AN ABSTRACT OF THE THESIS OF

Lacy S. Brown for the degree of Master of Science in Civil Engineering presented on September 6, 2012

Title: A Validation of the Oregon State University Driving Simulator

Abstract Approved:

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Karen K. Dixon

Driving simulation is widely accepted as a safe, effective, and economical alternative for investigating driver behavior in a variety of contexts. However, in order to apply simulator-based research results to real-world settings, the performance measures acquired through simulated driving experiments must first be validated. This research was aimed at validating the Oregon State University Driving Simulator based on speed, acceleration, and deceleration data. The validation effort consisted of a road test and a simulator test. The road test was completed on a five-lane urban principal arterial in Corvallis, Oregon, and the simulated environment matched the field conditions as closely as possible. Ten subjects participated in both tests. Minimum speed, maximum speed, average speed, 85^{th}-percentile speed, maximum acceleration and maximum deceleration data variables were analyzed using graphical comparisons as well as two-sample paired t-tests. With the exception of minimum speed, all data variables showed statistically significant differences on at least one of the three test sections. However, the researchers considered the magnitude of these differences to be insignificant in a practical setting (on average, 3.5 mph for speed variables and 0.80 ft/s^2 for acceleration and deceleration variables). Thus, the results of this research confirm the validity of the OSU driving simulator with regards to speed and acceleration.

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A Validation of the Oregon State University Driving Simulator

by

Lacy S. Brown

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Lacy S. Brown, Author

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1. INTRODUCTION

Oregon State University (OSU) completed construction of the Driving and Bicycling Simulator Laboratory in the fall of 2010. Research conducted in the laboratory is primarily focused on transportation safety as it relates to highway design, traffic control devices, human factors design, and unique and vulnerable users. While both the driving and bicycling simulators can be invaluable tools to help improve our understanding of driver behavior, research results cannot be generalized to real-world conditions unless the simulator has been validated. The validation process is especially important when the associated research results will be used to influence driving regulations or roadway design specifications.

The National Cooperative Highway Research Program (NCHRP) is currently in the process of updating the *Access Management Manual* (AMM) and developing a companion document which will be known as the *Application of Access Management Guidelines*, or AMAG. As part of these two efforts, the OSU Driving and Bicycling Simulator Laboratory is being utilized to better understand how drivers interact with various driveway configurations and driveway activity levels. The research team anticipates that the results of this simulation study may impact current access management guidelines, including access spacing requirements and perception-reaction time assumptions.

Because the research effort described above has the potential to significantly impact current access management standards, it was imperative to complete a validation of the driving simulator prior to completing the study. The validation effort was centered on the null hypothesis that speed, acceleration, and deceleration data collected in the simulator do not differ from what is observed in the real world. To test this hypothesis, the author selected a road test section and developed a corresponding simulated environment. In order to complete the research project and validation process as efficiently as possible, the author developed a single simulated environment for use in both efforts. The simulated environment was modeled after a local roadway in Corvallis, Oregon. The study roadway, NW 9th Street, is an urban arterial with a relatively high density of driveways serving a mix of commercial and residential land uses. By using a local roadway as the basis for the simulated environment, the validation process could be completed by comparing data collected in the real-world test drives and the simulated driving experiment. This thesis describes the entire validation process, including the development of the simulated environment, the experiment protocol and methodology for both the field and laboratory tests, and the validation analysis and results.

The following chapters describe, in detail, all aspects of the project and associated results. Chapter 2 focuses on the literature review and project background, including information on access management principles, characteristics of simulation studies, human factors considerations, and common validation methods. Chapter 3 presents details regarding the development of the simulated driving environment and comparisons with the real-world study corridor. The validation experiment is presented in Chapter 4, including a detailed methodology and data collection plan. The actual validation process and data analysis procedures are outlined in Chapter 5, and Chapter 6 presents the study results and outlines the next phase of the project. Lastly, Chapter 7 includes a list of all references cited and reviewed.

2. LITERATURE REVIEW

This literature review summarizes previous research efforts related to access management, driving simulation studies, and simulator validation studies. Because the validation effort utilized the same simulated environment as will be used for the access management research project, an understanding of access management techniques, including driveway design and driveway safety, helps to ensure the applicability of the simulated environment to both efforts. Additionally, an overview of general simulation considerations, such as human factors issues and simulator sickness, is also included. Lastly, this summary includes key findings of previous research efforts aimed at validating driving simulators.

2.1 ACCESS MANAGEMENT

The 2003 *Access Management Manual* (TRB, 2003) defines access management as the "systematic control of the location, spacing, design, and operation of driveways, median openings, interchanges, and street connections to a roadway." An updated (draft) version of the definition, which will be included in the new version of the *Access Management Manual* states,

> "Access management is the planning, regulation, and design of access between a roadway and land development. It encompasses a range of methods that preserve the safety and mobility of the traveling public by reducing conflicts on the roadway system and at its interface with other modes of travel."

The primary motivation for implementing access management techniques is to balance the provision of access and mobility, thereby improving safety for all users, including drivers, bicyclists, and pedestrians. While the concepts of access management cover a broad spectrum of application methods, from high-level land use planning to signal timing optimization, the techniques related specifically to driveway design and safety are most relevant to this research project. The following sections summarize previous research findings related to these two topics.

2.1.1 Driveway Design Considerations

Currently, the most comprehensive resource for the design of driveways and access points is the *Guide for the Geometric Design of Driveways* (Gattis, et al., 2010). The report identifies over 90 design elements that have been shown to affect the geometric design of a driveway or access point. Detailed guidance is provided for the driveway itself, driveway-roadway intersections, driveway-sidewalk intersections, traffic control, and specific accommodations for all types of road users. The authors identified six primary considerations for driveway design, including maintaining or improving the safety and operations of the roadway, providing a safe entrance and exit for all users, providing adequate sight distance for all users, supporting the requirements of public transportation when present, incorporating requirements of the Americans with Disabilities Act (ADA), and integrating existing bicycle and pedestrian facilities. Figure 1 illustrates a small sample of the key design elements identified in the document.

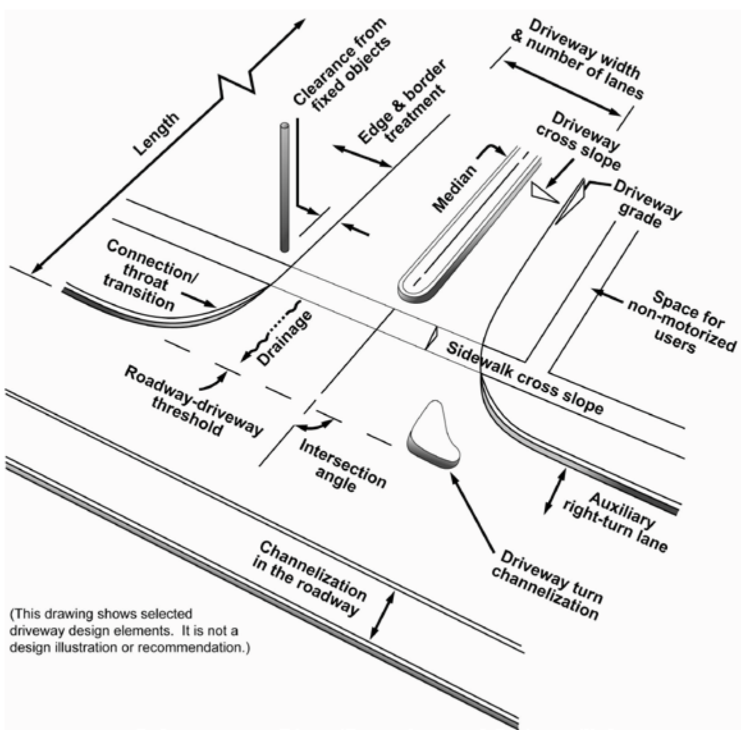

Figure 1. Driveway Design Elements (Gattis, et al., 2010)

As shown on Figure 1, the design of driveways is a complex task that can have significant impacts on the safety and mobility of all users of the driveway as well as the adjacent roadway. As an example, design factors such as turning radius, channelization, driveway width, and intersection angle can all have considerable effects on vehicle speed. Depending on the extent of the speed impacts, the volume of driveway traffic, and whether or not auxiliary turning lanes are provided, the operational and safety performance of the roadway could be significantly impacted (Fitzpatrick & Woolridge, 2001).

In recent years, the need to consider pedestrians and bicyclists in addition to drivers in the design of roadways and driveways has become increasingly apparent. While it is obvious that all facilities for all users should be provided in some capacity, the operational and safety trade-offs of providing these facilities is not as clear. Research by Dixon, van Schalkwyk, and Layton (2009) investigated the impacts of bicycle lanes and on-street parking on driveway operations and safety, particularly as related to sight distance. Their results suggest most current methods for implementing on-street parking result in inadequate driveway sight distance, although the addition of a bicycle lane between the travel way and parking facilities may improve sight distance and driveway visibility (depending on roadway speeds). Visibility can also be improved by widening landscape buffers which allow drivers to pull their vehicles closer to the roadway without impeding bicycle and pedestrian traffic.

While the design of individual driveways is a vital component of an efficient and safe transportation system, the focus of access management is the interaction of vehicles at locations with multiple driveways or driveways in close proximity to other intersections. One of the most well-known access management techniques is the control of driveway spacing. Access management guidelines often suggest that driveways be spaced no closer than the required stopping sight distance (SSD) for that particular roadway, which is based on the driver's perception-reaction time. *A Policy on Geometric Design of Highway and Streets* (AASHTO, 2011) recommends a perception-reaction (PRT) time of 2.5 seconds be used for all stopping sight distance calculations. While this value is widely accepted in the industry and has been used in practice since 1954, its relevance to urban areas with high driveway density and relatively high traffic volumes is currently under debate. Several research efforts have attempted to refine the assumed perception-reaction time value, however most were conducted on closed-courses or in rural areas and did not identify values significantly different from 2.5 seconds (Fambro, et al., 1997; Lerner, N., 1993). In addition, many access management experts also question whether or not stopping sight distance is the appropriate measure for driveway spacing. For example, in NCHRP Report 348, *Access Management Guidelines for Activity Centers* (1992), Koepke and Levinson suggested that driveway spacing should be based on roadway speed, access category, and the size of the traffic generator being served. However, research findings supporting new measures for driveway spacing are quite varied; thus, most agencies still use stopping sight distance as the basis for driveway spacing requirements.

2.1.2 Driveway Safety Considerations

Previous research has shown that the number of crashes at driveways is disproportionately high compared to crash rates at other types of intersections; thus, driveway safety is of particular importance (AASHTO, 2011). The safety of driveways is a complex issue that is affected by several factors and the impact of each factor is dependent on the unique nature of each location. In the past, researchers have completed significant research on the topic of driveway safety and identified seven main factors known to affect driveway safety. These factors are driveway spacing, proximity to intersections or interchanges, signalized intersection spacing and coordination, driveway design, roadway design, median configuration, and land use. Each of these factors is described in the following sections.

2.1.2.A Driveway Spacing

The majority of driveway-related crashes are attributed to conflicts between vehicles, which includes opposing turning movements and the interaction of approaching vehicles with stopped vehicles traveling in the same direction. Depending on its exact geometry and configuration, each driveway has a certain number of potential conflict points. However, when two driveways are spaced such that their functional areas overlap, additional conflict points are created as vehicles using one driveway are forced to interact with those using another driveway. This concept is illustrated on Figure 2.

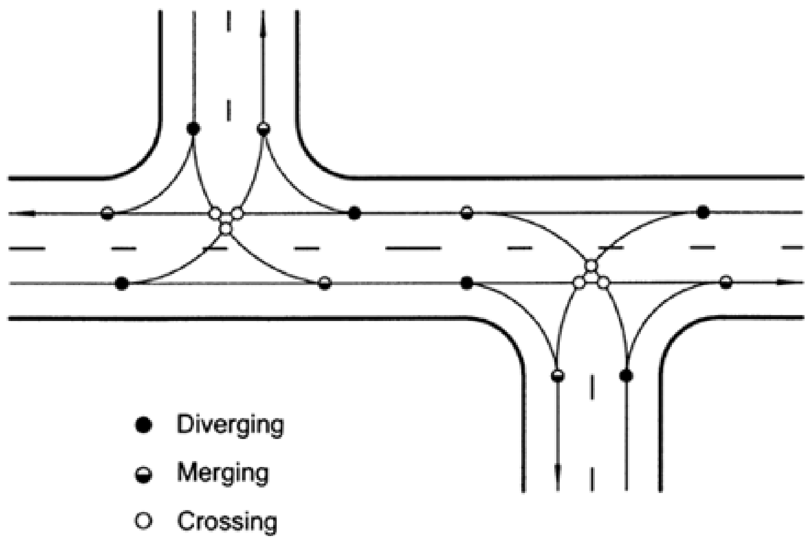

Figure 2. Typical Vehicle Conflict Points Associated with Driveways (Rodegerdts, 2004)

When the conflict areas of two driveways overlap, the potential for crashes is increased. Previous research efforts have attempted to quantify this increased safety risk. Research findings presented in NCHRP Report 420 (Gluck, Levinson, Stover, 1999) suggest that the addition of one access point per mile will result in a four-percent increase in crash rates. These findings are consistent with a similar research effort by Papayannoulis, et al. (1999) who estimated a 40-percent increase in crash rates at locations where driveway density increased from 10 to 20 access points per mile. Since 1999, several research studies have identified a correlation between driveway spacing and crash rates, although the relationship was not quantified (Brown and Tarko, 1999; Mouskos, et al., 1999; Eisele and Frawley, 2005).

2.1.2.B Proximity to Intersections and Interchanges

Driveway safety is not only affected by the distance between two driveways, but also by the distance between a driveway and an adjacent intersection or interchange. In 2008, Rakha et al. investigated the relationship between crash rates and the distance between an interchange and the nearest access point. Their analysis results indicate that increasing interchange-to-driveway spacing from 300 feet to 600 feet is associated with a 50-percent reduction in crashes. More generally, Gluck, Levinson, and Stover (1999) suggest that the distance between an access point and an adjacent intersection or interchange should be determined based on perception-reaction distance, weaving distance, transition distance, and downstream storage requirements.

2.1.2.C Signalized Intersection Spacing and Signal Coordination

When driveways are located between two signalized intersections, the spacing and coordination of those signals can significantly impact driveway safety performance. As would be expected, previous research has indicated that a decrease in signalized intersection spacing is associated with an increase in crash risk (Stover, 1996). The *Access Management Manual* (2003) suggests that increasing signalized intersection density from two to four signals per mile can increase the average crash rate by up to 200-percent, depending on the driveway density along the same segment.

2.1.2.D Driveway Design

The best way to ensure acceptable safety performance at a driveway is to design it properly according to local, regional, and national standards and unique site characteristics. Whenever possible, the general design considerations discussed in Section 2.1.1 (Driveway Design Considerations) should be followed. If unusual circumstances require exceptions to design standards, a certain level of uniformity among all driveways on a given roadway should be maintained in order to meet driver expectations. To ensure the safest operations possible, driveways that permit two-way operations should provide separate entrance and exit lanes and allow for continuous, simultaneous two-way movements (Stover and Koepke, 2002). Driveway travel lanes should be clearly defined and should not be excessively wide. Additionally, excessively wide continuous driveways that provide access to the full frontage of a lot (typically found at gas stations) should be avoided as they introduce confusion and extra conflict points, particularly between vehicles and pedestrians or bicyclists (Gattis, et al., 2010).

2.1.2.E Roadway Design

As mentioned in Section 2.1.1 (Driveway Design Considerations), one contributing factor of driveway-related crashes is the speed differential between turning vehicles and through vehicles. Auxiliary lanes can be one of the most effective means of minimizing the speed differential, if installed at locations where traffic volumes and roadway characteristics warrant them (TRB, 2003). However, in some instances, the presence of auxiliary lanes may also limit sight distance for drivers exiting the driveway, so sight distance and visibility for all users should be considered in addition to volume-based warrants. Other roadway design factors affecting driveway safety include the number of travel lanes, travel lane width, shoulder width, the presence of bicycle lanes, and, most importantly, median configuration (discussed below).

2.1.2.F Median Configuration

The presence and design of medians has a significant impact on driveway operations and safety, and thus a substantial amount of research has been conducted on the topic. The fact that median presence, regardless of type, improves safety over undivided roadways of similar traffic volumes and driveway densities is well documented. Continuous two-way left-turn lanes (TWLTLs) are a common median treatment in urban areas in the United States. Previous research efforts have indicated that while TWLTLs are well suited for roadways with high driveway density and low traffic volumes, they typically have a decreased safety performance compared to raised medians (Squires and Parsonson, 1989; Margiotta and Chatterjee, 1995). An Arkansas study by Gattis, Balakumar, and Duncan (2005) found that on rural and urban-fringe highways with speeds greater than 40 mph, the highest crash rates occurred on undivided roadways with curbs while the lowest crash rates occurred on roadways with wide shoulders and depressed medians.

The reason that medians are so effective at improving safety performance is that they often restrict left-turning movements at unsignalized intersections. Prohibiting left-turns into or out of a driveway can improve safety by removing the conflict between left-turning vehicles and opposing through vehicles (Stover and Koepke, 2002).

