribution of speeds observed in the simulator should ideally match speeds observed on the road, but this is not always the case. Simulator characteristics can explain some of the behavior differences, but there are other important characteristics that can lead to differences, including familiarity with the route and individual driver motivations.

A central challenge in making simulators useful for roadway design concerns how well driver behavior in the simulator matches driver behavior on the road. The results of this study begin to address the question of how simulators can support highway and traffic engineers. Overall, the results show that simulators with high physical fidelity demonstrate high behavioral fidelity and are likely to provide good estimates of mean speeds in typical engineering applications, such as roundabouts and roadway treatments designed to moderate drivers' speed. The use of the data from simulator studies can also be further refined through the use of the transformations developed as part of this research. The detailed analysis of both physical and behavioral fidelity included in this study suggests important opportunities to improve simulator fidelity and the need to carefully assess the match between simulator features and the properties of the roadway design issue.

In general, the NADS and WTI simulators showed the highest level of fidelity across the range of metrics examined; however, results also showed that no single metric can serve as a proxy for overall simulator fidelity. This illustrates how simulators can differ across different dimensions that affect the level of fidelity. The broad concept of an overall level of fidelity is also misleading and should instead be addressed in a multidimensional manner. In addition, there is a need, when considering fidelity, to consider the type of vehicle the simulator is designed to reproduce and the type of measure that is relevant in a given scenario. For example, the effect of using a motion base was minimal in the scenarios used in this study because there were few occasions of strong lateral or longitudinal g-forces. Indeed, the effect of simulator platform (e.g., miniSim versus NADS) was often less influential than was the effect of the details included in creating the virtual roadway (e.g., visual complexity).

The results of this research project confirm the importance of understanding how different dimensions of physical fidelity work together to provide overall fidelity. As noted earlier in this summary, even without perfect fidelity, drivers adapt and make use of the cues available to respond to the changes in the driving environment. Fewer cues for speed estimation may lead simulator drivers to attend to the speedometer more than they would on the road. Some of these differences in physical fidelity can degrade driver response to the point that behavioral fidelity is compromised, whereas in other cases drivers adapt compensating behaviors that allow for realistic responses but may not fully reflect how the driver would respond in the real world. Attending to the speedometer to maintain the instructed speed may distort how drivers respond to other elements of the roadway. These cases therefore require care when interpreting the results.

The interaction between physical fidelity levels and resulting behavioral fidelity also needs to be considered. First and foremost, the driver experiences the simulator software through the visual display, motion system, sound system, steering torques, and pedal forces. If the steering forces are not produced by the vehicle dynamics model, then the vehicle dynamics that the driver experiences will differ substantially from the true one. In a similar vein, if the simulator does not present vestibular cues, then much of the vehicle dynamics (accelerations) will not be perceived directly by the fast vestibular system but instead through slow visually perceived speed changes; therefore, drivers will perceive dynamics as much more sluggish than what the software might portray.

This research effort provides a valuable contribution to the understanding of the use of simulators for evaluating roadway designs. Prior efforts have focused on addressing research design projects on single platforms in a fixed configuration and have failed to address the discrepancies among outcomes on different platforms. This project directly addresses those issues to provide guidance to the research community and highway designers. The research shows how the simulator configuration affects speed in the simulator relative to the real worldreal world. In addition, it shows that model-based transformations can be used to estimate speed adjustments based on the simulator configurations for the platforms tested and can potentially be extrapolated to other configurations. The results show that using a high-fidelity simulator, such as the NADS, FHWA, or WTI simulator, with attention to accurately rendering the visual complexity of the roadway, will lead drivers in the simulator to drive at speeds quite comparable to those observed on actual roadways.

Overall, the research team for this project developed a set of tools that provide the foundation for future work that allows designers to transform results for simulator studies to make design decisions and to predict changes in driver behavior and performance based on evaluations conducted on simulators. This project is an important first step in understanding not only the translation of simulator data to real-world contexts, but also the hidden and complex issues that underlie this type of study, comparing multiple simulators with each other and with a real-world data set. Some of the key contributions of this project include the following:

- Proposed set of metrics and methods to characterize the physical fidelity of simulators.
- Proposed set of analytic methods and graphics to characterize the behavioral fidelity of simulators.
- Identification of simulator characteristics that may be most relevant to measuring speed in road design (e.g., visual complexity, field of view, and motion base).
- Linear model specific to each simulator to predict mean speed and speed variance for real-world context (for the scenarios selected).
- Driver model specific to each simulator to transform curve negation speed in the simulator to the real-world curve context.

Future Research

Understanding Real-World Values

The metrics and methods used in this study to characterize physical fidelity of simulators highlight a need to consider differences among actual vehicles in assessing simulator fidelity. When considering differences between real-world cues and those provided by the simulator, a more extensive survey of typical values of vehicle characteristics should be conducted, as it was revealed that parameters can vary from vehicle to vehicle in the same class. Understanding the range of possible real-world values will enable more accurate descriptions of simulator vehicles relative to their real-world counterparts than is possible when a single vehicle is chosen to represent a class of vehicles. Normalizing for these differences in variation could greatly improve the mapping from simulator characteristics to physical and behavioral fidelity.

