# Exploratory Advanced Research: Making driving simulators more useful for behavioral research – Simulator characteristics comparison and model-based transformation

**October 2013**

U.S. Department of Transportation
Federal Highway Administration

# FOREWORD

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; however, discrepant results across studies undermine the utility of these findings. This is particularly true when on-road behavioral data do not match driving simulator data. The goal of this project was to develop a mathematical transformation that will allow researchers and transportation engineers to better predict the behavior of drivers in real environments based on the results of experiments conducted in driving simulators.

This document represents the final technical report for this project. The results show that using a high-fidelity 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. The models developed in this project, and presented here, will enable the driving safety research community and highway designers to predict real-world driving behavior more accurately from behavior in driving simulators and to integrate the results from different simulators.

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National Advanced Driving Simulator
The University of Iowa
2401 Oakdale Blvd.
Iowa City, IA 52242

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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)** | | |
| $^oF$ | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | $^oC$ |
| | | **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)** | | |
| $^oC$ | Celsius | 1.8C+32 | Fahrenheit | $^oF$ |
| | | **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)

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# EXECUTIVE SUMMARY

Highway and traffic engineers face considerable challenges in creating designs that are consistent with drivers' capabilities and expectations, but 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; however, 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 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, where a low-fidelity desktop simulator could be used for rendering scene and roadway furniture, while a higher-fidelity simulator is 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 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. Specifically, highway design needs were identified and matched to specific simulator characteristics to facilitate the appropriate choice of simulator for a particular design problem. A proof of concept approach to characterizing simulator fidelity was developed and demonstrated to allow for comparison between simulators and the real-world. This project 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. This virtual environment was manipulated to vary the visual complexity of the driving environment and was tested on four simulator platforms, three of which were tested with and without motion. Driver judgment of fidelity and performance across the simulator platforms were compared. 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. These data were also used 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 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. 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.

Additional work is necessary to improve and refine the tools developed in this research. One area that requires refinement is the characterization of simulators. The 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 between vehicles on critical measures. These data can be used to enhance the psychophysical scaling needed to determine when a simulator is noticeably different from a typical vehicle. The extent to which different vehicle types influence highway design decisions, these differences must also be investigated to determine if 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 in order to provide the opportunity for continued evaluation and refinement. Use of a simulator to support a state DOT 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 is 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 final 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, 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. This requires a reliable and validated model of the driver. Additional work along these lines is 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. Ultimately, a comprehensive approach that integrates a driver model with IHSDM would provide benefits to highway designers as an efficient way of using previous data to assess new design decisions.

# CHAPTER 1—INTRODUCTION

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. 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]. Recent advances in simulation technology have resulted in the proliferation of driving simulators that vary in terms of the level of fidelity, complexity of operation, and cost of use. Such diversity makes it difficult to know which simulator is appropriate to address a given design question.

With few exceptions, driving simulators have generally fallen short of their potential as a design aid [7, 8, 9, 10]. The uncertainty regarding which issues would benefit from simulator based evaluations, the challenge of selecting an appropriate simulator for a given design issue, and the mismatch between simulator data and on-road data are three reasons why simulators have not been more widely used by highway and traffic engineers [11].

Making driving simulators more useful for highway and traffic engineers depends on understanding how the characteristics of simulators (e.g., the field of view of the display system and motion cueing) influence driver behaviors (e.g., speed choice and lane position control). Ideally, simulator characteristics would exactly match the characteristics of actual cars and roadways, but even the most sophisticated simulators cannot perfectly replicate an actual roadway. Minimizing the mismatches between the physical characteristics of the simulator and the roadway should minimize the differences between behavior observed in the simulator and on the road. Although important, the physical match of simulator features to what drivers experience on the road is but one feature of the overall driving experience. Other factors that are extremely difficult, or even impossible, to replicate in the simulator can affect behavior, such as the motivation for the trip or the consequences of a crash. Consequently, matching the physical features of the simulator to the roadway experience—physical fidelity—is an important, but not sufficient, condition to ensure that behavior in the simulator matches behavior observed on the road [12].

To date, the driving simulator community has focused on gross measures of physical fidelity, such as "high" or "low" fidelity or the field of view of the projector system. Physical fidelity is the degree to which the simulator performance characteristics match the actual characteristics of vehicles and roads. Matching the characteristics of vehicles (e.g., cars and trucks) and roads to some degree is needed to provide drivers with the information necessary to guide behavior, so physical fidelity is the first step in achieving the broader goal of behavioral fidelity [4]. Behavioral fidelity is the degree to which the behavior of the drivers in the simulator matches the behavior of drivers on the road. A necessary condition for behavioral fidelity is sufficient realism of the input control and handling characteristics of the simulator vehicle with respect to actual vehicle performance [13]. What constitutes sufficient realism depends on the specific situations being simulated and the study objectives, but ultimately it depends on matching behavior in the simulator to behavior on the road precisely enough to support design decisions.

The two types of fidelity are related to each other. Often, imperfect physical fidelity leads to imperfect behavioral fidelity [12]; however, even imperfect fidelity is often sufficient to support roadway design decisions. At the most basic level, a simulator might fail to replicate the cues needed to guide behavior. It is possible that a simulator with a display system that is not bright enough to render the actual texture of the roadway might lead drivers to drive faster in the simulator than they would on the actual road because the driver is not provided with sufficient optic flow information [14, 15]. Often such deficiencies are difficult to identify because multiple cues specify the situation and can be interchanged by drivers to guide behavior. Drivers' ability to negotiate curves in a fixed-base simulator illustrates how visual cues can substitute, although imperfectly, for vestibular cues [16, 17]. Drivers' ability to substitute one set of cues for another partially explains the difference between physical and behavioral fidelity. As a result, two very different simulators might produce similar behavior because drivers can adapt and use the cues that are available in each [18, 19].

Another factor that complicates the discussion of simulator fidelity concerns the degree to which the simulator might provide information needed for one task but not another. A simulator might be a high-fidelity simulator for one set of tasks and only a medium-fidelity simulator for other tasks. For example, a simulator with high resolution and a narrow field of view might render road signs very accurately and would be a high-fidelity simulator for driving that involved sign reading. In contrast, this same simulator might be a low-fidelity simulator for driving that involves 90 degree turns because it does not provide the preview of the road on which drivers rely during the turn [4]. Task-dependent fidelity and the difference between physical and behavioral fidelity motivates our comparison of behavior across four simulator platforms, four simulator configurations (i.e., two levels of motion-base and visual complexity), and six roadway scenarios (i.e., four roundabouts and two gateways).

## SIMULATOR FIDELITY AND ROADWAY DESIGN

Earlier stages of this project solicited input from engineers regarding situations in which simulators might help guide roadway design [11]. A series of discussions with 20 subject-matter experts (engineers from federal, state, and local agencies) described their use of behavioral data in roadway and infrastructure design and operations. Several design issues that are not being met by existing data or design standards were identified, in order of frequency of mention:

- Speed selection
- Lane selection
- Gap acceptance
- Sign comprehension and compliance
- Work zone driving

These issues guided the focus of this study, which focuses on speed selection. These interviews also identified specific design scenarios for which subject-matter experts expressed interest in using simulators. In order of frequency of mention, they were:

- Intersections and interchanges
- Work zones
- Speed selection
- Traffic control device (TCD) comprehension
- Road departure on curves
- Roundabouts

The simulator scenarios of most interest were intersections and interchanges, work zones, and speed selection. Of these scenarios, roundabouts and road treatments to promote speed reduction when transitioning from rural highways to towns were identified as promising for this project because these scenarios are relevant to highway design and some data from actual roads are available for comparison. Two roundabouts and two gateway scenarios were implemented and evaluated on four simulator platforms. The scenarios and simulators provide a representative sample of design issues and simulators that might be used to address those issues.

## OBJECTIVES

In the context of supporting the efficient, effective, and valid use of driving simulators for traffic engineering applications, this report has four primary objectives:

1. Provide a comprehensive description of the driving simulators used in this project.

2. Document and describe the physical fidelity in terms of the cues drivers use for vehicle control (i.e., sounds, vibrations, and forces).

3. Assess the behavioral fidelity of these simulators.

4. Present a model developed as part of this project to relate simulator behavioral data collected in a driving simulator to data collected on the road.

Section 1 summarizes the sample of driving simulators that is fully described in Appendix A. Section 1 also describes simulator features from the perspective of the cues provided to support driving tasks. Section 2 describes the behavioral fidelity of the simulators in terms of how well the speeds observed in the simulators match the speeds observed on the road. The final section presents a model of speed control through curves that can be used to relate simulator and roadway data.

# CHAPTER 2—PHYSICAL FIDELITY

Simulator fidelity can be described in many ways. Behavioral fidelity is associated with the simulator's ability to replicate the behavior observed in the world. Physical fidelity relates to the degree to which the simulator replicates the physical properties of the driving situation. Physical fidelity often provides a starting point for ensuring behavioral fidelity. This section provides a brief overview of each of the simulators followed by detailed measurements of the simulator characteristics. The simulators include the National Advanced Driving Simulator (NADS), the Federal Highway (FHWA) Driving Simulator, the Western Transportation Institute (WTI) Simulator, and the NADS miniSim. These represent a broad range of simulation capability and fidelity.

Table 1 summarizes these simulators.

**Table 1. Characteristics of the four simulators.**

| Characteristic | NADS | FHWA | WTI | miniSim |
|---|---|---|---|---|
| **Buck** | • Full-vehicle<br>• Passenger vehicle, SUV, heavy truck, farm tractor, front-end loader | • Full-vehicle<br>• Passenger vehicle | • Full-vehicle, half-vehicle<br>• Passenger vehicle (heavy truck pending) | • Quarter-vehicle<br>• Passenger vehicle, SUV, heavy truck |
| **Driving controls (steering, brake, etc.)** | • Integrated into full vehicle cab | • Integrated into full vehicle cab | • Integrated into full vehicle cab | • Seat and steering wheel from actual car mounted in quarter cab |
| **Screens (simulation environment)** | • Spherical<br>• Front projection<br>• Eight channels<br>• Edge blending<br>• Image warping | • Cylindrical<br>• Front projection<br>• Five front channels<br>• Three rear channels<br>• 10° edge blending | • Cylindrical<br>• Front projection<br>• Six channels<br>• Flat rear screen | • Three flat screens<br>• Plasma displays<br>• Gap between images<br>• No rear screens |
| **Physical size of each display/screen** | 150" (H)<br>96" (V) | 450" circumference, 118" radius<br>90" (H) | 120" (H)<br>96" (V) | 36" (H)<br>24" (V) |
| **Field of view** | 360° (H)<br>48° (V) | 240° (H)<br>5448° (V) | 240° (H)<br>38° (V) | 132° (H)<br>24° (V) |
| **Resolution (arcminutes per pixel)** | Front 120°: 1.6<br>Remaining: 2.1 | 1.42 (H)<br>2.11 (V) | 2.0 | 2.4 (H)<br>1.9 (V) |
| **Mirrors** | • Passive mirrors<br>• Active display panel in mirror fixture | • Passive mirror (center)<br>• Active display panel in mirror fixture | • Passive mirror (center)<br>• Active display panel in mirror fixture | • Emulated mirrors using on-screen images |

| Characteristic | NADS | FHWA | WTI | miniSim |
|---|---|---|---|---|
| **Audio sources** | • 4.1 surround<br>• Highly to generally localized horizontally | • 4.1 surround<br>• Highly localized horizontally | • 4.1 surround<br>• Highly localized horizontally | • 4.1 surround<br>• Generally localized horizontally |
| **Audio calibrated to real-world levels** | Yes | Yes, for 0-60 mph | Yes | No |
| **Motion base** | Hexapod on linear X-Y bed | X-Y tilt | Hexapod | None |
| **Degrees of freedom** | 13 | 3 | 6 | – |
| **Vibration** | • Vibration on wheels<br>• Vibration on steering column<br>• Multi-zone seat vibration | • Vibration on wheels<br>• Vibration on steering column<br>• Vibration on steering column | • Vibration on wheels<br>• Vibration on steering column<br>• Vibration on steering column | • Seat shaker |
| **Tactile feedback** | • Force feedback in steering<br>• Active counterforce in brake and accelerator pedals | • Force feedback in steering<br>• Passive resistance in brake and accelerator pedals | • Force feedback in steering<br>• Passive resistance in brake and accelerator pedals | • Force feedback in steering<br>• Passive resistance in brake and accelerator pedals |
| **Road definition** | • Tile-based geometries | • Programmable tile-based geometries | • Programmable tile-based geometries<br>• Custom-programmed geometries | • Tile-based geometries |
| **Available road geometries** | All | All | All | All |
| **Image complexity** | Near photo-realistic rendering | Near photo-realistic rendering | Near photo-realistic rendering | Near photo-realistic rendering |
| **Size of objects relative to real-world** | 1:1 | 1:1 | 1:1 | 1:1 |

## SAMPLE OF SIMULATORS

### National Advanced Driving Simulator (NADS-1)

The National Advanced Driving Simulator (NADS-1), referred to here as the NADS simulator, used a 1998 Chevy Malibu cab that’s mounted on a motion base with 13 degrees of freedom. Accelerator and brake pedals utilize software-controlled electrical motors to provide feedback. NADS-1 has a 360-degree visual display system. This system consists of eight projectors that project visual imagery inside the dome. All scenery is updated at 60 Hz. The NADS features the ability to swap among several types of vehicle cabs.


**Figure 1. NADS motion-base driving simulator.**

**FHWA Highway Driving Simulator**

The Federal Highway Administration's (FHWA) Highway Driving Simulator (HDS), referred to here as the FHWA simulator, is composed of a full 1998 Saturn vehicle cab mounted on a motion base with three degrees of freedom. The FHWA simulator has 240-degree visual display system. This system consists of five projectors that project onto a cylindrical screen that is 9 feet tall. All scenery is updated at 60 Hz.

**Figure 2. FHWA motion-base driving simulator.**

**WTI Simulator**

The Western Transportation Institute's (WTI) simulator consisted of a 2009 Chevy Impala sedan mounted on a Moog 200E motion platform with six degrees of freedom. The WTI simulator has a 240-degree forward field of view system augmented by a 60-degree rear view display system. The system consists 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.

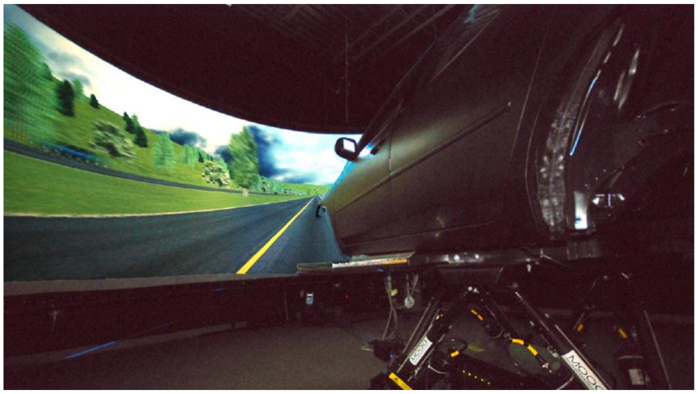

**Figure 3. WTI driving simulator.**

**NADS miniSim Simulator**

The NADS miniSim is a portable, lower-cost simulator that runs software similar to the NADS simulator, and is referred to here as the miniSim. The miniSim has no motion base. As configured for this study, the miniSim featured a quarter-cab configuration with a seat and steering wheel from an actual vehicle. It has three flat panel plasma displays and projects the image of a rear-view mirror on the center plasma display.

**Figure 4. NADS miniSim driving simulator.**

## METRICS OF PHYSICAL FIDELITY

As seen in Table 1, simulators are often characterized by a set of features that describe their hardware components. The hardware configuration is critical for conveying information to the driver, such as speed and curve geometry, as well as gas pedal force and brake pedal force. While capable hardware is a necessary condition for high behavioral fidelity, it is not a sufficient condition. The ability of driving simulators to convey the driving environment depends on both hardware and software. The software is as important, and in many cases, more important than the hardware because the software ultimately controls what is presented to the driver. The signals generated by the hardware and software influence how the driver perceives the environment and controls the state of the vehicle relative to the environment. Three requirements for supporting a realistic driving simulator include [20, 21, 16]:

1. Perception of distances, speed, and time to reach relevant objects in the world such as lead cars, traffic signs, obstacles, curves, and intersections.

2. Control of the car's speed and heading through steering wheel and brake and accelerator pedals.

3. Vehicle response to the control inputs.

Measurements of simulator characteristics concerning these three key requirements define important differences between simulators even if their hardware specifications are identical. The focus of the following analyses is on the types and quality of the multisensory information that the driver receives from the visual, tactile, auditory, vestibular, and haptic displays that make up a simulator. Table 2 describes a sample of measures used to quantify the physical fidelity of the driving simulators in this study. Appendix B describes a more complete set of metrics and the measurement process of each. Appendix B is constructed to support quantification of physical fidelity in a way that goes beyond simply describing the simulator hardware characteristics.

Assessing how each simulator characteristic might affect behavioral fidelity requires that each be related to what drivers experience on the road in typical vehicles. Because each characteristic has a different unit of measure (e.g., dB, Newton, second), the degree to which a metric differs from a typical car should be scaled and expressed in psychophysically meaningful units, such as the just noticeable difference—jnd). A jnd is defined as the smallest change in a stimulus that will be noticeable in a controlled situation in 50 percent of the trials. What is noticeable in such a controlled situation might not be noticeable in a more natural situation. With sound, 1 dB is a jnd, and a 10 dB increase in sound pressure level is typically perceived as a doubling of loudness. Units of a stimulus defined in terms of jnds make it possible to compare all features of a simulator using the same units, and the jnd units describe how likely it is that differences between simulators will affect driving. If a measurement in the simulator, such as the sound pressure level at 55 mph, is 10 jnds different from the actual car, then drivers are likely to notice. If the resistance in depressing the brake pedal is 0.5 jnds different from the actual car, then drivers are unlikely to notice. Translating the engineering units that describe the simulator into psychophysically meaningful units (such as jnds relative to a typical vehicle) is a promising method for describing and comparing the physical fidelity of simulators.

Table 2 is not exhaustive, but only illustrative of how physical fidelity might be described. A full analysis requires psychophysical data for each metric, measurement of a more complete set of metrics, and measurement of a representative sample of vehicles. An important challenge concerns the lack of psychophysical data needed to define jnds for each metric. Oftentimes those characteristics that are most important to fidelity are not the easiest to measure, while the less useful measures are more easily captured. jnd information is available for sound pressure levels and force sensed through the steering wheel and pedals, but not for many other features of the driving environment. One challenge in estimating jnds is the substantial variation between and within drivers over time [22].

Collecting data for a more complete set of data on simulator cues used by the driver presents a simpler challenge: some important variables are poorly defined and difficult to measure. For example, motion blur caused by the projectors when the vehicle is yawing results in degraded perception of yaw rate. However, motion blur was not included because its measurement requires sophisticated video recording equipment to capture rapid changes in a low-light environment.

Perhaps the biggest limit in describing physical fidelity concerns the comparison to a “typical” vehicle. “Typical” vehicles differ such that one vehicle might have very little road noise and feel, whereas a similar vehicle may have significantly more. For this analysis, the typical vehicle was defined as a Chevrolet Impala, for which the team had sufficient data because it was used in tuning the WTI simulator. As a result, it is expected that the WTI simulator will be more similar to the “typical” vehicle than the other simulators. Future work in defining the range of typical values across the vehicle fleet is needed; however, this was outside the scope of the current project. This analysis does highlight the potential for simulators to differ substantially if they are tuned to different vehicles.

Future research 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. Additionally, the approach used here could be expanded to include a wider range of typical vehicles, rather than a single example, and examine jnd from the ends of the range of typical vehicles.

**Table 2. Simulator characteristics that define physical fidelity.**

| **Simulator Dimension** | **Measure** | **Unit** | **Description and reference for jnd where applicable** |
|---|---|---|---|
| Perception Display | Left Road Marking Contrast | Dimensionless | Contrast between left lane marking and road concrete or asphalt [22]. |
| | Right Road Marking Contrast | Dimensionless | Contrast between right lane marking and road concrete or asphalt [22]. |
| Perception Sound | Sound Level at 0, 25, 45, 65, and 85 mph | dB | Sound level near driver's right ear [24]. |
| Perception Vibration | MagLowFreq at 25 and 45 mph | $m/s^2$ | STD of vibration acceleration below 10 Hz at 25 mph [25]. |
| Control Input Brake | Brake Hysteresis | N | Amount of force change needed to affect a change in brake pedal depression [26]. |
| | Brake Activation | N | Force needed to activate the brake [27]. |
| Control Input Accelerator | Accelerator Depression Offset | N | Force needed to activate the accelerator [27]. |
| | Accelerator Depression Stiffness | N | Average force increase per unit of depression (depression range is [0-1]) [27]. |
| | Accelerator Depression Hysteresis | N | Amount force increase needed to increase pedal depression [27]. |
| | Accelerator Release Stiffness | N | Average force decrease per unit of depression (depression range is [0-1]) [27]. |
| | Accelerator Release Hysteresis | N | Amount force decrease needed to decrease pedal depression [27]. |
| Vehicle Response | Maximum Acceleration | $m/s^2$ | Maximum acceleration reached from standstill with accelerator fully depressed [21]. |
| | Maximum Deceleration | $m/s^2$ | Deceleration reached with brake pedal fully depressed at 80 mph [21]. |

Each metric of physical fidelity for each simulator (e.g., sound level, seconds, etc.) is plotted, and Figure 5 through Figure 9 include a data point indicating the value associated with the reference vehicle (Chevrolet Impala) for this analysis. Where available, the graphs also include the jnd for that measure based on basic psychophysical research and related research on driver perception of vehicle characteristics. The sources of the jnd data are shown in Table 2. The jnd information provides a basis for assessing whether differences between how driving situations were rendered in the simulator differ from the reference vehicle. The typical value serves as a reference point that links the engineering data to both a typical value from an actual car and an associated jnd defining a range around that value where a driver would be unlikely to detect the difference. When the measured values from a simulator fall greatly outside the jnd around the typical vehicle, this indicates lower physical fidelity or greater difference from a Chevy Impala. The reference vehicle used in these data sets was the vehicle used to tune the WTI driving simulator. Therefore, there will naturally be a number of instances where the deviations from the reference value are near zero for the WTI simulator. In contrast, other simulators were not tuned to match this reference vehicle, and therefore their deviations might reflect their being tuned to match a different vehicle. As discussed later, this distinction highlights the need for future research to consider the definition of a "standard reference vehicle."

The following graphs present the physical fidelity metrics described in Table 2 for each driving simulator. Appendix B describes the variables and measurement protocol in more detail. In each graph, data from each simulator are identified by a unique line and symbol. The value of the typical vehicle (Chevrolet Impala) is shown as a horizontal line that extends by one jnd to either side of the typical value. Values that fall on this horizontal line are likely to be perceived as similar to the reference vehicle. In each of the following figures, the horizontal axis indicates the magnitude of the metric (e.g., sound pressure level in dB), and the vertical axis shows the specific metrics (e.g., sound pressure level at 65 mph). The Impala was used as the reference vehicle, but that does not imply that any simulator was better or worse if it deviated from the characteristics of this vehicle.

**Perception**

Perception of the driving scene depends on visual, auditory, and haptic cues. The following example illustrates how the physical characteristics that typically define simulators might not fully reflect the level of fidelity of the simulator.

The visual rendering of the scenarios, as measured from the projected roadway, differs considerably across simulators and between the simulators and the road, as can be seen in Figure 5. Most strikingly, the contrast ratio is much greater on the road than in the simulators. The contrast can influence the visibility of signage, traffic control devices, and road markings. In this study, the contrast of the lane markings might influence the degree to which changes in the curvature of the upcoming road would be discernible to the driver. The NADS and WTI simulators were closest in the reproduction of the contrast ratio associated with the right lane marking. However, none of the four simulators reproduced the contrast ratio associated with the left lane marking of an actual road, but that is expected given the limits of current projection technology. Appendix B includes the measurement protocol used to record each of the metrics in the following figures.

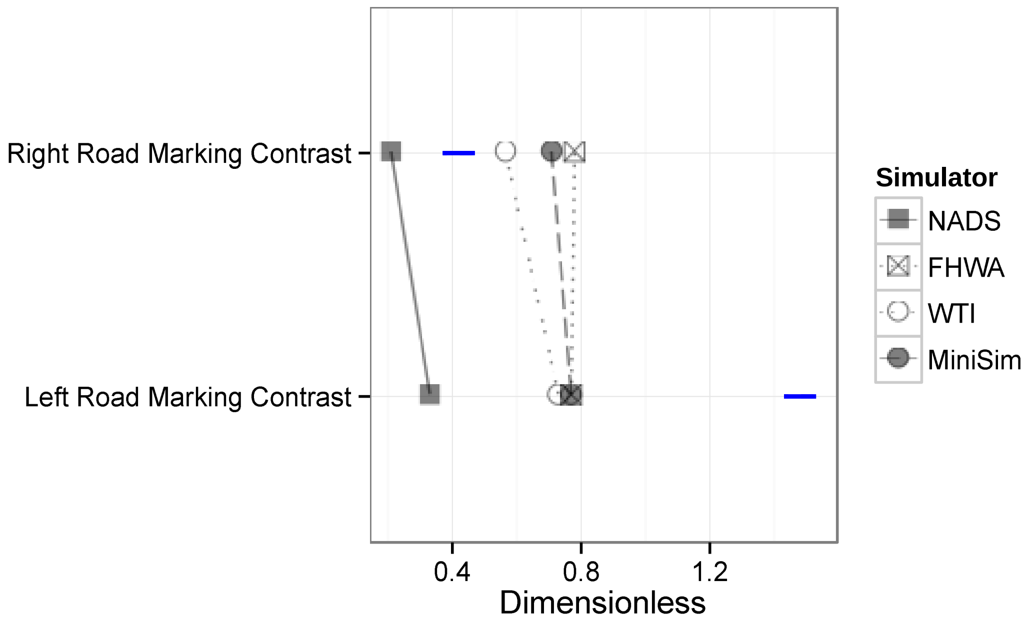


**Figure 5. Display-related simulator characteristics. The blue bars represent the value of the measure for the representative vehicle plus and minus one jnd.**

Sound characteristics are measured in terms of both frequency and loudness. Figure 6 shows that the miniSim and the NADS are systematically louder than the other simulators and that the WTI and FHWA simulators are more consistent with the reference vehicle. Indeed, the WTI simulator is nearly identical with the sound of the reference vehicle for all speeds. As noted earlier, the sound levels for the WTI simulator were tuned to this data, so it is not surprising that they closely align with the "typical" car, whereas the NADS and FHWA simulators did not. Overall, the sound profiles of the FHWA and WTI simulators are more consistent with this "typical" car than the miniSim and NADS.

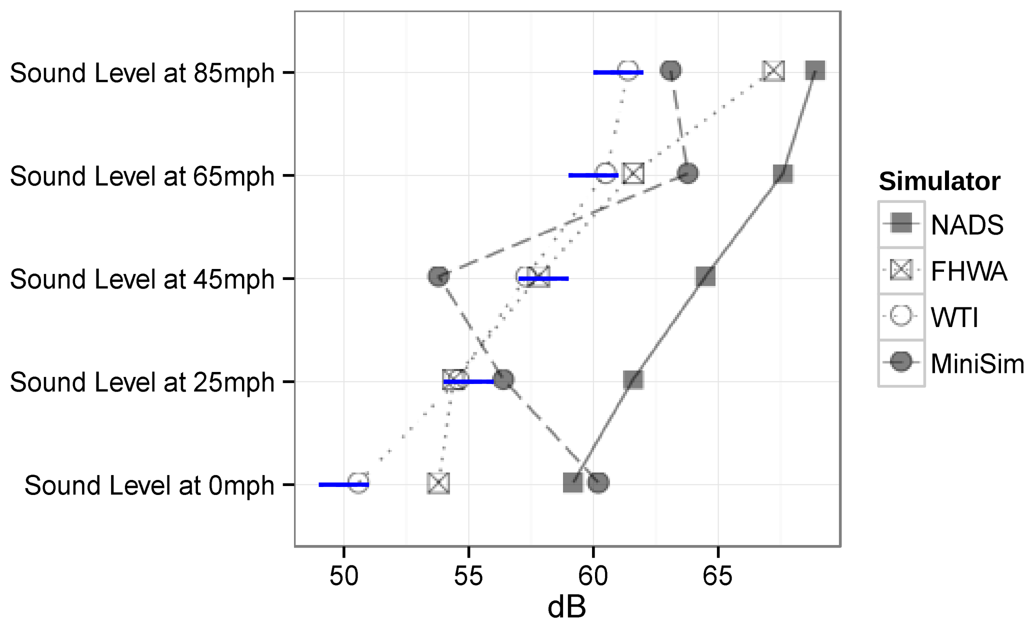


**Figure 6. Sound-related simulator characteristics. The blue bars represent the value of the measure for the representative vehicle plus and minus one jnd.**

The four simulators in this study had marked differences with respect to the motion systems (see Figure 7). The miniSim has no motion or vibration, and the NADS has a large and sophisticated motion and vibration system. The vibration measured in the NADS was considerably greater than in the other simulators, particularly at 45 mph. The miniSim has no motion base, so its measured response is zero for all metrics. Aside from the WTI simulator (which was tuned to match this reference vehicle), all the simulators diverge substantially on several measures related to vehicle vibration for the reference vehicle.