2.1.2.G Land Use

Although many can agree that a link between land use and driveway safety performance exists, little research has been conducted to determine the exact relationship. Land use is often indirectly accounted for in safety analyses through the inclusion of correlated data variables, such as roadway geometry and driveway density or frequency. A low-speed undivided, two-lane roadway with a medium driveway density is more common in a residential area, while a higher-speed four-lane divided roadway with high driveway density is likely in a commercial area. Research completed by Gattis, Balakumar, and Dunacan (2005) suggested a possible link between median type and land use, but the relationship was not quantified. Also, a study of Connecticut two-lane highways found a relationship between crash rates and driveway frequency and traffic intensity, after accounting for time of day (Ivan, Wang, Bernardo, 2000). More recently, Bindra, Ivan, and Honsson (2009) suggested that using actual land-use data (retail versus non-retail, number of employees, etc.) in crash prediction models provided much more accurate predictions of segment-intersection crashes than typical driveway data.

2.2 SIMULATOR STUDY CONSIDERATIONS

Research conducted using a driving simulator laboratory presents a unique set of challenges and characteristics not associated with other types of research studies. The two primary considerations unique to driving simulation studies are the occurrence of simulator sickness and the need for simulator validation. Both of these topics are discussed in the following sections.

2.2.1 Simulator Sickness

Simulator sickness, a phenomenon sharing some similarity to motion sickness, causes a small percentage of the population to experience symptoms ranging from eye strain to headache to vertigo and nausea while operating a driving simulator. There are several differing theories on the precise cause of simulator sickness, including cue conflict theory, poison theory, and postural instability theory. In essence, simulator sickness is the body's response to a discontinuity between the visual and vestibular (balance) systems. This discrepancy is caused by a lack of physical motion paired with the perception of movement within the simulated environment (Stoner, Fisher, and Mollenhauer, 2011).

In his 1993 paper, Kennedy, et al. presented a method for measuring simulator sickness using a questionnaire and weighting factors. The questionnaire included sixteen common symptoms rated on a scale from zero (none) to four (severe) to describe how the participant felt. Table 1 presents an adapted version of the Kennedy Simulator Sickness Questionnaire (SSQ).

Table 1. Kennedy Simulator Sickness Questionnaire (adapted from Kennedy, et al., 1993)

SSQ Symptom	SSQ Factor		
	Nausea	Oculomotor	Disorientation
General Discomfort	x	x	
Fatigue		x	
Headache		x	
Eyestrain		x	
Difficulty Focusing		x	x
Increased Salivation	x		
Sweating	x		
Nausea	x		x
Difficulty Concentrating	x	x	
Fullness of Head			x
Blurred Vision		x	x
Dizzy (eyes open)			x
Dizzy (eyes closed)			x
Vertigo			x
Stomach Awareness	x		
Burping	x		
Total (Categorical Sum)	N	O	D
Total Score	TS = (N+ O + D) x 3.74		
Weighted Score (Categorical)	N_s=N x 9.54	O_s=O x 7.58	D_s=D x 13.92

This type of simulator sickness evaluation provides valuable information for both immediate and long-term remediation. When given during an experiment, possibly after a short test-drive, the researchers can gauge a participant's probability of becoming ill during the remainder of the experiment. If the participant has a relatively high score, the researchers can decide to not continue with the experiment before the participant becomes ill, instead of waiting until the participant is unable to continue and valuable data are lost. On a larger scale, the evaluation responses can help to narrow down the causes of simulator sickness in each specific experiment. Because the survey is divided into three categories for nausea, vision (oculomotor problems), and disorientation, consistently high scores in one category versus another may reveal an issue with the vehicle or simulated environment that can be adjusted to reduce the symptoms in future experiment runs.

While the exact causes of simulator sickness are unknown, many considerations can be made during the development of a simulated environment and during the experiment itself to reduce the likelihood of subjects encountering symptoms of simulator sickness. When designing a simulated driving environment, simple adjustments to the placement of roadside objects, the geometry of the roadway, and the required route navigation can have a drastic impact on the probability of subjects getting sick. Research by Chrysler and William (2005) indicated that reducing the density of roadside objects and increasing the radius of horizontal curves would result in less simulator sickness. Several research efforts have also suggested that drivers who are required to make left and right turns during an experiment are much more likely to experience symptoms of simulator sickness than those who make no or very few turns (Edwards, et al., 2003; Mourant, et al., 2007). After development but prior to running the experiment, the best precaution against simulator sickness is to screen participants. Subjects who are already prone to motion sickness are much more likely to experience simulator sickness. Also, those with fatigue, hangovers, head colds or respiratory infections are more likely to feel symptoms of sickness while driving the simulator (Allen and Reimer, 2006). During the experiment, it has been shown that ambient air temperature is a strong contributing factor to simulator sickness. The laboratory space should be temperature controlled at 70-degrees or cooler and proper ventilation or air movement should also be provided while experiments are being run (Stoner, Fisher, and Mollenhauer, 2011).

2.2.2 Simulation Validation

Typically, the end goal of a driving simulation study is to gain a better understanding of the interaction between a driver and their surroundings, whether that is within the vehicle itself or in relation to the roadway and roadside environments. Because the value of simulation-based research is in the ability to test real-world scenarios in a safe, efficient, and cost-effective manner, being able to extrapolate research findings to the greater driving population and the built environment is of the utmost importance. However, until a simulator is validated against the real-world, any research results are only applicable to the simulated driving environment in which the study was completed.

Simulator validity is described in two categories – physical validity and behavioral validity. The similarity between the simulated vehicle and the on-road vehicle, including layout, dynamics, and visual displays, is known as physical validity. Behavioral validity, on the other hand, is a measure of how well the driving behaviors produced in a simulated environment match those in a real-world scenario (Blana, 1996). For this study, the author will focus on behavioral validity, which in turn can be measured in two ways. Blaauw (1982) and Törnros (1998) have defined behavioral validity in terms of absolute and relative validity. If a simulation is deemed to be absolutely valid, then a given measurement (speed, acceleration, deceleration, etc.) can be expected to have the same numerical value in both the simulated and real-world environments. Most simulator validation studies, however, are based on the concept of relative validity, in which the simulated and real-world environment produce measurements of a similar magnitude and direction.

Dating back to as early as 1979 (Watts, Quimby), numerous simulation validation studies have been completed on a variety of data variables. These studies have primarily been performed on three data measures – speed, lateral lane position, and braking responses. In these types of validation studies, the more common analysis methods have included descriptive statistics, analysis of variance (ANOVA), and general correlations.

2.2.2.A Validation Using Speed Data

Several studies have shown relative validity between a wide variety of driving simulators and on-road tests using one or more speed-based measurements.

In 1999, Klee, et al. performed a validation of the University of Central Florida driving simulator based on forward speed. Analysis results showed that drivers drove similarly at ten of the 16 measurement locations. Additionally, average speed trends from both tests indicated that drivers tended to travel at higher speeds in the field than in the simulator. In his 2005 study on work zone speeds, Bella validated the European Interuniversity Research Center for Road Safety (CRISS) driving simulator. Speed data collected in the field were, on average, higher than in the simulator, however the differences were not statistically significant. Similarly, Godley, Triggs, and Fildes (2002) studied driver performance related to rumble strips in an effort to validate the Monash University Accident Research Centre (MUARC) driving simulator. The researchers achieved relative validity in regards to deceleration patterns even though the travel speeds observed in the field were significantly higher than those in the simulator.

Data collected in other validation studies show the opposite trend, with travel speeds in the simulator test being higher than those in the field tests. A second validation effort by Bella (2008) investigated driver performance on rural two-lane roads and showed higher speeds in the simulator test than the field test. In that study, relative validity was achieved for all measurement locations and absolute validity was achieved at over 80-percent of the test locations. In 1997, Törnos achieved relative validity for speed data when comparing road tests and simulator tests that included a road tunnel. That research effort also showed higher speeds in the simulator test than the field test.

Previous research efforts have shown mixed results on whether drivers tend to travel at higher speeds in simulated or real-world environments. In general, using speed data as a basis for relative validation has proven successful in most research efforts.

2.2.2.B Validation Using Position Data

Lateral lane position measurements on both straight and curved roadway sections have also been used to conduct relative validation studies between simulation and on-road tests. One of the most robust simulator validation studies was conducted in 2002 by Blana and Golias, in which they tested 100 participants on simulated and real-world rural roadways. Although the researchers observed that the lateral displacement was consistently higher in the on-road drives versus the simulated drive, they also determined that speed had a significant impact on the magnitude of the measured lateral displacement, and thus were unable to attain relative or absolute validity. Wade and Hammond (1998) completed a similar study with a smaller sample size (26 participants) at the University of Minnesota's Human Factors Research Laboratory. The researchers used a combination of vehicle performance measures, kinematic variables, and participant perception surveys to compare the simulator to the real world, and were able to prove relative validity based on lateral lane position.

2.2.2.C Validation Using Braking Data

Braking responses have also been used as the basis for simulator validation studies, including braking response time, time to accelerator release, and total braking force. Lee, et al. (2002) compared the braking responses of drivers on a test track and in the Iowa Driving Simulator. The researchers noted that drivers decelerated more abruptly in the simulator than on the test track, and validity was not achieved based on braking performance measures. In 2000, McGehee, Mazzae, and Baldwin also attempted to validate the Iowa Driving Simulator using crash avoidance performance measures. They compared the average time to throttle release during driving experiments on a test track and in the simulator. The results showed that drivers reacted slower in the test track study (longer time to throttle release times), but they did not achieve relative or absolute validity due to the effects of several confounding factors.

2.3 SUMMARY

This literature review summarizes the available literature relevant to the topics of access management, simulated environment design, and simulator validation. While this research project focuses on the task of validating the simulator, the same simulated environment will be used for both the validation and access management-related efforts. Therefore, a thorough understanding of access management issues, including driveway design, operations, and safety, was necessary prior to completing the validation project. Through this literature review, the author identified several considerations for developing the simulated environment and designing the validation experiment:

- Because of the associated impacts on driveway safety and operations, special attention should be paid to the placement of driveways and intersections in the simulated environment;
- The need for accuracy in the placement of roadside objects such as buildings, trees, and light posts should be balanced with the associated risks of increased simulator sickness;
- If possible, the environment should be designed to reduce or avoid the need for left turns, right turns, and abrupt stops, as these tasks are associated with a higher incidence of simulator sickness;
- Proper participant screening and laboratory temperature-control may also reduce the likelihood of simulator sickness; and
- In order to ensure study results can be applied to the greater driving population, a validation of the simulator must be completed. The most common and successful comparisons between on-road and in-simulator measurements are based on speed-related variables.

3. SIMULATED ENVIRONMENT DEVELOPMENT

The key to effectively validating a simulated environment against a real-world environment is to match the roadway and roadside characteristics as closely as possible. This requires precise modeling of the roadway, roadside objects, adjacent land uses, and pavement marking and signage. However, the accuracy of a simulated environment must also be balanced with time and budget constraints, computing power limitations, and simulator sickness triggers (described in Chapter 2). The following sections describe the characteristics of both the real-world and simulated driving environments.

3.1 NW 9TH STREET CHARACTERISTICS

The larger NCHRP research effort is focused primarily on driver behavior at driveways and access points. Thus, the scenario for this experiment is modeled after an urban arterial in a commercial district with a high density of access points (an average of 50 access points per mile in the study area). Specifically, the scenario replicates two segments of NW 9th Street in Corvallis, Oregon. This section of NW 9th Street is a five-lane roadway with a center TWLTL and bicycle lanes in both directions. The annual average daily traffic (AADT) volume in the study area was approximately 16,000 vehicles per day (vpd) in 2009.

Because intersection behavior is not of interest in this experiment, and because unnecessary changes in vehicle speed can increase the likelihood of simulator sickness, signalized intersections were excluded from the test sections. Two different segments of NW 9th Street (from NW Fremont Avenue to Buchannan Avenue and from NW Garfield Avenue to NW Spruce Avenue) were modeled adjacent to each other in the simulated environment. Figure 3 illustrates the relative location of each of the segments.

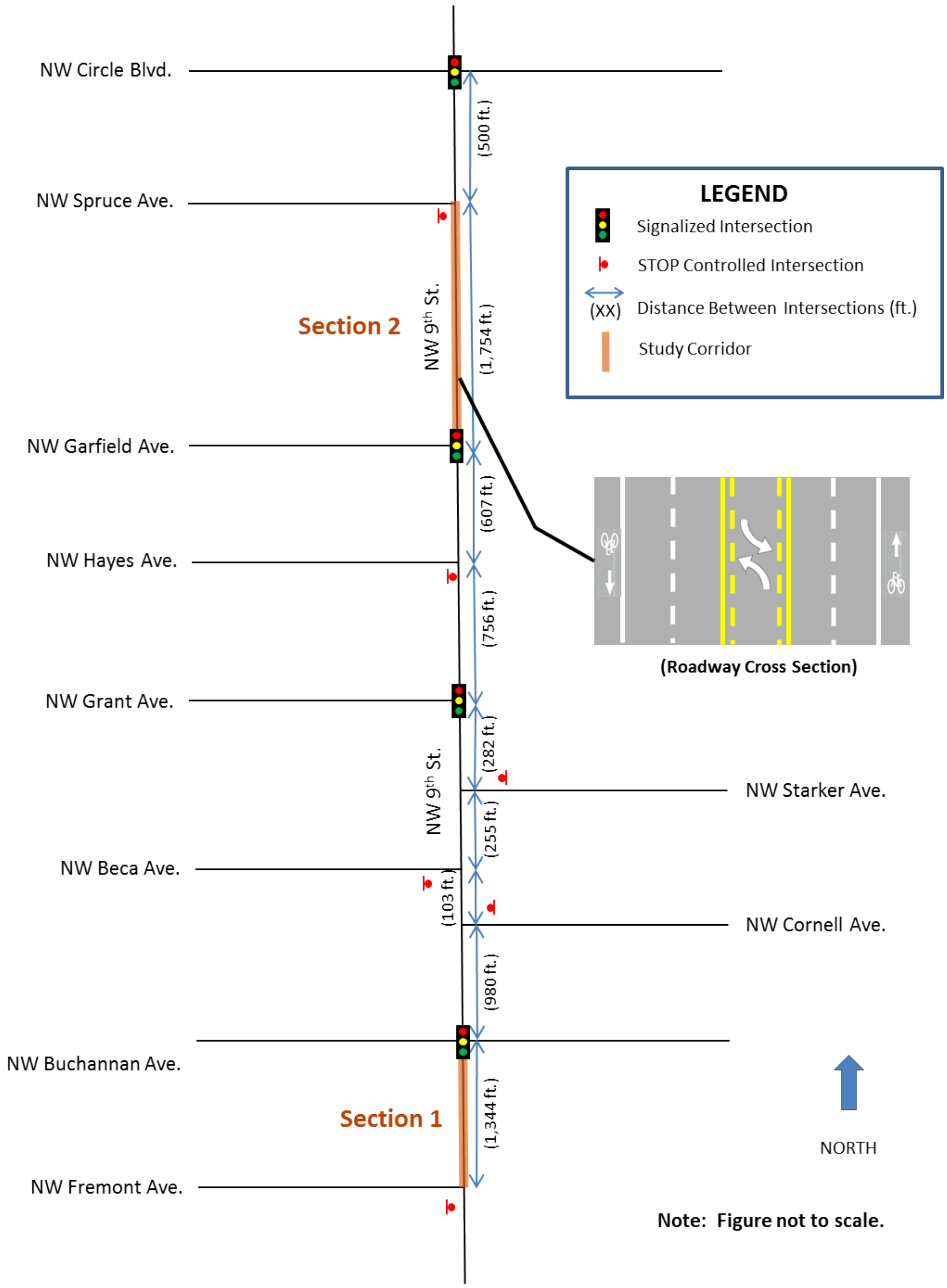

Figure 3. NW 9th Street Corridor and Test Sections

3.2 SIMULATED ENVIRONMENT CHARACTERISTICS

Through the use of advanced technology such as mobile light detection and ranging (LIDAR), simulated environments can be created in such detail that they are near replicas of real world driving environments. However, due to budget, time, and computing power limitations, most simulated environments are developed to be only as realistic as is necessary to answer the research question at hand. Because the simulated environment developed for this validation effort was also to be used in the NCHRP perception-reaction time study, the researchers made a concerted effort to match the roadway geometry, driveway placement, roadside objects, and adjacent land uses of the NW 9th Street Corridor. The following sections describe the specific characteristics of the simulated environment.

3.2.1 Roadway Geometry

In order to accurately match the roadway geometry of NW 9th Street, the researchers worked in conjunction with Real Time Technologies (the developers of the OSU simulator system) to develop a custom roadway section. This roadway tile consisted of a five-lane cross section with a median TWLTL and bicycle lanes in both directions. Each travel lane measured 12 feet wide, as did the TWLTL, and the bicycle lanes were four feet wide. The roadway edge consisted of a standard curb which was bordered by a nine-foot landscape buffer and a six foot wide sidewalk. While some sections of NW 9th Street do not have a landscape buffer between the roadway and the sidewalk, the researchers determined that this detail would likely have little effect on the experiment results and creating multiple roadside designs was not worth the time investment.

3.2.2 Driveway Geometry and Spacing

Besides the roadway geometry, the next most important aspect of the simulated environment development was matching the driveway geometry and spacing that exists on NW 9th Street. The researchers measured all driveway widths along NW 9th Street and matched each driveway to one of two simulated driveway objects, either 15 feet wide or 30 feet wide.

