Use of Driving Simulators to Investigate Driving Behavior

Ananna Ahmed, MS
University of Nebraska - Lincoln
2200 Vine Street
330 Whittier Research Center
Lincoln, NE 68583-0851
Email: ananna_ahmed@ymail.com

John Sangster, PE, PTOE, Ph.D.
University of Nebraska - Lincoln
2200 Vine Street
330L Whittier Research Center
Lincoln, NE 68583-0851
Ph: (402) 472-0314
Email: john.sangster@unl.edu

A paper prepared for the 5th Urban Streets Symposium

Number of words in text: 5,250
Number of figures and tables: 5 (2,250 equivalent)
Total word count: 7,500

Initial submittal: 15 May 2017

ABSTRACT

Safe and effective driving requires cognitive, perceptual, and motor skills of the driver to function in concert. All stakeholders involved in roadway operations (DOTs, automobile companies, legislatures, etc.) hold safety as a primary concern. However, uncertainty and human factors cause driving to remain a very dangerous task, with the leading cause of death for those between the ages of 15 and 45 being car accidents. Naturalistic driving data provides robust results for investigating driving behavior, but is cost-prohibitive to conduct and cannot provide the level of control necessary to assess correlation and causation regarding changes to the driving environment and their impacts on driver behavior. This paper examines human behavioral factors involved in the task of driving and the efficacy of the state of practice driving simulators in duplicating naturalistic driving behavior.

A number of key questions about the state of practice for driving simulators are investigated in this study. What are the limitations in the use of a driving simulator to evaluate driving behavior, for research and training purposes? What is the breadth of research that has been conducted using driving simulators? Finally, what are the capabilities of some common driving simulators being used today for research? Near-term increases in technology are likely to improve the ability of driving simulators to model real-world conditions, and the use of this safe and cost-effective research tool is likely to increase greatly.

BACKGROUND

The societal norms in the United States and much of the developed world require nearly every adult to own a license and a personal vehicle in order to perform the regular functions of their daily life. The Federal Highway Administration (FHWA) reported in 2014 that there were approximately 214 million licensed drivers in the United States.[1] The driving task itself can be explained as a number of discrete but interrelated activities. In discussing the different activities that make up the driving process, A Policy on Geometric Design of Highways and Streets by the American Associations of State Highway Transportation Officials (AASHTO), commonly referred to as the Green Book, breaks down driving behavior into three parts: control, guidance and navigation, listed in increasing order of complexity for the driver.[2] Control is representative of simple steering and speed control. Guidance incorporates road following, and path following in response to road and traffic conditions. Navigation, the most complex of the three, includes trip planning and route following. Drivers must successfully process control, guidance, and navigation tasks concurrently to ensure safe passage, and this is often where problems arise.

A major cause of risk in driving is due to the necessity to take action based on insufficient information. Consequently, a great deal of focus of officials and researchers is to improve the safety of our surface roadway network through advancements in road surface material and improvements in geometric design and pavement markings. Driving behavior, however, cannot be fully controlled, can only be incentivized, and modified using road design and planning. The multivariate nature of driving behavior makes it challenging to quantify, with a wide variety of stochastic ideas involved, and the fact that it is influenced greatly by the external environment, with distractions from both within and outside of the vehicle. A driver’s behavior is dependent upon the psychological, physiological, social, and economic state of the driver, as well as is a driver’s limitations in perception-reaction in terms of following his or her own standard behavior. To better understand how our designs will affect safety outcomes of drivers on the road, we must be able to assess the discrete behaviors of individual drivers, and how changes to the roadway and vehicle environments impact these behaviors.

Driving behavior as a whole is hard to quantify, and the discrete behaviors that make up driving behavior are not much better. Naturalistic data to study human factors is the best methodology to overcome observation bias, but data collection in this way is prohibitively expensive, and the data itself reveals a vast amount of variability from second to second in an individual driver’s patterns of behavior. In the best cases we are able to define a range of typical behavior centered on an average for any given parameter from naturalistic driving studies. Naturalistic studies provide a large enough dataset to get statistically significant measures on a wide variety of factors that impact safety, but it is prohibitively expensive for use in studying many research questions of importance, and a lower-cost alternative is necessary. Driving simulators present a cost-effective alternative methodology for the study of human factors relating to the driving task. Driving simulators also have the advantage of creating an experimental environment where safety is ensured, and variables can be controlled for at will.[3] Although driving simulators provide a promising cost-effective analysis method for the study of driving behavior, the breadth of what can be studied with them is not well defined, nor are the limitations and complications that arise from their use.