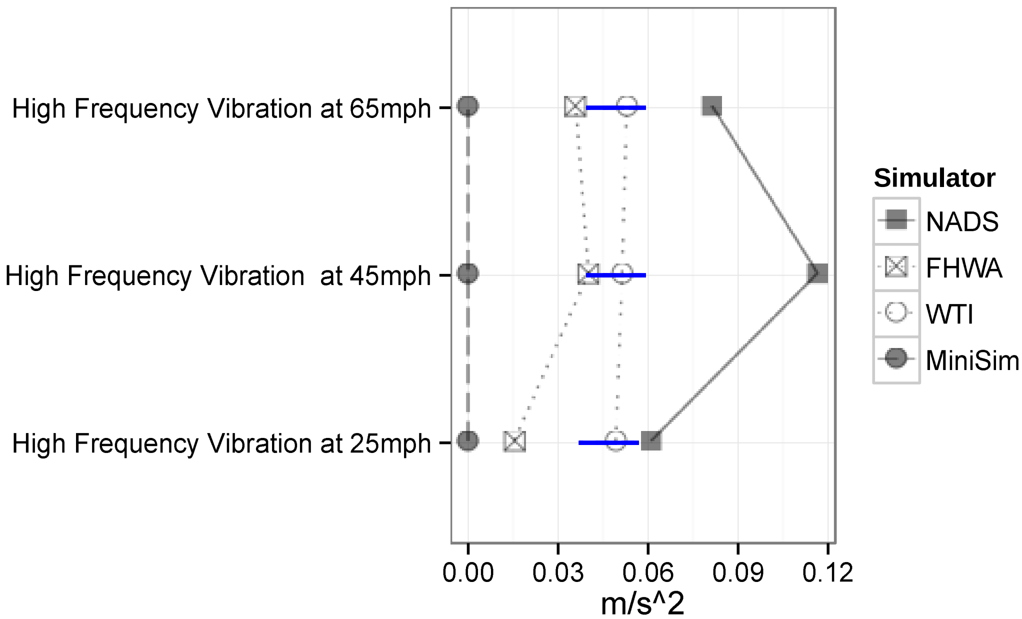


**Figure 7. Vibration-related simulator characteristics. The blue bars represent the value of the measure for the representative vehicle plus and minus one jnd.**

## Control Input

Measures of the brake and accelerator pedal feel, as quantified by stiffness, offset, hysteresis, and activation force, are relatively consistent across simulators. Many of the differences are encompassed by the jnd of the associated measure, as can be seen in Figure 8. The NADS and WTI simulators tend to have the brake and accelerator pedal feel most consistent with the reference vehicle.

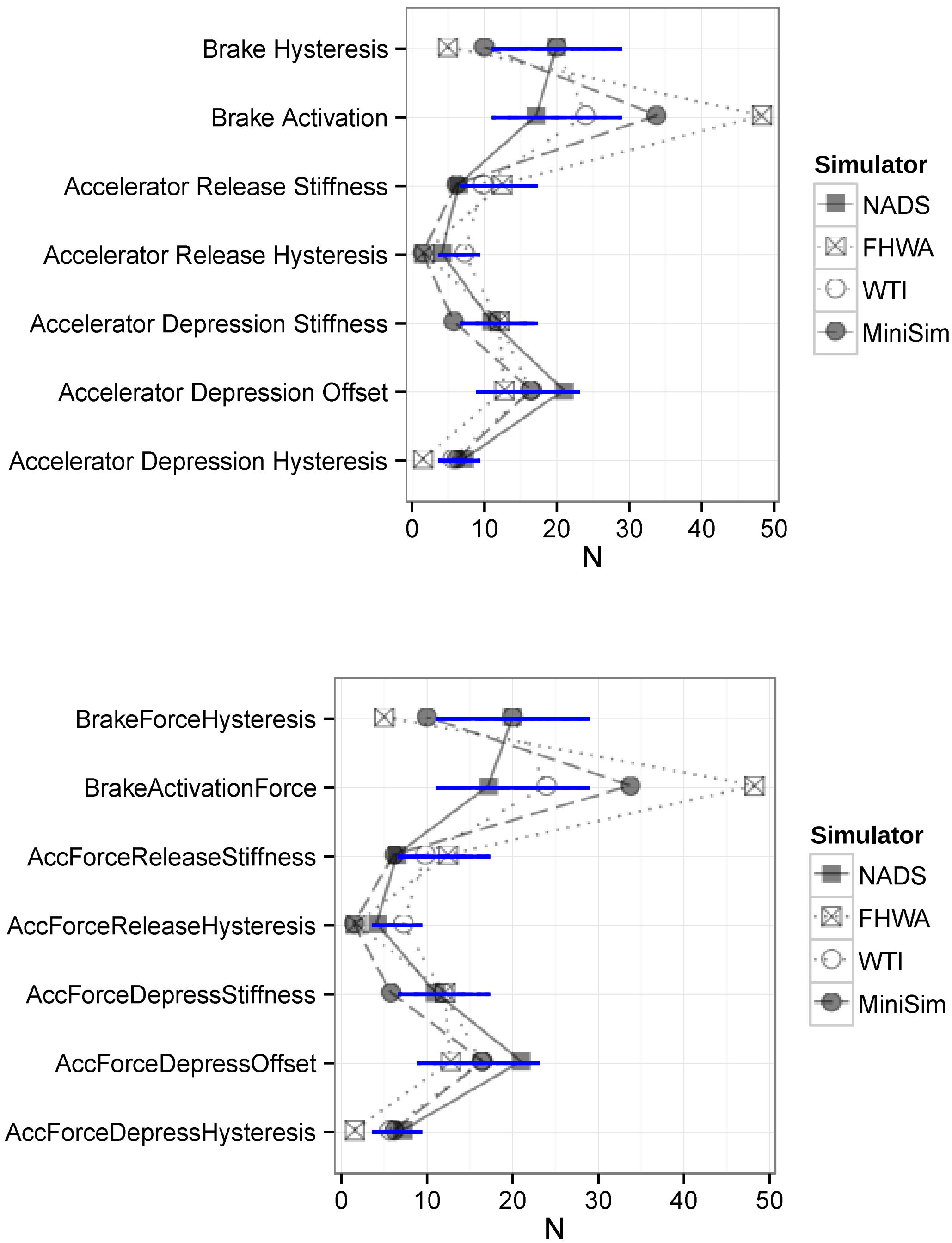


**Figure 8. Accelerator- and brake-pedal-related simulator characteristics. The blue bars represent the value of the measure for the representative vehicle plus and minus one jnd.**

## Vehicle Response

The vehicle response depends on the software model of the vehicle being simulated and the simulator hardware, so is relatively easy to adjust on almost any simulator; however, the interaction of the hardware and software results in some of the more critical measures, such as lag. Figure 9 shows two of the simplest measures of vehicle response: acceleration and deceleration in response to fully depressing either the accelerator or the brake. Again, the NADS and WTI simulators indicated vehicle response closest to the reference vehicle. The miniSim was the most dissimilar from the reference vehicle. Although drivers can easily adapt to minor differences in vehicle response by pressing the pedals more or less aggressively, this may not be effective in some driving scenarios that demand the full response of the vehicle.

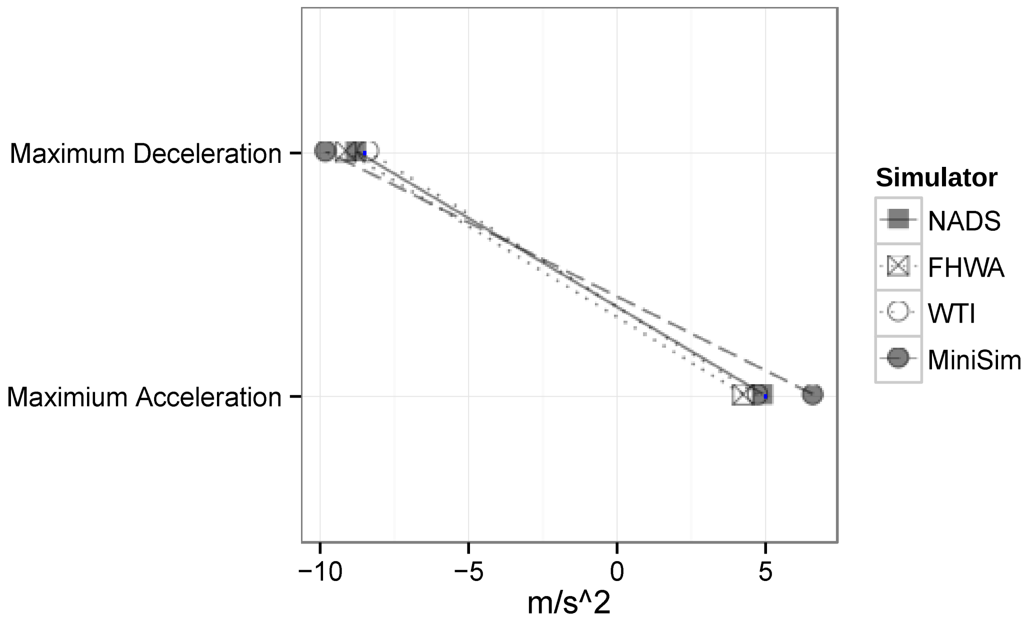


**Figure 9. Vehicle-response-related simulator characteristics. The blue bars represent the value of the measure for the representative vehicle plus and minus one jnd.**

## SUMMARY OF PHYSICAL FIDELITY

Generally, the NADS and WTI simulators showed the highest level of physical fidelity. However, it is apparent that no single metric can serve as a proxy for overall simulator fidelity. This illustrates how simulators can differ across different dimensions that effect level of fidelity. It is clear that the broad concept of overall level of fidelity is misleading and must instead be addressed in a multi-dimensional manner. It also points out the need, when considering fidelity, to consider the type of vehicle the simulator is designed to reproduce.

Just noticeable differences from a typical car provide a useful way to describe how simulators compare across simulator characteristics and may even indicate overall simulator fidelity; however, several issues must be addressed before this approach is applied more broadly. These issues include the fact that (1) only one reference vehicle was used, (2) drivers can adapt to differences between a simulator and real-world driving, (3) the meaningfulness of simulator characteristics varies in a complex manner across driving tasks, and (4) jnd values are not always available for specific simulator characteristics.

For example, cars differ substantially across most of the simulator characteristics measured. In some cases, differences between actual cars can be many jnds and might exceed the differences between simulators, depending on which vehicle is chosen as the reference. As a basis for comparison, validation data from one of the NADS vehicle models, a Chevrolet Malibu, can be expected to have different parameters than the Chevrolet Impala used in this project. Whereas some real-world vehicle reference is desirable for any simulator, these distinctions highlight the need for simulator users to document the parameters of the reference vehicle. In most cases, the particular reference vehicle used to tune the simulator is not likely to substantially alter driver behavior because drivers quickly adapt to substantially different vehicles; however, identifying which differences are important and which are not represents an important challenge.

Drivers easily adapt to a wide range of vehicle characteristics, such as maximum acceleration, maximum deceleration, steering ratio, steering stiffness, pedal stiffness, visual contrast, etc. The observed behaviors are more or less indistinguishable under normal driving conditions because humans adapt such that the human-machine system dynamics remain constant [28]. Put another way, behavior may not be as sensitive to variations in maximum braking force if drivers have experience adapting to different values in different vehicles. Even though a driver might perceive differences between a simulator and the car on the road (e.g., the difference is substantially larger than a jnd), the difference might not influence driver behavior substantially because drivers adapt to the cues and controls available to them. Even though differences in behavior may not be present, these differences between simulators may still result in differences in workload and driver strategies in obtaining the same driving performance.

Differences between simulators affect behavior when vehicle characteristics interact with particular driving tasks in a way that makes it difficult for drivers to adapt [7, 29]. The lack of motion cueing makes smooth cornering, smooth constant deceleration to a stop, or a slow speed very difficult because drivers use vestibular cues as feedback for speed and yaw rate control; the lack of correct vestibular cues results in multi-modal deceleration profiles as well as more oscillatory curve negotiation. A large lag in the dynamics between pedal and/or steering action and perceptible changes in the vehicle state makes stable control difficult. To be able to drive with a large lag, it is necessary to anticipate system behavior that is facilitated by the presence of vestibular cues. A low-contrast or low-resolution screen might cause biases in distance and time-to-collision perception, resulting in brake onset moments that are significantly earlier or later than normal. This bias might be exacerbated by the need for drivers in simulators without motion cues to rely more heavily on visual cues.

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 short, two types of jnd can be distinguished: one that quantifies a detectible change and one that quantifies a meaningful change. The human perception literature focused primarily on the detectible jnd. However, from a driver’s perspective, some small changes in the signals received during driving do not pose any difficulty in terms of maintaining a high level of safe driving performance. Thus a jnd based on meaningful change is more appropriate when targeting quantification of a simulator’s behavioral fidelity. Meaningful jnd in a simulator characteristic is defined as a change that forces drivers to adopt a significantly different driving strategy or accept a significantly lower performance level. Contrast this to detectable jnd, which is defined as a change that drivers can detect. Meaningful jnd is defined more from an external observer's perspective than traditional change jnd. These differences should be manifest in terms of drivers' ratings of simulator realism and in terms of the degree to which speeds adopted in the simulator match those observed on the road.

# CHAPTER 2—BEHAVIORAL FIDELITY

Physical fidelity describes how simulator characteristics match the characteristics of actual vehicles. Transforming these characteristics into psychologically meaningful units with jnd represents a first step in modeling the influence of simulator and roadway characteristics on driver behavior. Behavioral fidelity—the degree to which driver behavior in the simulator matches driver behavior on the road—is the ultimate measure of simulator fidelity. This section describes simulator-based data collection and on-road data collection to describe the behavioral fidelity of the four simulators. To further explore how simulator features affect behavioral fidelity, data were collected with and without the motion base engaged and with and without a more complex visual scene. The analysis focuses on speed production and includes drivers' assessments of simulator realism.

## METHOD

### Participants

Forty-eight people participated in the WTI, FHWA, and NADS simulators, and 23 people participated in the miniSim, for a total of 167 participants. The target age range for participants was 25 to 45 years. Table 3 lists the size and characteristics of the subsample with complete data that was submitted by each site for analysis. The average visual acuity of the subsamples in each site was approximately 20/20 tested with the Freiberg Visual Acuity testing software Landolt C Visual Acuity (http://www.michaelbach.de/fract/index.html) [30].

**Table 3. Subsample demographics for each research site.**

| Site | N | Percent female | Age | Annual mileage | Primary driving location | Roundabout experience | Percent simulator experience (max times) |
|---|---|---|---|---|---|---|---|
| WTI | 48 | 50% | 30.3 y | 16854 | Montana | 96% | 6%<br>(3 times) |
| FHWA | 48 | 44% | 36.9 y | 12955 | DC | 100% | 98%<br>(5 times) |
| NADS | 48 | 35% | 33.1 y | 18198 | Iowa | 98% | 56%<br>(3 times) |
| MINI | 23 | 57% | 33.7 y | 13854 | Iowa | 96% | 57%<br>(3 times) |

### Simulators

The selected simulators were described previously. With the exception of the miniSim, each driving simulator has a motion base. The experiment was conducted with the motion base either on or off to create one of the main independent variables (motion) to examine the effect of haptic and vestibular feedback on driving behavior. A detailed description of the simulators used in this experiment is included in Appendix A.

This study used simulators operating on three different software platforms, and the same scenarios were implemented on each simulator platform. Differences between the software platforms made it difficult to replicate scenarios exactly across the platforms, and substantial effort was devoted to reconciling minor idiosyncrasies of the simulators.

### Scenarios

Two types of road segments were selected based on discussions with FHWA about the potential application of driving simulators to investigate design issues with these elements: roundabout and gateway. These design issues were based on a series of interviews conducted by FHWA regarding situations in which simulators might help guide design [11]. The real-world examples of each road segment were selected based on the availability of spot-speed data from published reports, or from the authors and funding agencies of those reports. The virtual environment reproductions were based on the engineering schematics that were available for each site (for example, see Figure 10).

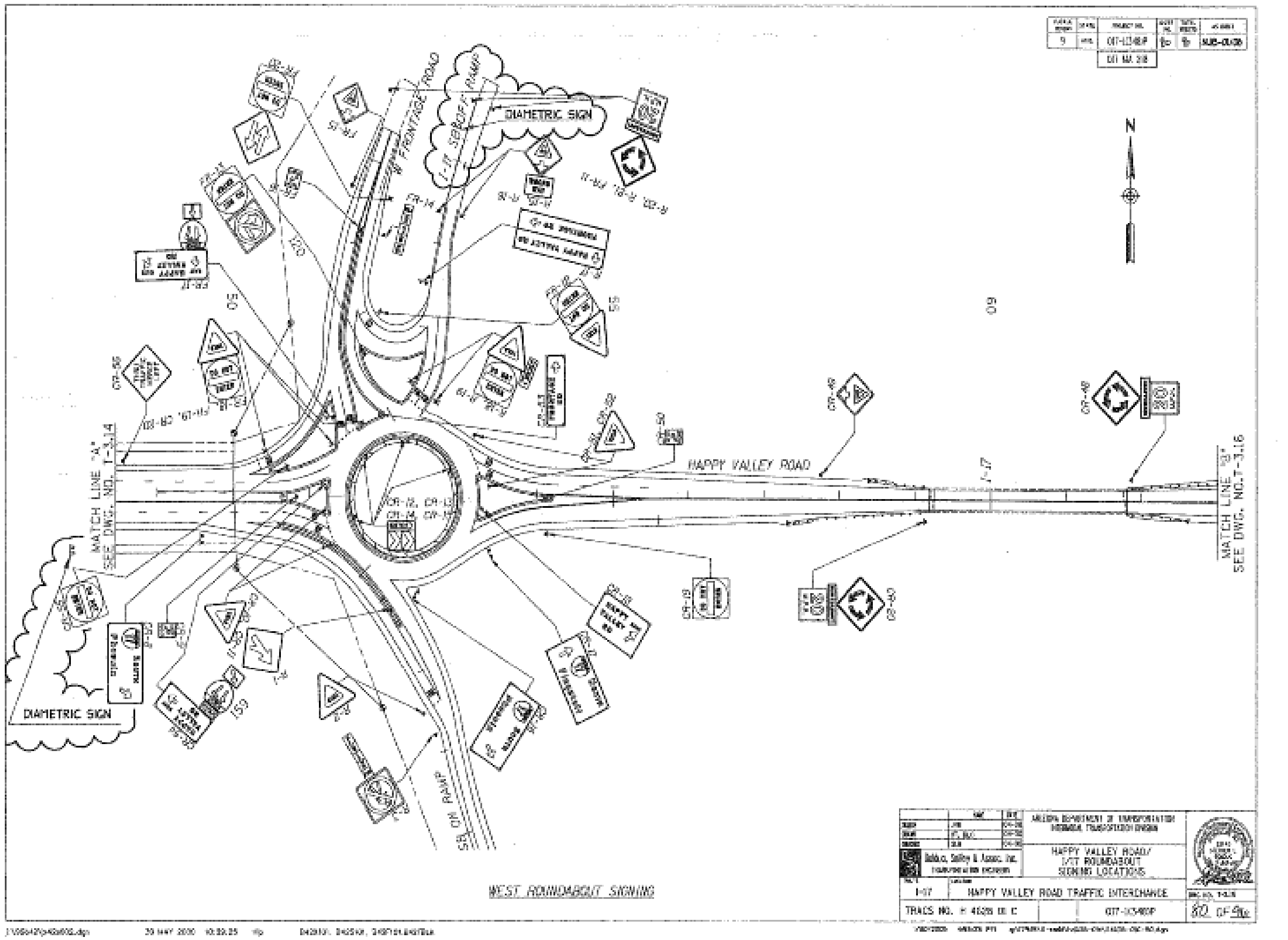


**Figure 10. Example of engineering schematics used to support the reproduction of the road segments (e.g., Arizona, West Roundabout).**

Figure 11 shows roundabout segments. The top of the figure shows a sequence of two roundabouts located on a rural two-lane arterial highway adjacent to the overpass of a major four-lane highway in Maryland [31]. Data was only collected from the one on the east side. Figure 11 also shows a sequence of two roundabouts located on a rural two-lane roadway connecting with a two-lane frontage road adjacent to an interstate highway in Arizona [32].


MD Roundabout – Real
(Google Earth, 2002)


MD Roundabout – Simulated


AZ Roundabout – Real
(Google Earth, 2002)


AZ Roundabout – Simulated

**Figure 11. Example of geometric matching of real (left) and simulated (right) roadway geometry of Maryland (MD) Roundabout (top) and Arizona (AZ) Roundabout (bottom).**

The speed reduction (gateway treatment) was designed to achieve a 25 mph speed limit on a two-lane suburban roadway by using converging chevron pavement markings, narrow lane markings, and speed advisories in Iowa [33]. This segment is referred to as "gateway" because it represents the gateway or transition from a rural road into a town. Two versions of this particular road segment were reproduced as shown in Figure 12. These represented the conditions before the installation of the speed reduction methods and after the installation of the gateway treatment.


**Figure 12. Example of geometric matching of real (top) and simulated (bottom) roadway geometry of a gateway in Iowa (IA).**

As illustrated in Figure 11, 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. A generic representation was used for the local features not affecting navigation (e.g., buildings) and the surrounding landscape.

Implementing identical scenarios on 4 different simulator platforms presented unique challenges. The implementation of driving scenarios for most research grade simulators involves a combination of the following elements: (1) a visual database that contains the 3D geometry and textures that are displayed when a person drives the simulator, (2) an underlying logical road network that contains information about road curvature, connectivity, road surface properties, etc. and (3) a script that initializes and authors all the dynamic elements (such as traffic, traffic signals, time of day, lighting conditions, etc.). Although visual databases for this study were built using an established cross-platform format called OpenFlight™, there wasn't a common underlying logical format for the road networks or the dynamic element scripts. Unlike the visual database development which was shared between sites, duplicative work had to be done at each site for the latter two elements. Furthermore, despite the existence of a common OpenFlight format for the visual databases, engineers at each simulator struggled with the hardware configuration and capabilities of each site's unique graphics systems. It took a significant amount of fine-tuning to take the standardized visual database and make it run effectively and smoothly at those sites that had older graphics hardware. Consequently, this lead to several unplanned iterations of development and testing. A lack of an established standard for road networks and dynamic element scripts was identified as one of the key impediments to making the sharing of driving environments an efficient and smooth process.

Based on these engineering schematics, the virtual environment reproductions matched the geometry, elevation, road design, and signage of each element. In addition, photographs from published reports and GIS data from Google Earth maps were used to recreate the terrain and landscape of the road segment (for example, see Figure 13).

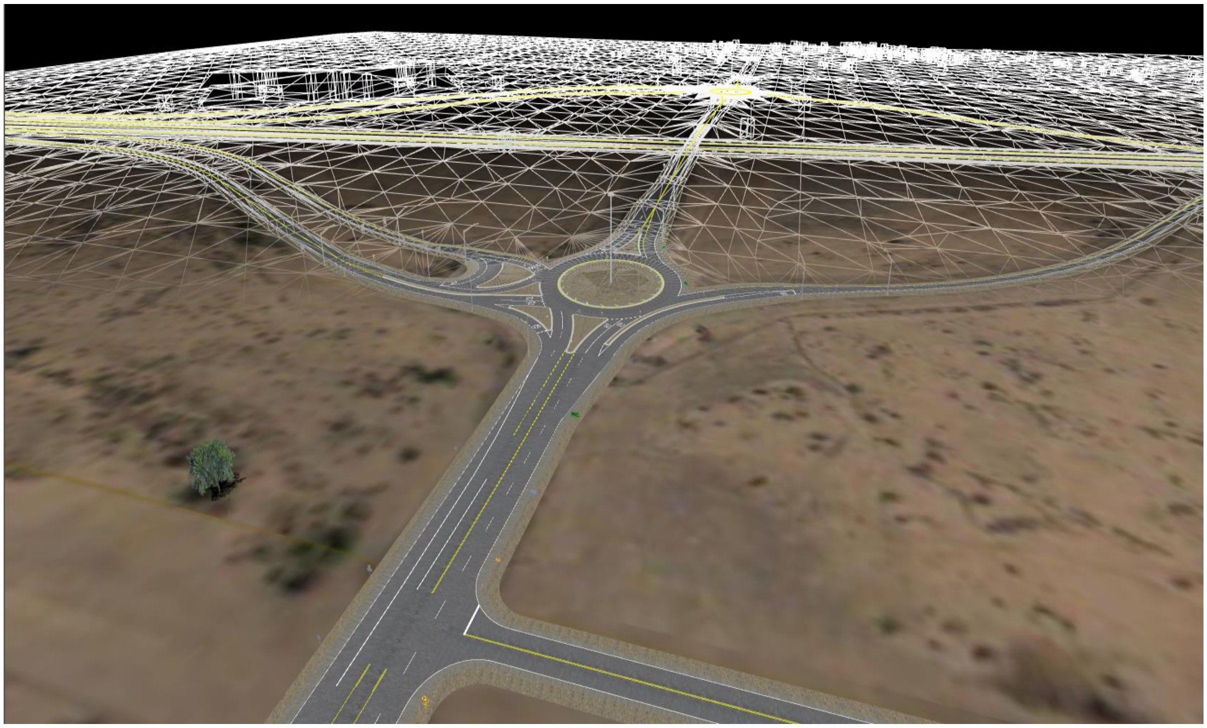

**Figure 13. Example of terrain texture maps and GIS data applied to reproduction of road segments for the Arizona Roundabout.**

The road segments were connected with "filler sections" that contained a roadway with a small and large radius curve located in a generic rural roadside environment as shown in Figure 14. The entire route comprised approximately 14 miles of roadway.

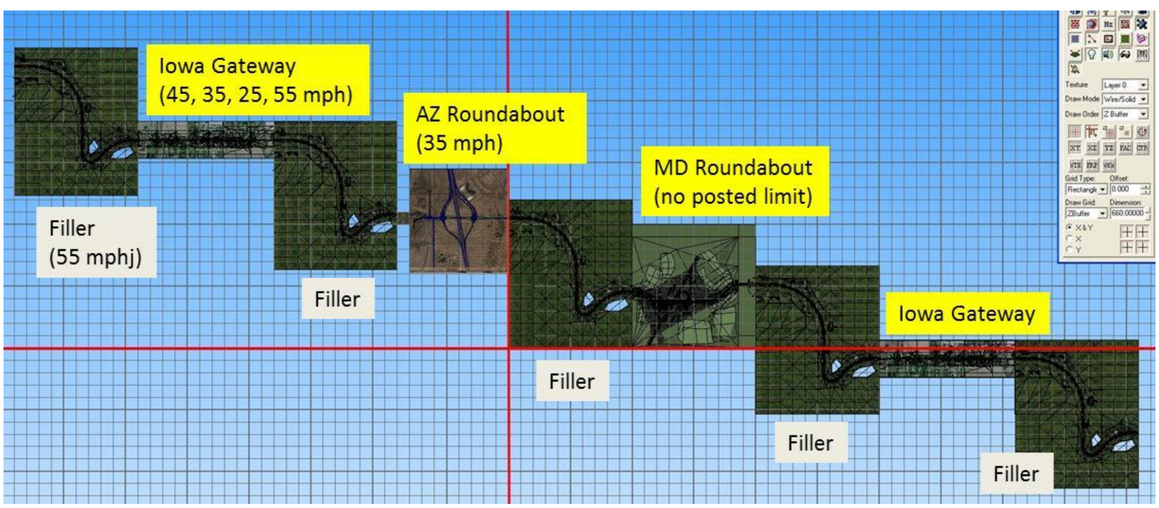


**Figure 14. Bird's-eye view of driving route based on connection of road segments with filler (curve) sections.**

Two driving routes were created based on the sequence of road segments. Specifically, the order of the BEFORE and AFTER treatment of speed reduction methods (Iowa, gateway treatment) determined the road segment sequence, given that the Arizona and Maryland roundabouts, as well as the filler sections, were presented in a fixed order. This was done to simplify the effort to build the driving environments.

**Table 4. Routes and road segment order and visual complexity.**

| | Low Visual Complexity | High Visual Complexity |
|---|---|---|
| **Sequence A** | IAGB, AZR, MDR, IGA | IAGA, AZR, MDR, IAGB |
| **Sequence B** | IAGA, AZR, MDR, IAGB | IAGB, AZR, MDR, IAGA |

Arizona Roundabouts– AZR, Maryland Roundabouts – MDR,
Iowa Gateway treatment before - IAGB, Iowa Gateway treatment after - IAGA

To examine the effect of level of detail in scene fidelity, a high and low visual complexity version of each route sequence was created. The level of visual complexity was defined in terms of the type and number of scene features in each road segment (see examples in Figure 15 through Figure 22):

- Low complexity – road design geometry and road-related features mandated with respect to road locations (roadside, clear zone elements such as signs, traffic control devices, guardrails), no scene environment elements (non-road related), no lighting or shading, generic terrain only to ground road geometry.

- High complexity – road design geometry and road-related features mandated with respect to road locations (roadside, clear zone elements such as signs, TCD, guardrails), scene environment (non-road related features), environment effects (object lighting, shading, weather), on- and off-road terrain (naturalistic for roadway and condition).

Figure 14 through Figure 30 show examples of still images from each driving simulator for both levels of complexity for each road segment. Given that the NADS and miniSim used the same visualization software, the images for these facilities are the same.

(a) FHWA (b) NADS/miniSim (c) WTI

**Figure 15. Images of Iowa, no gateway treatment, with high visual complexity, for each simulator.**

(a) FHWA (b) NADS/miniSim (c) WTI

**Figure 16. Images of Iowa, no gateway treatment, with low visual complexity, for each simulator.**

(a) FHWA (b) NADS/miniSim (c) WTI

**Figure 17. Images of Iowa, with gateway treatment, with high visual complexity, for each simulator.**

(a) FHWA (b) NADS/miniSim (c) WTI

**Figure 18. Images of Iowa, with gateway treatment, with low visual complexity, for each simulator.**

(a) FHWA (b) NADS/miniSim (c) WTI

**Figure 19. Images of Maryland roundabout, with high visual complexity, for each simulator.**

(a) FHWA (b) NADS/miniSim (c) WTI

**Figure 20. Images of Maryland roundabout, with low visual complexity, for each simulator.**


(a) FHWA (b) NADS/miniSim (c) WTI

**Figure 21. Images of Arizona roundabout, with high visual complexity, for each simulator.**

(a) FHWA (b) NADS/miniSim (c) WTI

**Figure 22. Images of Arizona roundabout, with low visual complexity, for each simulator.**

As shown in Figure 23, the intent of reproducing each road segment was to achieve a virtual environment that closely resembled the real-world environment, especially in terms of road geometry and roadside features that guided drivers through the road segment.