While the researchers intended to precisely match the driveway spacing present on NW 9th Street, this was not possible in all locations due to limitations of the software and roadway tiles. Each roadway tile has a fixed width (typically five, 10, or 20 meters), and the software cannot process roadway tiles that are less than five meters (16.4 feet) wide. However, even with these limitations, nearly all driveways were placed within 10 feet of their real-world location. Figure 4 shows the driveway types and locations, as designed in the simulated environment. It should be noted that the total roadway segment lengths shown on Figure 4 do not precisely match those on NW 9th Street, due to the geometry limitations just stated.

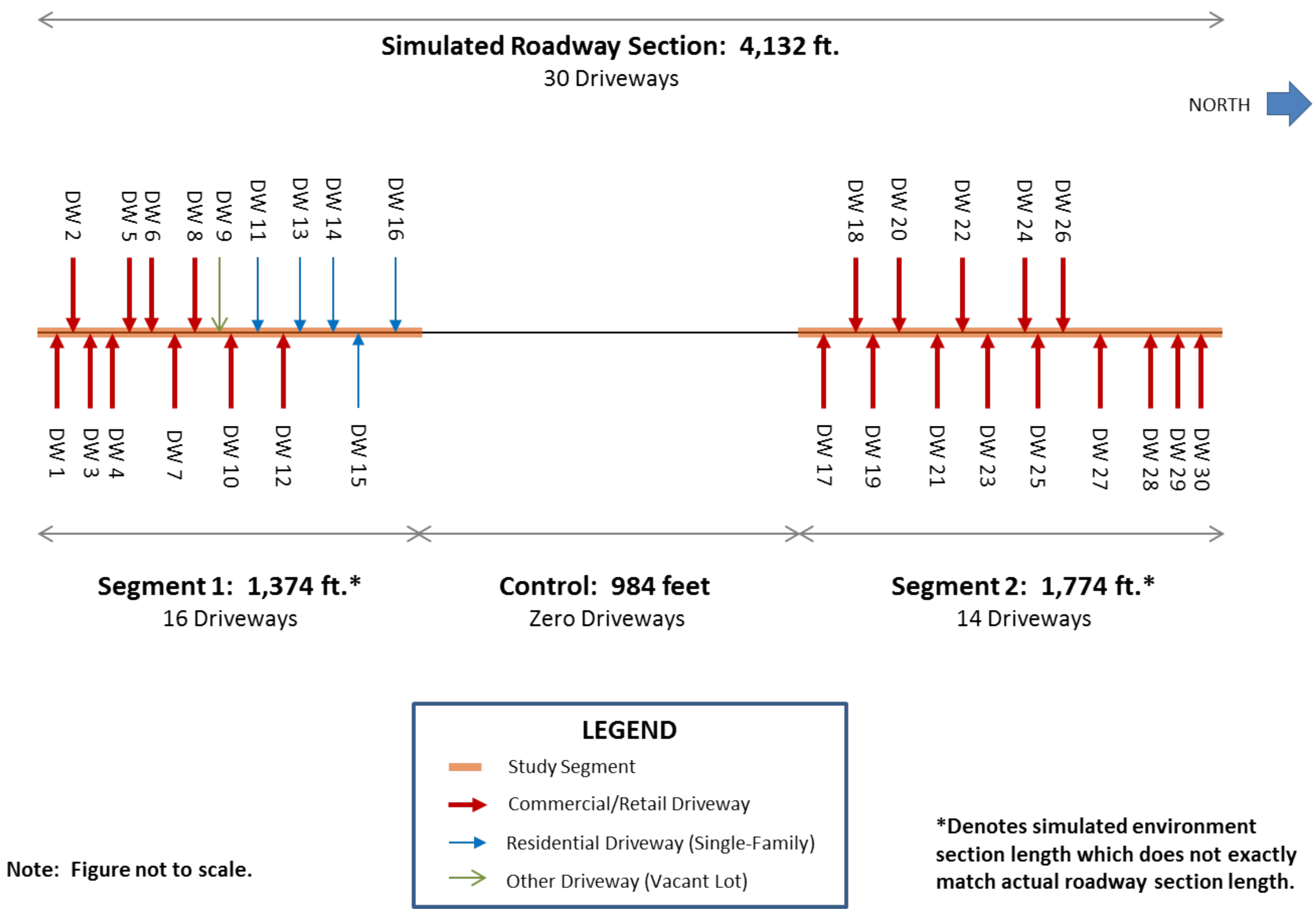

Figure 4. Simulated Environment Driveway Placement and Type

As shown on Figure 4, the simulated roadway section included a short control segment between test Segments 1 and 2. The total simulated roadway section was approximately 4,100 feet long with 30 driveways.

3.2.3 Roadside Design and Land Uses

Although the roadway and driveway design aspects were most important for this research effort, the roadside design and adjacent land uses had to be accurate enough to create a realistic driving environment that would elicit the same driving behavior as the real world roadway section. The researchers designed the simulated environment using pre-existing buildings, trees, and roadside objects. While the objects were not identical to those on NW 9^{th} Street, their location, size, and general appearance matched as closely as possible. A snapshot comparison of the same location in both the simulated and real world environments is shown on Figure 5.

Figure 5. Snapshot Comparison of Simulated (top) and Real World (lower) Driving Environments

The two snap shots shown on Figure 5 illustrate the view from the southernmost point of the test section, looking north, in both the simulated and real world environments.

3.2.4 Scenario Layout

Upon completion of the roadway test section, as described in Sections 3.2.1 to 3.2.3, the researchers created a larger scenario which included urban, suburban, and rural areas. In essence, the roadway test section was repeated six times around a large roadway loop, although the driveway activity and appearance of the roadside objects changed for each section. To reduce the likelihood that a participant would recognize the same repetitive test section, the researchers rotated each test section 180-degrees from the previous section, so drivers would encounter the driveways and land uses from a northbound and southbound perspective three times each.

Additionally, the researchers wanted to isolate the driving behaviors associated with each type of turning movement, so each of the roadway sections was assigned a certain type of driveway activity. The six sections included a control section with no driveway activity, right-turn-in only activity, left-turn-in only activity, right-turn-out only activity, left-turn-out only activity, and finally a section that included all turn types.

Lastly, the researchers programmed several distractor tests into the scenario. Distractor tests are intended to divert the participant's attention to portions of the experiment which are not directly related to the test question. Most participants will assume that the distractor test is part of the experiment, and will adjust their driving behavior during those portions of the experiment as opposed to the sections in which they are actually being tested. For this experiment, the researchers programmed a large red letter to appear at three points within the scenario and the participants were directed to say the first word that came to mind that started with that letter. All distractor tests were located in higher-speed, rural portions of the scenario and coincided with nearby bicycle activity.

Figure 6 shows the final scenario layout for the simulator test.

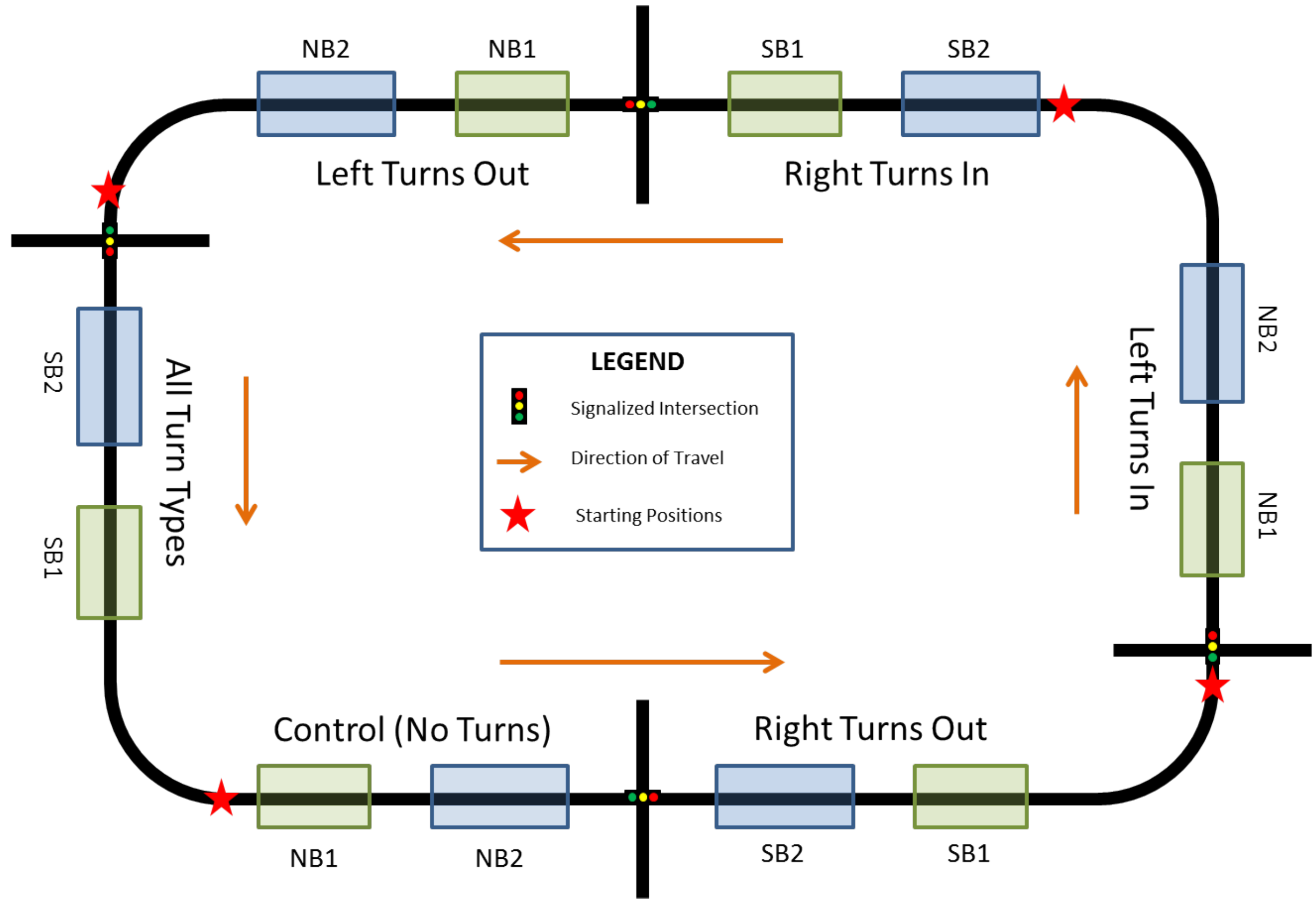

Figure 6. Final Scenario Layout for Simulator Test

The six test sections and corresponding driveway activity types are shown on Figure 6. The segments labeled as NB1, NB2, SB1, and SB 2 coincide with segments 1 and 2 from the northbound and southbound road tests, respectively. Figure 6 also shows four different starting positions. The researchers randomly assigned each participant a starting position prior to beginning the experiment. By varying the starting positions, any effects on driving performance caused by unfamiliarity with the vehicle would be spread out among the six test sections and would not significantly impact the results.

4. VALIDATION METHODOLOGY

The validation experiment consisted of two phases, a road test and a simulator test. A total of ten subjects, five males and five females, participated in both tests. Researchers collected similar driving behavior and driving performance data during both tests which was then used in comparative analyses for the validation effort. The following sections describe the experiment protocol and the types of data collected. Data analyses and results are included in Chapter 5.

4.1 EXPERIMENT PROTOCOL

4.1.1 Road Test

As described in Chapter 3, the researchers selected NW 9th Street, a local principal arterial, for the road test experiment. The test sections of NW 9th Street have four through travel lanes with a center TWLTL with bicycle lanes in both directions. The following sections describe the additional considerations and characteristics of the road test, including the time of day, the test vehicle, the data collection technology, and the road test route.

4.1.1.A Time of Day and Traffic Volume

The AADT volume in the study area is just over 16,000 vpd. Because the simulated environment included very light background traffic volumes, the author conducted road tests early in the morning or late in the evening when traffic volumes were lowest. This allowed the subjects to drive at their desired speed for most of the road test.

4.1.1.B Road Test Vehicle

A 1997 Ford Taurus with an automatic transmission was used for all road test runs. Using the same vehicle for all test runs provided consistent vehicle performance data and reduced the likelihood that specific vehicle characteristics would skew the validation analysis results. Although requiring all subjects to use the same (unfamiliar) vehicle would introduce a certain level of driver performance variability while the subjects adjusted to the vehicle, the researchers agreed that this variability could be accounted for in the data analysis process much easier than variability in vehicle types. Additionally, because the test subjects were also unaccustomed to the driving simulator vehicle, completing the experiment with two unfamiliar vehicles would likely produce more similar driving behavior than if conducted with one familiar and one unfamiliar vehicle.

4.1.1.C Data Collection Technology

During the road test, the researchers collected data via two types of technology. The first was an on-board diagnostics (OBD-II) recorder which recorded vehicle performance. This specific recorder, a CarChip E/X developed by DriveRight Technologies, can be seen in Figure 7. The CarChip is primarily marketed for use in personal and fleet vehicles to monitor vehicle diagnostics, but it can also be used to collect speed and travel time data, which is why it was used in this study.

Figure 7. CarChip OBDII Data Recorder, Similar to the Study Equipment

Additionally, the researchers fitted each driver with a pair of head-mounted eye tracking goggles prior to beginning the road test. The eye tracking goggles recorded the roadway environment as seen by the driver in addition to tracking the driver's glance patterns during the test. This specific eye tracking device was the Mobile Eye XG, developed by Applied Science Laboratories, and can be seen on Figure 8.

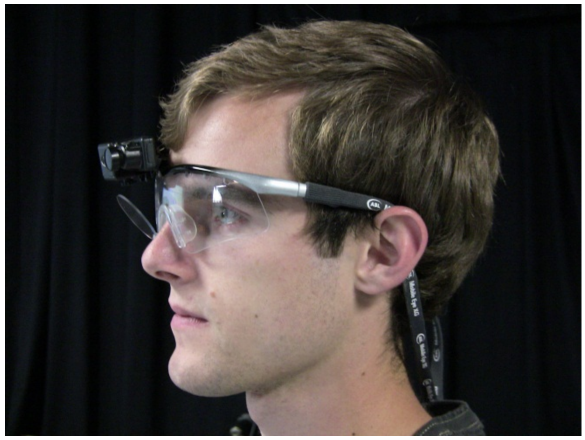

Figure 8. Mobile Eye XG Eye Tracking Equipment

4.1.1.D Road Test Route

All road test runs began in a vacant parking lot approximately 600 feet south of the first test section. The author instructed the test subjects to turn north onto NW 9th Street and travel northbound for approximately one and a half miles. They were then instructed to turn left at a signalized intersection 450 feet north of the second test section (NW Circle Boulevard), turn into a commercial parking lot, and exit back onto southbound NW 9th Street. They then drove south through both test sections again and returned to the vacant parking lot. The road test route is shown graphically on Figure 9.

The researchers directed each subject to drive normally, to favor the right lane over the left lane if no other vehicles were impeding their driving behavior, and to maintain their desired speed whenever possible. All test subjects were local residents and had a baseline familiarity with the test route.

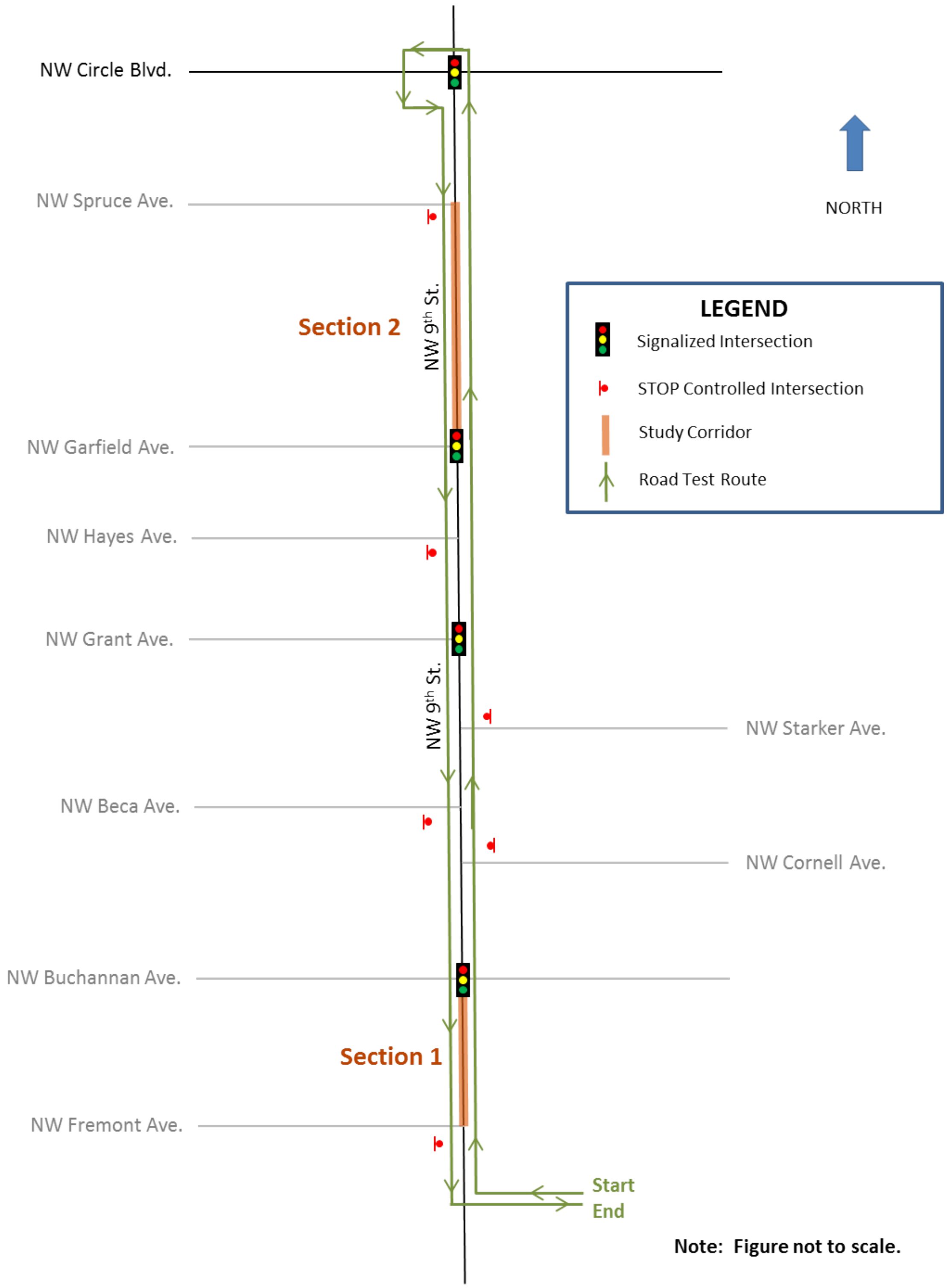

Figure 9. NW 9th Street Road Test Route

4.1.2 Simulator Test

The details of the simulated environment used for the simulator portion of the experiment are described in Chapter 3. The following sections describe the additional considerations and characteristics of the simulator test, including the specifications of the simulator system, the informed consent process, the simulator test and practice test, and the participant debriefing process.