Tuning Vehicle Characteristics

Looking to the future, a specific research direction to address vehicle characteristics could investigate methods to tune simulators with respect to a standard vehicle or a generic compiled vehicle (e.g., based on the average of a set of typical vehicles) or develop methods to quickly adjust tuning parameters to the type of vehicle (and expected "feel") of a given driver. In addition, the approach used in this report could be expanded to include a wider range of typical vehicles, rather than a single example.

Considering Virtual Fidelity

When describing overall simulator fidelity, weighting the factors that can be easily described provides insight into how simulators compare to each other and the real world; however, this does not provide a comprehensive understanding, because not all features that matter are easily measured and not all features contribute equally. When simulators are considered relative to a specific type of evaluation, weighting the factors that contribute based on their influence on the behavior of interest is a better approach to understanding the relative fidelity to address research questions. This would mean that a simulator might be a "high" fidelity simulator for accessing speed through a roadway design but a "low" fidelity simulator for another design problem. The results of this project point to the importance of considering the fidelity of the virtual environment in this assessment—visual complexity had a larger effect than the motion base. Along these lines, the presence of traffic might have a surprisingly strong effect on driver behavior.

Quantifying Simulator Characteristics

Further research is needed to quantify the variation of simulator characteristics, the degree to which drivers can adapt to different vehicle simulator characteristics, and the degree to which these characteristics influence behavior as well as driving strategies and operator workload. In addition, a larger number of simulator configurations should be compared to make the mapping from simulator characteristics to behavior tractable. To achieve this, researchers will need to develop focused studies that explore which simulator characteristics humans can adapt to and which distort behavior. Based on the results of this study, systematic variation of simulator features, such as visual complexity, as well as sound and vibration might be particularly fruitful.

Collecting Additional Real-World Data

To further understand the comparison between the simulator and the real world, additional real-world data is required to provide a more continuous and complete description of driver behavior. This project was limited to speed observed on the road at widely spaced points, and the current on-road data are sparse with no lane position data. Continuous speed data along with accelerator pedal modulation and lane-position data would provide a much richer basis for comparing behavior in the simulator to that observed on the road. Collecting instrumented vehicle data in 3 segments by using 15 subjects per condition so that a model can be developed would provide a strong foundation for continuing this research.

Examining Naturalistic Data

Naturalistic data provide another promising avenue for future research. Naturalistic data associated with crash and near-crash situations observed on the road could be replicated in the simulator where a more detailed assessment of driver behavior and potential countermeasures would be possible. This would provide a more comprehensive basis for using driving simulators to enhance traffic flow and also improve road safety. Rather than a focus on replicating speed observed on the road, the focus could be on replicating in the simulator the behavior that precipitates crashes.

Additional Information

The full final report of this project, *Making Driving Simulators More Useful for Behavioral Research—Simulator Characteristics Comparison and Model-Based Transformation* (October 2013), is available at: www.nads-sc.uiowa.edu/publicationStorage/20131399331159.N2013-016_Making%20driving%20simul.pdf.

The full report also includes the following additional information:

Simulator Characteristics Study

The researchers surveyed organizations that operate driving simulators to identify a full range of characteristics, capabilities, and limitations found in a representative sample of driving simulators. The survey evaluated a range of simulators from desktop to full-vehicle simulators using a variety of displays and controls.

The survey included a brief, informal literature review to ascertain the state of the technology and current practices in driving simulation. The researchers subsequently developed a survey of simulator characteristics based on the results of the review and input from subject matter experts in the field of driving simulation.

Simulator Descriptions

The full report provides a high-level description for each of the simulators included in the survey. These descriptions provide a broad overview of the distinguishing characteristics of each simulator system. Features listed include type of cab, visual display characteristics, motion and haptic capabilities, and audio capabilities.

Summary of Characteristics

The full report includes a summary of the primary characteristics of the driving simulators. This is intended to provide a basis for comparing the features that are likely to be most important to the goals of the project. A table lists characteristics that are related to dimensions of fidelity that will likely affect driver performance.

Measurement Protocol for Characterizing Simulators

The researchers made measurements of the visual, motion, vibration, haptics, tactile, and sound cues in each of the four simulators. They included specific measurements in the final report to assure that it can accurately quantify the degree to which a simulator satisfies the simulator perceptual-control requirements.

Participant Forms and Questionnaires

The full report includes a copy of the motion sickness screening form and motion sickness and simulator realism questionnaires provided to participants.

Contact Information

For more information on this project, contact Brian Philips at FHWA, 202-493-3468 (email: brian.philips@dot.gov).