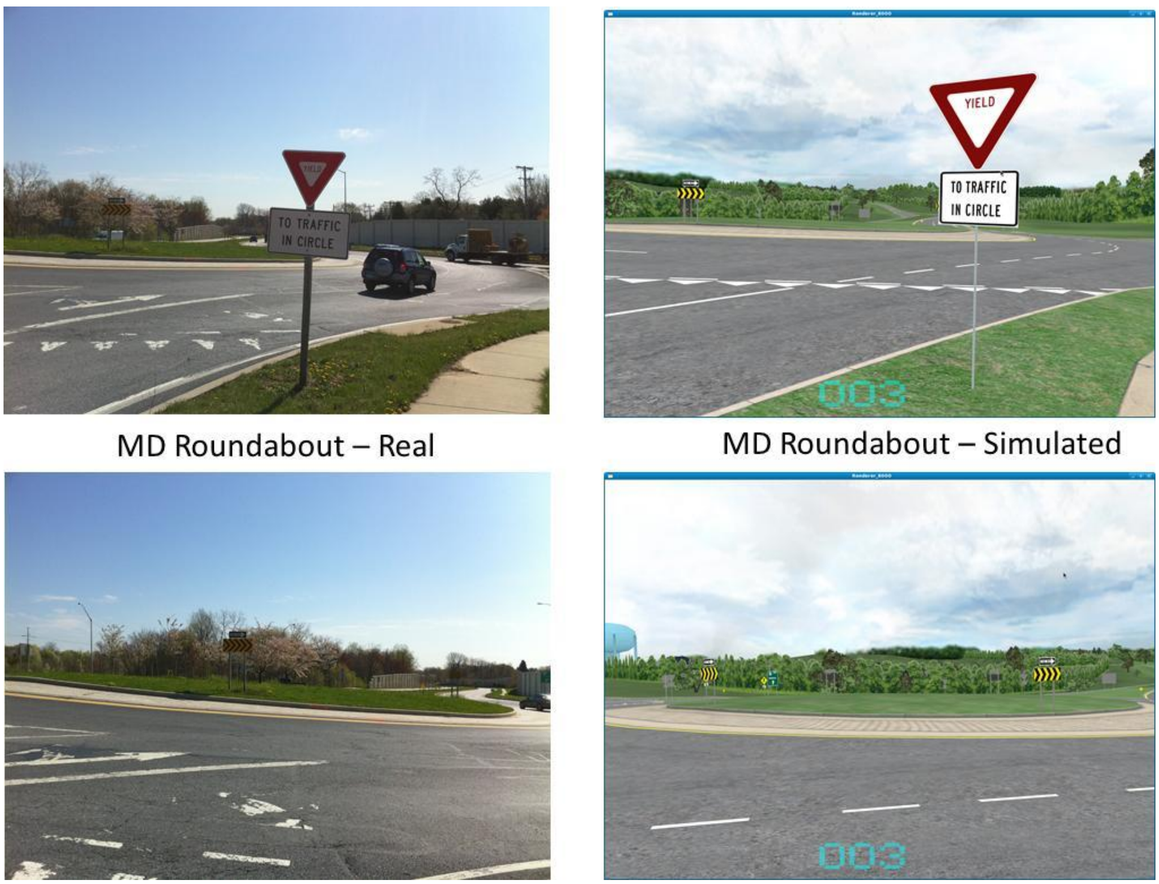


**Figure 23. Example virtual reproduction of Maryland roundabout (right) with respect to the real-world environment (left). (Note: The sound wall, entry deflection, and additional lane markings were added after the data collection phase at the real Maryland roundabout. Therefore, the reproduction represents the actual conditions during the collection of data before these elements were added).**

## Experimental Design

The study used a partial factorial mixed design with simulator (NADS, FHWA, WTI, and miniSim) and motion base (on and off) treated as between-subject variables. The miniSim does not have a motion base, so it was not possible to have a full factorial design.

Within-subject variables included visual complexity (high and low) and road segment (Arizona Roundabouts– AZR, Maryland Roundabouts – MDR, Iowa Gateway treatment before - IGB, Iowa Gateway treatment after – IGA). Each road segment was segmented into six stages to define speed trajectory through the segment.

Secondary independent variables were also created to account for potential confounds including sequence order of the road segments (Table 4) that defined the driving route (A, B), the order of visual complexity presentation (L-H, H-L) (Table 4), and learning effects from exposure (first drive, second drive). The order of segment sequence and visual complexity presentation were counterbalanced across participants.

## Procedure

The same general procedure governed data collection at each simulator facility, although there were minor variations depending on the logistical and operating requirements of a given site.

Existing databases of interested participants and local advertisements were used to recruit candidate participants. Candidates were contacted and verbally screened for eligibility and motion sickness as a predictor of susceptibility to simulator sickness (Appendix C).

Upon arrival at the simulator facility, the participants were briefed on the purpose and procedure for the experiment in order to complete the informed consent process. After consenting, demographic data were collected from the participants (Table 3), and a computer-based visual acuity vision test (http://www.michaelbach.de/fract/index.html) was performed. Participants were then introduced to the driving simulator and completed a practice drive.

The practice drive was comprised of the filler section from the main experiment (55 mph speed limit) and a similar roundabout (30 mph speed limit) as shown in Figure 24. To familiarize participants with the operation of the simulator vehicle and enable them to experience driving within the virtual environment, the practice drive included specific instructions to perform several driving tasks (e.g., increase and decrease speed, brake at a stop line, navigate a roundabout). After the practice drive, participants completed a self-report measure of simulator sickness (Appendix D). Participants with high symptoms of simulator sickness were excluded and did not complete the main experiment.

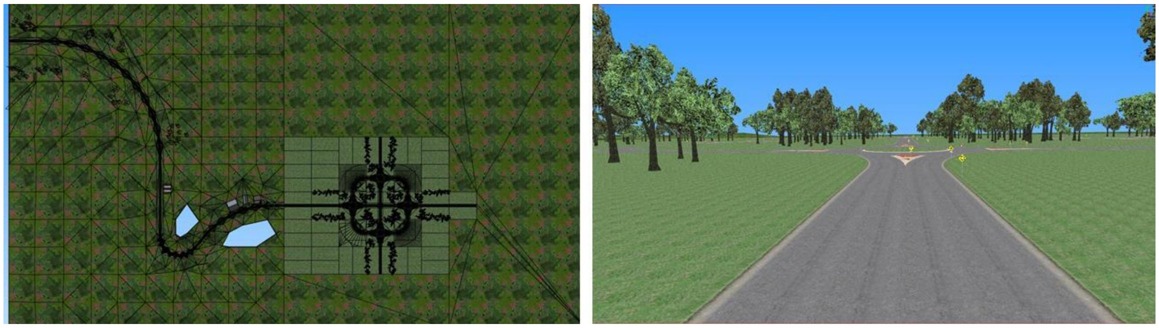

**Figure 24. Overview and scene image of practice driving route.**

Before completing the main drive, participants were shown a schematic of a roundabout to explain this type of road segment and a map of the driving route to illustrate that their task was to navigate directly along the route by proceeding straight through every road junction. Each participant then drove the route twice under different presentations of visual complexity and road segment orders (Table 4).

After each completed drive, participants completed the self-report measure of simulator sickness (Appendix D) and a questionnaire to assess the subjective realism of the driving environment and physical handling of the simulator vehicle (Appendix E). After the final drive, participants were debriefed and signed a receipt for the compensation provided to them for participation in the experiment.

### Driver Behavior Data

Comparison between a simulator and the real world requires that the same data at the same locations is available for both environments (see Table 5). For Iowa Gateway and Arizona Roundabout, only spot speed data were available (e.g., Figure 25), and for the Maryland Roundabout, spot speed and categorical lane position data were available.

**Table 5. Speed measurement points and availability of roadway data.**

| Stage | Iowa Gateway | | Arizona Roundabout | | Maryland Roundabout | |
|---|---|---|---|---|---|---|
| | Simulator | Roadway | Simulator | Roadway | Simulator | Roadway |
| 1 | 475 m before stop line | Yes | 200 m before yield line | No | 200 m before yield line | No |
| 2 | 200 m before stop line | No | Approximately 28 m before yield line | Yes | 28 m before yield line | Yes |
| 3 | 40 m before stop line | No | Yield line | No | Yield line | No |
| 4 | Stop Line | No | Apex of roundabout | Yes | Apex of roundabout | Yes |
| 5 | 40 m after stop line | No | Exit line | No | Exit line | No |
| 6 | 200 m after stop line | No | Approximately 28 m after exit line | Yes | 28 m after exit line | Yes |

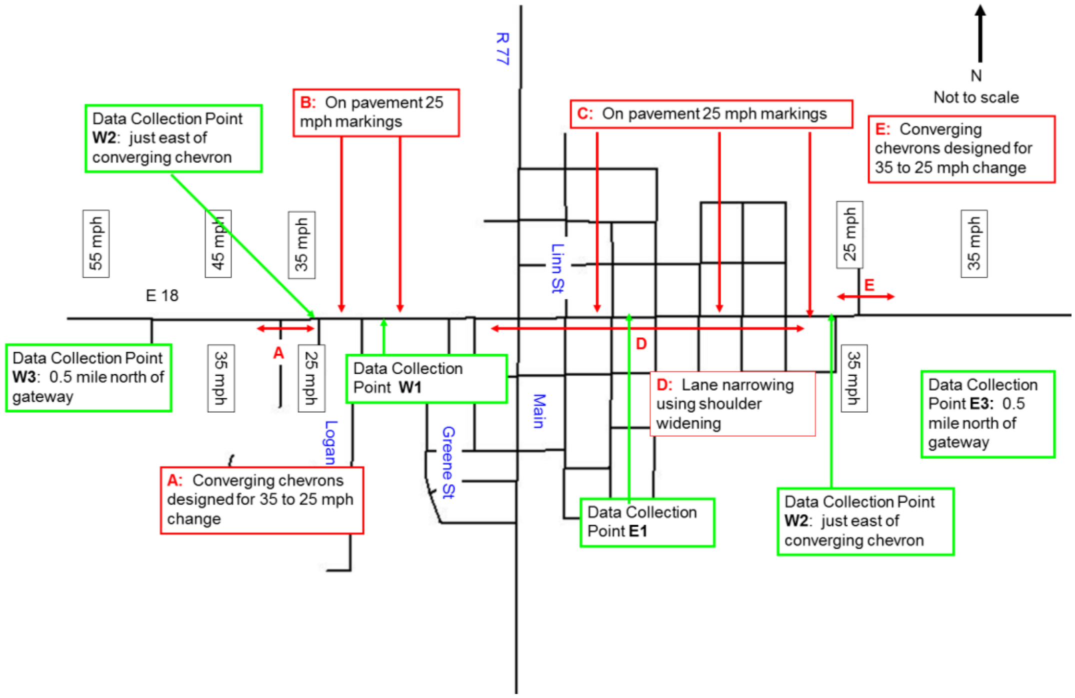


**Figure 25. Location of roadway speed data for the Iowa Gateway segment.**

The measurement points in the simulator were all taken at the center of the leftmost lane. The speed at the location on the driver's trajectory closest to these points was used for the comparisons.

## RESULTS: SUBJECTIVE RATINGS OF SIMULATOR REALISM

Each participant completed a simulator realism survey that included 31 questions about the experience of driving the simulator (Appendix E). These 31 responses were entered into a principal components analysis using Varimax rotation. Analysis of eigenvalues suggested that three factors could provide a reasonable summary of the 31 elements, accounting for 58 percent of the total variance. The first component accounts for 24 percent of the variance, the second for 20 percent, and the third for 14 percent. Based on these three components, component scores were calculated to summarize the response of each participant.

Questions related to "overall feel," "overall similarity," "feel on straight," "feel through roundabout," and "feel on curves" all load heavily on the first component. Questions related to "response of brake," "feel when braking," "feel when braking to stop," and "ability to stop" all load heavily on the second component. The third component concerns visual realism and readability of signs with questions related to "read signs," "sign appearance," "appearance of roads and markings," and "appearance of intersections" loading heavily on this component. The three components represent three dimensions of subjective simulator fidelity. In other words, all the different ratings can be described in terms of three aspects: overall feel, braking response, and visual realism.

Figure 26 through Figure 28 show the component scores of simulator realism for each simulator combination. The boxplots show the median value in the center of the box, and 25$^{th}$ and 75$^{th}$ percentile values defined the upper and lower bounds of the box. The lines from the top and bottom of the box extend to 1.5 times the interquartile range. This provides a more complete summary of the data than a plot of the mean value alone. Superimposed on the boxplots are the mean values and 95% bootstrap confidence intervals. The horizontal axis shows the seven simulator combinations.

The simulators differ considerably over the three dimensions of simulator realism. Simulator combination—the seven combinations of simulator and motion base—affects the ratings associated with overall feel of the simulator, $F(6, 160) = 3.14$, $p = 0.006$, $\eta^2 = 0.11$. Figure 26 shows that the NADS simulator with the advanced motion base on had the highest reported realism of overall of feel – which would be expected given that the NADS motion base has many more degrees of motion than the other simulators. The lowest realism of overall feel was with the FHWA simulator with motion – perhaps because this is the newest motion base within the sample of simulators and requires further tuning.

It also appears that the condition of motion off or on did not significantly change the motion realism scores for any simulator. This could be expected, given that on the selected route there was little need for heavy braking or g-force generation that might benefit from the motion base action. However, it also suggests that the reporting of motion realism may have been based on the perception of the motion system hardware rather than the resulting generation of realistic motion.

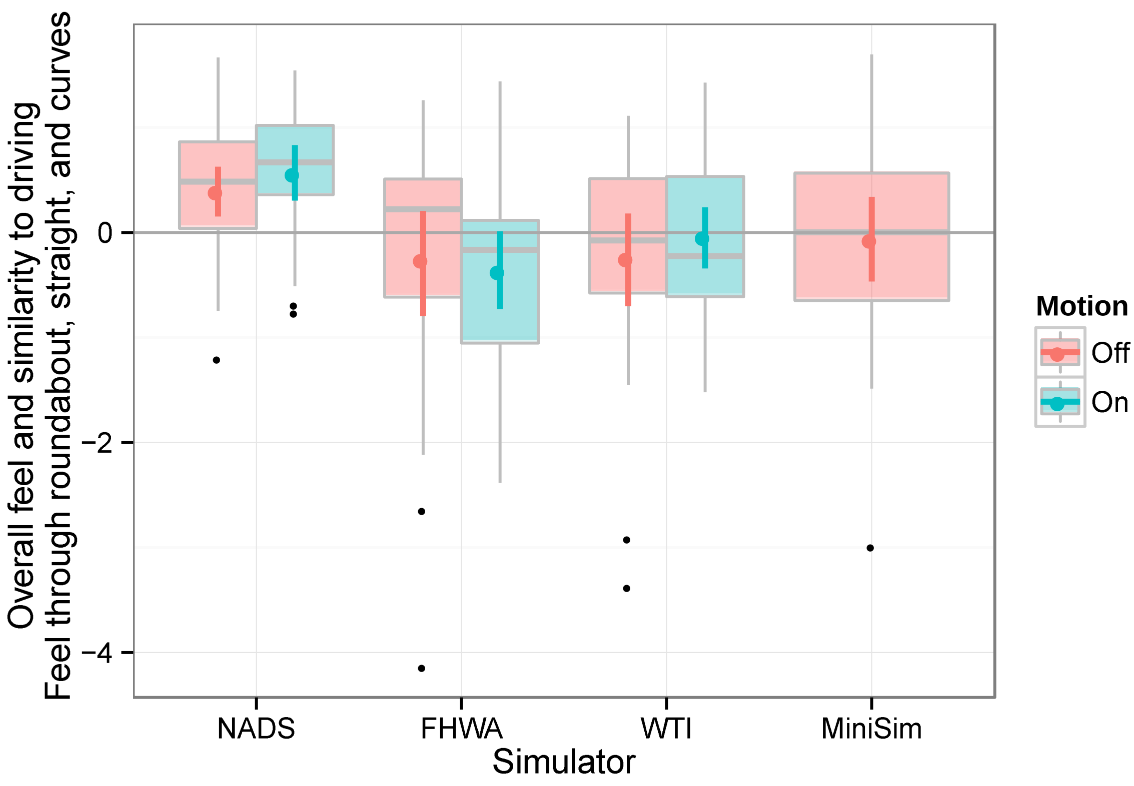


**Figure 26. Dimensions of simulator realism: overall feel.**

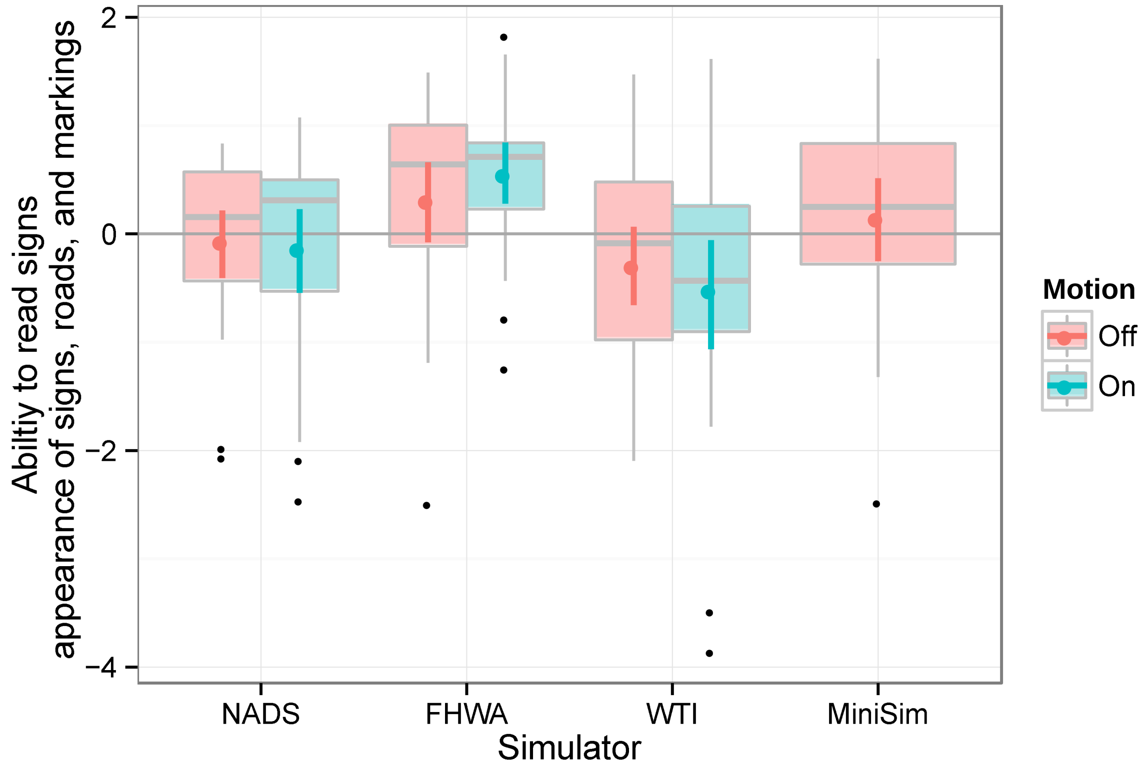


**Figure 27. Dimensions of simulator realism: ability to read signs.**

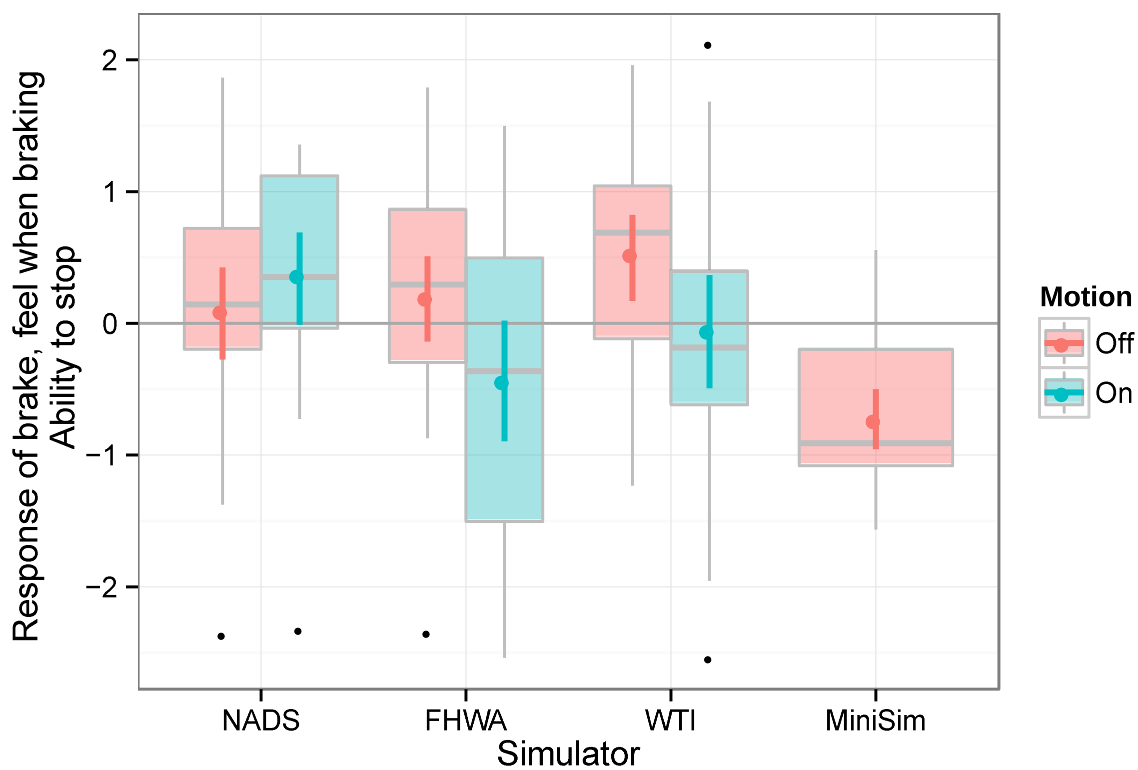


**Figure 28. Dimensions of simulator realism: braking feel.**

Figure 19 shows that the FHWA simulator provides the highest perceived realism of being able to read the signs and see the road, $F(6, 160) = 5.39$, $p<.001$, $\eta^2 = 0.17$. This may be expected because the FWHA simulator was developed to have visual properties to support research for road and signage design. Figure 28 shows that drivers feel best able to brake and stop with the NADS with the motion on and with the WTI – unexpectedly – with the motion off, $F(6, 160) = 3.47$, $p = 0.003$, $\eta^2 = 0.12$. The realistic effect of braking with the WTI system could be attributed to the realistic pedal feel and use of visual scene dipping to evoke the sensation of braking. Drivers in the FHWA simulator with the motion on and drivers in the miniSim felt least able to brake and stop.

These results show that no simulator configuration dominates the others in terms of perceived realism. NADS, with the motion base on, is judged most realistic overall; the FHWA simulator best supports drivers' ability to read signs; and the WTI simulator provides the best braking feel. Most surprisingly, across all these graphs, the effect of the motion base is relatively small and, in some cases, has a negative impact on realism.

Although perceived realism can influence behavior, similar to ratings of immersion [34], many aspects of driving are highly automatized and driven by perceptual motor patterns that operate somewhat independently of drivers' ability to reflect on them. As a consequence, subtle cues from the motion base might have a powerful positive effect on drivers' ability to control the vehicle, which might not be reflected in their ratings of realism. Comparing drivers' speed in the simulators and on the road allows us to test this possibility and determine how simulator characteristics affect behavioral fidelity, which is considered in the following section.

Each driver completed a simulator sickness questionnaire after each drive [35]. The questionnaire consists of 16 items with response on a scale ranging from "none," which is coded as zero, to "slight," "moderate," and "severe," which is coded as three. The questionnaire is typically assessed in terms of three dimensions that are based on a linear combination of the individual question responses: nausea, oculomotor, and dizziness. The dimensions are also combined into an overall score based on the factor structure, producing a maximum score of 224. Answering "slight" to all items produces a score of 79. The outlying values shown in Figure 29 were removed. As suggested by the overlapping confidence intervals, the effect of the simulator configurations failed to reach statistical significance, $F(6, 160) = 0.91$, $p = .49$, $\eta^2 = 0.03$. Two outlying data points were removed from this figure, one at 86.0 in the miniSim, and the other at 123.4 in the WTI with the motion off. Analysis of the three underlying dimensions showed a similar lack of effect with all $p > .30$. Unlike subjective simulator realism, the incidence of simulator sickness symptoms for those subjects who completed did not differ substantially between simulator configurations.

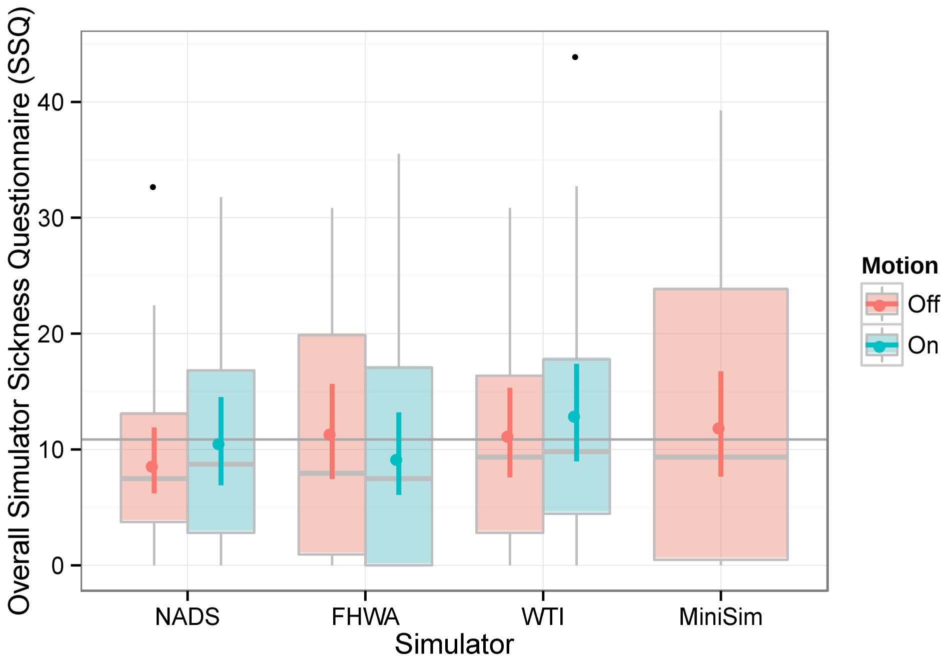


**Figure 29. Effect of simulator configuration on simulator sickness symptoms.**

Simulator sickness should not only be considered in terms of the scores of those who successfully completed the study, but also in terms of those who did not complete due to feelings of discomfort associated with driving through the virtual environment of the simulator. Table 6 provides a summary of the attrition rates with and without motion across the simulator platforms. This attrition rate depends on the simulator characteristics, but also on the driver characteristics. The drivers in the FHWA simulator were screened for propensity to motion sickness and also had previous experience in the simulator. As a consequence, these drivers were selected to be less prone to simulator sickness.

**Table 6. Attrition rate due to simulator sickness.**

| | | **NADS** | **FHWA** | **WTI** | **miniSim** |
|---|---|---|---|---|---|
| Motion | Off | 31% | 17% | 14% | 25% |
| | On | 27% | 4% | 27% | N/A |

## RESULTS: COMPARISONS BETWEEN SPEEDS IN THE SIMULATORS AND ON THE ROAD

The following analysis assesses the effect of simulator, motion, and visual complexity on driver behavior in the simulator. Figure 30 through Figure 35 show the mean speed and standard deviation of speed (dot and vertical line) across drives in each simulator for each stage of the road segment. Road segment refers to the roundabouts and gateway, and stage refers to the position within the segment. The dashed horizontal line represents the grand mean of the speed across all simulators, and the solid line represents the mean for each combination of visual complexity and motion base. Because the motion base and visual complexity did not affect drivers very strongly, the dashed and solid lines often overlay each other, resulting in graphs that appear to have only one solid line in the center.

Gray boxes superimposed on the graphs show data from the actual roadway. The gray boxes are centered on the mean speed recorded on the roadway are two standard deviations high. Ideally, the mean speed from the simulators would fall within these bounds, and the bars for the simulator data would be the same length as the box—the mean and the standard deviation for the simulator data would match the on-road data. The lack of gray boxes indicates situations where no on-road data exists to match the simulator data.

The second graph in each figure shows the data relative to the mean speed observed in the simulators for each stage. Because the stage of each segment has such a powerful effect on speed, removing it from the graph makes the effect of simulator, motion, and visual complexity more clear.

The ANOVA table accompanying each graph provides a statistical assessment of the influence of the experimental conditions. Across all the segments stage had a strong effect as one might expect—the effect size ($\eta^2$) was over an order of magnitude greater than the other effects in almost all cases. Somewhat surprisingly the motion base had little effect. The effect of the simulator was largely driven by drivers in the miniSim responding differently than those in the higher fidelity simulators. Depending on the segment, visual complexity had a stronger influence than the effect of simulator.