4.1.2.A Driving Simulator Specifications

The OSU driving simulator itself consists of a full size 2009 Ford Fusion cab mounted on top of a high performance electric pitch motion system. The motion base moves +/- 4 degrees with the center of rotation around the driver head position. Three front screens (measuring 11 feet by 7.5 feet) and projectors are used to project an 180 degrees by 40 degrees front view. The driver's rear view is displayed on a fourth screen projected behind the vehicle. The two side mirrors and the dashboard have embedded LCD displays. The system is shown in Figure 10.

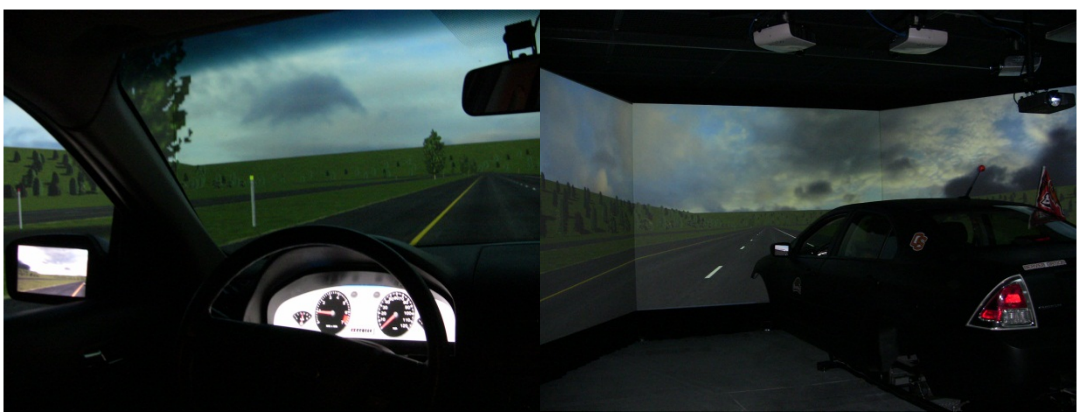

Figure 10. OSU Driving Simulator Vehicle and Projection System

The simulator laboratory is also equipped with four video cameras, three of which are installed within the vehicle. The three in-vehicle cameras record the driver's feet and vehicle pedals, the driver's face, and the driver's hands (as well as the dashboard and console). The fourth camera is installed above and behind the vehicle, providing a birds-eye view of the simulated environment. Video footage from all four cameras is displayed real-time on a large TV monitor located in the partitioned control center and also recorded via a multi-channel DVR system. Recorded videos can later be reviewed independently or simultaneously in a split-screen video file.

4.1.2.B Informed Consent Process

Prior to beginning the experiment, the researchers met with each participant and informed them of the simulator laboratory protocol, safety procedures, and what to expect during the experiment. Each participant then reviewed and signed an informed consent form per requirements by the International Review Board (IRB) for all human subjects testing. As part of the larger NCHRP project, each participant also provided a small amount of personal information, including age and driving restrictions. Lastly, the researchers described the common symptoms of simulator sickness as well as some ways to alleviate the symptoms, and instructed the participants to stop the experiment at any point if they did not feel well enough to continue.

4.1.2.C Simulator Practice Drive

Requiring each participant to complete a practice drive before beginning the actual experiment served two primary purposes. First, the practice drive gave each subject the opportunity to become acclimated to a simulated driving environment as well as become familiar with the steering, acceleration, and deceleration performance of the vehicle. Secondly, once the subject completed the test drive, the researchers could assess the likelihood that the subject would experience simulator sickness during the experiment, through verbal questioning as well as observing the subject’s physical behavior.

As described in Chapter 2, several factors in a simulated environment are known to increase the likelihood of simulator sickness, such as densely populated roadside objects, sharp curves, and frequent stops. For that reason, the environment used in the practice drive was a rural four-lane divided highway with minimal roadside objects, long tangent roadway sections, and large-radii curves. Each subject drove in the practice environment for approximately three to five minutes, either until they were comfortable driving in the environment or until they began to feel ill. After stopping the practice drive, the researchers asked each participant if they were comfortable with the driving environment and if they felt any severe symptoms of simulator sickness. In the case of the ten subjects tested for this validation effort, all felt comfortable continuing with the rest of the experiment.

4.1.2.D Simulator Test

After confirming that the participant was comfortable continuing with the experiment, the author loaded the simulated environment for the test. Each participant was randomly assigned one of four start points within the simulated environment. While the environment was loading, the researcher adjusted and calibrated the eye tracking goggles. The researcher then directed the participant to drive normally, to obey all traffic control devices and signage as they normally would, to favor the right travel lane over the left travel lane whenever convenient, and to not make any turns at any of the signalized intersections. The researcher also informed the participants that a large red letter would randomly appear on the screen during the experiment and that they should say, out loud, the first word that came to mind that began with that letter. After the researcher answered any and all questions, the participant then started the experiment.

In addition to the video footage captured via the eye tracking goggles, the researcher also recorded footage of the driver and the overall experiment using the four in-lab video cameras. The simulator automatically recorded output data related to the vehicle performance.

The simulator test lasted approximately 12 to 15 minutes from start to finish.

4.1.2.E Participant Debriefing

After completing the simulator test, the researchers asked each participant a few general questions regarding the experiment, including whether or not they experienced any symptoms of simulator sickness and if they had any suggestions for improving the driving environment or vehicle performance. The researchers then answered any questions the participant had regarding the experiment itself, and then paid the participants for their time. The amount of compensation was based on a graded scale dependent on how much of the experiment they completed, with a minimum payment of $10 and a maximum payment of $25.

4.2 DATA COLLECTION

The data collected during both the simulator and road tests included driving performance variables, such as speed and acceleration, and driver eye movements and glance patterns. The data collection methods and specific measurements collected are described in the following sections.

4.2.1 Eye Tracking

The research team utilized head-mounted eye tracking goggles to collect eye movement and gaze pattern data during the road tests and simulator tests. Since the larger NCHRP research effort is focused on driver responses to driveway activity, including perception-reaction time, the researchers intended to use the eye tracking data to compare the time and location at which drivers looked at specific driveways as an additional measure of validity. Although the researchers collected eye tracking data for all participants during both the road and simulator tests, the data recorded during the road tests was not usable. Since the road tests needed to be run during light traffic conditions (to reduce interference of background traffic), but also during day light hours (so drivers could easily see driveway activity), most of the test runs were completed late in the evening when the sun was setting. Even though the sun was not directly in the eyes of the drivers, the intermittent side glare of sun light caused the eye tracking technology to misread eye movements or not record eye movement at all. The research team decided that since accurate eye tracking data was only available for a few participants and for only partial test sections, comparative analyses between the road tests and simulator tests could not be completed.

4.2.2 Vehicle Speed, Location, and Travel Time

The simulator system is capable of recording a significant amount of vehicle performance data at intervals down to 1/100th of a second. These data variables can include velocity, acceleration and deceleration, lane position, headway and tailway distances, braking force, and steering position, just to name a few. However, for this validation effort the limiting factor was the amount of data that could be collected during the road test. The researchers only had access to technology that was able to collect vehicle velocity for the road study in one-second intervals, which then allowed for the calculation of acceleration and deceleration as well as distance traveled. Therefore, this validation effort only utilized the vehicle speed, vehicle acceleration and deceleration, travel time, and travel distance data variables from the simulator output. While the simulator software recorded the data in 1/100th of a second intervals, the researchers later reduced this data to one-second intervals.

5. DATA ANALYSIS AND RESULTS

This chapter presents a summary of the data collected and the analysis results for both the road test and simulator test phases of the validation effort. Section 5.1 and Section 5.2 summarize the data collected during the road test and simulator test, respectively. The results of the comparative and statistical analyses are presented in Section 5.3.

5.1 ROAD TEST DATA

As described in Chapter 4, the road test vehicle was equipped with a CarChip OBDII Recorder that collected speed and travel time data for all test runs. Even though the eye tracking video data was not accurate enough to be used in comparative analyses, the researchers were able to use the video footage to match the CarChip data to the test section start and stop points. From the speed and travel time data, the researchers calculated the corresponding acceleration and deceleration rates as well as the distance traveled.

Once the speed profiles were plotted, it was apparent that the signalized intersections along NW 9th Street had a greater impact on driver behavior than initially anticipated. Because of this, the researchers reexamined the speed data and video footage to estimate the influence area of the nearby signalized intersections. By removing these influence areas from the data set, the remaining data more accurately represented free-flow speeds and unimpeded driving behavior. Figure 11 and Figure 12 present the speed profiles for all test runs on Segment 1 (Northbound and Southbound) and Segment 2 (Northbound and Southbound), respectively. The shaded boxes indicate the free-flow portions of the test sections in which driver behavior and speed were not impacted by the presence of nearby signalized intersections.

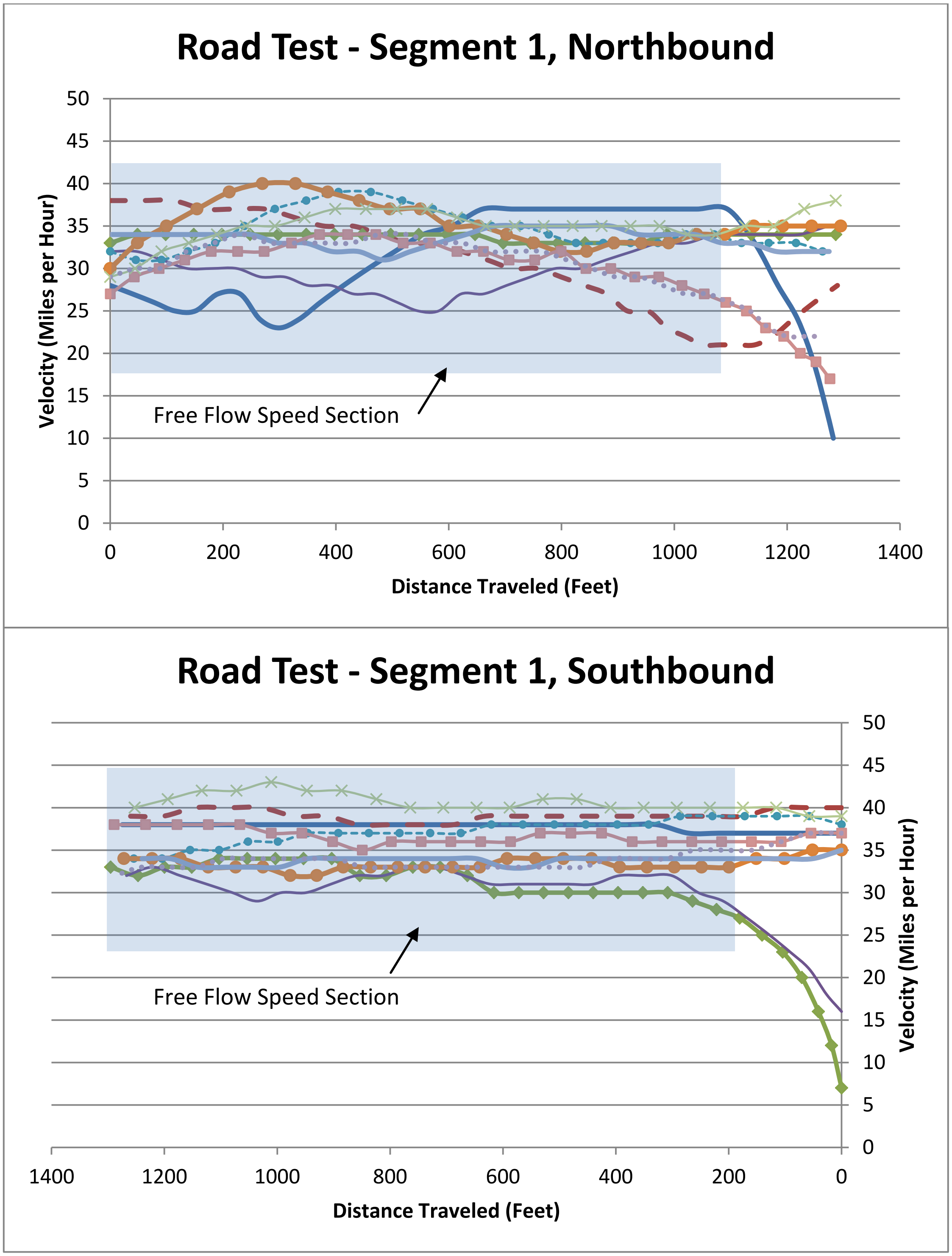

Figure 11. Road Test Speed Profile, Segment 1, Northbound and Southbound

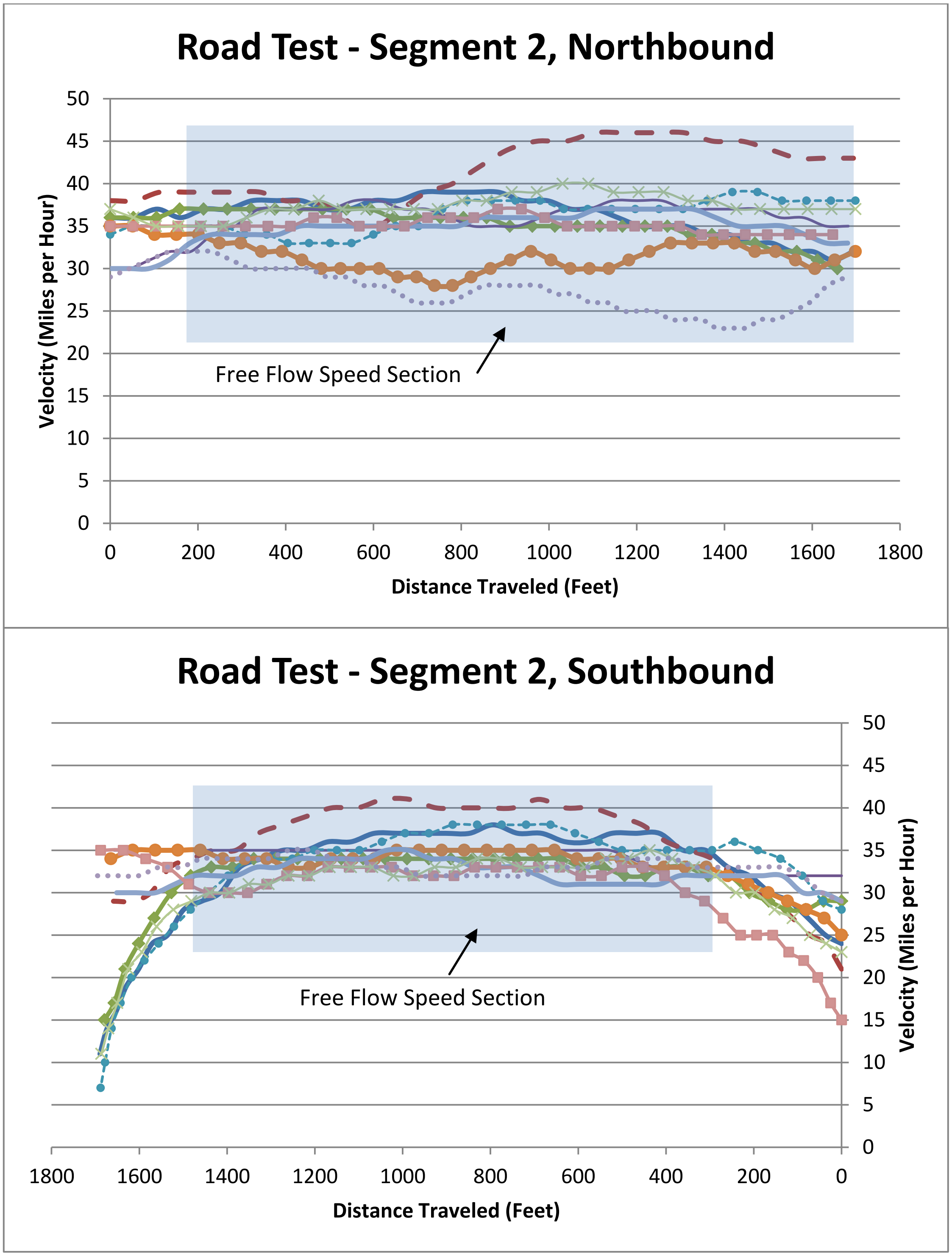

Figure 12. Road Test Speed Profile, Segment 2, Northbound and Southbound

As shown on Figure 11 and Figure 12, the shape of the individual speed profiles vary by segment due to the presence of signalized intersections as well as the presence and behavior of other vehicles on the roadway. However, the average speeds through the free flow sub-sections of all four segments remain very close to 35 mph for all test sections. Individual speed measurements ranged from 23 mph to 46 mph.