References

1. Lunenfeld, H., & Alexander, G. J. (1990). *A user's guide to positive guidance* (3rd ed., Publication No. FHWA-SA-90-017). Washington, DC: Federal Highway Administration.
2. Evans, L. (1987). Factors controlling traffic crashes. *Journal of Applied Behavioral Science, 23*(2), 201–218.
3. Shankar, V., Mannering, F., & Barfield, W. (1995). Effect of roadway geometrics and environmental factors on rural freeway accident frequencies. *Accident Analysis & Prevention, 27*(3), 371–89.
4. Kaptein, N., Theeuwes, J., & Van der Horst, R. (1996). Driving simulator validity: Some considerations. *Transportation Research Record: Journal of the Transportation Research Board, 1550,* 30–36.
5. Hughes, R. (2005). Research agenda for the application of visualization to transportation systems. *Transportation Research Record: Journal of the Transportation Research Board, 1937*(1), 145–151.
6. Manore, M. (2007). Visualization education and training. *TR News 252,* 24–28.
7. Lee, J., Lee, J. D., McGehee, D. V., Brown, J. L., Richard, C. M., Ahmad, O., Ward, N. J., Hallmark, S., & Lee, J. (2011). Matching simulator characteristics to highway design problems. *Transportation Research Record: Journal of the Transportation Research Board, 2248,* 53–60.
8. Blaauw, G. J. (1982). Driving experience and task demands in simulator and instrumented car: A validation study. *Human Factors, 24*(4), 473–486.
9. Godley, S. T., Triggs, T. J., & Fildes, B. N. (2002). Driving simulator validation for speed research. *Accident Analysis & Prevention, 34,* 589–600.
10. Hildreth, E. C., Beusmans, J. M. H., Boer, E. R., & Royden, C. S. (2000). From vision to action: Experiments and models of steering control during driving. *Journal of Experimental Psychology: Human Perception and Performance, 26*(3), 1106–1132.
11. Sidaway, B., Fairweather, M., Sekiya, H., & McNittGray, J. (1996). Time-to-collision estimation in a simulated driving task. *Human Factors, 38*(1), 101–113.
12. Reymond, G., Kemeny, A., Droulez, J., & Berthoz, A. (2001). Role of lateral acceleration in curve driving: Driver model and experiments on a real vehicle and a driving simulator. *Human Factors, 43*(3), 483–495.
13. Siegler, I., Reymond, G., Kemeny, A., & Berthoz, A. (2001). Sensorimotor integration in a driving simulator: Contributions of motion cueing in elementary driving tasks. In *Proceedings of the Driving Simulation Conference 2001.* Sophia-Antipolis, France.

14. Brunswik, E. (1952). T*he conceptual framework of psychology.* Chicago, IL: University of Chicago Press.

15. Kirlik, A. (2009). Brunswikian resources for event-perception research. *Perception, 38,* 376–398.

16. Bella, F. (2008). Driving simulator for speed research on two-lane rural roads. *Accident Analysis & Prevention, 40*(3), 1078–1087.

17. Dagdelen, M., Reymond, G., Kemeny, A., Bordier, M., & Maozi, N. (2009). Model-based predictive motion cueing strategy for vehicle driving simulators. *Control Engineering Practice, 17*(9), 995–1003.

18. Inman, V. W., Williams, J., Cartwright, R., Wallick, B., Peter Chou, P., & Baumgartner, M. (2007). *Drivers' Evaluation of the Diverging Diamond Interchange* (Publication No. FHWA-HRT-07-048). McLean, VA: Federal Highway Administration.

19. Lee, J. C., Kidd, D. D., & Scarbrough, W. (2003). *Roundabouts: An Arizona case study and design guidelines.* Phoenix, AZ: Arizona Department of Transportation.

20. Shechtman, O., Classen, S., Awadzi, K., & Mann, W. (2009). Comparison of driving errors between on-the-road and simulated driving assessment: A validation study. *Traffic Injury Prevention, 10*(4), 379–385.

21. Emmerson, J. (1969). Speeds of cars on sharp horizontal curves. *Traffic Engineering and Control, 11*(3), 135–137.

22. McRuer, D., & Weir, D. (1969). Theory of manual vehicular control. *Ergonomics, 12*(4), 599–633.

23. Lehtonen, E., Lappi, O., & Summala, H. (2012). Anticipatory eye movements when approaching a curve on a rural road depend on working memory load. *Transportation Research Part F: Traffic Psychology and Behaviour, 15*(3), 369–377.

24. Wang, F., & Easa, S. M. (2009). Validation of perspective-view concept for estimating road horizontal curvature. *Journal of Transportation Engineering, 135*(2), 74–80.

25. Odhams, A. M. C., & Cole, D. J. (2004). Models of driver speed choice in curves. In *7th International Symposium on Advanced Vehicle Control (AVEC 04)*. Delft: Royal Dutch Association of Engineers.

26. Land, M. F. (1998). The visual control of steering. In R.L. Harris & M. Jenkin (Eds.), *Vision and Action* (pp. 163-180). Cambridge, UK: Cambridge University Press.

27. Van Winsum, W., Godthelp, H. (1996). Speed choice and steering behavior in curve driving. *Human Factors, 38*(3), 434–441.

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