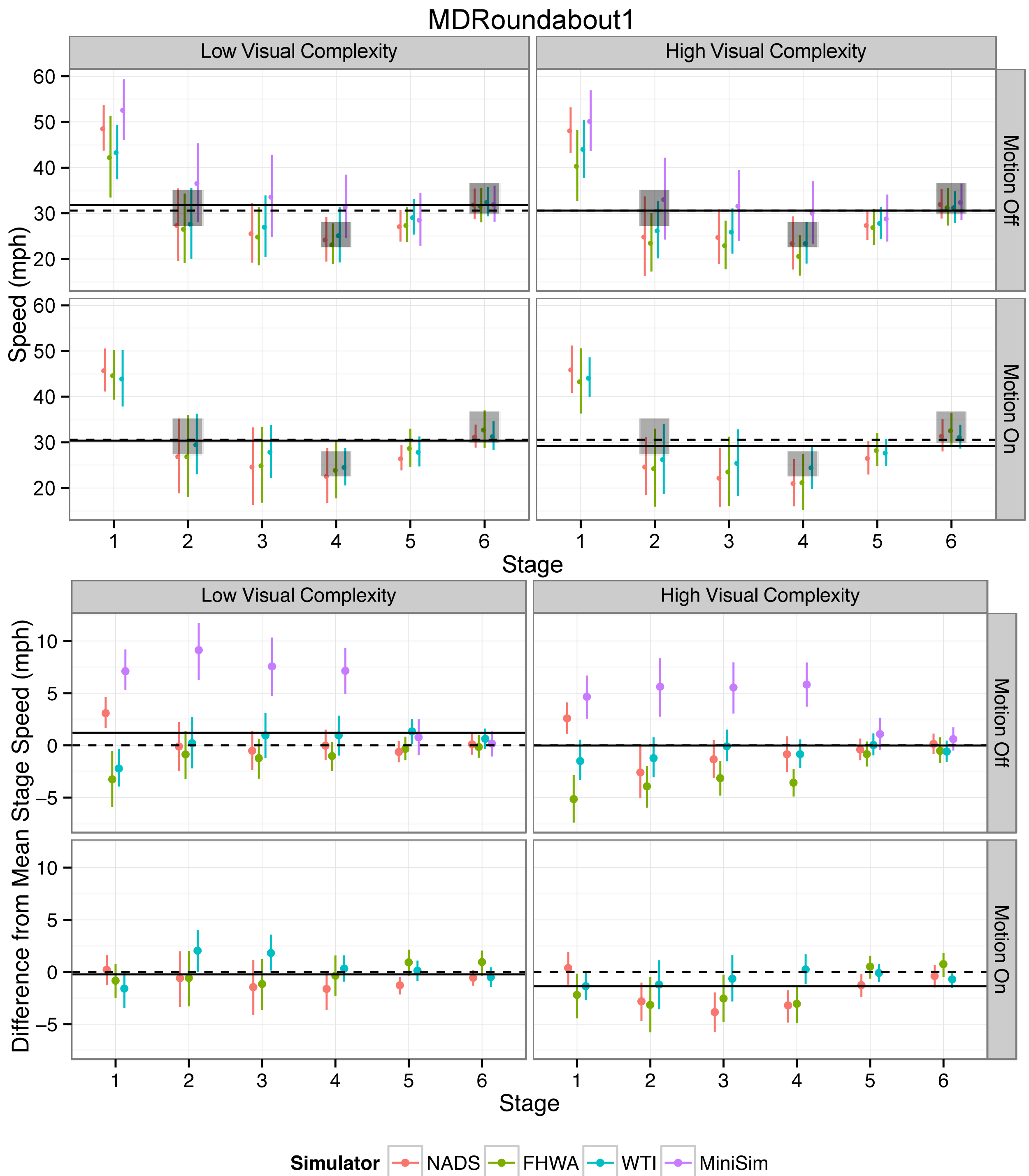


**Figure 30. Speed profile for the first Maryland roundabout. The dot represents the mean, and the vertical line represents the standard deviation. The dashed line is the overall mean, and the solid line is the mean for each combination of visual complexity and motion base. The gray box is the mean and standard deviation of the on-road data where available. The lower graph shows the same data with the speed of each stage subtracted.**

**Table 7. ANOVA comparing simulators for the first Maryland roundabout.**

| **Effect** | ***F*** | ***p*** | $\eta^2$ |
|---|---|---|---|
| Simulator | $F(2, 138) = 1.08$ | 0.343 | 0.009 |
| Motion | $F(1, 138) = 0.00$ | 0.945 | 0.000 |
| Stage | $F(5, 690) = 787.03$ | <.001 | 0.622 |
| Visual Complexity | $F(1, 138) = 26.23$ | <.001 | 0.010 |
| Simulator x Motion | $F(2, 138) = 0.97$ | 0.383 | 0.008 |
| Simulator x Stage | $F(10, 690) = 6.55$ | <.001 | 0.027 |
| Motion x Stage | $F(5, 690) = 0.30$ | 0.912 | 0.001 |
| Simulator x Visual Complexity | $F(2, 138) = 0.98$ | 0.379 | 0.001 |
| Motion x Visual Complexity | $F(1, 138) = 0.00$ | 0.968 | 0.000 |
| Stage x Visual Complexity | $F(5, 690) = 9.08$ | <.001 | 0.006 |
| Simulator x Motion x Stage | $F(10, 690) = 0.86$ | 0.567 | 0.004 |
| Simulator x Motion x Visual Complexity | $F(2, 138) = 0.11$ | 0.892 | 0.000 |
| Simulator x Stage x Visual Complexity | $F(10, 690) = 1.13$ | 0.335 | 0.001 |
| Motion x Stage x Visual Complexity | $F(5, 690) = 0.67$ | 0.645 | 0.000 |
| Simulator x Motion x Stage x Visual Complexity | $F(10, 690) = 0.98$ | 0.463 | 0.001 |

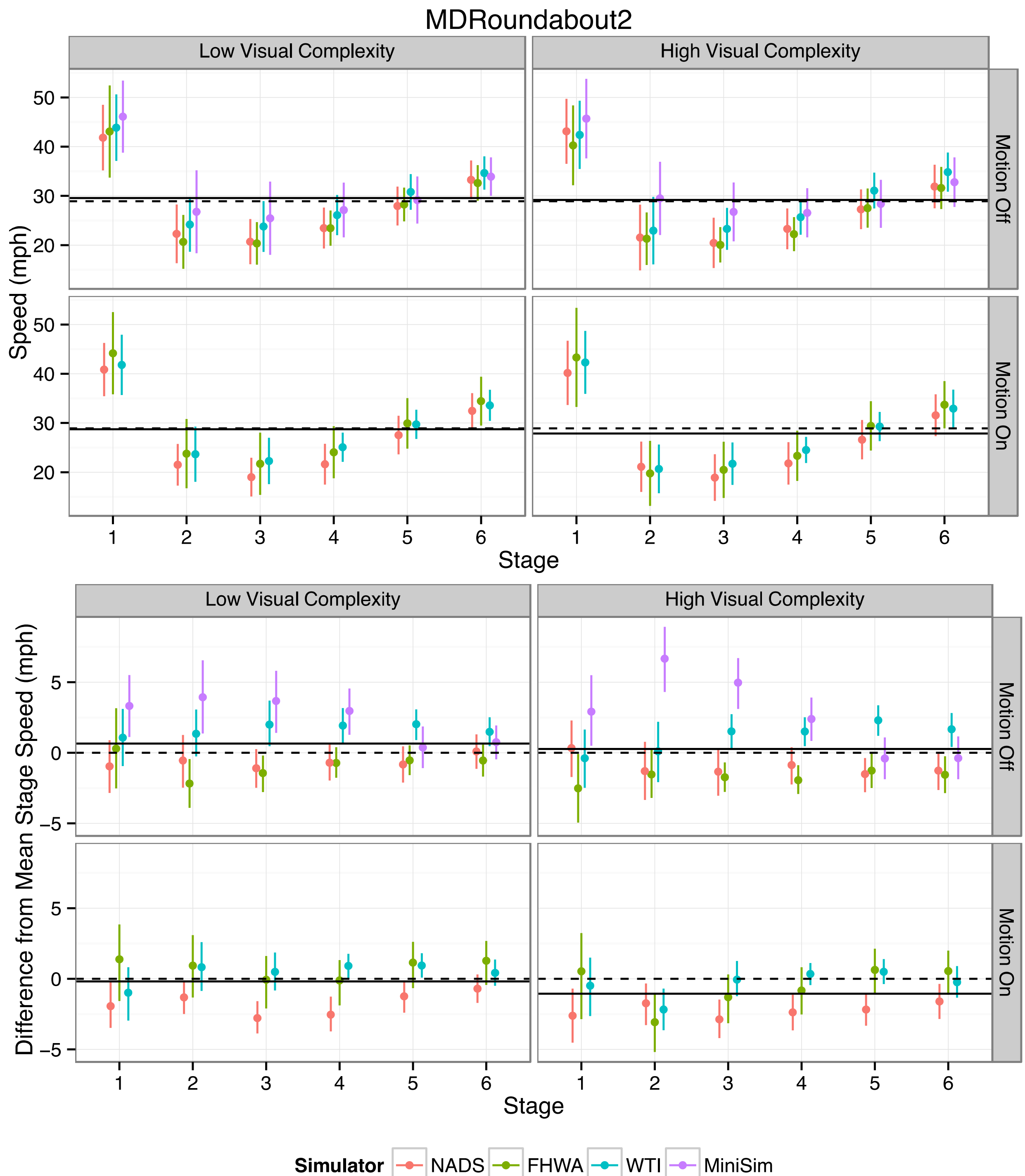


**Figure 31. Speed profile for the second Maryland roundabout. The dot represents the mean, and the vertical line represents the standard deviation. The dashed line is the overall mean, and the solid line is the mean for each combination of visual complexity and motion base. The gray box is the mean and standard deviation of the on-road data where available. The lower graph shows the same data with the speed of each stage subtracted.**

**Table 8. ANOVA comparing simulators for the second Maryland roundabout.**

| **Effect** | ***F*** | ***p*** | $\eta^2$ |
|---|---|---|---|
| Simulator | $F(2, 138) = 3.43$ | 0.035 | 0.029 |
| Motion | $F(1, 138) = 0.30$ | 0.583 | 0.001 |
| Stage | $F(5, 690) = 1127.07$ | <.001 | 0.684 |
| Visual Complexity | $F(1, 138) = 14.41$ | <.001 | 0.005 |
| Simulator x Motion | $F(2, 138) = 1.75$ | 0.178 | 0.015 |
| Simulator x Stage | $F(10, 690) = 1.69$ | 0.078 | 0.006 |
| Motion x Stage | $F(5, 690) = 0.36$ | 0.874 | 0.001 |
| Simulator x Visual Complexity | $F(2, 138) = 1.24$ | 0.293 | 0.001 |
| Motion x Visual Complexity | $F(1, 138) = 0.57$ | 0.453 | 0.000 |
| Stage x Visual Complexity | $F(5, 690) = 1.92$ | 0.089 | 0.001 |
| Simulator x Motion x Stage | $F(10, 690) = 0.41$ | 0.941 | 0.002 |
| Simulator x Motion x Visual Complexity | $F(2, 138) = 0.04$ | 0.956 | 0.000 |
| Simulator x Stage x Visual Complexity | $F(10, 690) = 1.50$ | 0.135 | 0.002 |
| Motion x Stage x Visual Complexity | $F(5, 690) = 2.86$ | 0.015 | 0.002 |
| Simulator x Motion x Stage x Visual Complexity | $F(10, 690) = 2.81$ | 0.002 | 0.003 |

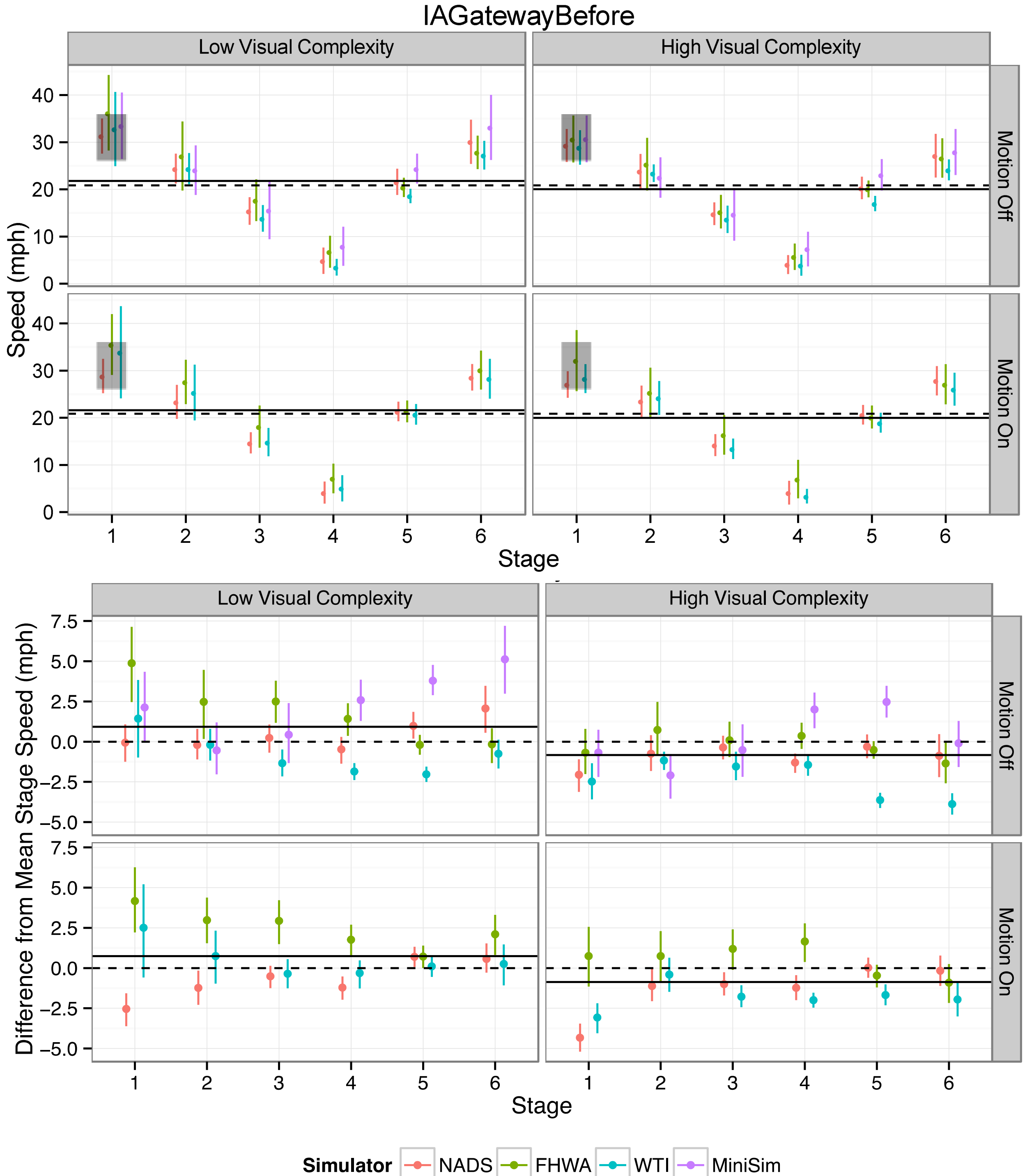


**Figure 32. Speed profile before the Iowa Gateway treatment. The dot represents the mean, and the vertical line represents the standard deviation. The dashed line is the overall mean, and the solid line is the mean for each combination of visual complexity and motion base. The gray box is the mean and standard deviation of the on-road data where available. The lower graph shows the same data with the speed of each stage subtracted.**

**Table 9. ANOVA comparing simulators for before the Iowa gateway treatment.**

| **Effect** | ***F*** | ***p*** | $\eta^2$ |
|---|---|---|---|
| Simulator | *F*(2, 138) = 14.36 | *p<.001* | *0.061* |
| Motion | F(1, 138) = 0.61 | 0.438 | 0.001 |
| Stage | *F*(5, 690) = 1785.71 | *p<.001* | *0.840* |
| Visual Complexity | *F*(1, 138) = 77.51 | *0.000* | *0.044* |
| Simulator x Motion | *F*(2, 138) = 2.06 | 0.132 | 0.009 |
| Simulator x Stage | *F*(10, 690) = 7.04 | *p<.001* | *0.040* |
| Motion x Stage | *F*(5, 690) = 1.38 | 0.229 | 0.004 |
| Simulator x Visual Complexity | *F*(2, 138) = 3.13 | *0.047* | *0.004* |
| Motion x Visual Complexity | *F*(1, 138) = 0.01 | 0.910 | 0.000 |
| Stage x Visual Complexity | *F*(5, 690) = 13.04 | *p<.001* | *0.019* |
| Simulator x Motion x Stage | *F*(10, 690) = 0.43 | 0.930 | 0.003 |
| Simulator x Motion x Visual Complexity | *F*(2, 138) = 1.37 | 0.257 | 0.002 |
| Simulator x Stage x Visual Complexity | *F*(10, 690) = 1.60 | 0.101 | 0.005 |
| Motion x Stage x Visual Complexity | *F*(5, 690) = 0.14 | 0.983 | 0.000 |
| Simulator x Motion x Stage x Visual Complexity | *F*(10, 690) = 1.52 | 0.126 | 0.004 |

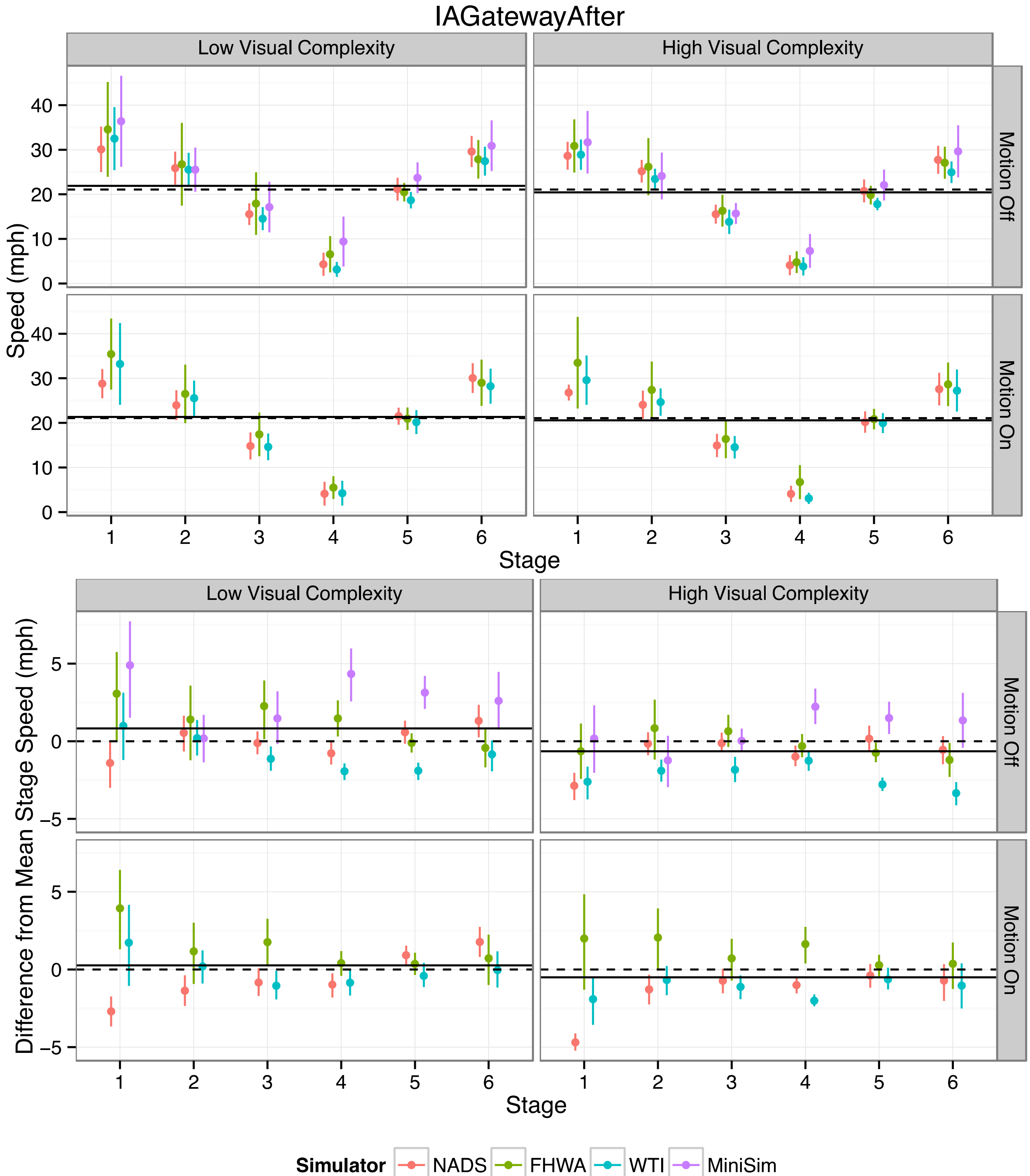


**Figure 33. Speed profile for after the Iowa gateway treatment. The dot represents the mean, and the vertical line represents the standard deviation. The dashed line is the overall mean, and the solid line is the mean for each combination of visual complexity and motion base. The gray box is the mean and standard deviation of the on-road data where available. The lower graph shows the same data with the speed of each stage subtracted.**

**Table 10. ANOVA comparing simulators for after the Iowa gateway treatment.**

| **Effect** | ***F*** | ***p*** | $\eta^2$ |
|---|---|---|---|
| Simulator | *F*(2, 138) = 7.45 | *0.001* | 0.040 |
| Motion | *F*(1, 138) = 0.57 | 0.452 | 0.002 |
| Stage | *F*(5, 690) = 1585.26 | *p<.001* | 0.816 |
| Visual Complexity | *F*(1, 138) = 32.76 | *p<.001* | 0.015 |
| Simulator x Motion | *F*(2, 138) = 1.19 | 0.306 | 0.007 |
| Simulator x Stage | *F*(10, 690) = 6.47 | *p<.001* | 0.035 |
| Motion x Stage | *F*(5, 690) = 1.01 | 0.410 | 0.003 |
| Simulator x Visual Complexity | *F*(2, 138) = 0.80 | 0.453 | 0.001 |
| Motion x Visual Complexity | *F*(2, 138) = 1.93 | 0.167 | 0.001 |
| Stage x Visual Complexity | *F*(5, 690) = 8.67 | 0.000 | 0.010 |
| Simulator x Motion x Stage | *F*(10, 690) = 0.54 | 0.862 | 0.003 |
| Simulator x Motion x Visual Complexity | *F*(2, 138) = 1.43 | 0.243 | 0.001 |
| Simulator x Stage x Visual Complexity | *F*(10, 690) = 1.60 | 0.103 | 0.004 |
| Motion x Stage x Visual Complexity | *F*(5, 690) = 0.29 | 0.917 | 0.000 |
| Simulator x Motion x Stage x Visual Complexity | *F*(10, 690) = 1.02 | 0.427 | 0.002 |

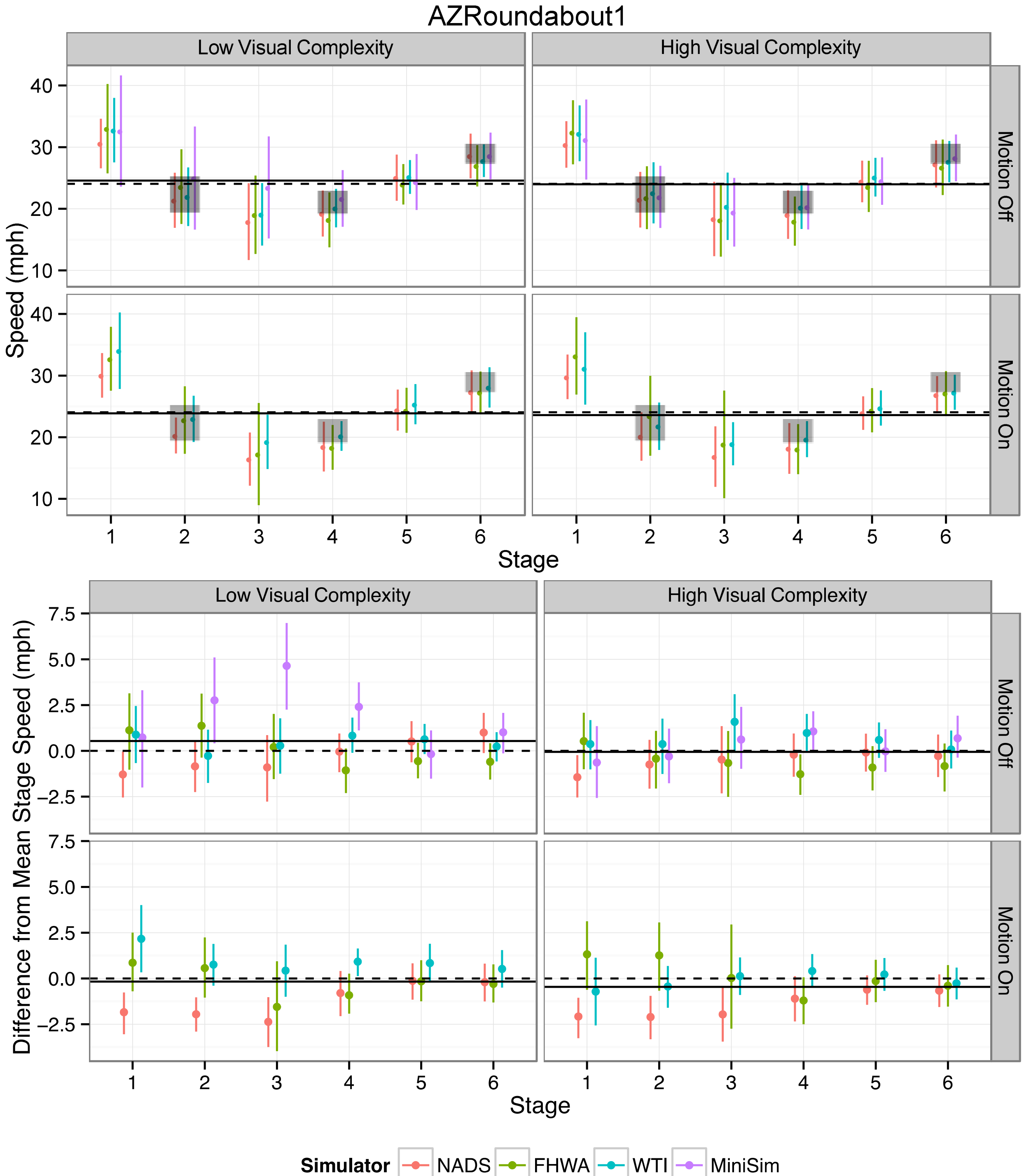


**Figure 34. Speed profile for the first Arizona roundabout. The dot represents the mean, and the vertical line represents the standard deviation. The dashed line is the overall mean, and the solid line is the mean for each combination of visual complexity and motion base. The gray box is the mean and standard deviation of the on-road data where available. The lower graph shows the same data with the speed of each stage subtracted.**

**Table 11. ANOVA comparing simulators for the first Arizona roundabout.**

| Effect | *F* | *p* | $\eta^2$ |
|---|---|---|---|
| Simulator | $F(2, 138) = 2.02$ | 0.137 | 0.015 |
| Motion | $F(1, 138) = 0.27$ | 0.607 | 0.001 |
| Stage | $F(5, 690) = 516.43$ | 0.000 | .535 |
| Visual Complexity | $F(1, 138) = 1.48$ | 0.226 | 0.001 |
| Simulator x Motion | $F(2, 138) = 0.37$ | 0.690 | 0.003 |
| Simulator x Stage | $F(10, 690) = 3.74$ | $p<.001$ | 0.016 |
| Motion x Stage | $F(5, 690) = 0.48$ | 0.793 | 0.001 |
| Simulator x Visual Complexity | $F(2, 138) = 0.13$ | 0.880 | 0.000 |
| Motion x Visual Complexity | $F(1, 138) = 0.01$ | 0.917 | 0.000 |
| Stage x Visual Complexity | $F(5, 690) = 2.39$ | 0.037 | 0.001 |
| Simulator x Motion x Stage | $F(10, 690) = 0.06$ | 1.000 | 0.000 |
| Simulator x Motion x Visual Complexity | $F(2, 138) = 2.44$ | 0.091 | 0.003 |
| Simulator x Stage x Visual Complexity | $F(10, 690) = 1.10$ | 0.361 | 0.001 |
| Motion x Stage x Visual Complexity | $F(5, 690) = 0.34$ | 0.886 | 0.000 |
| Simulator x Motion x Stage x Visual Complexity | $F(10, 690) = 1.31$ | 0.220 | 0.002 |

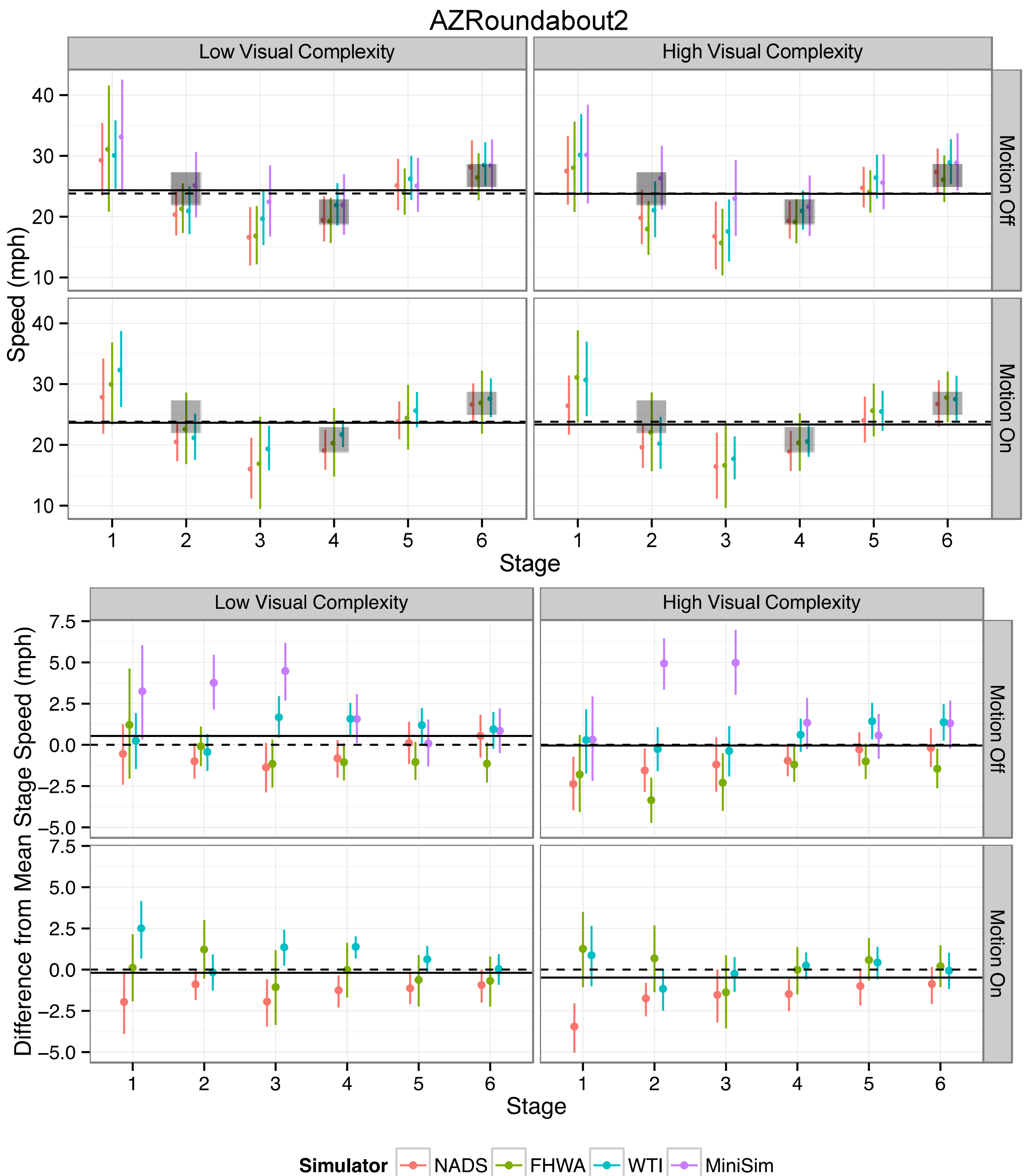


**Figure 35. Speed profile for the second Arizona roundabout. The dot represents the mean, and the vertical line represents the standard deviation. The dashed line is the overall mean, and the solid line is the mean for each combination of visual complexity and motion base. The gray box is the mean and standard deviation of the on-road data where available. The lower graph shows the same data with the speed of each stage subtracted.**