The two figures also show that the variability in speed between drivers reduced as the road test progressed. Because all drivers began the road test traveling northbound, turned around, and then traveled southbound (as described in Chapter 4), they all encountered Segment 1, northbound first and Segment 1, southbound last. This change in speed variability is most likely due to the adjustment period for each driver to become familiar with the road test vehicle. For this reason, Segment 1, northbound was excluded from the data analysis.

Additionally, the Segment 2, northbound speed profile shows increasing variability as drivers approached the end of the section. This is likely related to the road test route, in which the drivers were instructed to turn left at NW Circle Boulevard (approximately 450 feet north of the test section). Drivers may have been adjusting their speed and making appropriate lane changes prior to the end of the test section in preparation for the upcoming route change. Also, the intersection of NW 9th Street and NW Circle Boulevard is much larger and busier than any of the other intersections along the road test route. Since all of the drivers had some level of familiarity with the route, they may have been adjusting their driving behavior based on previously defined expectations of traffic volumes (vehicle, bicycle, pedestrian, and transit), queues, and driveway activity. While the overall speed variability definitely changed throughout the segment, the researchers kept the test section in the data set because the speed profiles remained relatively consistent except for the upper and lower outliers.

Table 2 summarizes the descriptive statistics for each road test section, including acceleration, deceleration, minimum and maximum speeds, as well as average and 85th-percentile speeds.

Table 2. Descriptive Statistic Summary for Road Test Sections

Segment	Max. Accel. (ft/s^2)	Max. Decel. (ft/s^2)	Max. Speed (mph)	Min. Speed (mph)	Average Speed (mph)	85th %tile Speed (mph)
NB 1	2.493	-2.200	36.2	27.7	32.5	35.6
SB 1	1.613	-1.760	36.8	33.8	35.5	36.4
NB 2	1.907	-1.613	37.8	31.6	35.1	37.3
SB 2	1.907	-1.907	35.9	31.2	34.2	35.5
NB Average	2.200	-1.907	37.0	29.7	33.8	36.4
SB Average	1.760	-1.833	36.4	32.5	34.8	35.9
Total	1.980	-1.907	37.6	31.7	35.1	36.4

5.2 SIMULATOR TEST DATA

The simulator test consisted of six test sections, each with different types of driveway activity, as described in Chapter 3. Each of the six test sections consisted of two segments, corresponding to Segment 1 and Segment 2 of the road test. Because alternating roadway sections were rotated 180-degrees, the Control section (no driveway activity), Left-turns In section, and Left-turns Out section correspond to the northbound road test section, while the Right-turns In section, Right-turns Out section, and All-Turns section correspond to the southbound road test section. Each test subject started the experiment at one of four randomly selected start points, as described in Chapter 4.

The speed profiles for each of the 12 segments (six northbound, six southbound) are shown on Figure 13 through Figure 18. It should be noted that these speed profiles were adjusted to only include the portions of the segments identified as having free-flow conditions in the road test data. For example, the road test data showed that free-flow conditions began on Segment 1, Southbound after the first 200 feet and continued to the end of the segment (approximately 1,285 feet). Therefore, the corresponding simulator test segments (Segment 1 of Right-turns Out, Right-turns In, and All Turns) include data only between locations 200 feet and 1,285 feet.

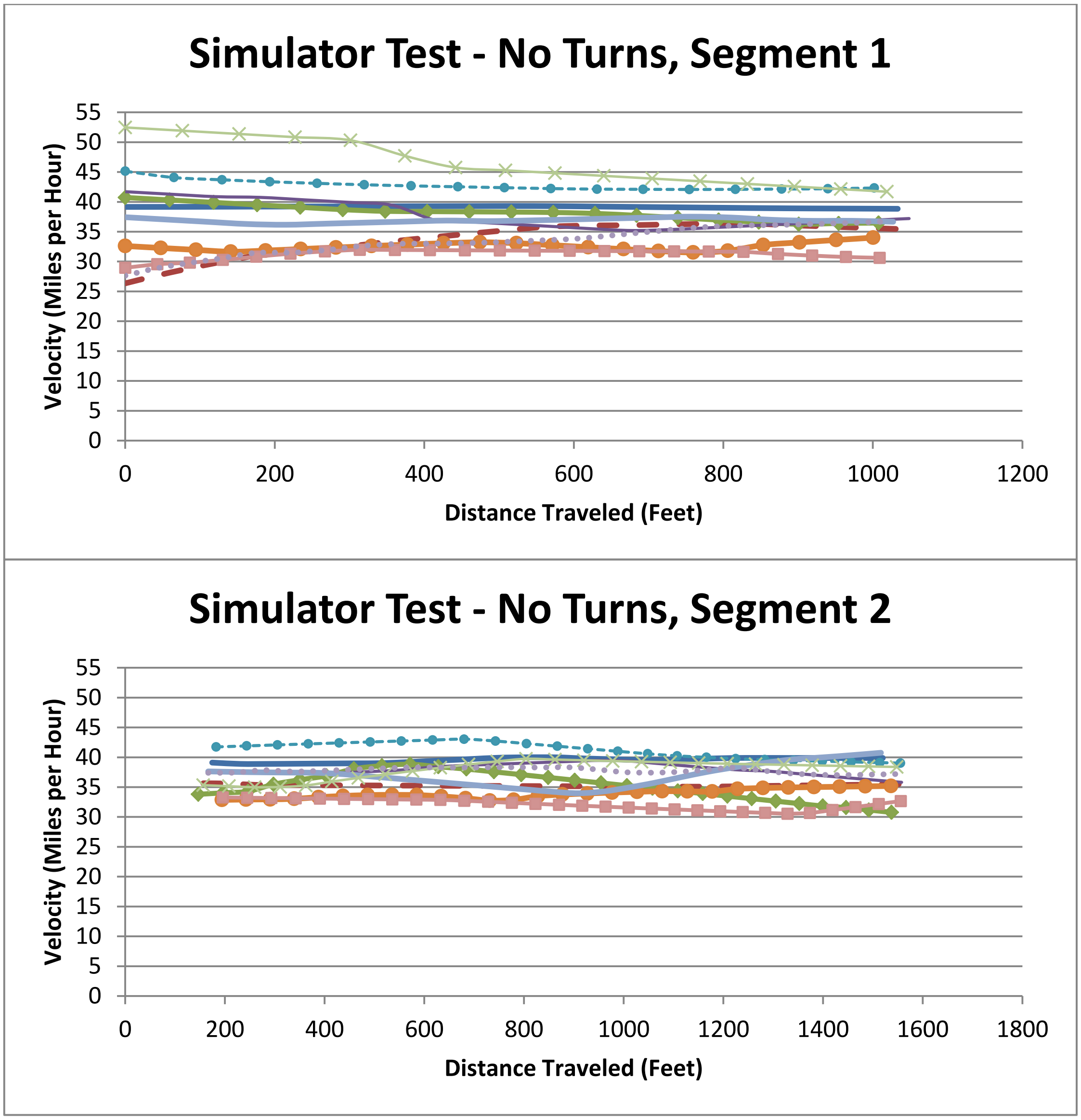

Figure 13. Simulator Test Speed Profile, Control Section (No Turns), Segment 1 and 2

Figure 13 shows the speed profiles for Segment 1 and 2 within the control section. The speeds in the first 400 feet of Segment 1 show a much higher variability than the remainder of the segment, which is likely due to Segment 1's proximity to the transition area where drivers are exiting a higher-speed rural area and entering the lower-speed urban area. Despite the increased variability, the researchers decided not to exclude any data points based on these speed profile patterns.

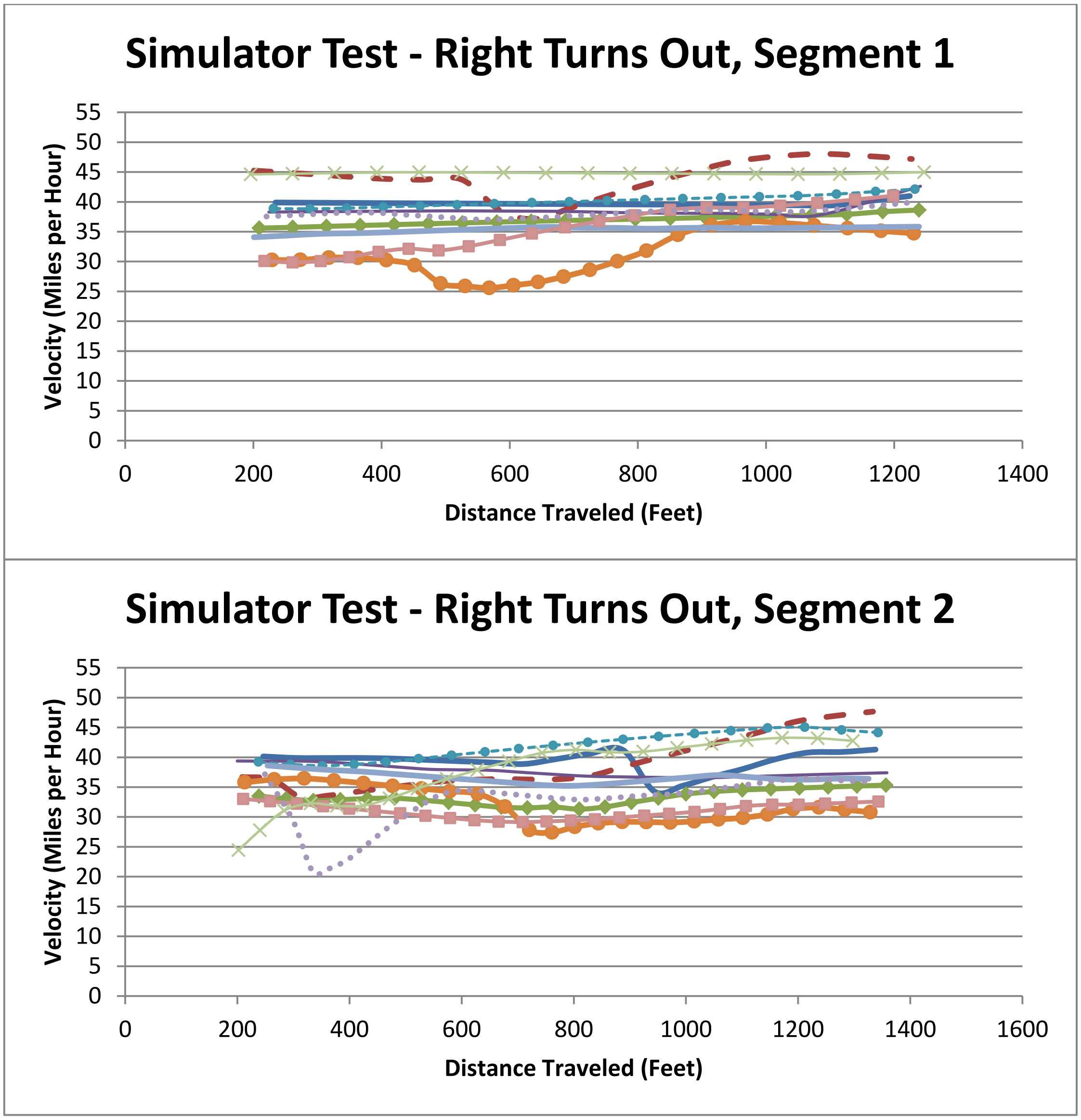

Figure 14. Simulator Test Speed Profile, Right Turns Out Section, Segment 1 and 2

As shown on Figure 14, Segment 1 and Segment 2 of the Right-Turns Out section exhibit relatively constant speed profiles along their entire length. While some drivers did make braking maneuvers in response to driveway activity, the overall trends are consistent and the researchers did not exclude any data based on the Right-Turns Out speed profile patterns.

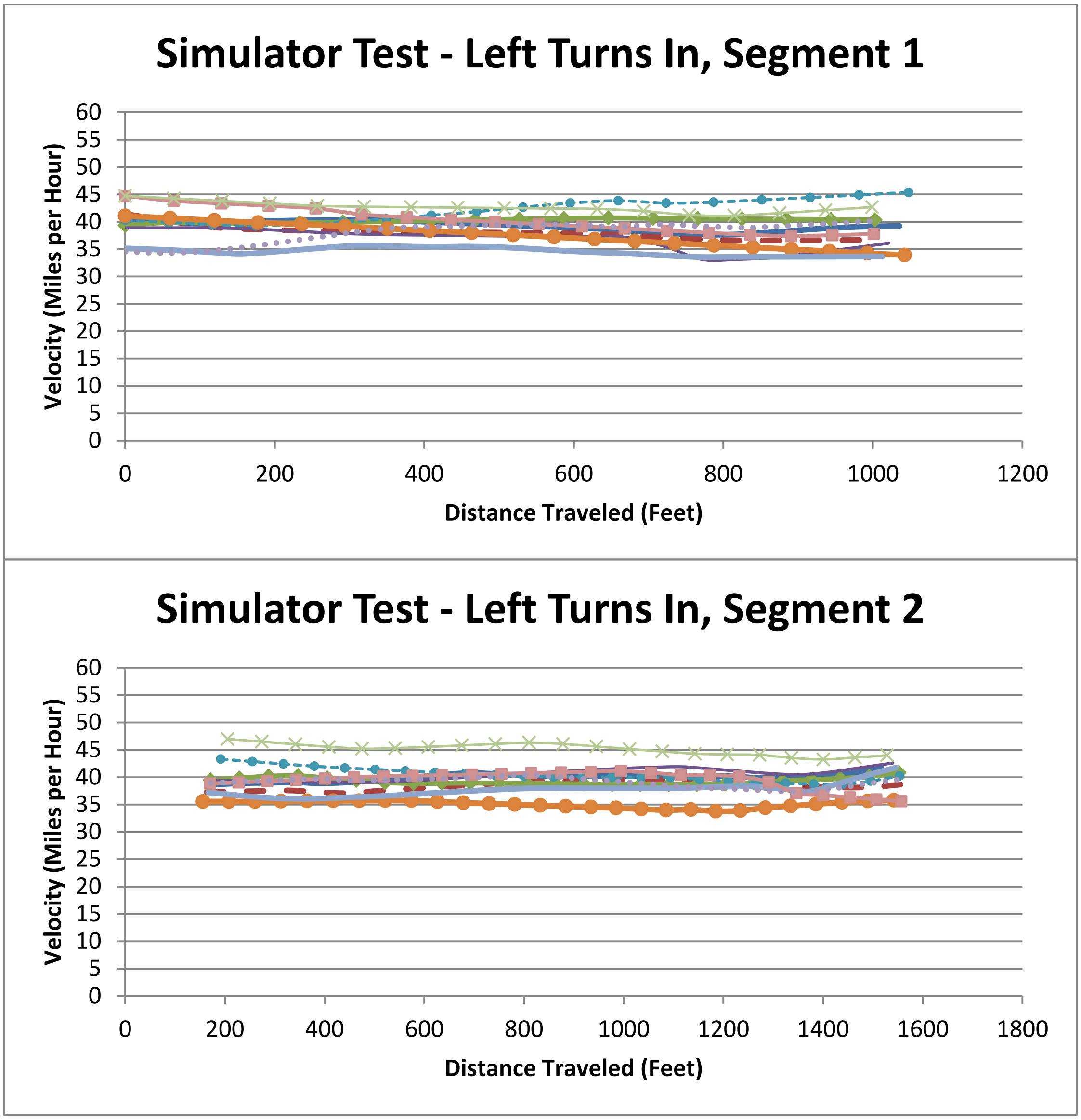

Figure 15. Simulator Test Speed Profile, Left Turns In Section, Segment 1 and 2

Figure 15 presents the speed profiles for Segment 1 and 2 of the Left-Turns In section. As shown, all speed profiles for both segments are consistent with minimal variability, and the researchers included all data in the statistical analyses.