The purpose of this paper is to examine how human factors can be defined and parameterized for a simulator-based study, by compiling the research on relevant aspects of driver behavior studied using driving simulators. The vast majority of literature related to driving simulators only examines an individual parameter of the driving task, and fails to address the broader question of what potential exists for this type of study.

DRIVER BEHAVIOR

The concept of driving behavior can be broken down into several categories, which are of interest to stakeholders in various branches of science, such as medicine, psychology, and engineering.[4] Each of these have separate research questions for which specific portion or complete behavioral quantification of drivers is necessary. The following sections discuss how fundamental driving behavioral categories are further subdivided and how they can be studied using a driving simulator in an applicable manner.

Driving Task: Control

Control of the vehicle while driving requires an extensive amount of continuous information gathering. Environmental information including information about other vehicles, surrounding objects, light-weather-surface condition, etc., plays a role in control. Spatial and temporal information about other vehicles generally takes precedence over other types because it affects road safety directly.[5] Improper control is often a result of inattention and distraction while driving.

In a driving simulation scenario, the effort of drivers to maintain vehicle control is measured in two ways. First, visual behavior is documented using an eye-tracking device to determine how frequently information is being collected by the driver. Secondly, physical control can be documented through the driver’s braking behavior.[6] While driving, where and how frequently the driver is looking have an important influence on the control of the vehicle and can be used as an important parameter to perform comparative studies between experienced and novice drivers.[7] Distraction or additional cognitive workload can be interpreted from these two types of data. Hancock et al. suggested in their study that inattentive and distracted driving have more incidents of hard braking.[8]

Steering Control

Steering control requires more than visual cues, such as auditory or tactile cues while driving on a real road. Visual cues, undoubtedly, are an important part of steering control. However, information that a driver derives by sense of motion, such as those produced by sound and vibration of vehicle operation on road, complement a driver’s steering control to a significant degree.[9] Driving simulators can provide many of the visual cues commonly experienced in real-time driving, but lack the ability to provide binocular cues, known as motion parallax, due to gazing movement of a driver's eye.[10] In addition, fixed based simulators cannot provide motion cues. Although, moving base simulators can provide motion cues, they do not provide all the haptic, kinesthetic and vestibular cues that altogether influence the steering control behavior of a vehicle operator. Some simulators now can provide haptic seat and steering and tactile cue controls but their usefulness is yet to be evaluated.

How to measure steering control in a driving simulator can be approached differently based on the specific research question under investigation. A driver's reaction time to take action on steering is one way of measuring steering control.[11] In experimental design like this, an object that requires a driver's action on steering movement is either suddenly or progressively added to the scenario and reaction time can manually be measured as a time unit, or can be interpreted as a speed-distance function from simulator spatial data output.

Another way of measuring steering control is through steering rotation behavior. In human factors research, this parameter should be able to give a more direct measure of interpreting steering behavior precisely. In this type of design, additional instrumentation of a steering control sensor is necessary to produce a signal of steering angle over time or distance driven.[12] Advanced driving simulators are incorporating this approach in their built-in system. An example output of similar experiment is presented in **Figure 1**, below, from Oliver and Pentland.

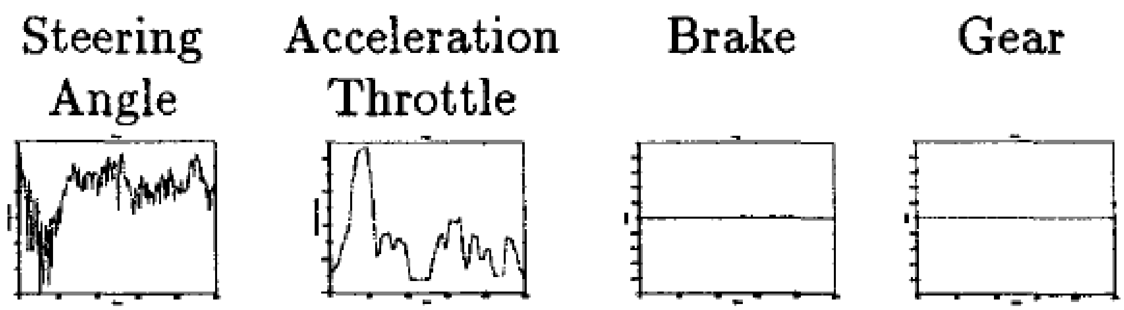

Figure 1 Measuring Steering Angle and Acceleration Throttle by Oliver and Pentland [12]