**Table 12. ANOVA comparing simulators for the second Arizona roundabout.**

| **Effect** | ***F*** | ***p*** | $\eta^2$ |
|---|---|---|---|
| Simulator | *F*(2, 138) = 2.95 | 0.056 | 0.024 |
| Motion | *F*(1, 138) = 0.03 | 0.867 | 0.000 |
| *Stage* | *F*(5, 690) = 408.54 | p<.001 | 0.464 |
| *Visual Complexity* | *F*(1, 138) = 6.43 | 0.012 | 0.003 |
| Simulator x Motion | *F*(2, 138) = 0.94 | 0.394 | 0.008 |
| *Simulator x Stage* | *F*(10, 690) = 2.20 | 0.016 | 0.009 |
| Motion x Stage | *F*(5, 690) = 0.82 | 0.533 | 0.002 |
| Simulator x Visual Complexity | *F*(2, 138) = 0.10 | 0.903 | 0.000 |
| Motion x Visual Complexity | *F*(1, 138) = 1.23 | 0.269 | 0.001 |
| *Stage x Visual Complexity* | *F*(5, 690) = 4.91 | p<.001 | 0.003 |
| Simulator x Motion x Stage | *F*(10, 690) = 0.75 | 0.678 | 0.003 |
| *Simulator x Motion x Visual Complexity* | *F*(2, 138) = 2.68 | 0.072 | 0.003 |
| *Simulator x Stage x Visual Complexity* | *F*(10, 690) = 2.72 | 0.003 | 0.003 |
| Motion x Stage x Visual Complexity | *F*(10, 690) = 0.40 | 0.848 | 0.000 |
| Simulator x Motion x Stage x Visual Complexity | *F*(10, 690) = 1.81 | 0.055 | 0.002 |

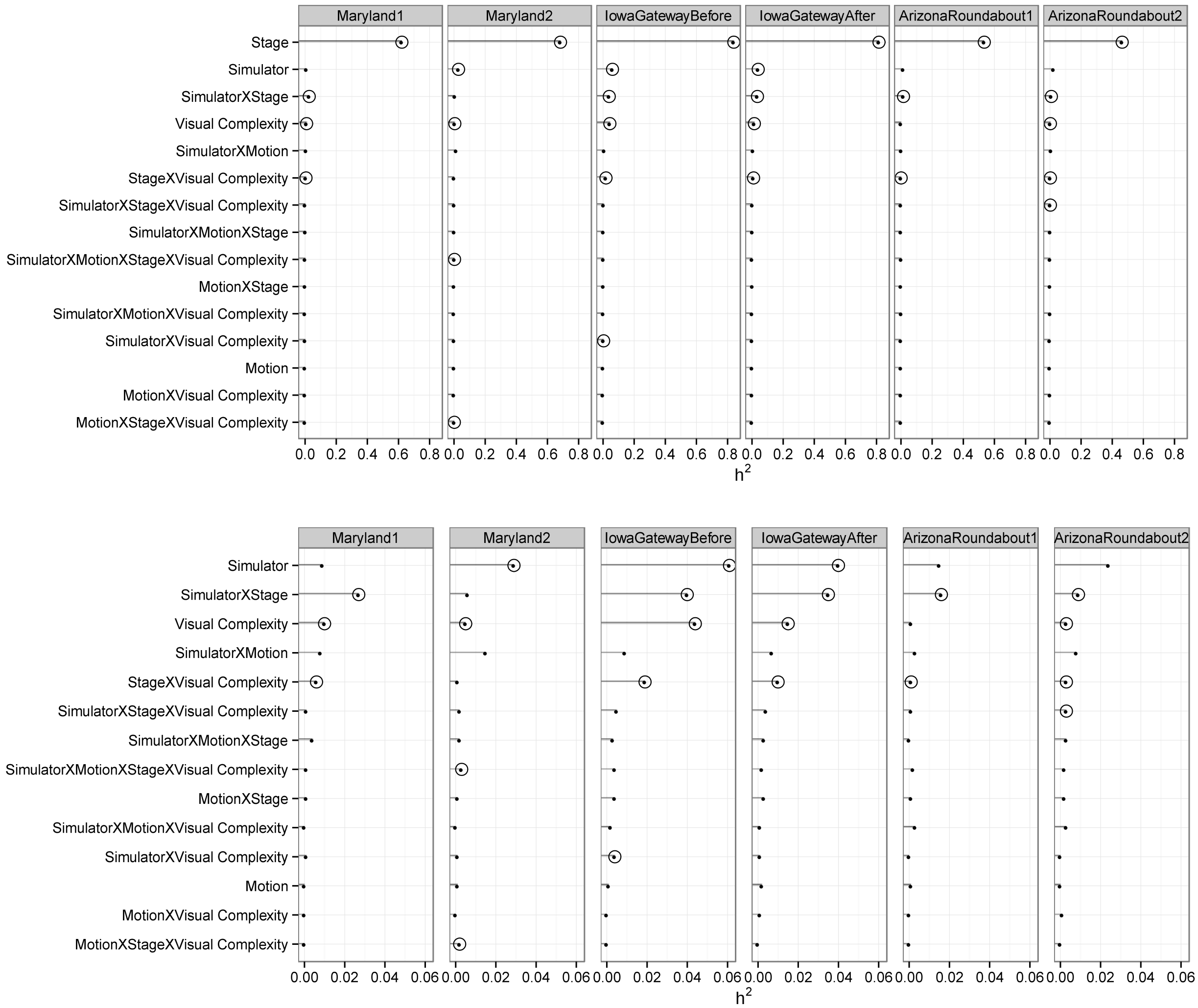


**Figure 36. The effect size of each independent variable, excluding the effect of stage, for each segment. The open circle indicates those effects that reached statistical significance at *p*<.05. The lower graph shows the same data, but without stage to highlight the other effects.**

Figure 36 shows that across all the segments the effect of stage had a more powerful influence on speed than any other main effect or interaction. This represents the effect of the road environment on driver responses. The effect size of stage ranged from 0.46 to 0.84, whereas the next largest effect size was for simulator, with an effect size of 0.06. The strong effect of stage is not surprising given that the roundabout geometry and posted speed limits compelled a change in speed. Even so, the small effect of the driving simulator is notable. The effect of motion failed to reach statistical significance for all segments and only influenced speed through an interaction in two segments, and in those cases the effect size was very small: 0.003. The effect of visual complexity, either as a main effect or through interactions with other variables, was much more influential, exceeding the influence of the simulator in some segments. Specifically, the effect of visual complexity in the Iowa gateway segments, $F(1, 138)= 77.51$, $p<.001$, $\eta^2= 0.044$, exceeds the effect size of the simulators in the Maryland roundabout, $F(1, 138)= 1.08$, $p>.05$, $\eta^2= 0.009$.

The influence of visual complexity was substantial in some cases, such as for the drivers in the miniSim in the first stage of the Iowa gateway, where it led to an approximately 5 mph speed reduction. In most other cases, the influence of visual complexity was generally modest, affecting speed by approximately 1 mph, whereas the effect of simulator was quite large in some cases, such as drivers of the miniSim traversing some stages of the Maryland roundabout almost 10 mph faster than drivers in the other simulators. The substantial differences between the miniSim and the other simulators noted in the previous section (e.g., field of view and lack of motion base) clearly contribute to this difference.

For many segments, the on-road data match quite well—the gray box representing the roadway data often includes the simulator data. For example:

- In the case of the Maryland roundabout, all but the miniSim matched the values of speed for the three locations when the visual complexity was low, but not when it was high. This may be due to an increased frequency of glances to the speedometer in low-fidelity simulators or experimental conditions.

- Similarly, for the gateway condition with high visual complexity, the speed of drivers in all four simulators corresponded very closely to the on-road measures.

Both roundabouts show a very similar difference between simulators and road data as well as across simulators.

- Drivers in the miniSim generally approach too fast and maintain that speed until the apex (stage 5). In fact, the minimum speed is reached at the apex, which is later than in the other simulators and in reality, where the minimum speed is reached somewhere between the yield line (stage 4) and the apex.

- Drivers in the three high-fidelity simulators show a slower approach speed than those in the miniSim, but they also show a strong initial deceleration that causes their speed to drop below the real-world in stage 2 (i.e., approximately 28 m before the yield line). Drivers in NADS show a large deceleration, and drivers in WTI decelerate least in the Maryland roundabouts. In contrast, the miniSim drivers reach their minimum speed in stage 5, whereas drivers in the other simulators reach it in stage 4.

- On the straight section, after drivers have entered the gateway and have already been exposed to speed limit signs, they are expected to have checked their speeds using the speedometer and corrected their speed to the speed limit. This offers one explanation for why the simulator speeds match the real-world, as well as why the speeds between the simulators are similar.

The figures show some notable differences from the on-road data. The on-road data has a smaller standard deviation than most of the other simulator data. This is particularly obvious in the case of the miniSim, where the error bars are noticeable longer than for the other simulators and the roadway. The mean speed of miniSim drivers was also generally greater than the other simulators and the road.

### Direct Comparison of On-Road and Simulator Data

Figure 30 through Figure 35, presented earlier, show the mean speed of drivers in the simulators relative to the mean speed observed on the road for those cases where the data were available. Generally the simulator data correspond well to the road data, with the mean values falling near the middle of the gray box defined by the mean and standard deviation of the roadway data. Figure 37 provides a more direct comparison by showing how the speed in the simulator corresponds to each observed speed on the road.

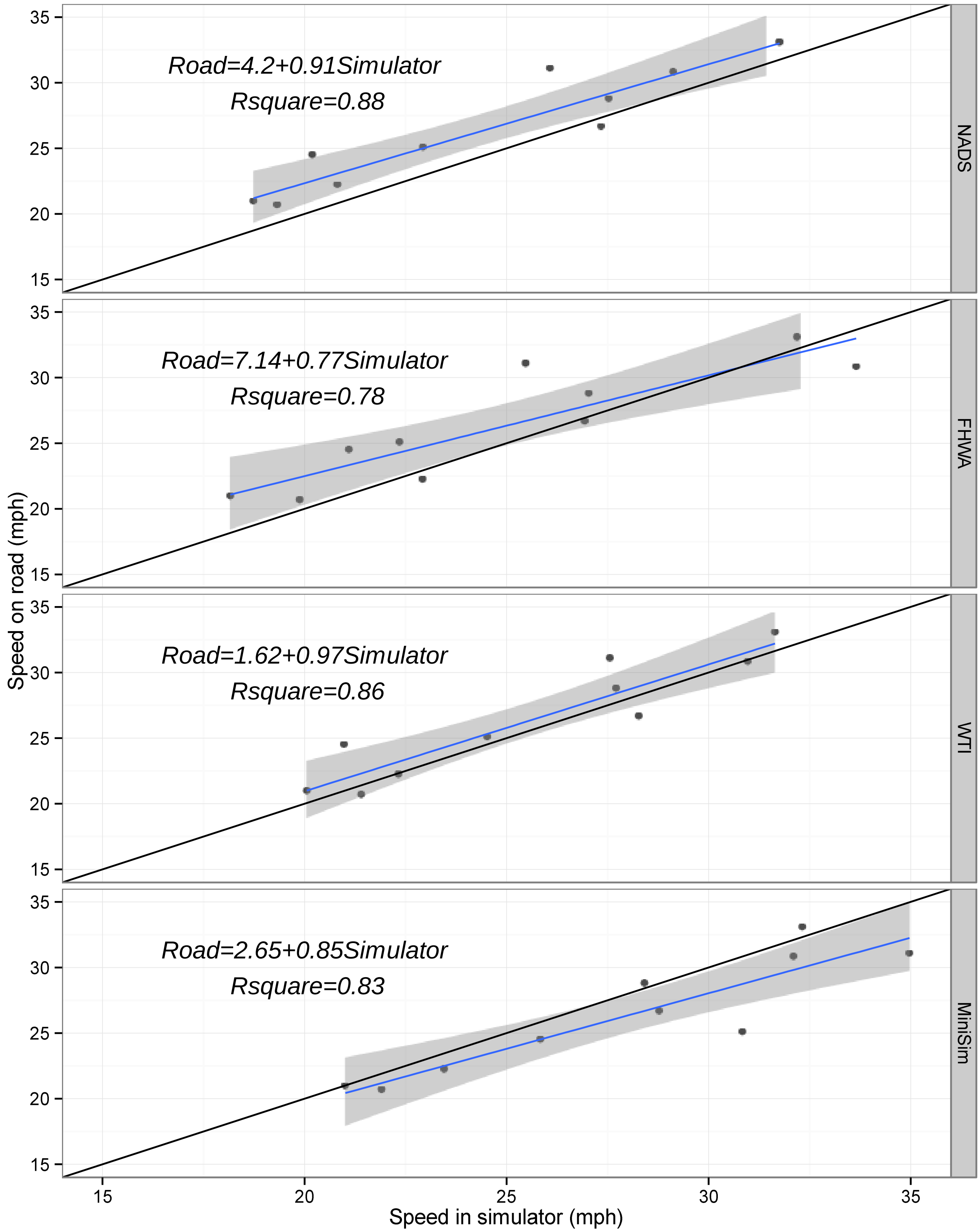


**Figure 37. Linear regression relating mean speed in the simulator to speed on the road. The diagonal line represents perfect correspondence between the simulator and the on-road data. The gray band represents the 95% confidence interval of the linear regression.**

Figure 38 shows the speed of drivers in the simulator on the horizontal axis and the speed of drivers on the road on the vertical axis. Each point in these figures corresponds to a road segment and stage combination where on-road data were available—the gray boxes in the previous figures. The diagonal line represents perfect correspondence between the simulator and roadway. If simulator speeds perfectly match the on-road speeds, then all points would fall on the diagonal.

Generally, the mean speed in the simulator corresponds to speed on the real road—the points lie near the diagonal. A linear regression for each simulator quantifies this relationship, shown by a blue diagonal line in the graph. The slope and intercept of these regression models describe how the simulator data differ from the on-road data. The gray band indicates the 95 percent confidence interval, which generally overlaps the diagonal, indicating that drivers' speeds in the simulator are similar to speeds on the road.

The positive intercept of the regression models indicates the general tendency, at lower speeds, to drive faster in the simulator compared to on the road. A perfect match between the simulator and roadway data would have an intercept of zero. The WTI simulator has the smallest intercept (1.62), indicating that drivers in the WTI simulator drive closest to real-world speeds road at low speeds, whereas drivers in the FHWA simulator drive substantially slower (7.14 mph) at low speeds. Fitting a single linear regression model to the data from all the simulators with a separate intercept for each simulator shows a statistically significant difference in the intercept, $F(3, 35) = 4.90$, $p = 0.0059$.

The slope of the regression model indicates the degree to which an incremental increase in speed observed in the simulator corresponds to an increase in speed on the road. Ideally, increasing speeds observed in the simulator would correspond perfectly with increasing speeds on the road—resulting in a slope of 1.0. The WTI simulator has the slope (0.97) closest to 1.0 (exact match to the real-world speed) of all the simulators, and the FHWA simulator has a substantially different slope (0.77). Slopes of less than 1.0 indicate that, at high speeds, drivers in the simulator drove faster than those on the road. Fitting a single linear regression model to the data from all the simulators with a different slope for each simulator fails to show a statistically significant effect of slope, $F(3, 32) = 0.39$, $p = .75$.

It is also important to consider the interaction between the slope and the intercept. For the FHWA simulator, at speeds below 31 mph, drivers in the simulator drove more slowly than those on the road, but above that, drivers in the simulator were faster than those on the road. As long as the intercept is greater than zero and the slope less than one, there is a speed at which this changeover would happen for each simulator; however, it may not be in the range of speeds observed. The diagonal lines in Figure 37 highlight this effect—points below the diagonal represent situations where the simulator drivers drove faster than those on the road.

The slope and intercept of the regression model can adjust the simulator speed to estimate the corresponding on-road speed. The degree to which this is possible depends on how well the linear regression represents the data. The variance accounted for by the model, which is indicated as $R^2$ in the figure, quantifies the degree of fit of the model. Models with a high R-square value indicate that the simulator data can be reliably transformed to predict the on-road data. Figure 37 shows the WTI and NADS simulators have similar R-square values, .86 and .88, respectively. The FHWA had an R-square value of .78, with the miniSim had an R-square value of .83. All simulators show relatively high R-square values that do not differ by a statistically significant degree. Even the most extreme the difference between .88 and .78 fails to reach statistical significance based on a Fisher z transform of the R-square values, $z = .25$, $p = .63$ The relatively high R-square values indicate that the mean speed data from the simulator can be related to the on-road data successfully.

Figure 38 shows the standard deviation of the speed and a substantially different pattern of correspondence between the simulator and the on-road data. The points and the regression lines are substantially below the diagonal, indicating that speed was more variable in the simulator than on the road. The regression models show that the intercept and slope differ much more from the ideal of 0.0 and 1.0. In addition, the R-square value is much lower—.12 for the NADS—and even the best fit—.72 for the WTI—is substantially lower than the lowest R-square value for the regression models for the mean speed.

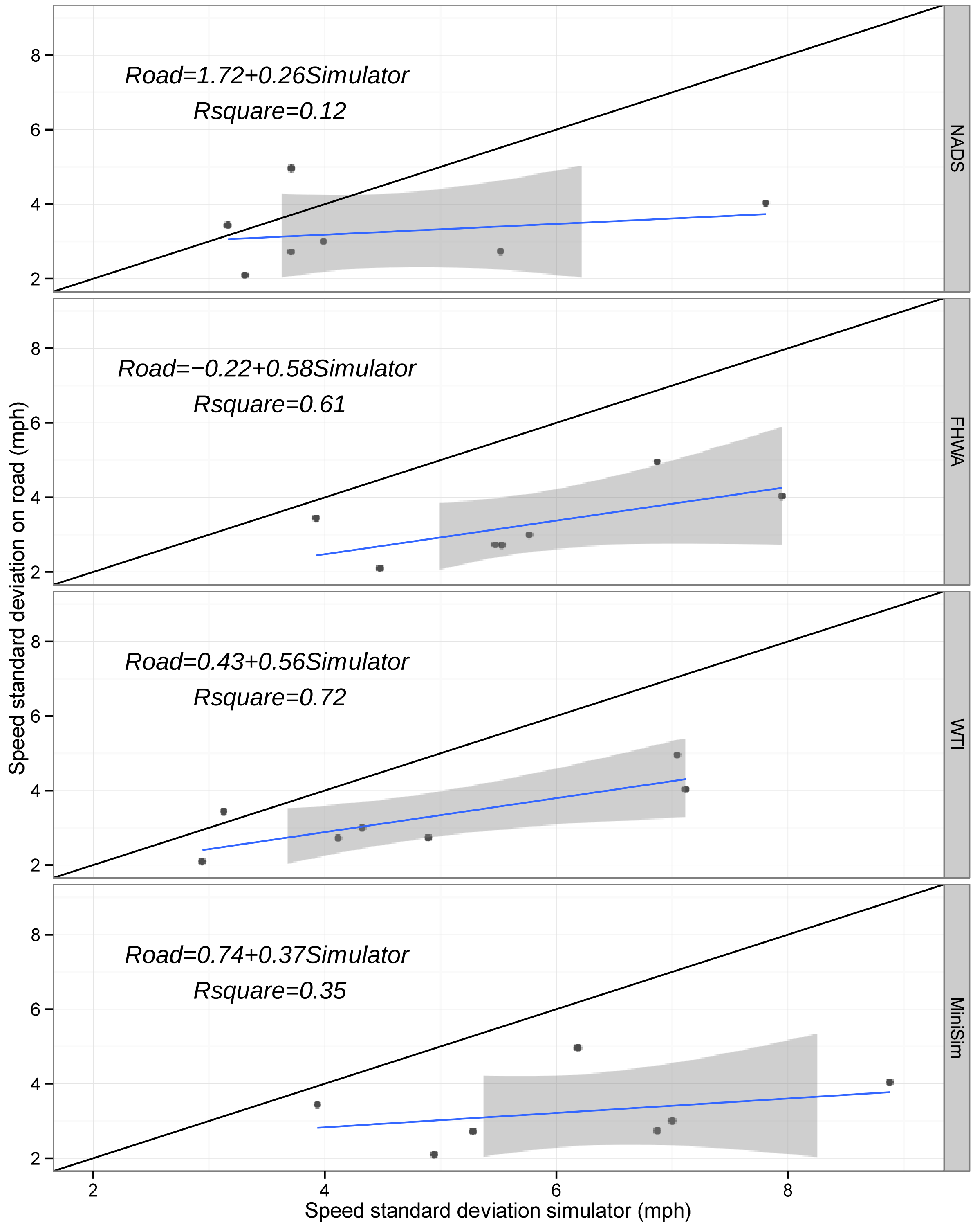


**Figure 38. Linear regression models relating standard deviation of speed in the simulator to speed on the road. The diagonal line represents perfect correspondence between the simulator and the on-road data. The gray band represents the 95% confidence interval of the linear regression.**

Overall, the mean speeds in the simulator and on the road correspond closely. This is not the case with the variability of the speed as measured by the standard deviation. Speed varies more in the simulator than on the road, and the regression models account for a relatively small part of this discrepancy, making it difficult to match the simulator data to the on-road data. One explanation for this result 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 consequently 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, such as the $85^{th}$ percentile speed.

This pattern of results suggests that a more detailed assessment of the distribution of speeds for each simulator and across road segments would be valuable. One approach to directly examining how speed on the simulator compares to that observed on the road is to transform the speed in the simulator into a z-score by subtracting the mean speed observed on the road from that observed in the simulator and dividing by the standard deviation of the speed observed on the road. This method converts speed in the simulator into a z-score representing the number of standard deviation units from the mean speed on the road at each stage along the road segments—a z-score deviation from the speed observed on the road. Values above or below zero indicate poor correspondence between the simulator and the road.

In addition to the z-score deviation, the absolute value of the z-score deviation can be calculated. The absolute value of the z-score deviation reflects how much drivers' speeds in the simulator deviated from that observed on the road—in both the positive and negative directions. A high mean absolute value of the z-score deviation indicates poor correspondence. Because positive and negative deviations cancel each other out, the mean of z-score deviation could be zero even when the mean of the absolute value of the z-score is large.

The mean of the z-score deviation indicates a general bias in mean speeds in the simulator compared to those observed on the road that depends on the simulator configuration. Figure 39 shows a boxplot superimposed on the probability density function of the z-score deviation of speed for each simulator configuration. The vertical axis shows the simulator configuration with "on" and "off" indicating whether or not the motion base was activated, and "high" and "low" indicating the visual complexity of the scene. The plot also includes the mean value and the 95% confidence interval superimposed on the boxplot. The confidence interval is quite small relative to the breadth of the distribution.

Ideally, the difference between speeds observed in the simulator and those observed on the road would have a distribution with a mean of zero and a standard deviation of one. Drivers drove faster and more variably in the miniSim and more slowly in the NADS relative to the speeds observed on the road. The figure shows that the breadth of the distribution (higher standard deviation) may be more indicative of simulator fidelity than the mean speed. The WTI distribution is relatively narrow and close to zero, the miniSim distribution is relatively broad and above zero, and the NADS distributions are below zero.

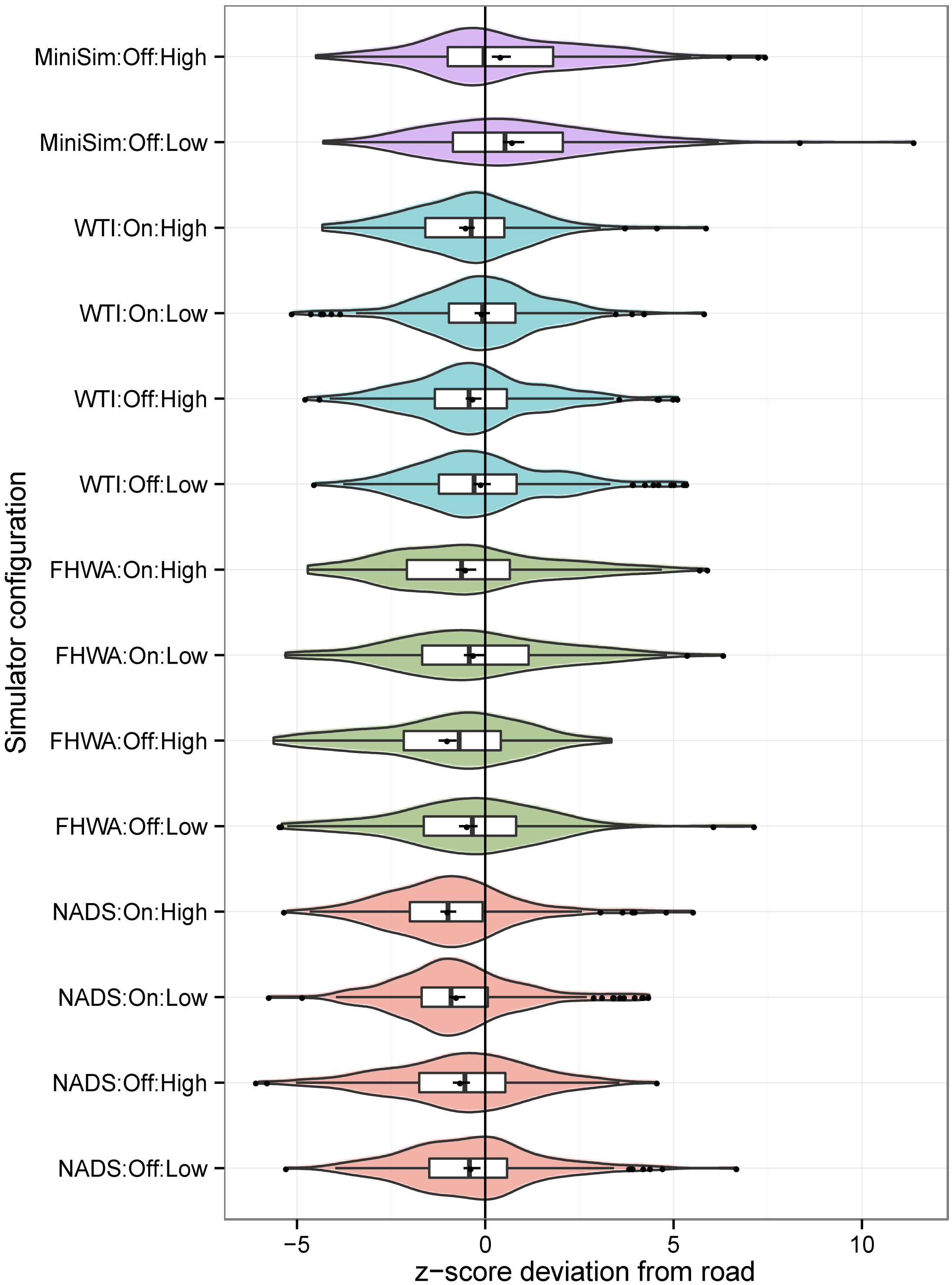


**Figure 39. Boxplots superimposed on the distribution of the z-scores deviation of speed relative to the road data. Mean values with 95% confidence intervals are superimposed on the boxplots. The vertical line indicates zero, the point where the simulator and on-road data match.**

Figure 40 shows the distribution of mean absolute z-score deviations for the simulator configurations. Larger values indicate a greater difference between speeds observed in the simulator and speeds observed on the road. The miniSim and the FHWA simulator with the motion base activated had values greater than the overall mean. In contrast, the WTI simulator had values substantially less than the mean when the motion base was activated. Figure 39 and Figure 40 confirm and extend the results of the regression analysis. The WTI and NADS simulators lead drivers to adopt speeds that are more consistent with those observed on the road than those drivers in the FHWA and miniSim simulators. The following section develops a driver model to transforming the simulator data to match roadway data.