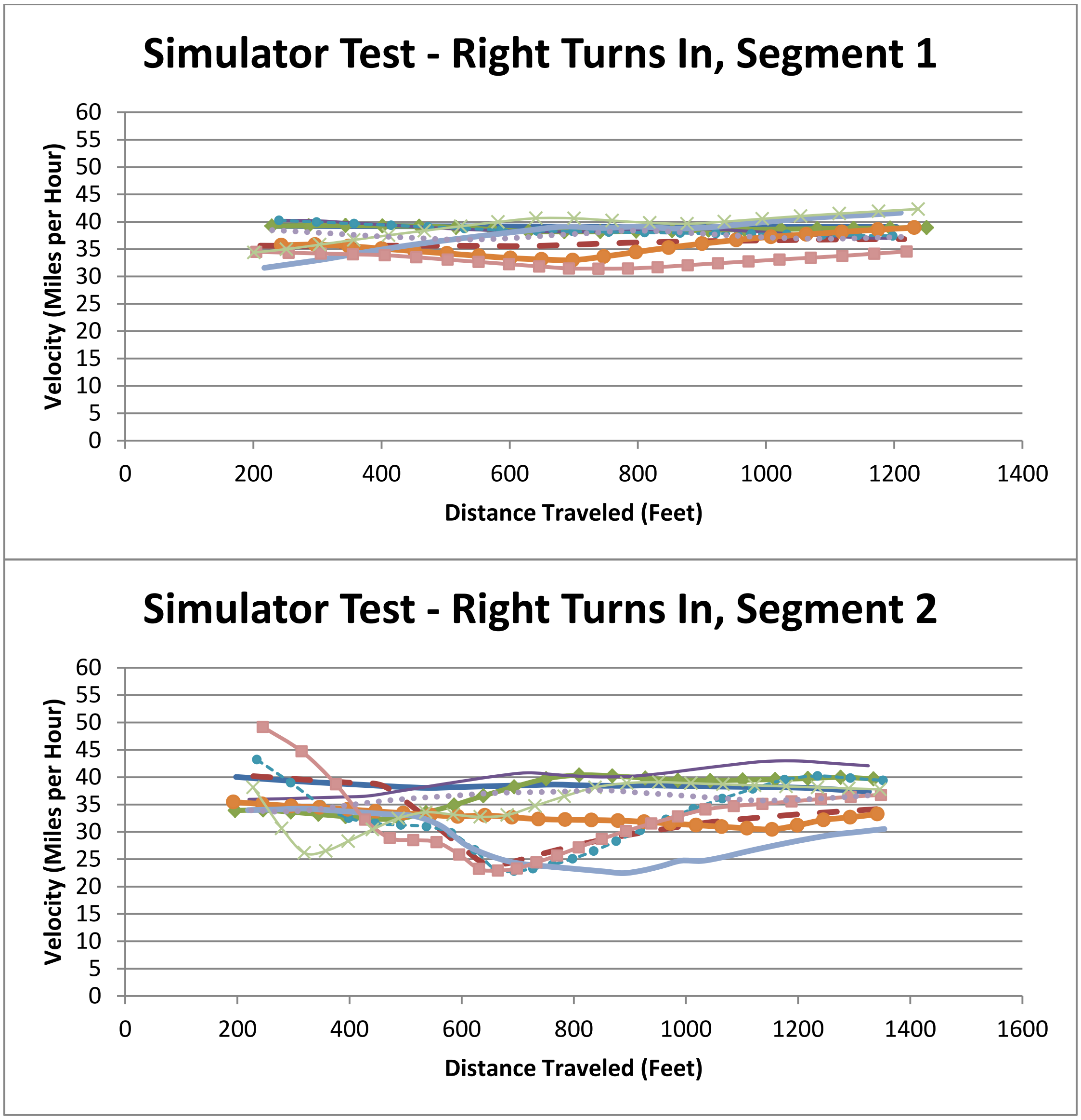

Figure 16. Simulator Test Speed Profile, Right Turns In Section, Segment 1 and 2

The speed profiles for Segment 1 of the Right-Turns In section, shown on Figure 16, are very consistent and show minimal variability between drivers. However, speeds in Segment 2 were affected by driveway activity, as shown by the variability in the speed profiles. While overall Segment 2 speed profiles are less consistent than other test sections, the patterns are not extreme or unexpected, and thus the researchers retained all data for the Right-Turns In section as part of the analysis.

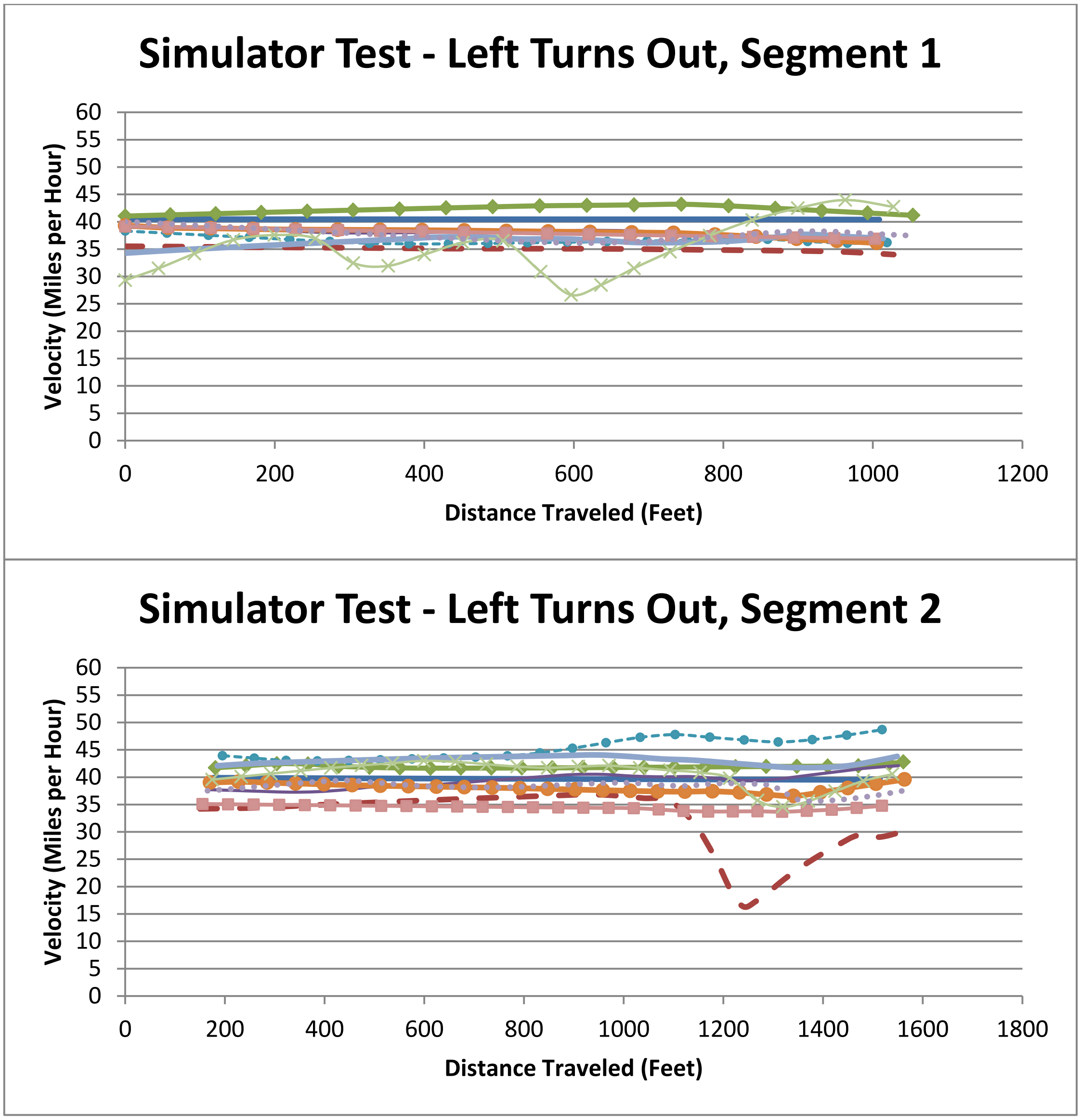

Figure 17. Simulator Test Speed Profile, Left Turns Out Section, Segment 1 and 2

The speed profiles shown on Figure 17 indicate that one driver in each segment responded to a driveway-related event that the other drivers either did not encounter or did not respond to with a braking maneuver. For this reason, the researchers removed each of the outlying speed profiles from the data set prior to analysis.

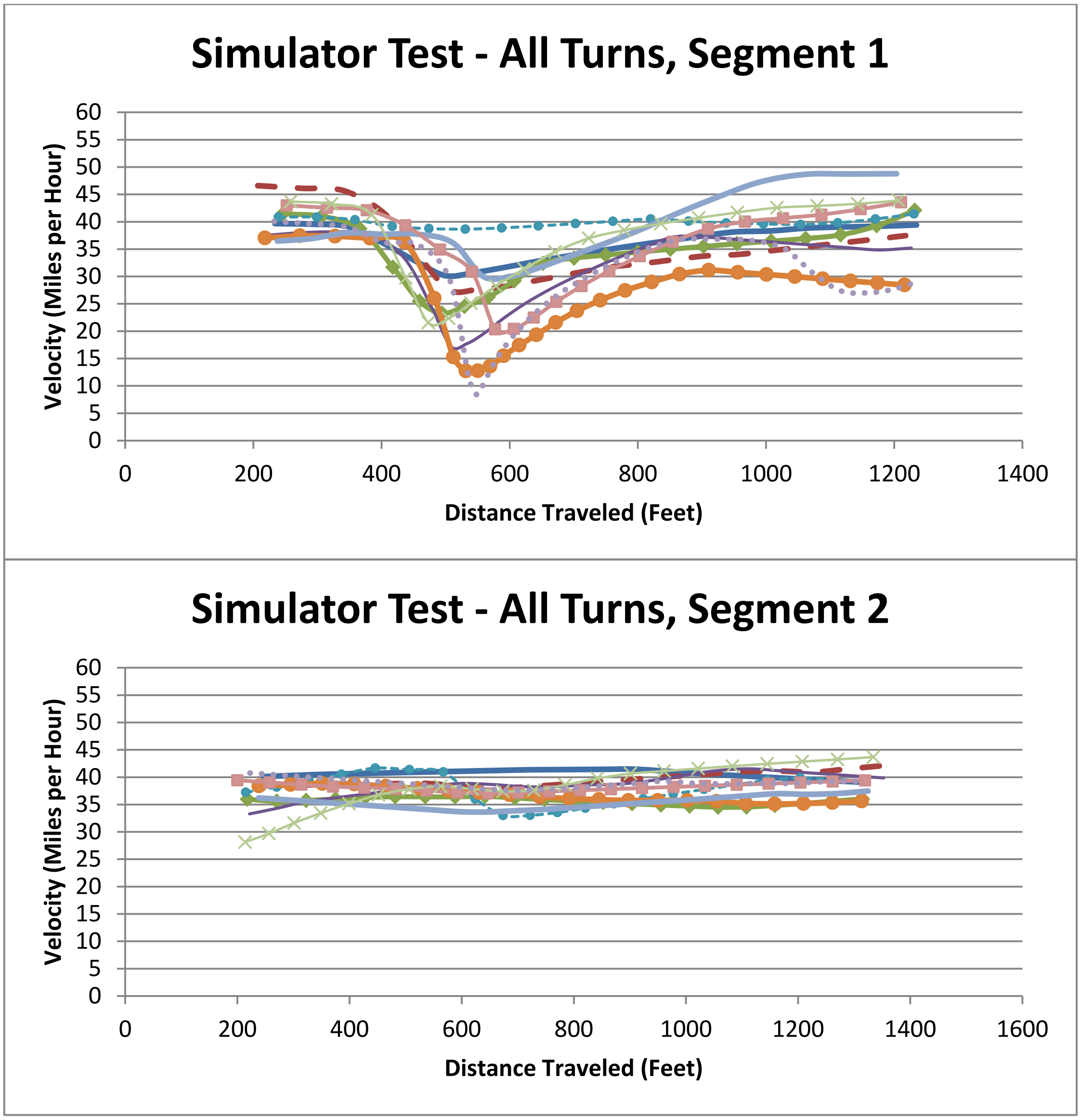

Figure 18. Simulator Test Speed Profile, All Turns Section, Segment 1 and 2

Segment 1 of the test section which included all turn types showed the most significant response to driveway activity of any of the test sections, as illustrated on Figure 18. This extreme braking event was in response to a programmed vehicle exiting a driveway right in front of the subject vehicle. Because no such events occurred during the road test, the researchers excluded all Segment 1 data from the analysis data set, however the analysis did include all speed profiles from Segment 2.

Table 3 summarizes the descriptive statistics of the simulator test speed profiles for each section, for all northbound test sections, for all southbound test sections, and for the average of all test sections.

Table 3. Descriptive Statistic Summary for Simulator Test Sections

	Max. Accel.	**Max. Decel.**	**Max. Speed**	**Min. Speed**	**Average Speed**	**85th %tile Speed**
Section	(ft/s^2)	(ft/s^2)	(mph)	(mph)	(mph)	(mph)
Control	0.762	-0.997	39.0	34.7	36.9	38.5
Right Out	1.733	-2.545	40.4	33.5	37.2	39.5
Left In	0.943	-1.056	41.4	37.2	39.2	40.5
Right In	1.196	-2.261	39.7	32.1	35.8	38.5
Left Out	1.075	-1.753	40.4	35.9	38.4	39.8
All Turns	2.310	-6.909	41.3	29.0	36.1	40.4
NB Average	0.927	-1.268	40.3	35.9	38.2	39.6
SB Average	1.301	-1.814	40.0	34.1	37.3	39.4
Total Average	1.337	-2.587	40.4	33.7	37.3	39.6

5.3 DATA ANALYSIS AND COMPARISONS

As discussed in Sections 5.1 and 5.2, the simulator test and road test data show similar trends in driving performance. Travel speeds remained relatively constant through all roadway sections in both the simulator and roadway test, with the few exceptions that were discussed previously and removed from the data set. The maximum, minimum, average, and 85th-percentile speeds were all higher in the simulator test than the road test, although the magnitude of the difference is relatively small (typically less than 3 mph). For acceleration and deceleration data, the road test showed more extreme acceleration behavior while the simulator test showed more extreme deceleration behavior. These trends can be seen in Table 2 and Table 3. Further graphical comparisons and statistical analyses are discussed in the following sections.

5.3.1 Graphical Comparison of Acceleration Curves

Although the formal statistical analyses focused on free flow conditions to reduce variability among drivers, the researchers also investigated the acceleration speed profiles independently. Because the road test mainly included acceleration and deceleration events related to signalized intersections that were not present in the simulator test, and the simulator test included acceleration and deceleration events related to specific driveway activity that could not be replicated in the field, the only acceleration information available for the researchers to compare was the initial acceleration period at the beginning of each test. Similarly, the researchers could not compare the deceleration curves between tests because the final deceleration period of the road test involved maneuvering through a parking lot, while the simulator test only required a straight-line stop.

The researchers looked at the speed data for the initial acceleration period of each test and, based on when drivers typically reached free flow speeds, selected a distance of 1,000 feet from the starting point to analyze acceleration patterns.
Figure 19 shows the acceleration data for the simulator and road tests, as well as fitted exponential curves. The researchers included the curves to aid in the visual comparison of both data sets; however, it should be noted that the curves were derived using Excel, not formal statistical modeling.

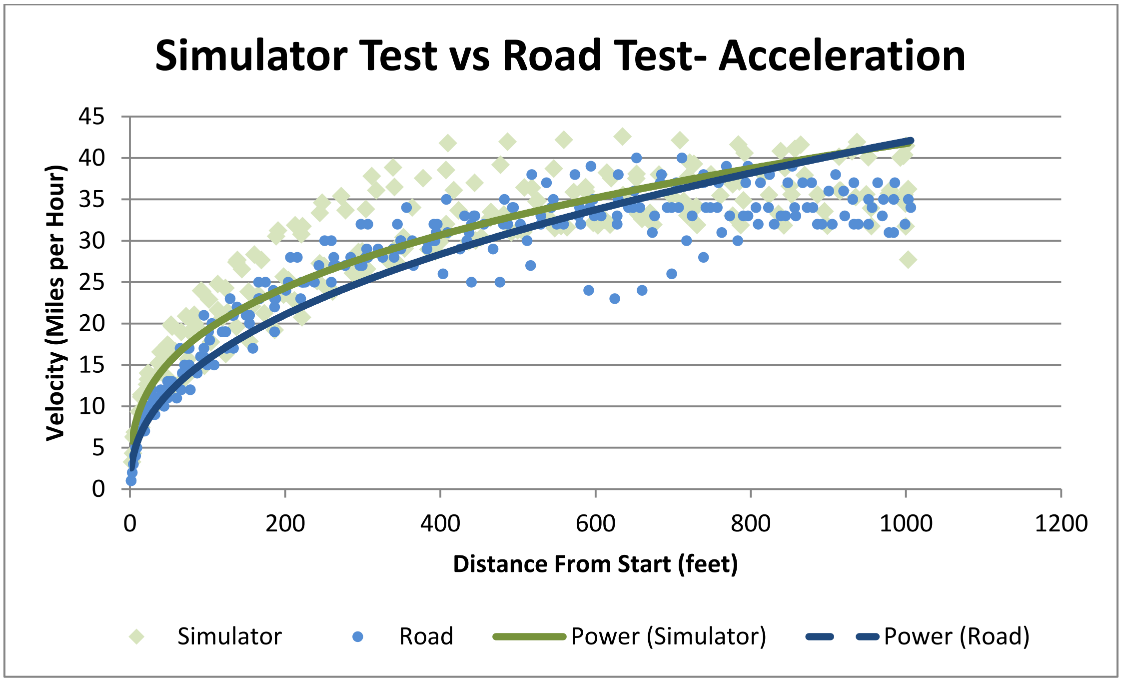

Figure 19. Comparison of Simulator and Road Test Acceleration Curves

As shown in Figure 19, while the road test profile shows a slightly sharper acceleration curve, the overall profiles for the simulator and road test acceleration periods exhibit very similar trends and magnitudes.

5.3.2 Formal Analysis of Speed, Acceleration, and Deceleration Data

The final phase of the validation effort involved statistical analyses which included all speed, acceleration, and deceleration variables presented in Sections 5.1 and 5.2. Because the same set of test subjects participated in the simulator and road tests, the author utilized a two-sample paired t-test to compare the two data sets.