Speed Control

Over the years, several researchers have done work on speed control behavior of drivers in simulator environment, and questions have been raised about the validity of simulators for duplicating realistic speed behaviors. A number of researchers found that speed in the simulator increased due to lack of perceived danger, but Godley et al. found that, counterintuitively, in simulator versus naturalistic data drivers drove slower in simulator than on an instrumented data collection car.[13] Exact numeric correlation or absolute validity of driving simulators for use with speed studies have been found to be inconclusive. However, driving simulators remain a unique application for experiments which deal with independent variables or contrasts, discounting the importance of physical validity in favor of experimental control, and there are numerous conductions under which simulation would be the best approach to analyze speed control evaluation despite its lack of field validation.[14]

Measuring speed control is relatively straightforward in the context of a driving simulator study. Speed data is typically collected at a frequency of 30 Hz, or twice per second, and can be aggregated for sections of uniformity on a facility to obtain measures of mean speed data.[15] This type of speed data is a part of the basic functionality of all driving simulators, and is a standard data output. Speed study investigations that require data relative to fixed objects can specify data aggregated by time, distance, or location. Examples include the study of speed control behavior near speed limit signs, bridge structures, rumble strips, etc. Having high frequency real-time point data is beneficial for providing a distribution or confidence interval around the location or road sign of concern.

Driving Task: Guidance

Guidance was one of the first human factor based models that attempted to explain why drivers choose take or avoid certain actions.[16] Also, guidance skills have a direct impact on road safety and failure in high severity crashes.[2]

Safe Path Maintenance

Safe path maintenance, also known as lane maintenance or lane keeping, is one of the primary learning objectives of driving instruction. In a dynamic and interactive situation like driving, safe path keeping is not only important for an individual vehicle, but also for the overall network of vehicles. Over the last few years, a large portion of crashes have been caused by failures of lane keeping: involuntary moving to next same direction lane, opposing direction lane, or getting close to lane margins.[17] Assistive automated vehicles have included lane keeping warning or action methods in their basic design for this reason.

In a simulator based environment, an easy way to evaluate lane keeping skill of a driver is to track lateral positioning of the vehicle over time as shown in **Figure 2**, below.[18] For example, one possible scenario could measure the behavior of a participant when driving on a curved road with traffic control cones. Distracted driving experiments could benefit from this method and keep count of the cones hit by the driver and produce count distribution data for further analysis.

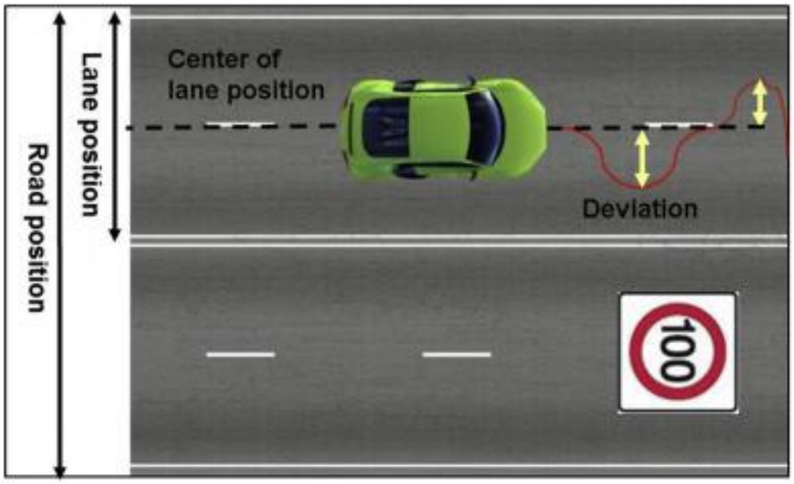

Figure 2 Measure of lane keeping by Azizan et al. [18]

Car-following Behavior

When a vehicle is following another vehicle, the acceleration pattern is the most descriptive way of explaining the driver's behavior, because acceleration is influenced by perception of the driver's relative velocity and the headway between two cars.[19] During an experiment to measure car following behavior in a driving simulator, a participant generally has to drive through several different settings of driving scenarios such as urban streets, rural highways, expressways, etc. and various subdivisions of each of these. The adjustment of speed perception and response to different categories of cues varies significantly based on setting. When a driver is exposed to a scenario, drivers tend to develop an assessment of the traffic environment that impacts how they may need to react in near future.[20] Perception of such assessments regarding surrounding environment and lead car determines a safe headway for the driver. Many studies have found correlation of headway with age, gender and experience of drivers.[21]

Car following behavior is quantified in a simulator setup through the definition of parameters to incorporate in data analysis based on the situation. In most of the simulator studies the common parameters in the study of car following behavior include headway, a driver's action as a measure of the percentage of gas and brake pedal application, and the speeds of lead and car following car, but categorizing which headway is safe is vastly dependent on particular study design.[20] This data is readily available as a standard output from simulator data, and both graphical and tabular data can be generated. In an exclusive car following behavior study, further explanatory parameters can be included like give way to same and opposing direction vehicles, reaction time to existing road traffic, use of directional indicators, etc.[21]

Passing Maneuvers

There are multiple human factors and driver characteristics to be considered in understanding passing maneuvers. Cognitive limitations such as lack of driving experience and cognitive overload play an important role.[22] Personality factors such as risk-taking and extraversion, a term referring to human factors and external events associated with passing that are unknown to the driver, also creates variation in passing behavior.[23] Passing behavior is dominated by a driver's faculty of decision-making, assessment of risk, and their willingness to take risks.