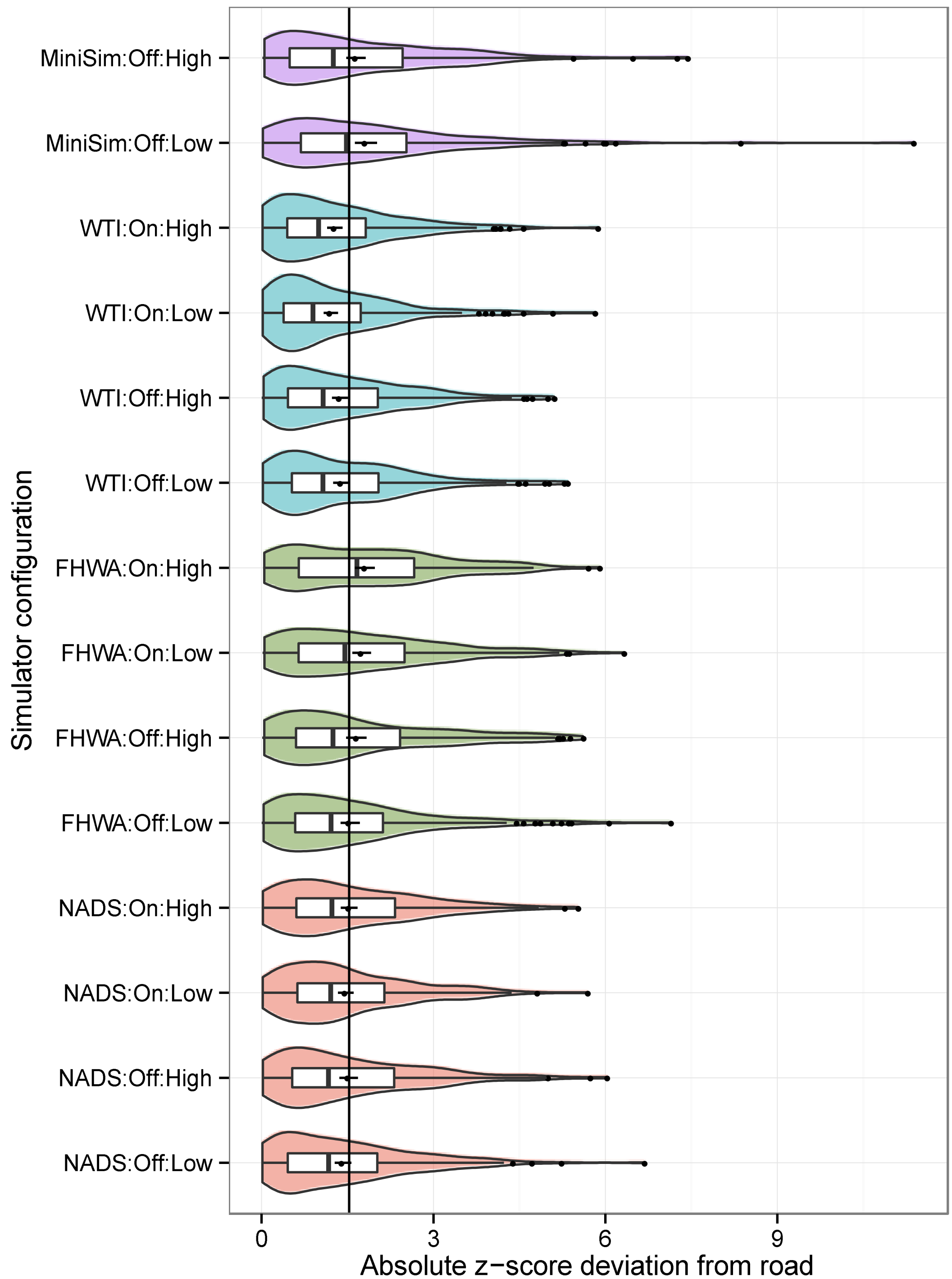


**Figure 40. Boxplots superimposed on the distribution of the absolute value of z-score deviations from the speed observed on the road. Mean values with 95% confidence intervals are superimposed on the boxplots. The vertical line represents the overall mean deviation.**

# CHAPTER 3—MODEL-BASED TRANSFORMATION OF SIMULATOR DATA

The comparisons of behavior in the driving simulators and on the roadway show generally good agreement, but also reveal some systematic mismatches. Ideally, the distribution of speeds observed in the simulator would match the distribution of speeds observed on the road. There are many reasons for mismatches between behavior observed in the simulator and on the road. Simulator characteristics account for some of these differences, but demand characteristics, familiarity with the route, and motivations of the drivers are other important characteristics that can lead to differences between simulator and on-road driving.

Regression equations relating mean speeds in the simulator to mean speeds on the road showed a strong association. Similar to other comparisons between simulator and on-road behavior, the mean speed differed slightly in absolute terms, but in relative terms the mean speed was quite similar [12, 36]. For many design issues, matching simulator and road data in absolute terms is important, so a method to transform simulator data to predict on-road behavior is needed. A computational model based on the perceptual, cognitive, and motor control processes that govern driver speed maintenance can explain these differences in a way that is not possible with a simple regression model. The advantage of this approach relative to the regression model is that it uses a theoretical approach to explain the underlying constraints that bound the driver response in addition to providing a way to transform the distribution of speeds observed in the simulator to those observed on the road. This approach is not only more robust but also provides architecture for refinement as new design cases are considered.

This section describes a model of speed maintenance in curve negotiation derived from previous research in this area, particularly the Driver Performance Model (DPM) of the Interactive Highway Safety Design Model (IHSDM) [37, 38].

The characteristics of the road segments are described in terms of inputs to this model, and the speed maintenance model is fit to the simulator and roadway data. This model-based approach offers promise in transforming simulator data to match roadway data by building on existing models of driver behavior to describe how drivers perceive and respond to road characteristics.

Also, estimating parameters of the models using simulator and roadway data shows why drivers behave differently in the simulator and relates simulator data to roadway data. The ratio of parameter estimates for the simulator relative to the roadway data indicates how the speed distributions from the simulator can be transformed to match the road data.

In the following analysis, we briefly review applicable driver models to the roundabout scenarios considered in this report—curve speed models—and then integrate these models into a simple speed maintenance model. Parameters of this model are estimated with the roadway data and with the data from two divergent simulator configurations—the NADS simulator with the motion base active and the miniSim. These simulator configurations differ most from each other, and the miniSim differs most from the road data.

## MODELS OF CURVE NEGOTIATION

The strong influence of drivers' speed choice on both highway safety and capacity has spawned substantial efforts to model drivers' speed choice [39]. These efforts have produced a series of models that predict drivers’ speed as a function of roadway geometry [40, 41]. Although development of these models began over 50 years ago, it is still an active research topic that has not produced a definitive model [42, 43]. Frequently these models summarize drivers’ speed choice without describing the mechanisms that guide drivers’ speed selection [44]. Such models are statistical models of the observed speed distributions that predict speed as a function of horizontal and vertical curvature [45, 46, 47].

Process models complement statistical models and describe the drivers’ perceptual, decision making, and motor control processes [14, 48]. Process models of drivers’ speed maintenance through curves have considered drivers’ speed choice as a function of visual features of the approach to the curve [49, 50]. These models often build on control theory and cognitive science to describe drivers' speed selection in terms of an error-correcting mechanism that strives to minimize the deviation from a desired speed. This desired speed in a curve (i.e., curve speed) often reflects a balance between maintaining the desired speed on a straight road (i.e., free speed) and the need to maintain safety margins regarding lateral acceleration and lane position. Specifically, desired speed might reflect drivers’ ability to steer the vehicle through a curve while maintaining an appropriate distance from the lane boundary, often expressed in terms of the time to line crossing (TLC) [51]. Often these safety margins have been defined in terms of TLC, but safety margins based on lateral acceleration and the limits of adherence of the vehicle also account for the inverse relationship between lateral acceleration and speed through a curve [16]. The TLC perspective describes anticipated errors associated with steering through a curve and therefore may explain speed choice in curve negotiation.

Drivers’ ability to steer the vehicle through a curve and avoid a small TLC value depends on steering competence and the steering demand imposed by road width, road curvature, and vehicle speed. Traffic in the opposing lane can also affect speed choice by limiting drivers’ ability to safely cross the center lane boundary. Without traffic, 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 curvature and lane width decrease and as speed increases. A smaller-radius curve requires a larger steering wheel angle, and because motor control error depends on the magnitude of response, smaller-radius curves will lead to greater steering errors. Small steering errors at high speed quickly lead a driver toward the lane boundary. This forces drivers to slow to maintain a constant TLC [51]. Models based on steering error and the assumption that drivers seek a constant TLC in negotiating curves predict that the maximum lateral acceleration will decrease with speed. This inverse relationship between lateral acceleration and curve radius represents a long-standing finding from both simulator and on-road observations [52]. Drivers choose speeds through curves that are less than what might be expected, assuming drivers adopt the same maximum lateral acceleration at all speeds.

The description of speed control through curves based on TLC suggests drivers rely on visual cues alone and fails to account for the effect of a simulator motion base on speed. Curve speed might also reflect drivers’ maintenance of a safety margin with respect to lateral acceleration. Extreme values of lateral acceleration decrease with the square of speed [16]. In the simulator, this relationship was moderated such that extreme values of lateral acceleration decreased more abruptly when the motion base was not active [16]. Models that assume that drivers modulate their speed so they experience only moderate longitudinal and lateral acceleration (e.g., 0.30 g) often produce behavior consistent with actual driver behavior [53].

Models based on TLC or lateral acceleration safety margins tend to focus on radius of curvature and to a lesser extent on lane width, while neglecting other road features. Across many studies, the radius of curvature is the predominant influence on curve speed, but superelevation, lane width, and deflection angle also influence curve speeds, albeit to a much smaller degree [54]. Assuming no traffic impedes speed choice, the vast majority of variance in drivers' speed through curves depends on radius of curvature.

In considering the effect of radius of curvature and lane width on drivers' speed maintenance, several points of consensus exist. Driver models for speed choice generally include one or more of the following: preview information to anticipate the upcoming roadway, internal model to reflect experience with similar curves, and parameters to reflect different driving styles [38, 55]. Preview information is relatively limited. Drivers often begin slowing only at a point approximately three seconds from point of curvature and decelerate through the midpoint of a curve [56]. This behavior agrees with eye glance data that show drivers fixate on a tangent point approximately one to two seconds ahead [57, 58]. Curve negotiation depends largely on past experience and is guided by an internal model that relates visual cues of the upcoming path to an appropriate speed [38]. Individual differences regarding risk tolerance and experience lead to substantial variation in speed profiles, which are reflected in both free speed and acceptable lateral acceleration. To some degree, these individual differences reflect how drivers choose to balance travel time and risk [44]. A driver model that incorporates limited preview, drivers' internal model of curves, and individual differences might account for both the central tendency and the distribution of drivers' speed profiles in the simulator and on the road.

One approach that fulfills these requirements is the driver performance model developed for Interactive Highway Safety Design Model (IHSDM). IHSDM includes a driver performance model (DPM) that simulates the moment-to-moment actions of a driver with five functions: perception, speed decision, path decision, speed control, and path control [38]. The model adopted here draws heavily on DPM. DPM was designed to support roadway design and was validated with both simulator and roadway data. Within DPM, speed control is one element of a broader model that predicts both lateral and longitudinal control. Although frequently treated independently, lateral and longitudinal controls are coupled in that drivers can choose a path that "cuts the corner" and effectively increases the radius of curvature. This analysis focuses on the speed decision and speed control elements of DPM.

Consistent with other models of speed choice, DPM assumes that drivers seek to maintain their free speed, $V_f$, as they approach and exit a curve. Levison et al. [38] assumed that drivers adjust their speed ($V$) and aim to follow a desired speed through the curve ($V_c$) that avoids uncomfortable values of lateral acceleration, $a_{lat}$, based on visual cues that indicate the radius of curvature of the approaching curve and experience with similar curves. Rather than considering only the physical constraints on curve negotiation, which suggest a constant value of $a_{lat}$ across curve radii, substantial evidence suggests that acceptable lateral acceleration varies inversely with speed. Levison et al. [59] showed that assumptions regarding drivers' steering error influence the acceptable lateral acceleration ($a_{latmax}$), which varies inversely with the square root of the radius of curvature, resulting in a desired curve speed that varies with the cube root of the radius of curvature as shown in Equation 1. Alternatively, an exponential function shown in Equation 2 also fits observed roadway data well [40]. In these equations, $\alpha_{CV}$ is a constant value. Figure 44 shows the implications of these equations for the desired speed and lateral acceleration through curves. Both models show that speed decreases as the radius of curvature decreases, but that speed decreases more with the Emmerson model. This lower speed results in lower lateral acceleration in tight curves. The last of the three graphs in Figure 44 shows the lateral acceleration associated with the speed predicted by the two models, with the Levison model predicting unrealistically high lateral acceleration in small-radius curves.

The equation shown in Figure 41 results in unrealistically high speeds for curves with very small or very large radii; consequently, we use the equation shown in Figure 42 in this analysis.

$$V_C = \alpha_{CV} R^{1/4}$$

**Figure 41. Equation.**

$$V_C = V_f(1 - e^{-\alpha_{CV} R})$$

**Figure 42. Equation.**

The equation in Figure 43 shows how changes in speed to accommodate the curve follow a moderate deceleration, $a_{lon}$, that balances the cost of longitudinal acceleration ($C_a$) with the cost associated with the time ($C_t$) [59]. Costs here refer to the desire to avoid harsh acceleration ($C_a$), but also minimize travel time ($C_t$). A single constant ($\alpha_{alon}$) can reflect the effect of $C_a$ and $C_t$. The deceleration in approaching the curve is assumed to follow the same function as acceleration in departing from the curve. The pedal modulation and associated change in longitudinal acceleration that follows have a time constant ($\tau_{alon}$) such that it takes 500 ms to fully depress the accelerator [38]. This time constant reflects both the biomechanics of the driver interacting with the pedal and the aggressiveness of the driver's response.

$$a_{lon}(t) = \tau_{alon}\alpha_{alon}\,\Delta V + (1 - \tau_{alon})\,a_{lon}(t-1)$$

**Figure 43. Equation.**

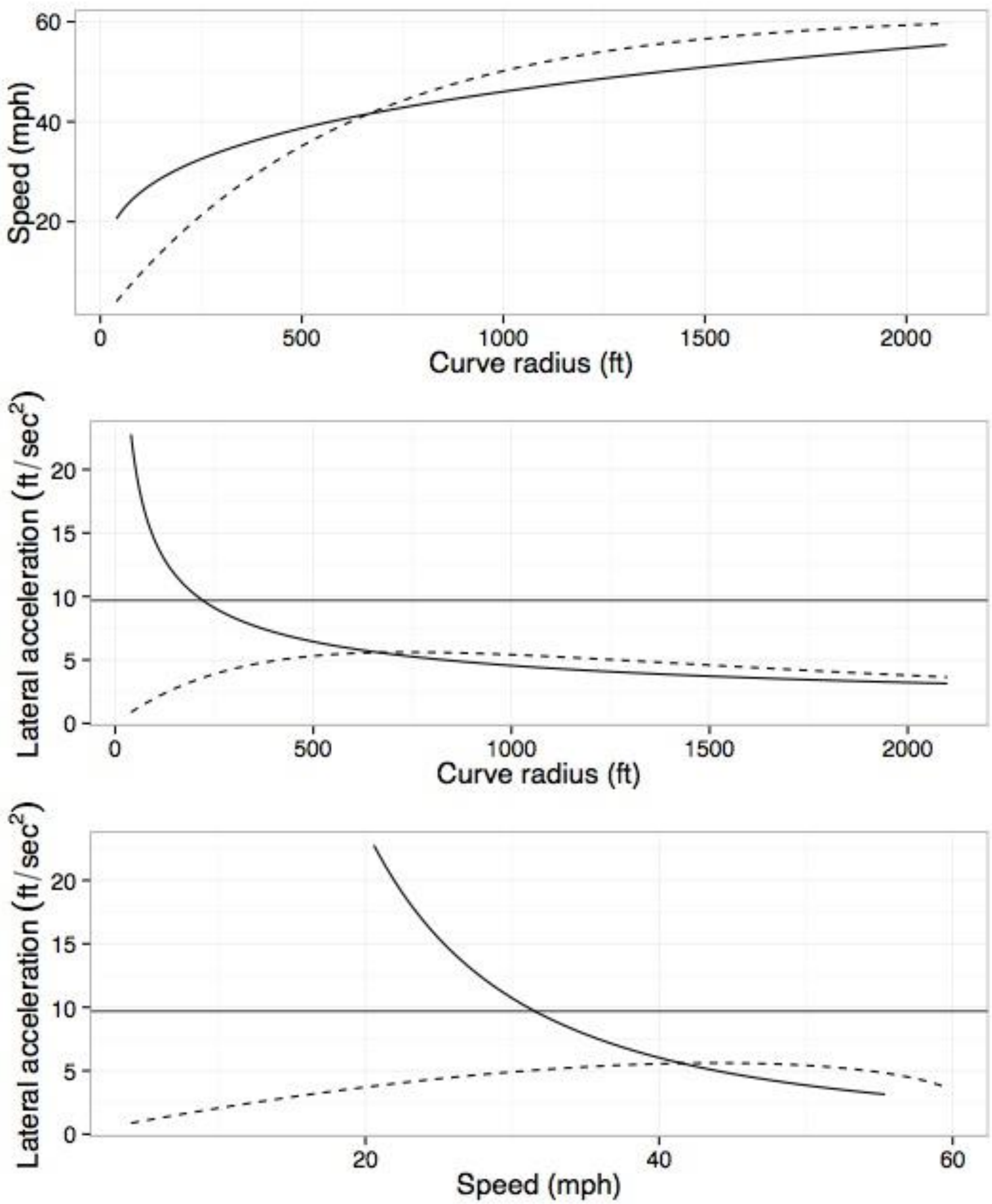


**Figure 44. Desired speed and associated lateral acceleration through curves as a function of their radii. The solid line is based on an analytic model [59] and the dotted line is based on empirical data [40].**

## ROAD CHARACTERISTICS AND INPUT TO THE DRIVER MODEL

This analysis focuses on four of the six road segments considered in the simulator data collection: the two roundabout intersections from Arizona (Figure 45 and Figure 46) and Maryland (Figure 47 and Figure 48). The top section of each of these descriptions shows a bird's-eye view of the route through the roundabout, with each of the six stages annotated. Each road segment has six stages, where stages are defined as the points at which speed data were collected. The width and shading of the segment indicates the curvature at each point on the segment. The bottom section shows the curvature (the inverse of the radius of curvature) across the segment, also annotated with the stages. Stage 1 in the first Arizona roundabout occurs approximately 500 feet into the segment on a gentle curve as indicated by the gray shading and the height of the curvature graph. In all cases, stage 4 occurs at the apex of the curve in the roundabout, which is the point of greatest curvature. The curvature data shown in these figures are the primary input to the driver model, which determines the speed maintenance behavior of the driver model. To the extent that these curvature data deviate from the actual road curvature, or the curvature perceived by the driver, the model will make poor predictions. One source of such deviations can arise from the way the road network is defined—large polygons can create discontinuities and erratic curvature data.

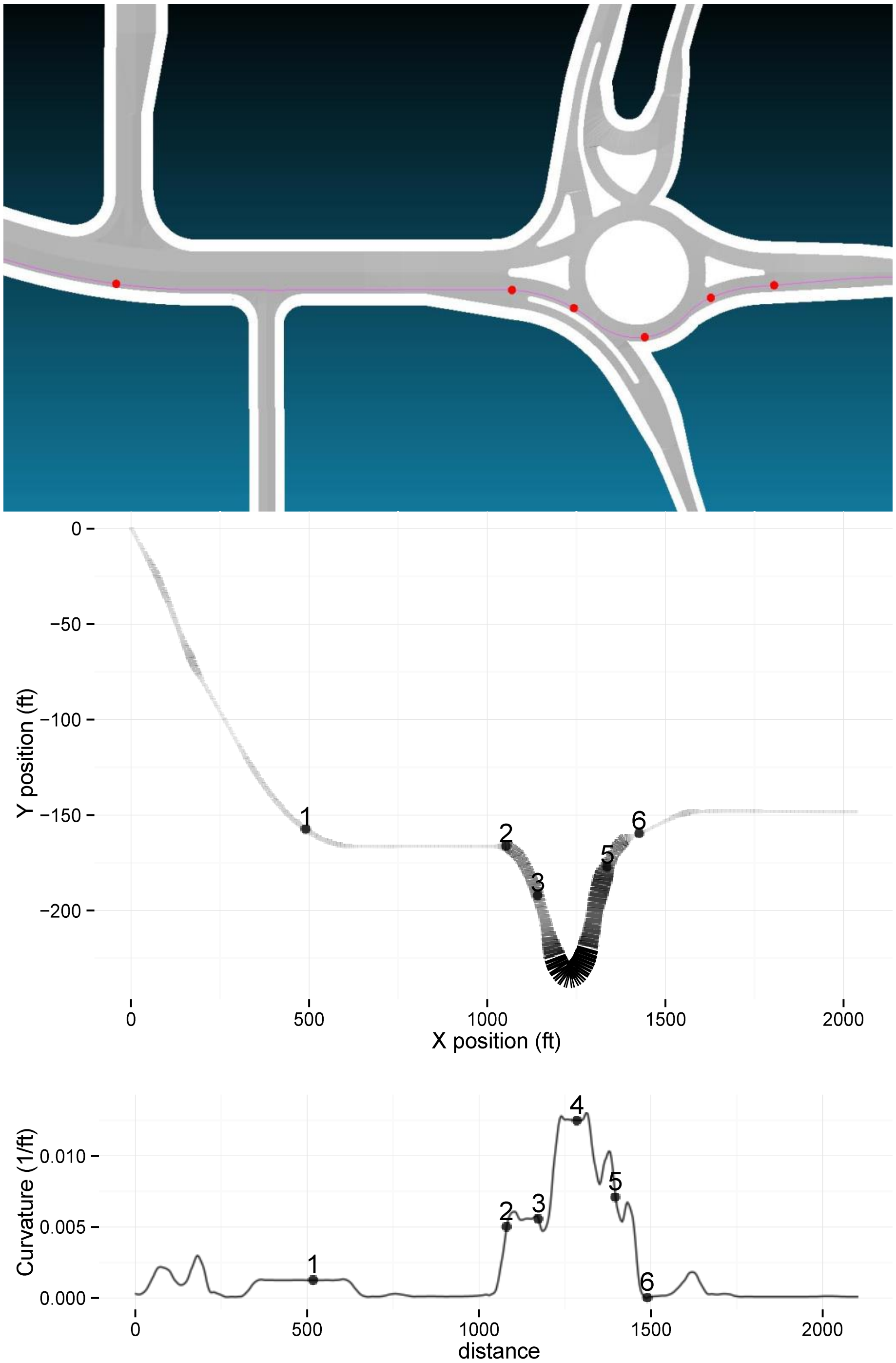


**Figure 45. Layout of the first Arizona roundabout. The width of the line in the center graph corresponds to the radius of curvature shown in the bottom graph.**

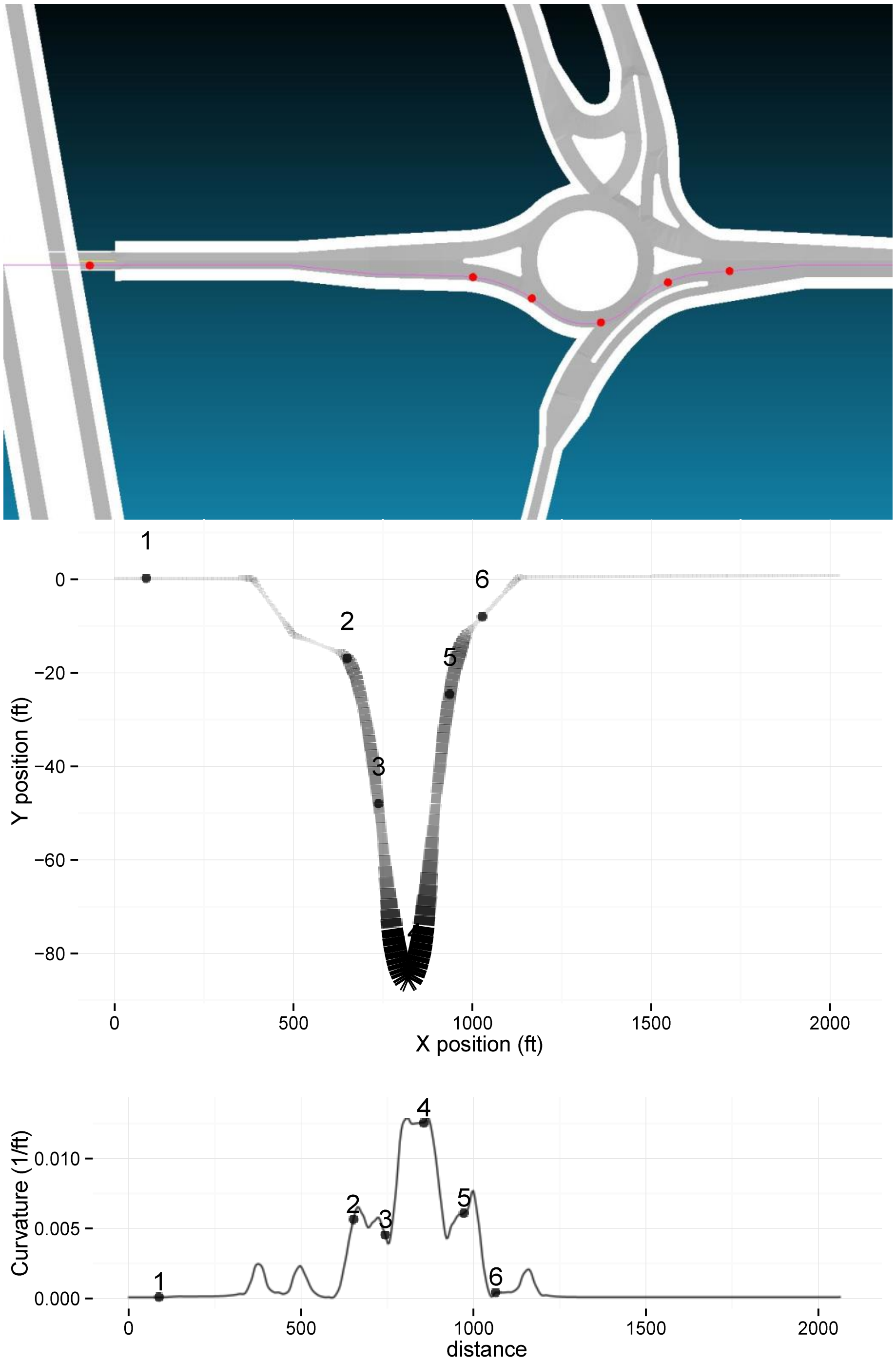


**Figure 46. Layout of the second Arizona roundabout. The width of the line in the center graph corresponds to the radius of curvature shown in the bottom graph.**

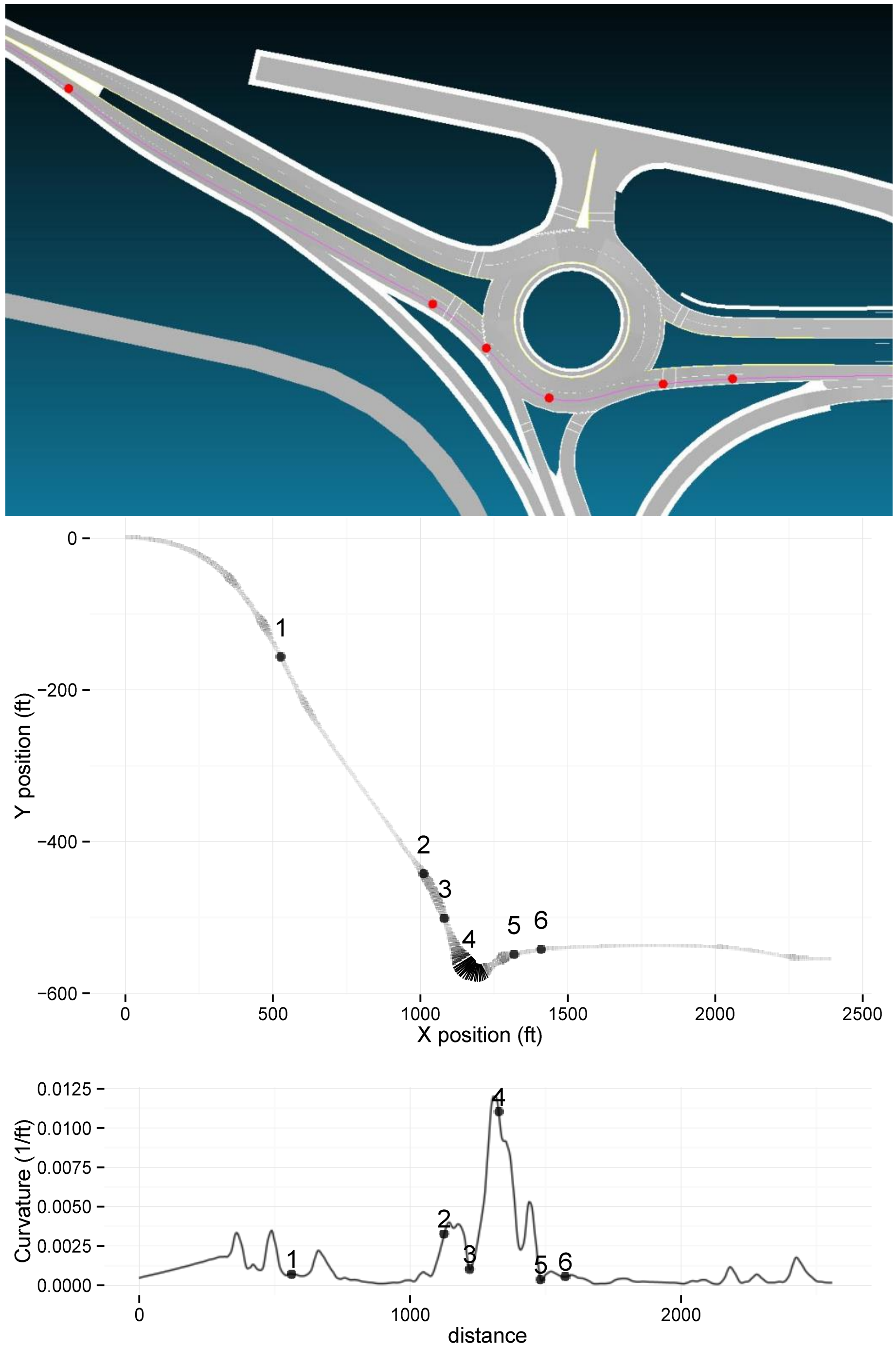


**Figure 47. Layout of the first Maryland roundabout. The width of the line in the center graph corresponds to the radius of curvature shown in the bottom graph.**

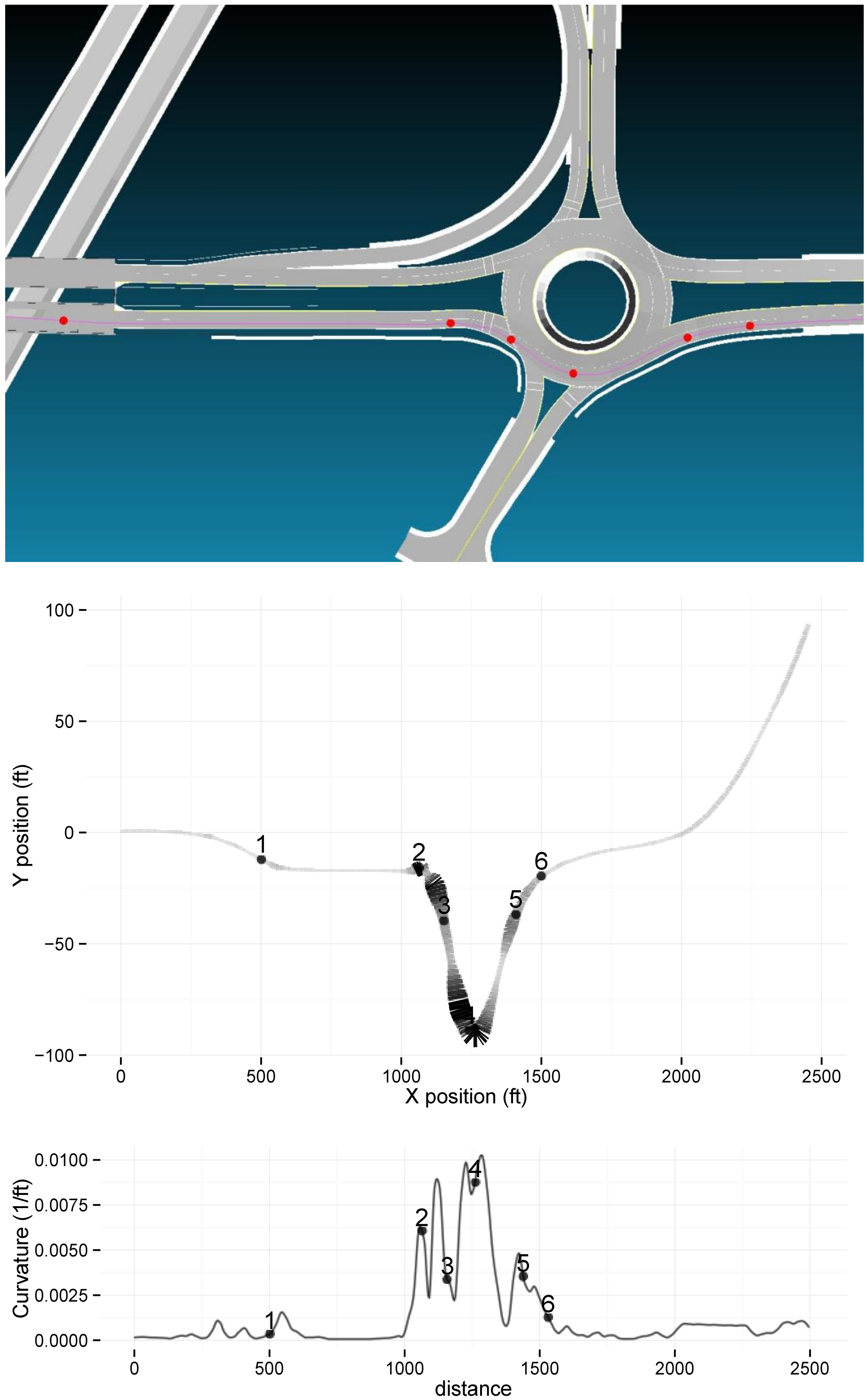


**Figure 48. Layout of the second Maryland roundabout. The width of the line in the center graph corresponds to the radius of curvature shown in the bottom graph.**

## MODEL FITTING AND PARAMETER ESTIMATES

The driver model generates a second-by-second speed profile of drivers negotiating the roundabout, which can be compared to the discrete locations for which speed data was available from the real world. Four model parameters combine with the road curvature to affect this trajectory (Table 13). The curve speed model maintains consistent speed when not limited by curve geometry ($V_F$). At each step in the simulation, the speed is assessed relative to desired speed and to the speed relative to the curve ahead. The time drivers look ahead to assess the desired speed ($\tau_{Lookahead}$) is set to .75 seconds. The value of desired speed at the current location is combined with the value at the look-ahead time in a weighted average, where the current location is weighted .25 and the look-ahead value is weighted .75. As in the look-ahead time, these values were selected to minimize the mean square error. When this weighted desired speed differs from the current speed, the driver model responds by accelerating or decelerating. The look-ahead time and the weighting value were estimated using the Maryland data and then held constant for the Arizona data.