As described earlier in this chapter, the researchers excluded some collected data from this analysis, most notably the entire Segment 1, northbound data set from the road test and the entire All Turns, Segment 1 data set from the simulator test. After the exclusion of these data sets, the researchers strategically matched each road test data set to the appropriate simulator data set, wherever possible. For example, if Subject 1 encountered a vehicle turning left into a driveway on Northbound Segment 2, but no other driveway activity within that segment, then that driver's road test data set was paired with the Left-Turn-In Segment 2 simulator data set. If a driver encountered no driveway activity within a segment of the road test, their data was compared to the control section of the simulator test. Similarly, if a driver encountered multiple turn types within a single road test segment, the researchers matched that data with the corresponding simulator data for the All Turns section. When corresponding data was not available, either due to previous exclusions or a lack of appropriate data (i.e., the simulated environment included right turn activity in the northbound direction only), the researchers used the northbound or southbound average values for that segment.

The researchers utilized box plots and quanitle-quanitle (Q-Q) plots to ensure that the data sets were normally distributed with equal variances. All data variables met the normality and variance requirements of the paired t-test, and these investigative plots are included in the Appendix.

A two-sample paired t-test compares the means of two dependent data sets, such as the same group of subjects being given two treatments, or in this case, participating in both the simulator and road tests. Paired t-tests provide increased statistical power over unpaired t-tests of the same sample size since using the same population sample for both treatments accounts for many of the potential confounding factors typically associated with random sampling.

For this validation effort, the null hypothesis is that the difference in means between the simulator and road test data sets equals zero. If the tests result in insignificant p-values and the null hypothesis is not rejected, the researchers can then infer that speed, acceleration, and deceleration measurements in the simulator do not statistically differ from corresponding real-world measurements. The threshold for significant versus insignificant p-values is typically a value of 0.05. However, a general rule of thumb concerning p-values is that values less than 0.01 provide convincing evidence of a statistical difference, while values between 0.01 and 0.05 show moderate to suggestive evidence and values between 0.05 and 0.10 show suggestive but inconclusive evidence (Ramsey and Schafer, 2002).

Because the researchers developed the analysis data set based on the road test driveway activity, all data are summarized by the road test segments.
Table 4 presents the results of the paired t-test analyses, including p-values (significance denoted by asterisks and bold type) and 95-percent confidence intervals.

Table 4. Paired t-Test Analysis Results

Data Variable	**Statistic**	**Northbound Segment 2**	**Southbound Segment 1**	**Southbound Segment 2**
Minimum Speed (mph)	p-value	0.08292	0.1304	0.1786
	avg. difference	-3.36	-2.36	-1.37
	95% CI	(-7.257 ,0.537)	(-5.567, 0.847)	(-3.494, 0.754)
Maximum Speed (mph)	p-value	0.2961	**0.001307****	**0.00005****
	avg. difference	-1.57	-3.42	-3.61
	95% CI	(-4.772, 1.632)	(-5.105, -1.735)	(-4.469, -2.751)
Average Speed (mph)	p-value	0.1777	**0.0155***	**0.00059****
	avg. difference	-2.21	-2.76	-2.18
	95% CI	(-5.629, 1.209)	(-4.857, -0.663)	(-3.135, -1.224)
85th Percentile Speed (mph)	p-value	0.332	**0.0022****	**0.00007****
	avg. difference	-1.5096	-3.25	-3.43
	95% CI	(-4.841, 1.821)	(-4.994, -1.508)	(-4.272, -2.585)
Maximum Acceleration (ft/s^2)	p-value	0.05717	**0.03505***	0.2467
	avg. difference	0.7909	0.8232	0.445
	95% CI	(-0.0298, 1.612)	(0.072, 1.574)	(-0.368, 1.258)
Maximum Deceleration (ft/s^2)	p-value	**0.002613****	0.1864	0.2151
	avg. difference	-0.6667	-0.964	0.93878
	95% CI	(-1.024, -0.309)	(-2.456, 0.564)	(-0.669, 2.547)

The results presented in Table 4 illustrate that eight of the 18 paired t-tests completed resulted in significant p-values suggesting a statistical difference in mean values; two resulted in moderately suggestive evidence (p-values between 0.01 and 0.05, denoted by a single asterisk) and six resulted in convincing evidence (p-values less than 0.01, denoted by a double asterisk).

Even though the maximum, average, and 85th percentile speeds show statistically significant differences between the simulator and two of the three road test sections, the 95-percent confidence intervals indicate that these differences are 5 mph or less in all instances. In the case of acceleration and deceleration measurements, only one of the three test sections resulted in significant differences for each data variable, and in both cases the 95-percent confidence interval shows differences less than 1.6 ft./s^2. With the exception of the maximum deceleration variable, all t-tests resulted in average differences that were of the same sign and relative magnitude across all three test segments. For the deceleration variable, two of the three segments showed a negative difference (indicated higher deceleration rates in the simulator), while one segment showed a positive difference.

5.3.3 Summary of Analysis and Results

The authors compared speed, acceleration, and deceleration data from the road test and simulator tests using descriptive statistics, graphical comparisons, and two-sample paired t-tests.

The researchers graphically compared speed profiles for the simulator and road tests for all test sections, and the free-flow speed segments showed consistent speeds in the 35mph-40mph range for all test subjects. In general, free flow speeds observed in the simulator test were slightly higher than those observed during the road test.

The authors also graphically compared the speed profiles during the initial acceleration periods of the tests. While the road test showed slightly higher acceleration rates, the two acceleration curves were very similar in shape and magnitude.

The t-tests analyzed four speed data variables (minimum, maximum, average, and 85^{th}-percentile speeds) as well as maximum acceleration and deceleration variables across three different roadway test sections. Of the 18 tests completed, six showed convincing evidence of a statistically significant difference between the simulator and road test results, two showed moderately suggestive evidence of a difference, and the remaining ten showed no evidence of a difference. While several data variables did show statistically significant differences between the two tests, the 95-percent confidence intervals indicated that these differences were less than 5 mph for all speed data variables and less than 1.6 ft/s^2 for all acceleration and deceleration variables.

Based on the graphical and statistical comparisons described above, the author believes that the analysis results confirm the validity of the driving simulator based on the speed-based variables tested. While the analyses resulted in statistically significant differences for some data variables on one or more test sections, the magnitude of these differences is considered minor in practical terms.

6. SUMMARY & CONCLUSIONS

The National Cooperative Highway Research Program is currently in the process of updating the Access Management Manual and developing the companion document, titled Access Management Application Guidelines. As part of this effort, the Oregon State University (OSU) Driving Simulator Laboratory will be utilized to investigate the current standards of practice regarding driveway spacing, stopping sight distance, and perception-reaction time. Because the results of this research may impact nationally accepted standards and guidelines, a critical component of this effort is verifying the accuracy of the driving simulator and its associated performance measures. The research presented in this document focused on the validation of the OSU driving simulator based on speed, acceleration, and deceleration data.

The validation effort was centered on the null hypothesis that speed, acceleration, and deceleration data collected in the simulator do not differ from what is observed in the real world. To test this hypothesis, the author selected a road test section and developed a corresponding simulated environment. A total of ten subjects completed both the road test and simulator test, and the author used a combination of descriptive statistics, graphical comparisons, and two-sample paired t-tests to compare the performance measures of each test.

The experiment consisted of a road test and a simulator test using the same ten subjects for both tests. The road test occurred on a section of NW 9^{th} Street, which is an urban principal arterial in the city of Corvallis, Oregon. This section of NW 9^{th} Street has a five lane cross-section with a median two-way left-turn lane and bicycle lanes in both directions. The test section of NW 9^{th} Street consisted of two different roadway segments with a total combined length of approximately 3,000 feet. The two segments included a total of 30 driveways, most of which served commercial land uses, and did not include any signalized intersections.

For the simulator test portion of the experiment, the researchers designed the simulated environment to match the road test environment as closely as possible. The roadway geometry was exactly the same in both environments and the simulated driveway centerline locations were within 10 feet of the real world driveway centerlines. Roadside objects and adjacent land uses were represented in the simulated environment by generic buildings, trees, and light posts that were of the correct size and shape.

Researchers used an OBDII-port recorder to collect travel time, speed, acceleration, and deceleration data during the road test. The same data variables were automatically recorded by the software program during the simulator test. During both tests, researchers also utilized eye tracking goggles to collect eye movement data as well as driver point-of-view video footage. Due to sun glare that affected the quality of the eye tracking data during the road test, ultimately the eye tracking data could not be used for the validation effort.

In addition to descriptive statistics and graphical comparisons of the speed profiles, the researchers completed two sample paired t-tests to analyze the simulator and road test datasets. The six data variables analyzed were minimum speed, maximum speed, average speed, 85^{th}-percentile speed, maximum acceleration, and minimum acceleration. The researchers compared these six data variables for three different roadway segments, resulting in a total of 18 paired t-tests. Of the 18 paired t-tests, eight combinations showed a statistically significant difference between the simulator and road tests. The maximum, average, and 85^{th}-percentile speeds were statistically different on two of the three test segments, while the maximum acceleration and deceleration values were statistically different on only one of the three test segments.

Although several of the paired t-tests resulted in p-values suggesting statistically significant differences between the simulator and road test datasets, the estimated differences were not large. On average, the speeds measured in the simulator test were 3.5 mph higher than those recorded during the road test. The statistically significant differences in acceleration and deceleration rates were, on average, 0.80 ft/s^2. With regards to the acceleration rates, the simulator data set showed lower values than the road test. The analysis using the deceleration data resulted in two of the three segments showing higher deceleration rates in the simulator test, while one segment showed the reverse trend. This was the only data variable that showed inconsistent trends across the three test sections, and thus should be investigated further.

Practically speaking, the magnitude of these differences, particularly for the speed variables, is not significant. The researchers believe that these results confirm the validity of the OSU Driving Simulator performance measures with regards to speed and acceleration.

6.1.1 Next Steps and Future Work

With the completion of most large-scale projects, ideas regarding the application of the research results as well as considerations to improve or expand upon the research effort itself are often spurred. The next steps and ideas for future work are outlined below:

6.1.1.A Next Steps

- As previously mentioned, this validation effort was the preliminary phase of a larger research project funded by NCHRP. The results of this validation effort will serve as supporting evidence of the validity and accuracy of performance measures collected in the OSU Driving Simulator Laboratory; and
- If future research efforts intend to extrapolate absolute values for speed, acceleration, or deceleration, the small differences in measurements described in this report can be accounted for in one of two ways. The simulator hardware and software can be adjusted such that the measurements better reflect real-world driving behavior, or the resulting data variables collected during research efforts can be manually adjusted to account for the differences.

6.1.1.B Future Work

- Completing the same or similar road and simulator tests with a larger number of subjects would increase the strength of the results and would better refine the estimated differences between the data variables, particularly in regards to the deceleration rates; and
- Investigating the validity of additional data variables would strengthen the argument that the OSU Simulator Laboratory is accurate and valid in a wider range of contexts. Performance measures such as lateral lane position or headway could be studied through a similar experiment. Additionally, investigating ways to improve the collection of eye tracking data in the road test environment would provide another layer of validity that is very applicable to simulator research in this laboratory.

7. WORKS CITED

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APPENDIX

LIST OF ABBREVIATIONS

Abbreviation	Description
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADA	Americans with Disabilities Act
AMM	Access Management Manual
AMAG	Access Management Application Guidelines
ANOVA	Analysis of Variance
LiDAR	Light Detection and Ranging
NCHRP	National Cooperative Highway Research Program
OSU	Oregon State University
PRT	Perception-Reaction Time
SSQ	Simulator Sickness Questionnaire
TRB	Transportation Research Board
TWLTL	Two-Way Left-Turn Lane