The magnitude of the deceleration is proportional to the difference between the desired speed and the actual speed. The commanded acceleration depends on a relationship derived by Levison et al. [59] that reflects a balance between the cost of high acceleration and the time to adjust speed and is limited by a maximum acceleration of .30 g. The same longitudinal acceleration governs adjustment to speed on curve entry and on curve exit [59].

**Table 13. Model parameters estimated to transform the simulator data.**

| Model parameter | Definition and rationale |
|---|---|
| $V_F$ | Mean free speed may be biased if perceptual cues fail to indicate speed. |
| $\alpha_{CV}$ | The influence of the curve radius on desired speed through the curve. This parameter reflects the simulators' ability to render the texture and edges that specify the curvature of the upcoming road and replicate perception of the lateral acceleration through the curve. |
| $\alpha_{alon}$ | The degree to which the differences between desired and actual speed influence changes in acceleration. |
| $\tau_{alon}$ | Time constant of changes in longitudinal acceleration. |

## MODEL-BASED TRANSFORMATIONS

Model-based transformations aim to relate driver behavior observed in the simulator to behavior on the actual roadway. A transformation is possible by first estimating model parameters that produce the speed trajectories observed on the road. The limited on-road data available for this project make such estimates difficult. Ideally, a continuous record of both accelerator and brake pedal modulation and speed along the curve would be used. Here only three samples of speed were available. The model parameters that account for these data are shown in the last rows of

Table 14 and Table 15. The column labeled “Fit” indicates the degree to which the model predictions fit the observed on-road data. It is one minus the sum of the squared deviation of the actual speed and the speed predicted by the model divided by the sum of the squared deviation of the actual speed. The column labeled “Bias” represents the mean difference between the prediction of the model and the actual speed in miles per hour, where the dynamic model is comprised of Equations 2 and 3.

The model parameters are estimated for each simulator configuration based on the data collected from the simulators. The resulting parameters reflect how simulator characteristics influence driver behavior. The model can transform the simulator and estimate roadway data by adjusting the model parameters by a scaling parameter based on the ratio of the roadway parameter to the simulator parameter. The rightmost columns of Table 14 and Table 15 indicate the scaling to adjust the model parameters to translate speeds observed in the simulator to actual roadway speed profiles.

The novel contribution of this method is that it describes differences in how drivers negotiate curves, not through the typical summary of dependent measures, but 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 that on the road. The practical utility of this contribution is that it can be used to transform speed observed in the simulator to speed observed on the road. The degree of fit shown in the tables indicate how well these transformed values are likely to actually match speeds observed on the road.

**Table 14. Model parameters and transformations for Maryland roundabout segments.**

| Simulator | Motion | Visual complexity | $V_F$ | $\alpha_{CV}$ | $\alpha_{alon}$ | $\tau_{alon}$ | Fit | Bias | Scale $V_F$ | Scale $\alpha_{CV}$ | Scale $\alpha_{alon}$ | Scale $\tau_{alon}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NADS | Off | Low | 47.5 | .0030 | .32 | .55 | .966 | 1.8 | 1.00 | 0.33 | 1.25 | 0.85 |
| NADS | Off | High | 47.5 | .0030 | .32 | .55 | .962 | 2.3 | 1.00 | 0.33 | 1.25 | 0.85 |
| NADS | On | Low | 47.5 | .0030 | .08 | .60 | .963 | -0.1 | 1.00 | 0.33 | 5.00 | 0.92 |
| NADS | On | High | 47.5 | .0030 | .08 | .60 | .957 | 0.6 | 1.00 | 0.33 | 5.00 | 0.92 |
| FHWA | Off | Low | 49.0 | .0030 | .24 | .90 | .958 | 2.4 | 0.97 | 0.33 | 1.67 | 1.38 |
| FHWA | Off | High | 47.5 | .0030 | .08 | .60 | .949 | 0.9 | 1.00 | 0.33 | 5.00 | 0.92 |
| FHWA | On | Low | 47.5 | .0030 | .32 | .55 | .968 | 1.3 | 1.00 | 0.33 | 1.25 | 0.85 |
| FHWA | On | High | 49.0 | .0030 | .24 | .90 | .959 | 2.5 | 0.97 | 0.33 | 1.67 | 1.38 |
| WTI | Off | Low | 48.0 | .0030 | .08 | .80 | .964 | 0.1 | 0.99 | 0.33 | 5.00 | 1.23 |
| WTI | Off | High | 49.0 | .0030 | .24 | .90 | .956 | 1.2 | 0.97 | 0.33 | 1.67 | 1.38 |
| WTI | On | Low | 48.0 | .0030 | .08 | .80 | .963 | 0.7 | 0.99 | 0.33 | 5.00 | 1.23 |
| WTI | On | High | 49.0 | .0030 | .24 | .90 | .956 | 1.9 | 0.97 | 0.33 | 1.67 | 1.38 |
| miniSim | Off | Low | 47.5 | .0040 | .16 | .60 | .978 | 0.7 | 1.00 | 0.25 | 2.50 | 0.92 |
| miniSim | Off | High | 47.5 | .0040 | .16 | .60 | .976 | 1.3 | 1.00 | 0.25 | 2.50 | 0.92 |
| Roadway | | | 47.5 | .0010 | .40 | .65 | .996 | -0.9 | 1.00 | 1.00 | 1.00 | 1.00 |

**Table 15. Model parameters and transformations for Arizona roundabout segments.**

| Simulator | Motion | Visual complexity | $V_F$ | $\alpha_{CV}$ | $\alpha_{alon}$ | $\tau_{alon}$ | Fit | Bias | $V_F$ Scale | $\alpha_{CV}$ Scale | $\alpha_{alon}$ Scale | $\tau_{alon}$ Scale |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| NADS | Off | Low | 46.5 | .0045 | .015 | .85 | .845 | 4.6 | 1.00 | 0.66 | 0.66 | 0.88 |
| NADS | Off | High | 46.5 | .0045 | .015 | .85 | .827 | 5.0 | 1.00 | 0.66 | 0.66 | 0.88 |
| NADS | On | Low | 46.5 | .0045 | .015 | .85 | .795 | 5.5 | 1.00 | 0.66 | 0.66 | 0.88 |
| NADS | On | High | 46.5 | .0045 | .015 | .85 | .878 | 5.7 | 1.00 | 0.66 | 0.66 | 0.88 |
| FHWA | Off | Low | 46.5 | .0045 | .015 | .85 | .826 | 4.4 | 1.00 | 0.66 | 0.66 | 0.88 |
| FHWA | Off | High | 46.5 | .0045 | .015 | .85 | .866 | 5.4 | 1.00 | 0.66 | 0.66 | 0.88 |
| FHWA | On | Low | 46.5 | .0045 | .015 | .85 | .882 | 4.4 | 1.00 | 0.66 | 0.66 | 0.88 |
| FHWA | On | High | 46.5 | .0045 | .015 | .85 | .866 | 4.0 | 1.00 | 0.66 | 0.66 | 0.88 |
| WTI | Off | Low | 46.5 | .0045 | .030 | .75 | .871 | 3.7 | 1.00 | 0.66 | 0.33 | 1.00 |
| WTI | Off | High | 46.5 | .0045 | .015 | .85 | .867 | 3.6 | 1.00 | 0.66 | 0.66 | 0.88 |
| WTI | On | Low | 46.5 | .0045 | .015 | .85 | .887 | 3.3 | 1.00 | 0.66 | 0.66 | 0.88 |
| WTI | On | High | 46.5 | .0045 | .015 | .85 | .858 | 4.3 | 1.00 | 0.66 | 0.66 | 0.88 |
| miniSim | Off | Low | 46.5 | .0045 | .010 | .75 | .917 | 2.4 | 1.00 | 0.66 | 1.00 | 1.00 |
| miniSim | Off | High | 46.5 | .0045 | .010 | .75 | .883 | 3.3 | 1.00 | 0.66 | 1.00 | 1.00 |
| Roadway | | | 46.5 | .0030 | .010 | .75 | .874 | 0.7 | 1.00 | 1.00 | 1.00 | 1.00 |

# CHAPTER 4—DISCUSSION

A central challenge in making simulators useful for roadway design concerns how well driver behavior in the simulator matches driver behavior on the road. These results 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 be further refined through the use of the transformations developed as part of this research. A detailed analysis of both physical fidelity and behavioral fidelity 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.

Generally, the NADS and WTI simulators showed the highest level of fidelity across the range of metrics examined. However, it is apparent that no single metric can serve as a proxy for overall simulator fidelity. This illustrates how simulators can differ across different dimensions that affect level of fidelity. It is clear that the broad concept of overall level of fidelity is misleading and must instead be addressed in a multi-dimensional manner. It also points out the need, when considering fidelity, to consider the type of vehicle the simulator is designed to reproduce and type of measure that is relevant in a given scenario. For example, the effect of 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 the effect of the details included in creating the virtual roadway (e.g., visual complexity).

These results confirm the importance of understanding how different dimensions of physical fidelity work together to provide overall fidelity. 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 drivers to attend to the speedometer more than they would on the road. Some of these differences in physical fidelity degrade driver response to the point that behavioral fidelity is compromised, while 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 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, the motion system, the sound system, the steering torques, and the 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. Similarly, 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 through slow visually perceived speed changes, and 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 between outcomes on different platforms. This project directly addresses those issues to provide guidance to research community, and highway designers. Specifically, this research shows how the simulator configuration affects speed in the simulator relative to the real world and 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 a speeds quite comparable to those observed on actual roadways.

Overall, 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 a real-world data set. Some of the key contributions of this project include:

- 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 which simulator characteristics that may be most relevant to measuring speed in road design (e.g., visual complexity, field of view, 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

The metrics and methods used to characterize physical fidelity of simulators highlighted the need to consider differences between 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 by several jnds 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 fidelity and behavioral fidelity.

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. Additionally, the approach used in this report could be expanded to include a wider range of typical vehicles, rather than a single example, and examine jnd from the edge of the range of typical vehicles.

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, but does not provide a comprehensive understanding because not all features that matter are easily measured, and not all features contribute equally. Particularly 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 study 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.

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. For that we 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.

A general issue that goes beyond the features of the simulator is the sample of drivers and their goal structure. Drivers in the simulator are well aware of being observed and may moderate their behavior accordingly—they may be less likely to violate traffic regulations. In contrast, drivers on the road are unlikely to know they are being observed when their speeds are recorded. In addition, some samples of drivers in the simulator might not be representative of the broader driver population. As an example, many drivers had previously participated in prior studies. Drivers who have volunteered frequently for simulator studies may introduce a self-selection bias and reduce the representativeness of the sample relative to typical drivers. Valid simulator data requires a sample of drivers representative of those experiencing the situation in the world, a sample of simulated vehicles representative of those experiencing the situation in the world, and a simulator configuration capable of rendering the vehicle and roadway accurately. Rarely can all these requirements be met, but the model-based transformation of data in this study suggests a principled approach to relate simulator data to that observed on the road.

To better understand the comparison between the simulator and the real world, additional real-world data that provides a more continuous and complete description of driver behavior. This study was limited to speed observed on the road at widely spaced points. The current on-road data are sparse with no lane position data, and the graphs show that relatively few of the road segments and stages include on-road data, making comprehensive assessment of simulator performance difficult. 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 three segments using 15 subjects per condition so that a model can be developed would provide a strong foundation for continuing this research.

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, but 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.

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# APPENDIX A: SIMULATOR CHARACTERISTICS SURVEY

## INTRODUCTION

The purpose of Task 3 is to develop a set of driving simulator characteristics that can be included, excluded, or manipulated across the various scenario configurations that will be implemented in Phase 2. Differences in simulator capabilities and characteristics across a variety of driving simulators can have a significant impact on driver behavior and performance, and these differences will influence the transforms used to map results obtained in various simulators to the real-world driving experience. Consequently, an understanding of the capabilities and limitations of a range of driving simulator configurations is critical to developing a robust set of transforms.

In support of this task, a survey was developed and administered to organizations that operate driving simulators in order to identify a full range of characteristics, capabilities, and limitations found in a representative sample of driving simulators. A range of simulators from desktop to full-vehicle simulators using a variety of displays and controls was evaluated in this survey. This document describes the methodology for developing and administering the survey and presents the survey results, which include descriptions of each simulator and a summary table containing key characteristics that will likely be relevant to the conduct of Task 4.

## METHODS

Two primary activities were performed to develop the survey. First, a brief, informal literature review was conducted to ascertain the current state of the technology and current practices in driving simulation. A survey of simulator characteristics was developed based on the results of the review and on input from subject matter experts in the field of driving simulation. This section describes these activities.

## LITERATURE REVIEW

A review of the current literature related to driving simulator characteristics was performed to identify relevant characteristics that influence drivers' perception and behavior and to identify the range of simulation solutions that are currently in use. The literature search focused on articles that describe new simulator technologies; however, articles that describe established technologies were also obtained in order to gain an overall view of the current state of the technology and current practices. The review included articles related to the following topics:

- Simulation environment, including types of cabs, types of transmissions, vehicle dynamics, etc.
- Visual subsystem, including display visual resolution, field of view, projection system, number of screens, optic flow, level of detail, etc.
- Sound subsystem, including intensity, frequency spectrum, auditory cues, room acoustics, etc.
- Haptic subsystems, including motion base, degrees of freedom, motion base characteristics (e.g., speed, displacement, acceleration), other haptic signals

- Scenario subsystems, including available scenario elements, scenario development flexibility, level of control, etc.

## SURVEY

The survey was developed based on the results of the literature review and on input provided by subject-matter experts in the field of driving simulation. The survey asked questions about the following categories of simulator characteristics:

- **Vehicle Subsystem:** This section included questions about the cab configuration and available controls and displays.
- **Visual Subsystem:** This section included questions about the screen configuration, projector/display characteristics, visual rendering capabilities, and mirrors.
- **Sound Subsystem:** This section included questions about the auditory signals in the cab, including sound sources and sound quality (e.g., frequency response, dynamic range, localization, veridicality of sounds, etc.)
- **Haptic Subsystem:** This section included questions about motion base; vibration; steering, brake, and accelerator feedback; and other haptic cues.
- **Vehicle Dynamics:** This section included questions about the characteristics and performance of the simulator's vehicle dynamics.
- **Scenario Subsystem:** This section included questions about the availability and control of specific scenario elements and their characteristics. Questions about data capture were also included in this section.
- **Experimentation Environment:** The questions in this section referred to features in the simulator cab, and in the room in which the simulator is housed, that may affect simulator sickness.

The survey was administered to six organizations, some of which housed more than one simulator; altogether, surveys were completed for nine simulator systems. Each simulator was assigned an identification code in order to facilitate the organization of characteristics by simulator system and to simplify reporting. Table 16 lists the driving simulator identification codes and the organization that houses each simulator.

**Table 16. Driving Simulators Included in the Survey**

| Simulator ID | Simulator Name/Type | Organization |
|---|---|---|
| CHPS | DriveSafety – Custom Buck | Battelle Center for Human Performance and Safety |
| DS500 | DriveSafety – DS500C | Western Transportation Institute |
| HDS | Highway Driving Simulator | FHWA Office of Safety Research and Development |
| NADS-1 | NADS | National Advanced Driving Simulator |
| NADS-2 | NADS-2 | National Advanced Driving Simulator |
| NADS MiniCab | NADS miniSim – ¼ Cab | National Advanced Driving Simulator |
| NADSMiniDesk | NADS miniSim – Desktop | National Advanced Driving Simulator |
| RTI | RTI Simulator | Western Transportation Institute |
| WIHIFI | Wisconsin High Fidelity Driving Simulator | University of Wisconsin-Madison |

The completed survey responses were entered into an Excel spreadsheet and organized by question, with responses listed across all simulators for each question.

**Results**

This section presents the results of the simulator survey, including a general description of each simulator followed by a table that summarizes the key characteristics that are likely to be relevant to the conduct of Task 4. A brief discussion of the behavioral implications of the simulator characteristics follows the table.

## SIMULATOR DESCRIPTIONS

This section 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. Some characteristics, such as scenario capabilities, are generally similar between the simulators surveyed and are generally not included in the descriptions. Indeed, many of the simulators are based on the same operating system and have most software-based capabilities in common. For example, the four NADS simulators are based on the same operating system and therefore can provide the same scenario-related capabilities.

It should be noted that visual display resolution is expressed in terms of angular resolution, defined as the visual angle subtended by the width of one pixel when viewed from the driver’s eyepoint. This vision-limited resolution is used as a benchmark for comparing overall display performance.

**CHPS (Battelle)**

The CHPS simulator is a fixed-base simulator with a half-cab buck based on a 1985 Ford Merkur coupe with automatic transmission. The buck features a full range of driving controls and displays using physical instruments. Additional controls are available for performing secondary tasks, including radio dials/buttons, HVAC, and task-specific buttons and displays. Displays for performing the primary driving task (e.g., speedometer, tachometer, warning indicators, etc.) are implemented as physical instruments in the buck.

The visual system projects the scenario onto three flat screens that cover 174° horizontal field of view (HFOV) by 44° vertical field of view (VFOV) using three projectors. Each projector projects an image of 1024 x 768 pixels, which provides approximately 3.4 arcminutes of resolution. No edge blending is provided, and a vertical seam can be seen where images meet at the edges. Although the simulator has left and right physical mirrors, there is no rear view imagery projected behind the vehicles. The simulator is capable of providing rear-view imagery by emulating left-side, center, and right-side mirrors projected on the forward screens. A 4.1 surround-sound audio system presents high-fidelity, horizontally localized sound that can be presented at real-world sound pressure levels. Road vibration is generated using vibration actuators mounted on the steering column and under the seat. Steering sensation is enhanced using motorized force feedback, while the brake and accelerator pedals provide spring-loaded resistance. No other haptic cues are provided in the simulator. Roadway geometries are defined using fixed road segments or tiles. Except for a limited number of tiles that are programmable, tiles cannot be edited and new tiles cannot be created.

**DS500**

The DS500 simulator is a fixed-base simulator with a quarter-cab buck based on a GM Saturn vehicle with automatic transmission. The buck features a full range of driving controls and displays using physical instruments. Additional controls are available for performing secondary tasks, including radio dials/buttons, HVAC, and task-specific buttons and displays. Displays for performing the primary driving task (e.g., speedometer, tachometer, warning indicators, etc.) are implemented as physical instruments in the buck.

The visual system projects the scenario onto five rear-screen displays that cover 175° HFOV by 26° VFOV. Each 800 x 600-pixel display projects an image that provides 2.6 arcminutes of resolution. The simulator provides rear-view imagery by projecting left-side, center, and right-side mirror imagery onto appropriate locations on the forward screens. A 4.1 surround-sound audio system presents high-fidelity, horizontally localized sound at real-world sound pressure levels. Road vibration is generated using vibration actuators mounted on the steering column and under the seat. Steering sensation is enhanced using motorized force feedback, while the brake and accelerator pedals provide spring-loaded resistance. Eight motors in the seat provide additional haptic cues to the driver.

**HDS**

The HDS simulator supports a full-vehicle cab buck based on a 1998 Saturn SL sedan. The buck features basic driving controls and displays using physical instruments in the buck. Additional controls are available for performing secondary tasks, including typical vehicle controls (radio dials, HVAC, etc.) as well as touchscreen- and speech-based controls and displays. An electrically actuated motion base with three degrees of freedom (DOF) provides haptic cues to the driver to provide motion sensation.

The projection system includes five forward screens that cover 240° HFOV by 48° VFOV, and each projector projects an image with 2048 x 1536 pixels, yielding approximately 1.5 arcminutes of resolution. The projected images use edge blending and image warping to produce a corrected, seamless image at the driver's eyepoint. In addition, the visual subsystem features high dynamic range (HDR) rendering, allowing images to exhibit a greater range of tonal detail than is available using traditional rendering techniques. The simulator presents rear-view imagery on active display panels mounted in the left-side, center, and right-side mirrors. A 4.1 surround-sound audio system presents high-fidelity sound in a configuration that maximizes engine and road noise sounds. Spatial localization of sound is possible by reconfiguring the speaker placement. The simulator currently provides steering resistance using passive spring loading; however, an upgrade is underway that will include motorized force feedback. The brake and accelerator pedals can provide active actuation, such as is used in collision avoidance systems and cruise control. The HDS scenario is tile-based; however, road geometries can be custom-programmed.

**NADS-1**

The NADS-1 simulator supports several vehicle types, including passenger vehicles, SUVs, heavy trucks, farm tractors, and front-end loaders. The simulator can accommodate a full- or half-vehicle buck. The simulator is capable of instrumenting a full range of driving controls, including automatic transmission gear selectors and manual transmission shifters, using physical instruments in the buck. Additional controls are available for performing secondary tasks, including typical vehicle controls (radio dials, HVAC, etc.) and touchscreen-based controls and displays. Displays for performing the primary driving task (e.g., speedometer, tachometer, warning indicators, etc.) include physical instruments in the buck, emulated instruments displayed on the forward visual screens, and emulated instruments displayed on their own screens.

The visual system projects the scenario onto a spherical display surface that covers 360° HFOV by 48° VFOV using eight video channels. Three projectors provide 120° HFOV in the forward view; each of these projectors provides an image of 1600 x 1200 pixels with 1.6 arcminutes of resolution. The imagery for the remaining 240° of peripheral and rear view are projected at 1280 x 1024 pixels, resulting in a resolution of 2.1 arcminutes per pixel. The projected images use edge blending and image warping to produce a corrected, seamless image at the driver's eyepoint. The simulator presents rear-view imagery on physical mirrors or on display panels mounted in the left- and right-side mirrors, depending on the buck in use. A 4.1 surround-sound audio system presents high-fidelity, horizontally localized sound at real-world sound pressure levels.

The NADS-1 simulator features a 13-DOF motion base comprised of a Stewart platform with a yaw turntable mounted on an X-Y linear bed that provides large-excursion linear travel (up to 64 feet). Four vibration actuators are mounted under the cab to provide road-surface-specific cues. Steering feel is provided using motorized torque feedback, and the brake and accelerator feature active motorized counterforce control. The brake and accelerator pedals and vehicle dynamics can emulate ABS, haptic alerts (e.g., collision warnings), active braking (e.g., collision avoidance), and safety systems (ACC, ESC, etc.). Additional cues such as haptic seat, haptic steering, and visual and audio cues are integrated on a project-specific basis. Roadway geometries are defined using fixed road segments or tiles, and new tiles are routinely created for geo-typical or geo-specific environments.

**NADS-2**

The NADS-2 simulator is a fixed-base simulator that supports several vehicle types, including passenger vehicle, SUV, heavy truck, farm tractor, and front-end loader. The simulator can accommodate a full- or half-vehicle buck. The simulator is capable of instrumenting a full range of driving controls, including automatic transmission gear selectors and manual transmission shifters, using physical instruments in the buck. Additional controls are available for performing secondary tasks, including typical vehicle controls (radio dials, HVAC, etc.) and touchscreen-based controls and displays. Displays for performing the primary driving task (e.g., speedometer, tachometer, warning indicators, etc.) include physical instruments in the buck, emulated instruments displayed on the forward visual screens, and emulated instruments displayed on dedicated screens.

The visual system projects the scenario onto a spherical display surface that covers 140° HFOV by 40° VFOV using three 1400 x 1050-pixel video channels (five channels are possible) at a resolution of 2.0 arcminutes per pixel. A single 65-inch plasma screen mounted behind the buck provides rear imagery with a 1920 x 1080-pixel array. The simulator presents rear-view imagery on physical mirrors or on display panels mounted in the left- and right-side mirrors, depending on the buck in use. A physical mirror is used to view the center rear view reflected from the rear plasma screen. A 4.1 surround-sound audio system presents high-fidelity, horizontally localized sound at real-world sound pressure levels.

The NADS-2 simulator does not provide any road vibration to drivers through the wheels or steering column. However, haptic cues are provided using multi-zone seat vibration. Steering sensation is enhanced using motorized force feedback, and the brake and accelerator feature active motorized counterforce. The brake and accelerator pedals can emulate ABS, haptic alerts (e.g., collision warnings), and active braking (e.g., collision avoidance).

**NADS MiniCab**

The NADS MiniCab simulator is a fixed-base, quarter-cab, pedestal-type simulator, with a buck that includes a real vehicle seat, steering wheel, brake, accelerator, and dashboard. Passenger vehicles, SUVs, and heavy trucks can be simulated, with dynamics models for each vehicle type. The simulator features the standard driving controls using physical instruments and can simulate automatic transmission gear selectors for passenger vehicles and SUVs, and manual transmission shifters for heavy vehicle simulation. The steering wheel control includes a turn-signal stalk with instrumented switches. Controls available for performing secondary tasks include task-specific controls and a touchscreen. Displays for performing the primary driving task (e.g., speedometer, tachometer, warning indicators) are implemented as emulated instruments displayed on their own dedicated screens.

The projection system includes three flat panel plasma displays that cover 132° HFOV by 24° VFOV in the forward view. The 1024 x 768-pixel displays produce a 16:9 widescreen aspect ratio using rectangular-shaped pixels, yielding 2.4 arcminutes per pixel in the horizontal aspect and 1.9 arcminutes per pixel vertically. As with all simulators based on the NADS operating system, the visual system can simulate thermal and infrared imaging through visual database textures. The simulator emulates left-side, center, and right-side mirrors by projecting their respective images on the forward displays. A stereophonic audio system with an additional subwoofer presents high-fidelity sounds that are generally localized horizontally and are limited to frequencies greater than 80 Hz and intensities below 80 dBA. Sound intensities are not calibrated to match sound pressure levels of real-world data.

The NADS MiniCab simulator provides road vibration to drivers using a transducer in the seat. Steering sensation is enhanced using motorized force feedback, while the brake and accelerator pedals are spring-loaded. An optional seatbelt tug mechanism and an optional haptic seat with four transducers are used to provide additional haptic cues. Other hardware can be integrated via a network interface.

**NADS MiniDesk**

The NADS MiniDesk simulator is a fixed-base, desktop simulator that includes a steering wheel, brake pedal, and accelerator. Passenger vehicles, SUVs, and heavy trucks can be simulated, with dynamics models for each vehicle type. The simulator features the standard driving controls using physical instruments and can simulate automatic transmission gear selectors for passenger vehicles and SUVs, and manual transmission shifters for heavy vehicle simulation. Turn signals are actuated via buttons on the steering wheel. Controls available for performing secondary tasks include task-specific controls and an optional touch screen. Displays for performing the primary driving task (e.g., speedometer, tachometer, warning indicators) are implemented as emulated instruments displayed on their own dedicated screens.