NORMALITY PLOTS

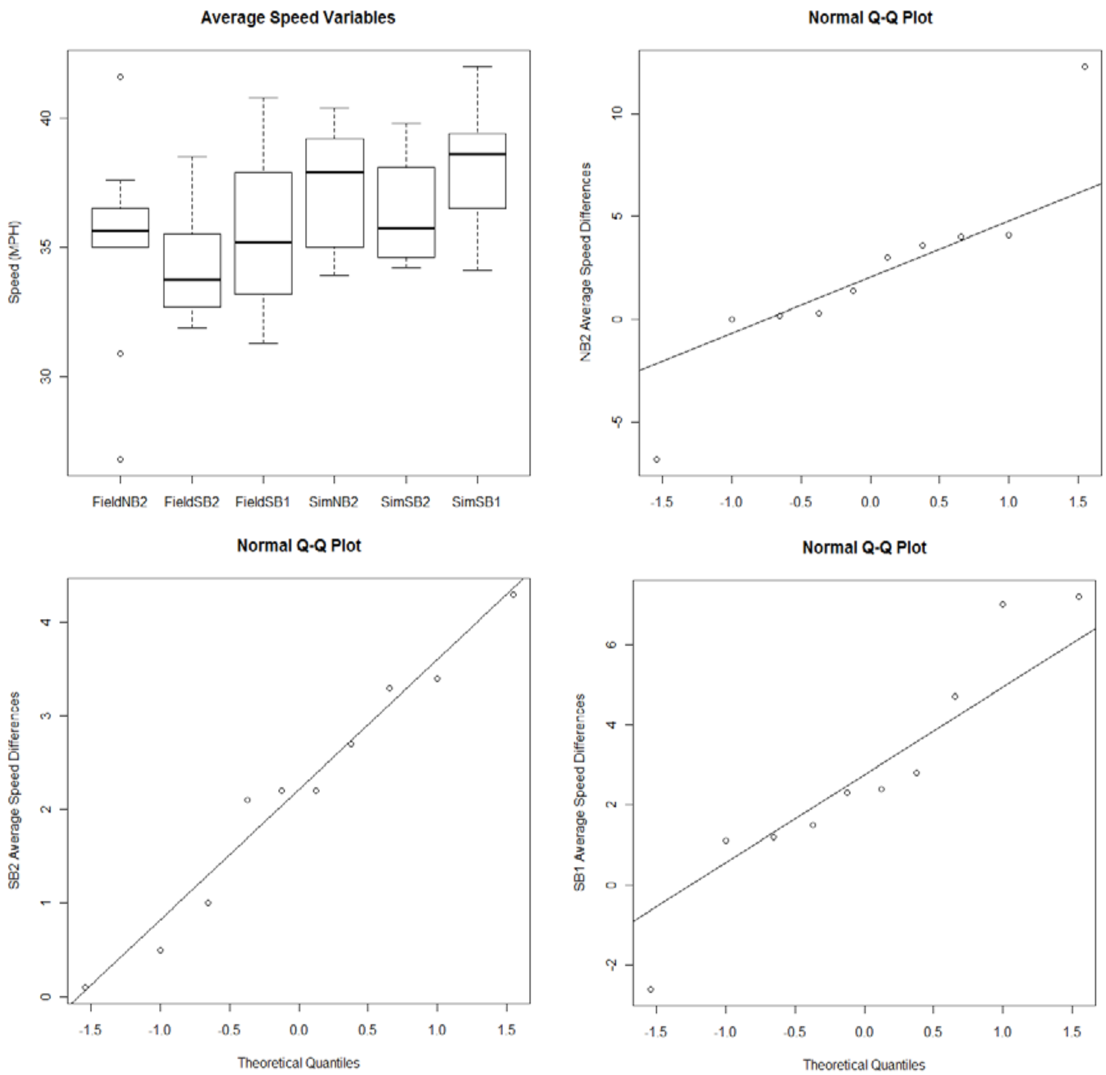

Figure A1. Boxplot and QQ Plots for Average Speed Variables

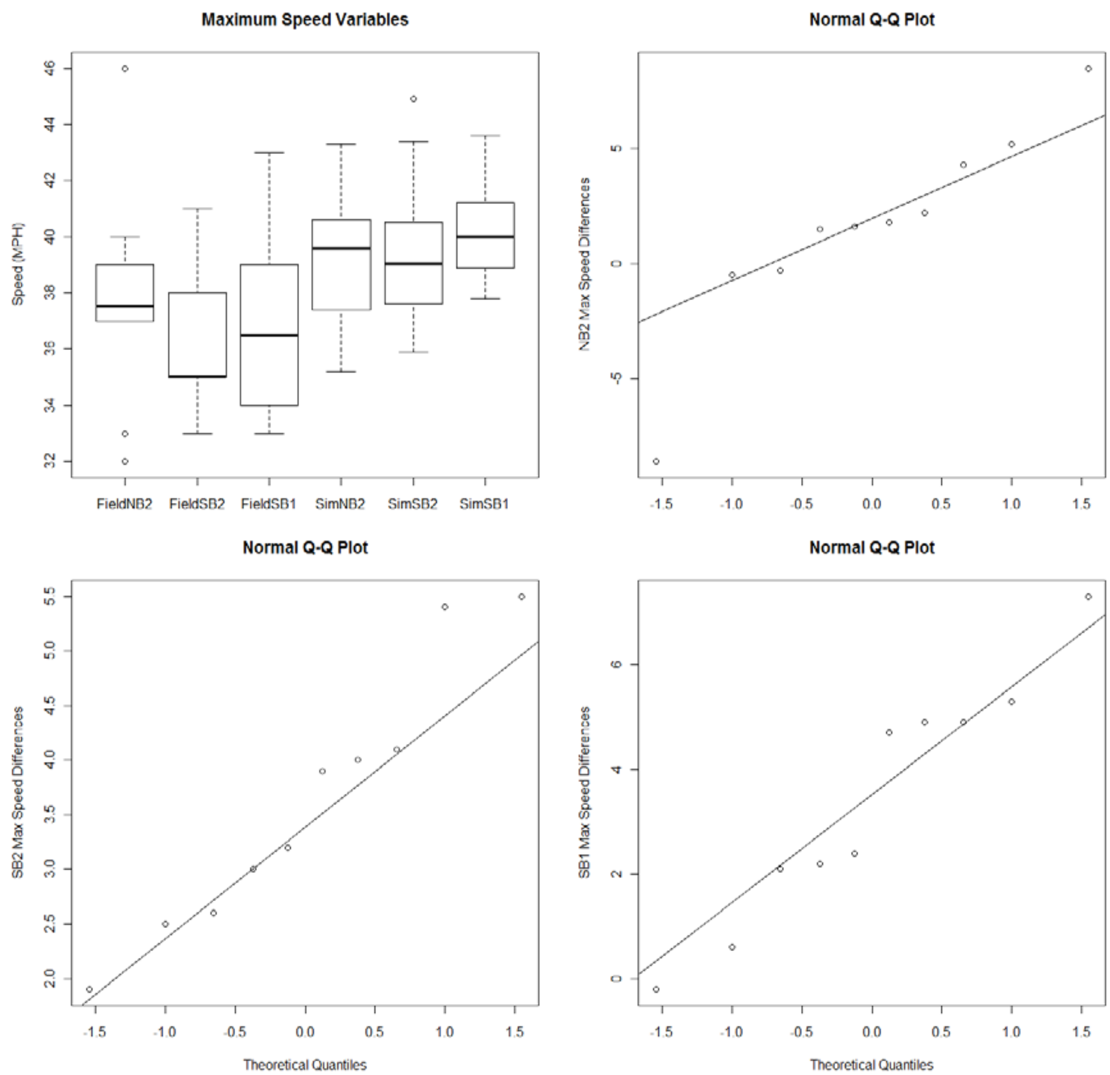

Figure A2. Boxplot and QQ Plots for Minimum Speed Variables

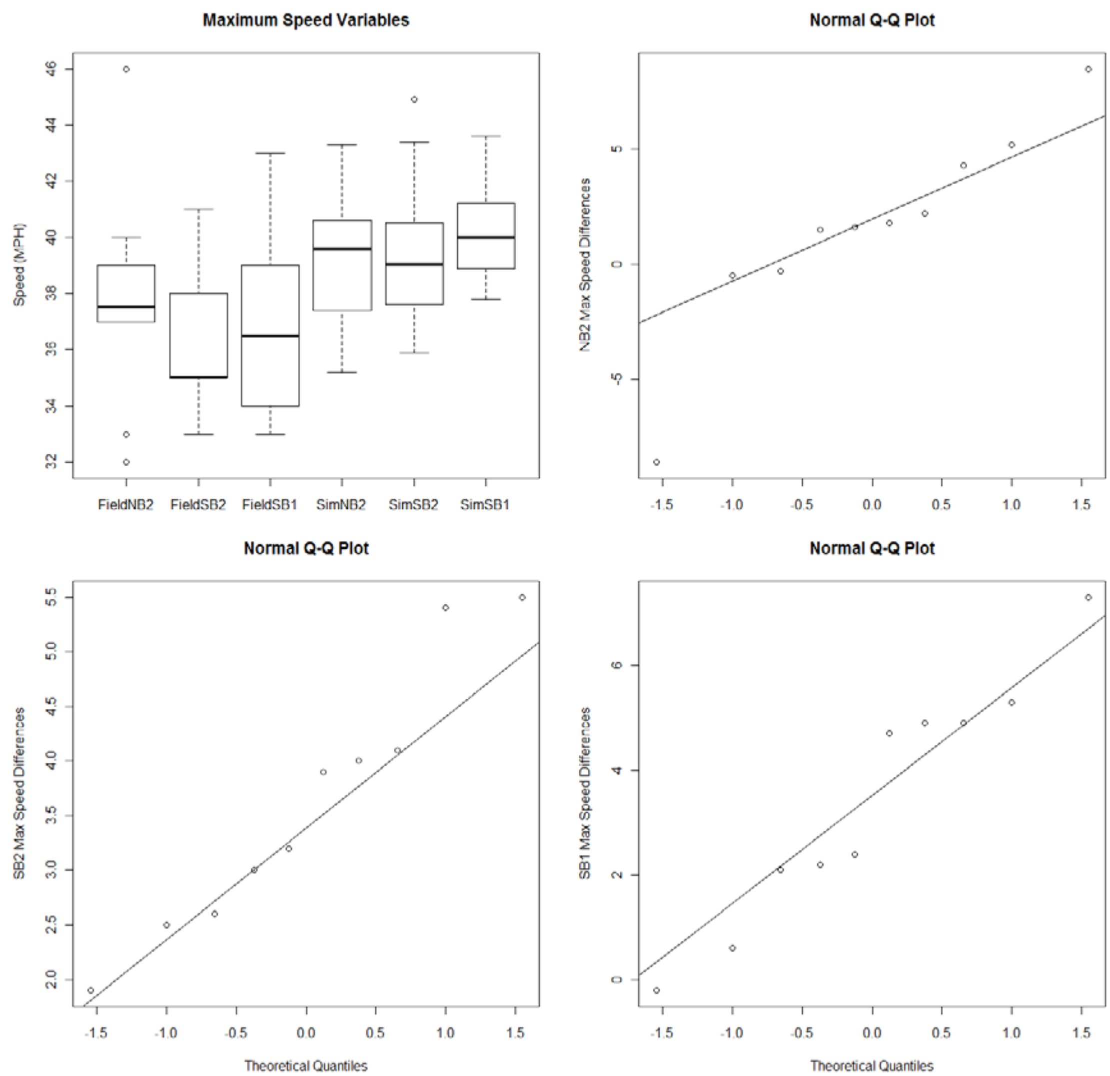

Figure A3. Boxplot and QQ Plots for Maximum Speed Variables

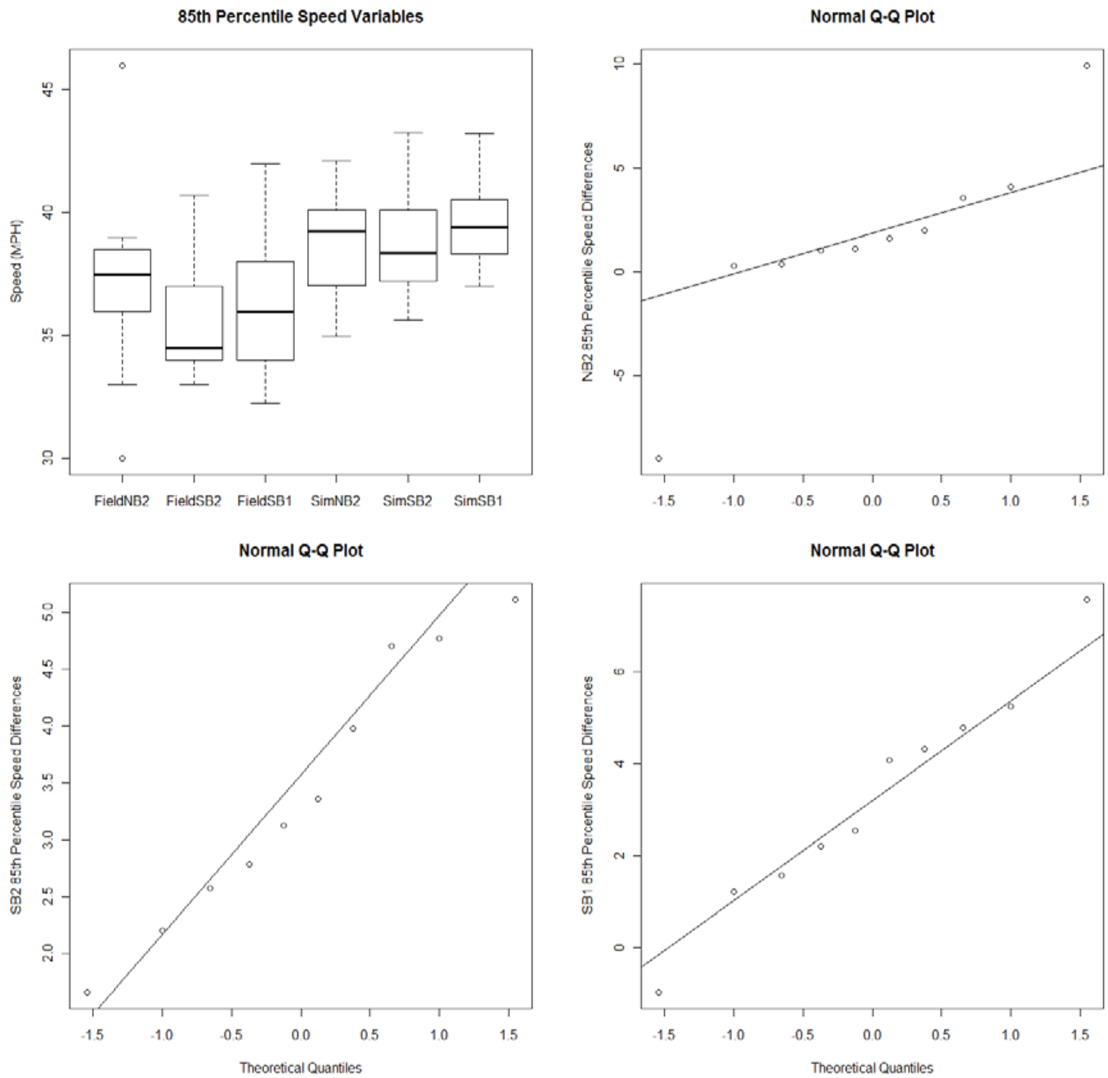

Figure A4. Boxplot and QQ Plots for 85th-Percentile Speed Variables

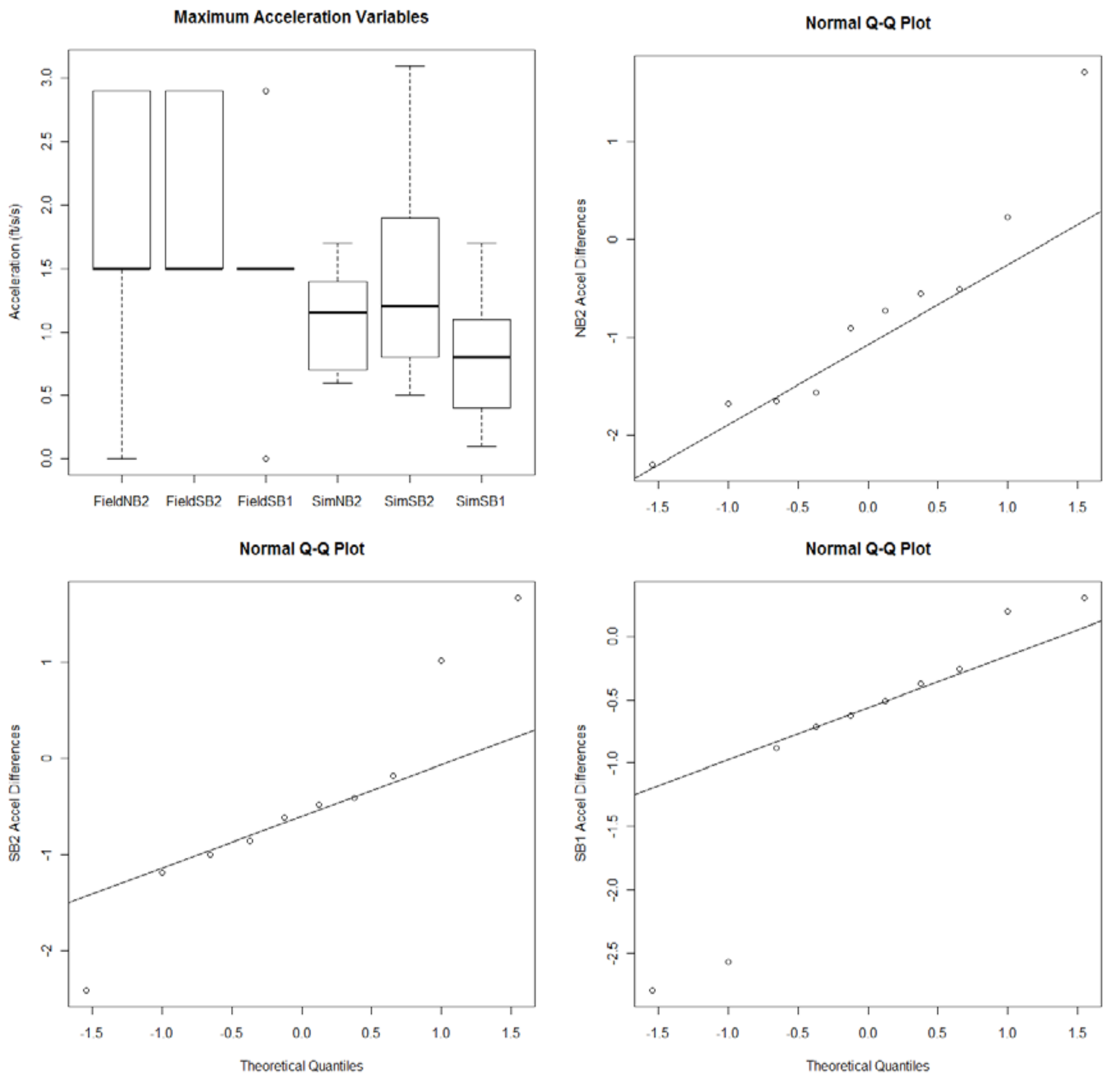

Figure A5. Boxplot and QQ Plots for Maximum Acceleration Variables

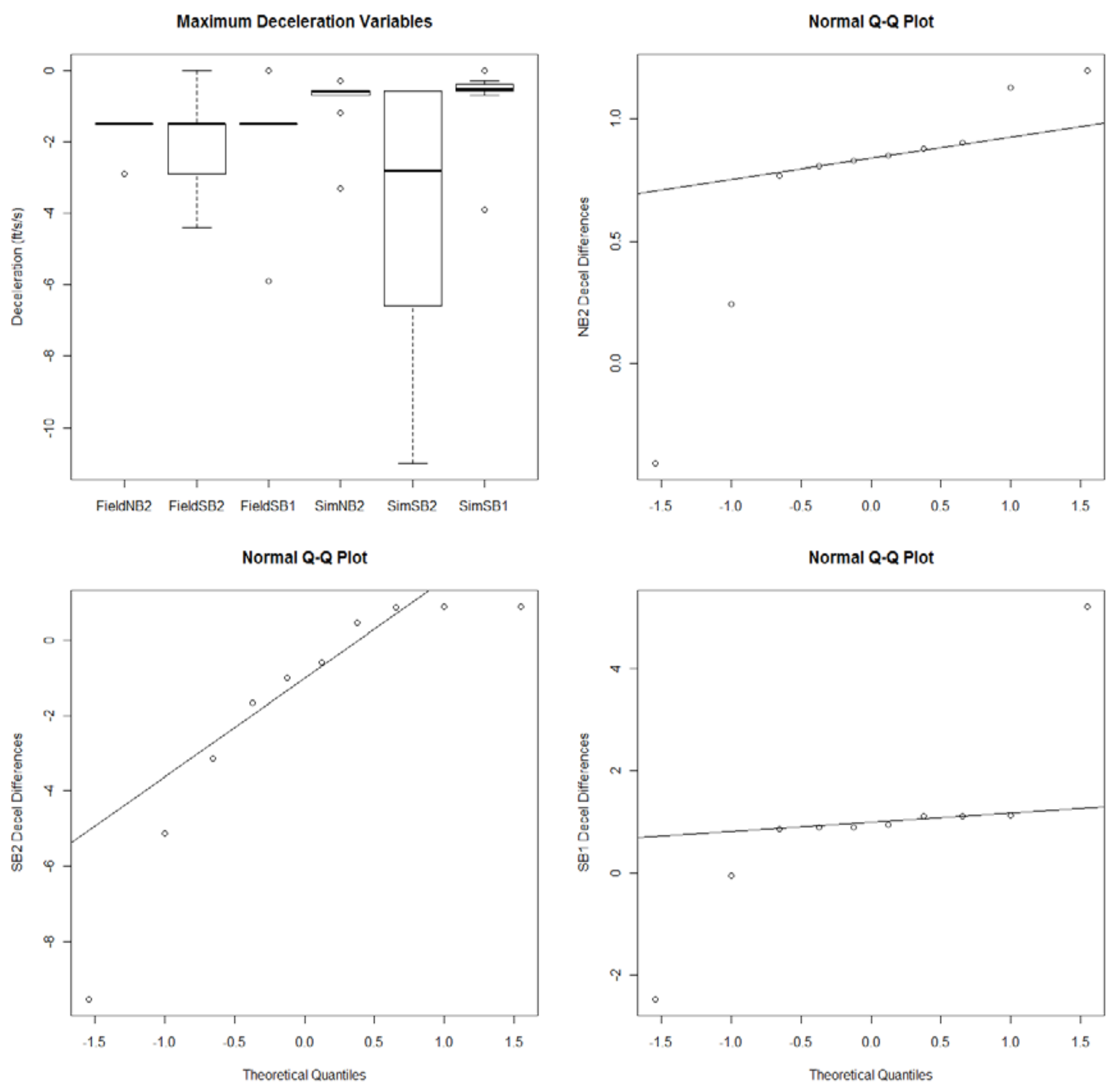

Figure A6. Boxplot and QQ Plots for Maximum Deceleration Variables