The projection system can include one or three flat panel LCD displays. Each screen covers 25° HFOV and 14.5° VFOV; when three screens are used, the displays provide a HFOV of approximately 78°. Each display has 1600 x 900 physical pixels (LCD cells); however, the image is presented at a lower spatial resolution of 1280 x 1024 logical pixels, which provides 1.2 arcminutes per pixel horizontally and 0.8 arcminutes per pixels vertically. The simulator emulates left-side, center, and right-side mirrors by projecting their respective images on the forward displays. A stereophonic audio system with an additional subwoofer presents high-fidelity sounds that are generally localized. Sound intensities are not calibrated to match real-world sound pressure levels. The NADS MiniDesk simulator provides road vibration to drivers via vibration on the steering column. Steering sensation is enhanced using motorized force feedback, while the brake and accelerator pedals are spring-loaded.

## RTI

The RTI simulator supports passenger vehicles and light trucks; an Isuzu N-Series heavy truck has been acquired but is not currently instrumented. The simulator can accommodate a full- or half-vehicle buck as well as a desktop configuration. The buck features basic driving controls and displays using physical instruments in the buck. Steering wheel buttons, HVAC, and touch screen controls are available for performing secondary tasks, and the touch screen can be programmed to emulate a navigation system. Displays for performing the primary driving task (e.g., speedometer, tachometer, warning indicators, etc.) are implemented as emulated instruments displayed on their own dedicated screens.

The visual system projects the scenario onto a cylindrical screen that covers 240° HFOV by 38° VFOV using five video channels. Each projector covers 48° HFOV with a 1600 x 1200-pixel image that provides 2.0 arcminutes per pixel of resolution. An additional flat screen provides rear imagery for a center mirror. The projected images use edge blending, auto alignment, and image warping to produce a corrected, seamless image. The simulator presents rear-view imagery on a physical mirror for the center mirror and on active display panels mounted in the left- and right-side mirrors. Stereoscopic vision is available in the software, but is not implemented in the visual subsystem. A 5.1 surround-sound audio system is mounted outside the buck, and four additional speakers are mounted inside the buck. This system presents high-fidelity sound that is highly localized horizontally and is presented at real-world sound pressure levels.

The RTI simulator features a six-DOF Stewart platform motion base. Additional vibration actuators are mounted on the steering column, wheels, and seat to provide road vibration. Steering sensation is enhanced using motorized force feedback, and the brake and accelerator pedals provide spring-loaded resistance. Roadway geometries are defined using fixed road segments or tiles that are programmatically changeable as well as using custom-programmed geometries.

## WIHIFI

The WIHIFI simulator accommodates a full-vehicle (passenger vehicle) buck. The buck features basic driving controls and displays using physical instruments in the buck. Radio controls, HVAC, task-specific controls, and touchscreen controls are available for performing secondary tasks. A navigation system will be included. Most of these controls are instrumented. Displays for performing the primary driving task (e.g., speedometer, tachometer, warning indicators) are implemented as emulated instruments displayed on their own dedicated screens.

The visual system projects the scenario onto a cylindrical screen that covers 240° HFOV using five video channels; each projector throws an image of 1920 x 1080 pixels. The projectors offer two resolution modes: 1) low-resolution mode projects an image with 1.875 arcminutes per pixel and 2) high-resolution mode projects an image with 0.92 arcminutes per pixel. An additional flat screen provides 40° HFOV rear imagery for a center mirror. The projected images use edge blending to produce a seamless image. The simulator presents rear-view imagery on a physical mirror for the center mirror and on active display panels mounted in the left- and right-side mirrors. A five-speaker audio system is mounted outside the buck, and four additional speakers are mounted inside the buck. This system presents high-fidelity sound that is horizontally localized. The sound system is not calibrated to match real-world sound pressure levels.

The WIHIFI simulator features a single DOF, linear travel motion base that simulates vehicle pitch. Road vibration is generated by actuators mounted on the steering column, wheels, and seat. Steering sensation is enhanced using motorized force feedback, and the brake and accelerator pedals provide spring-loaded resistance. Roadway geometries are defined using fixed road segments or tiles that are programmatically changeable.

## SUMMARY OF CHARACTERISTICS

Table 17 summarizes the primary characteristics of the driving simulators. It is not intended to comprehensively list all of the characteristics from the survey; rather, it provides a basis for comparing the features that are likely to be most important to the goals of the project. Specifically, the table lists characteristics that are related to dimensions of fidelity identified in Task 1 that will likely affect driver performance. These dimensions include:

- Resolution, contrast, and other visual display characteristics (conspicuity, gap acceptance, sign recognition, and target identification, etc.)
- Field of view (channels) and optic flow (for situational cues and speed perception)
- Face validity of cab configuration
- Driver control input feel (for steering and braking performance)
- Auditory cues
- Motion and vibration (to simulate pavement edge drop-offs, speed control through curves)

The table can be used to quickly compare characteristics across all of the simulators evaluated. Vehicle dynamics characteristics and some characteristics that describe scenario elements are excluded from Table 17 because the results were too cumbersome to present in the table or the responses did not vary significantly between simulator systems. Differences between simulators for each simulator characteristic can be identified using the related tables.

**Table 17. Summary of simulator characteristics.**

| Characteristic | CHPS | DS500 | HDS | NADS-1 | NADS-2 | NADSMiniCab | NADSMiniDesk | RTI | WIHIFI |
|---|---|---|---|---|---|---|---|---|---|
| Vehicle Subsystem | | | | | | | | | |
| Buck | • Half-vehicle<br>• Passenger vehicle | • Quarter-vehicle<br>• Passenger vehicle | • Full-vehicle<br>• Passenger vehicle | • Full-vehicle<br>• Passenger vehicle, SUV, heavy truck, farm tractor, front-end loader | • Full-vehicle<br>• Passenger vehicle, SUV, heavy truck, farm tractor, front-end loader | • Quarter-vehicle<br>• Passenger vehicle, SUV, heavy truck | • Desktop<br>• Passenger vehicle, SUV, heavy truck | • Full-vehicle, half-vehicle<br>• Passenger vehicle (heavy truck pending) | • Full-vehicle<br>• Passenger vehicle |
| Driving controls (Steering, brake, etc.) | • Integrated in vehicle | • Integrated in vehicle | • Integrated in vehicle | • Integrated in vehicle | • Integrated in vehicle | • No rear screens | • Separate controls | • Integrated in vehicle | • Integrated in vehicle |
| Visual Subsystem | | | | | | | | | |
| (Simulation Environment) | • 3 flat screens<br>• Front projection<br>• No edge blending<br>• No rear screens | • 5 flat screens<br>• Rear projection<br>• No edge blending<br>• No rear screens | • 5 flat screens<br>• Front projection<br>• 10% edge blending<br>• Image warping<br>• No rear screens | • Spherical<br>• Front projection<br>• 8 channels<br>• Edge blending<br>• Image warping | • Spherical<br>• Front projection<br>• 3 channels<br>• Image warping<br>• Plasma rear screen | • 3 flat screens<br>• Plasma displays<br>• Gap between images<br>• No rear screens | • 3 flat screens<br>• LCD displays<br>• Gap between images<br>• No rear screens | • Cylindrical<br>• Front projection<br>• 5 channels<br>• Flat rear screen | • Cylindrical<br>• Front projection<br>• 5 channels<br>• 10° edge blending<br>• Flat rear screen |
| Physical size of each display/screen[1] | 100" (H)<br>72" (V) | 32" (H)<br>24" (V) | 93" (H)<br>90" (V) | Not Measured<br>(Not rectangular due to shape of screens) | Not Measured<br>(Not rectangular due to shape of screens) | 36" (H)<br>24" (V) | 18" (H)<br>10" (V) | 120" (H)<br>96" (V) | 118" (H)<br>66" (V)<br>(See footnote[2]) |
| View | 174° (H)<br>44° (V) | 26° (V) | 48° (V) | 48° (V) | 40° (V) | 24° (V) | 14.5° (V) | 38° (V) | |
| Resolution (arcminutes per pixel) | | | | 20°: 1.6<br>Remaining: 2.1 | | 1.9 (V) | 0.8 (V) | | Res Mode)<br>0.92 (Hi Res Mode) |
| ANSI Contrast[3] | 30:1 | – | – | 15.3:1 | 20.4:1 | 494:1 | 81:1 | – | – |
| Legibility distance[4] | 16 ft | – | 27 – 33 ft | Not Measured | Not Measured | 34 ft | 32 ft | Not Measured | Not Measured |
| | • Emulated mirrors using on-screen images | • Emulated mirrors using on-screen images | • Active display panel in mirror fixture | • Passive mirrors<br>• Active display panel in mirror fixture | • Passive mirrors<br>• Active display panel in mirror fixture | • Emulated mirrors using on-screen images | • Emulated mirrors using on-screen images | • Passive mirror (center)<br>• Active display panel in mirror fixture | • Passive mirror (center)<br>• Active display panel in mirror fixture |
| High Dynamic Range | No | No | Yes | No | No | No | No | No | No |

| Characteristic | CHPS | DS500 | HDS | NADS-1 | NADS-2 | NADSMiniCab | NADSMiniDesk | RTI | WIHIFI |
|---|---|---|---|---|---|---|---|---|---|
| Sound Subsystem | | | | | | | | | |
| Audio sources | • 4.1 surround<br>• Generally localized horizontally | • 4.1 surround<br>• Generally localized horizontally | • 4.1 surround<br>• Generally localized horizontally | • 4.1 surround<br>• Highly to generally localized horizontally | • 4.1 surround<br>• Highly to generally localized horizontally | • 4.1 surround<br>• Generally localized horizontally | • 4.1 surround<br>• Generally localized horizontally | • 4.1 surround<br>• Highly localized horizontally | • 4.1 surround<br>• Highly localized horizontally |
| Frequency response | 35 - 20,000 Hz | 35 - 20,000 | 50 - 18,000 Hz | 30 - 10,000 Hz | 30 - 10,000 Hz | 80 - 20,000 Hz | 35 - 20,000 Hz | 33 - 20,000 Hz | – |
| Audio calibrated to real-world levels | | | | | | | | | |
| Haptic Subsystem | | | | | | | | | |
| Motion base | None | None | Electrically actuated | Hexapod on linear X-Y bed | None | None | None | Hexapod | Linear travel |
| Degrees of freedom | – | – | 3 | 13 | – | – | – | 6 | 1 |
| Vibration | • Vibration on steering column<br>• Seat shaker | • Vibration on steering column<br>• Seat shaker | • Vibration on steering column<br>• Seat shaker | • Vibration on wheels<br>• Vibration on steering column<br>• Multi-zone seat vibration | • Multi-zone seat vibration | • Seat shaker | • Vibration on steering column | • Vibration on wheels<br>• Vibration on steering column<br>• Vibration on steering column | • Vibration on wheels<br>• Vibration on steering column<br>• Vibration on steering column |
| Tactile feedback | • Force feedback in steering<br>• Passive resistance in brake and accelerator pedals | • Force feedback in steering<br>• Passive resistance in brake and accelerator pedals | • Passive resistance in steering<br>• Passive resistance in brake and accelerator pedals | • Force feedback in steering<br>• Active counterforce in brake and accelerator pedals | • Force feedback in steering<br>• Active counterforce in brake and accelerator pedals | • Force feedback in steering<br>• Passive resistance in brake and accelerator pedals | • Force feedback in steering<br>• Passive resistance in brake and accelerator pedals | • Force feedback in steering<br>• Passive resistance in brake and accelerator pedals | • Force feedback in steering<br>• Passive resistance in brake and accelerator pedals |

| Characteristic | CHPS | DS500 | HDS | NADS-1 | NADS-2 | NADSMiniCab | NADSMiniDesk | RTI | WIHIFI |
|---|---|---|---|---|---|---|---|---|---|
| Scenario Subsystem | | | | | | | | | |
| Road definition | • Tile-based geometries | • Tile-based geometries | • Programmable tile-based geometries<br>• Custom-programmed geometries | • Tile-based geometries | • Tile-based geometries | • Tile-based geometries | • Tile-based geometries | • Programmable tile-based geometries<br>• Custom-programmed geometries | • Programmable tile-based geometries |
| Available road geometries (see footnote)[5] | All except roundabouts | All except roundabouts | All | All | All | All | All | All | All |
| Control of scenario elements using controlling (triggering) agents (see footnote)[6] | • All triggers except eye-glance to object<br>• All available scenario elements controllable | • All triggers except eye-glance to object<br>• All available scenario elements controllable except dynamic arrow panels | • All triggers except eye-glance to object<br>• All available scenario elements controllable | • All triggers except eye-glance to object<br>• All available scenario elements controllable | • All triggers except eye-glance to object<br>• All available scenario elements controllable | • All triggers except eye-glance to object<br>• All available scenario elements controllable | • All triggers except eye-glance to object<br>• All available scenario elements controllable | • All triggers<br>• All available scenario elements controllable except environ-mental conditions | • All triggers<br>• All available scenario elements controllable except environ-mental conditions |
| Image complexity | Moderate detail and shading of scenario elements | Moderate detail and shading of scenario elements | Near photo-realistic rendering | Near photo-realistic rendering | Near photo-realistic rendering | Near photo-realistic rendering | Near photo-realistic rendering | Near photo-realistic rendering | Near photo-realistic rendering |
| Size of objects relative to real-world | 1:1 | | 1:1 | 1:1 | 1:1 | 1:1 | 1:0.61 (real to virtual) | 1:1 | 1:1 |
| Density of objects visible on the screen | 2.5M triangles/sec | – | 22.8 M triangles/sec (lit, shaded, and textured). 1.34 Billion triangles/sec | Varies depending on processing load | Varies depending on processing load | Varies depending on processing load | Varies depending on processing load | 2M polygons/sec minimum | – |
| Experimental Environment | | | | | | | | | |
| Eye tracking<br>• vendor<br>• tracking resolution<br>• tracking accuracy<br>• % valid | • ASL 4000<br>• <0.5<br>• <1°<br>• Not measured | • faceLab<br>• <0.1°<br>• 0.5 – 1.0°<br>• >85% | • None | • faceLab<br>• <0.1°<br>• 0.5 – 1.0°<br>• 65 – 90% (scenario dependent) | • faceLab<br>• <0.1°<br>• 0.5 – 1.0°<br>• 65 – 90% (scenario dependent) | • faceLab<br>• <0.1°<br>• 0.5 – 1.0°<br>• 65 – 90% (scenario dependent) | • faceLab<br>• <0.1°<br>• 0.5 – 1.0°<br>• >90% | • faceLab<br>• <0.1°<br>• 0.5 – 1.0°<br>• > 90% | • None |

The range of values for each characteristic in Table 17 provides the spectrum of fidelity for characteristics across the simulators in the survey. In Task 4 of this project, we will use the information from the current task to compare characteristics across simulators to determine how suitable particular simulator platforms are for addressing a specific research question. To simplify these descriptions, the ranges for each characteristic in Table 17 were recast into low, medium, and high fidelity categories. Table 18 presents the fidelity definitions for each simulator characteristic. It should be noted that these classifications contain an element of arbitrariness in that they are defined partly by the range they cover (the bins were developed from the simulators examined in the survey so the range of values in each bin could differ if simulators with other characteristics are considered). Nonetheless, this table provides classifications that will facilitate our Task 4 activities.

**Table 18. Definitions of fidelity of simulator characteristics.**

| Characteristic | Low Fidelity | Medium Fidelity | High Fidelity |
|---|---|---|---|
| Vehicle Subsystem | | | |
| Buck | Desktop | Quarter or half vehicle | Half or full vehicle |
| Driving controls (Steering, brake, etc.) | Desktop steering wheel and separate foot controls | Actual vehicle controls (partial set) | Actual vehicle controls (full set) |
| Visual Subsystem | | | |
| Screens (Simulation Environment) | Desktop monitor | Flat screens | Spherical/cylindrical screens |
| Continuity between projected images | Gaps between screens<br>Frames around screens | No gaps between images (may be a vertical line where images meet) | Seamless image using edge blending |
| Physical size of each display/screen | < 32" x 24" | 32" x 24" to < 93" x 90" | ≥ 93" x 90" |
| Field of View | < 140° | 140° to 240° | > 240° |
| Resolution (arcminutes per pixel) | > 2.5 arcmin/pixel | 2 – 2.5 arcmin/pixel | < 2 arcmin/pixel |

| Characteristic | Low Fidelity | Medium Fidelity | High Fidelity |
|---|---|---|---|
| ANSI Contrast | < 15:1 | 15:1 to 100:1 | > 100:1 |
| Legibility distance | < 20 ft | 20 ft to 30 ft | > 30 ft |
| Rear-view imagery | No rear imagery | Rear imagery emulated using images on forward screens | Rear imagery using passive mirrors with rear screen or active panels in mirror fixtures |
| Sound Subsystem | | | |
| Audio sources | No localization | Generally localized | Highly localized |
| Audio calibrated to real-world levels | Not calibrated | Calibrated | Calibrated |
| Haptic Subsystem | | | |
| Motion base | No motion base | Motion seat (stationary vehicle or desktop; seat moves) | Motion base |
| Degrees of freedom (DOF) | | 1-2 DOF | ≥ 3 DOF |

| Characteristic | Low Fidelity | Medium Fidelity | High Fidelity |
|---|---|---|---|
| Vibration | No vibration | Shaker (vibration) in seat/steering column | Shaker (vibration) in seat/steering column and foot pedals.<br>Active haptic signals to the controls (e.g., collision avoidance / warning) |
| Tactile feedback | Passive feedback in steering, brake, and accelerator controls | Active feedback in steering control<br>Passive feedback in brake and accelerator controls | Active feedback in steering, brake, and accelerator controls |
| Scenario Subsystem | | | |
| Image complexity | Simple geometric representations of scenario elements | Moderate detail and shading of scenario elements | Near photo-realistic rendering of scenario elements |
| Size of objects relative to real-world | < 1:1 | 1:1 | 1:1 |

## DISCUSSION

The objective of Task 3 was to identify driving simulator characteristics that are candidates for being manipulated, held constant, or not included in the Phase 2 studies. To this end, we obtained information about the driving simulator capabilities from a broad range of simulators managed by project team members and by the FHWA. These capabilities were characterized using a set of common dimensions to define the full range of capabilities across simulators. Finally, this information about the range of simulator capabilities was used for descriptive purposes to develop suitable low, medium, and high fidelity categories for each simulator characteristic. A remaining step is to integrate this information with the results from the task analysis being conducted in Task 2 to determine the implications of the different simulator characteristics for investigating specific research issues/questions in Phase 2 of this project. This integration will take place in Task 4.

It is important to note that the levels of fidelity described in Table 18 do not refer to overall simulator systems, but rather to individual characteristics within these systems. These individual characteristics are collapsed into “bins” of physical fidelity, in order to categorize them according to how closely they match corresponding real-world systems. However, the level of physical fidelity exhibited by a characteristic does not determine the usefulness of that characteristic for addressing the issues associated with specific problems. For instance, a simulator with “low-fidelity” visual systems – or limited resolution - might be the best simulator for some studies, but may be inappropriate for others. Therefore, physical fidelity is not intended to indicate the quality of a simulator characteristic or its appropriateness for various applications.

Characterizing differences in capabilities and characteristics across a variety of driving simulators is important because these differences represent some of the options available to investigate the relationship between data obtained from simulators and data obtained from real-world driving. Consequently, an understanding of the capabilities and limitations of a range of driving simulators is critical to eventually developing a robust set of transforms and gaining a better understanding of —for example— which simulator characteristics are most important for eliciting realistic driving behaviors in certain driving situations.

At a general level, the effectiveness of a simulator at producing results that are consistent with (or transformable to) the real-world driving experience logically increases as the fidelity of the relevant simulator characteristics increases. While this trend may be clearest for the extreme endpoints of the fidelity spectrum, it is not sufficiently understood at intermediate fidelity levels (i.e., those covered by many of the simulators in this report). In particular, the key questions are: what simulator characteristics are associated with driving performance that is consistent with (or transformable to) real-world driving, and how does driver performance vary as simulator characteristics vary?

The results from the current task, when combined with those of Task 2 (the scenario task analyses), will make it possible to identify research questions/issues that can provide insight regarding the relationship between simulator characteristics and driving performance. In particular, Table 18 provides a simple way to characterize specific simulators. However, the relationships between simulator characteristics and eventual driving performance also depend on details associated with the driving task, which is where the task analysis from Task 2 becomes relevant. More specifically, the task analysis identifies key information sources, driver information needs, and scenario assumptions; some of these may be affected by specific simulator characteristics, while others may not.

An example of this involves lane maintenance directly within a roundabout. In particular, drivers rely on information about markings and road curvature to maintain lane position. However, if the field of view in a simulator display is too small to show this information at appropriate distances, then driver performance and speed will likely be affected since they must maneuver through the roundabout without this information (i.e., drivers may cut the turn, resulting in less deceleration and higher exit speeds). For this part of roundabout navigation, collecting data across two or more simulator platforms with varying fields of view could provide useful information about how the lack of this key information affects the usefulness of simulators with different field of view fidelity for modeling real-world data.

In other situations, however, the same variable (i.e., field of view) may have little or no impact on driver performance. One example of this is scanning for other vehicles at cross-streets that might require that drivers stop or slow during an approach to a roundabout. Sufficient information (i.e., that no vehicle is nearby) may be available far enough away that this activity can be completed with even the lowest field of view fidelity level. For this driving task and situation, the field of view characteristic may provide little information about the relationship between simulators vs. real-world driving; on the other hand, it suggests that this characteristic is potentially suitable for evaluating information in this specific task on a wide range of simulators.

While some characteristics, such as field of view, will likely be suitable candidates for the Phase 2 study, others may be less useful overall. For example, Table 17 indicates that scenario presentation capabilities are similar across simulators. Therefore, it is not likely that scenario development issues will arise due to a lack of capability. One possible exception is in preparation of identical scenarios in more than one simulator system. Most of the simulators in the survey use roadway tiles to design the scenario environments, but some provide little or no support for editing tiles or creating new ones. Consequently, it may be difficult to specify exact channel lengths or road widths with some simulators.

In Task 4, the information obtained in this Task 3 simulator analysis will be integrated with the driver information needs obtained from the Task 2 task analyses to determine the implications of the different simulator characteristics on investigating specific research issues/questions in Phase 2.

# APPENDIX B: MEASUREMENT PROTOCOL FOR CHARACTERIZING SIMULATORS

Measurements of the visual, motion, vibration, haptics, tactile, and sound cues in each of the four simulators were made. Here we detail the specific measurements that were made in each simulator to assure that we can accurately quantify the degree to which a simulator satisfies the simulator perceptual-control requirements.

- Steering System
  - Steady state steering angle torque relationship at different speeds.
  - Natural return to zero from different steering angles at different speeds.
  - Effective steering ratio at different speeds (i.e., the gain between steering angle and path curvature at different speeds.
- Gas Pedal System
  - Depression force relationship.
  - Gas pedal depression acceleration relationship at different speeds.
- Brake Pedal System
  - Depression force relationship.
  - Force deceleration relationship from different speeds.
- Sound System
  - Speed sound-spectrum and speed sound-level relationship.
- Motion System
  - Lateral and longitudinal vehicle model acceleration versus actual cab accelerations as measured by accelerometers.
  - Speed vibration relationship.
- Visual System
  - Contrast between lane makings and road surface.

**Table 19. Tools for measuring simulator characteristics.**

| **Measurement Tool** | **Purpose** |
|---|---|
| Force meter | Measure steady state forces on pedals and steer. |
| 3-DOF accelerometers | Measure motion base responses to control actions.<br><br>Measure motion base vibrations as a function of speed. |
| Sound level meter | Sound level at different speeds, including background sound level when the car engine is off but the computers, projectors, and motion base are humming. |
| Audacity audio recording software | Record full spectrum of sound as a function of speed, acceleration, and deceleration levels. |

| Measurement Tool | Purpose |
|---|---|
| Microphone | Pick up sound at the driver's head as a function of speed, acceleration, and deceleration levels. |
| Light meter | Overall light level in the forward direction from the driver's eye.<br><br>Intensity of lane markings and road surface to also compute contrast between lane boundaries and road surface. |
| DAQ system | Collect data from force meter, accelerometers, sound level, steering angle and pedal depressions. These data are synchronized with data recorded directly from the simulator to associate, for example, brake pedal force with deceleration rate. |
| Custom C++ and Matlab software | Software to collect, synchronize, visualize, and analyze these data. |

The steady state torques were obtained on a large virtual skid-pad if the simulator used different frictions depending on the terrain or road surface (e.g., NADS-1). Some simulators apply the same friction across the entire world, and when the world is flat these data can be collected anywhere (e.g., RTI).

A zip-tie was attached tightly to the steering wheel on the left and right sides. The force meter has a curved hook that was attached around the zip-tie such that the force meter could be pulled tangential to the steering wheel to get unbiased force measurements. For negative steering angles, the force meter was attached to the right side of the steering wheel, and for positive steering angles, it was attached to the left side.

The speed was set to a fixed speed of 25, 45, or 65 mph with a steering angle of 45 or 90 at all speeds except in the NADS-1 because that would reach its sliding rail limit; therefore, in the NADS-1, steering angles of 22.5 and 45 degrees were used at 45 and 65 mph.

Most steering wheels had some form of hysteresis either purposefully coded into the steering logic or simply because of the hardware frictions inherent in the passive or active steering system. To avoid steering torques that would be too variable, the steady state torque measured was the maximum one before the steering wheel would move away from its steady state angle or 22.4, 45, or 90 degrees.

## APPENDIX C: MOTION SICKNESS HISTORY SCREENING FORM

Adapted for verbal administration when recruiting over the phone (Kennedy, Lane, Berbaum, & Lilienthal, 1993).

Motion sickness has many symptoms, but not all individuals experience the same symptoms. Common symptoms that may occur alone or in combination include: general discomfort, drowsiness, headache, sweating, nausea, blurred vision, dizziness, or faintness.

For your safety, we need to assess the risk that you might become ill in our driving simulator. Please consider the following questions that best characterizes your experience.

How often would you say you get airsick?

Always_4_Frequently_3_Sometimes_2_Rarely_1_Never_0

From your experience at sea, how often would you say you get seasick?

Always_4_Frequently_3_Sometimes_2_Rarely_1_Never_0

From your experience, how often would you say you get carsick as a front seat passenger?

Always_4_Frequently_3_Sometimes_2_Rarely_1_Never_0

From your experience, how often would you say you get carsick as a rear seat passenger?

Always_4_Frequently_3_Sometimes_2_Rarely_1_Never_0

Have you ever been motion sick under any conditions other than ones listed so far?

No_0_Yes_1_If so, under what conditions?______________________

In general, how susceptible to motion sickness are you?

Extremely_4_Very_3_Moderately_2_Minimally_1_Not at all_0

Have you ever experienced illness in a driving simulator?

No 0 Yes 4

Scoring Criteria:

Sum scores for questions 1 through 7. For a total score of **7 or highe**r, **strongly discourage** participation. For a total score of **4 to 6**, discuss with participant if there were any unusual circumstances or mitigating conditions that made the participant answer they way he/she did. **Consider a waiver and accept, otherwise discourage participation. Rationale for waiver:**

**Accept** participant with total score of **3 or less**.

Score: ______

Disposition (circle one): Accept Discourage participation

Notes:

## APPENDIX D: SIMULATOR SICKNESS QUESTIONNAIRE

Please circle all symptoms as they affect you now.

| **Symptom** | **Severity** | | | |
|---|---|---|---|---|
| General discomfort | None | Slight | Moderate | Severe |
| Fatigue | None | Slight | Moderate | Severe |
| Headache | None | Slight | Moderate | Severe |
| Eye strain | None | Slight | Moderate | Severe |
| Difficulty focusing | None | Slight | Moderate | Severe |
| Salivation increased | None | Slight | Moderate | Severe |
| Sweating | None | Slight | Moderate | Severe |
| Nausea | None | Slight | Moderate | Severe |
| Difficulty concentrating | None | Slight | Moderate | Severe |
| “Fullness of the head” | None | Slight | Moderate | Severe |
| Blurred Vision | None | Slight | Moderate | Severe |
| Dizziness with eyes open | None | Slight | Moderate | Severe |
| Dizziness with eyes closed | None | Slight | Moderate | Severe |
| *Vertigo | None | Slight | Moderate | Severe |
| **Stomach awareness | None | Slight | Moderate | Severe |
| Burping | None | Slight | Moderate | Severe |

*Vertigo is loss of orientation with respect to vertical upright.

**Stomach awareness is discomfort just short of nausea.

## APPENDIX E: SIMULATOR REALISM QUESTIONNAIRE

(* only the marked items were used after the second drive)
For each of the following items, circle the number that best indicates how closely the simulator resembles an actual car in terms of appearance, sound, and response. If an item is not applicable, circle N/A.

| | General Driving | Not at all Realistic | | | | | | Completely Realistic | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Response of the seat adjustment levers | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 2 | Response of the mirror adjustment levers | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 3 | Response of the door locks and handles | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 4 | Response of the fans | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 5 | Response of the gear shift | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 6 | Response of the brake pedal | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 7 | Response of accelerator pedal | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 8 | Response of the speedometer | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 9 | Response of the steering wheel while driving straight | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 10 | Response of the steering wheel while driving on curves | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 11* | Feel when accelerating | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 12* | Feel when braking | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 13* | Ability to read road and warning signs | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 14 | Appearance of car interior | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 15* | Appearance of signs | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 16* | Appearance of roads and road markings | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 17* | Appearance of rural scenery | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 18* | Appearance of intersections | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 19* | Appearance of rear-view mirror image | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 20 | Sound of the car | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 21 | Overall feel of the car when driving | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 22* | Overall similarity to real driving | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 23* | Overall appearance of driving scenes | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 24* | Feel of driving straight | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |

| | General Driving | Not at all Realistic | | | | | | Completely Realistic | |
|---|---|---|---|---|---|---|---|---|---|
| 25* | Feel of driving through roundabouts | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 26* | Feel of driving on a curved road | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 27* | Feel of accelerating from a stopped position | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 28* | Feel of braking to a stop | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 29 | Ability to stop the vehicle | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 30 | Ability to respond to other vehicles | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |
| 31 | Ability to keep straight in your lane | 0 | 1 | 2 | 3 | 4 | 5 | 6 | N/A |