Simulator data has been used in conducting speed studies for passing maneuvers, the development of a classification system for passing maneuvers, and in developing behavioral models for drivers' passing maneuver behavior.[24], [25] Previous studies also established that passing maneuvers are affected by vehicular speed, sight distance, available gap and most importantly, geometric design of the roadway.[25] Collecting detailed data and interpreting them to compare passing maneuvers is complex both for real-time and simulated data. Data collection should provide a sufficient volume of data points to study the trajectories of the passing, passed, and opposing vehicles. Farah et al. suggested a combined output of all the factors mentioned above and made a subjective evaluation about passing behavior, labeling it as careful or not careful.[19] Simulators have been used to collect data about speeds, positions, and acceleration of the subject vehicle and other relevant vehicles were collected over a scale of time to produce analysis of passing maneuvers. **Figure 3**, shown below, from Bar-Gera et al. provides an example of such data collection. Overall, interpreting the output of simulators widely depends on how factors are defined and specified in the initial experimental design.

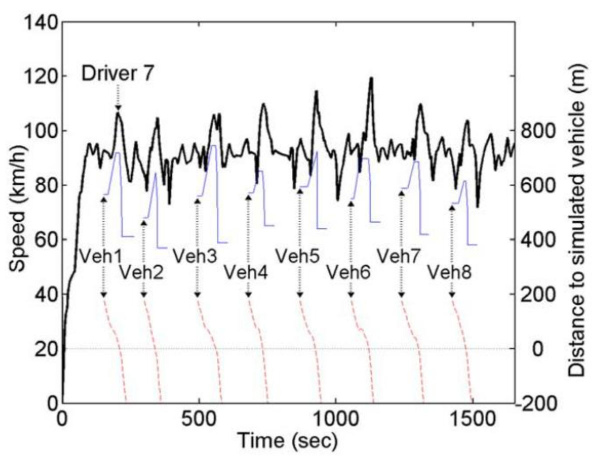

Figure 3 Measuring Speed and Headway over time by Bar-Gera and Shiner [25]

Merging Behavior

Merging sections are some of the most crash prone locations on a roadway. Additionally, merging movements can create bottlenecks and cause significant delay. A driver must decide in a very small window of time when merging on a roadway. The difficulty is compounded by the nature of the conflicting vehicles, which travel at a higher speed than the driver. Failure to make an appropriate decision may have great consequence; hence, studying driver behavior is necessary to ensure and efficient operation of roadway facilities.[26] Merging action requires risk taking, combining observation tasks and action taking with interaction with other vehicles in close proximity.[27] Studies have found inefficient merging behavior to be correlated with age, gender, and visibility factors, and can create a ripple effect on traffic flow by causing speed breakdown, flow oscillation, and consequently, congestion.[28]

In a driving simulator based experiment design, establishing guidelines for safe merging behavior is important. Safe or expected merging behavior can be interpreted using regular output data of before and after speed, movement time, accepted gap time, etc.; in a more elaborate design, desired range of merging movement taper can be added in the simulated scenario.[29] An additional method for comparing merging behavior is measuring vehicle-merging trajectory from current position and speed to merging position.[27]

Lane Changing Behavior

Drivers choose to change lanes using judgement about the surrounding dynamic environment with a need or desire to upgrade their convenience on the road. In some cases, like a roadside emergency or a work zone, drivers are forced to change lanes. Gipps suggested that major contributors to a lane changing decision process are necessity, desirability, and safety.[30] VISSIM, a popular microscopic traffic simulator, classifies lane changes as either a necessary lane change or free lane change.[31] Necessary lane changes are made to reach the next connector of a route, while free lane changes are an outcome of the desire for more space or speed. A driver must be comfortable with both sight distance and width of lanes (both on and off lanes) in order to initiate a lane changing movement.[32]

Lane changing behavior is generally evaluated in two phases. The first phase maneuver is from the moment a driver acts on steering to the attainment of the maximum heading angle. The second phase ends when the wheel angle returns to zero.[33] These phases are illustrated in **Figure 4**, below.

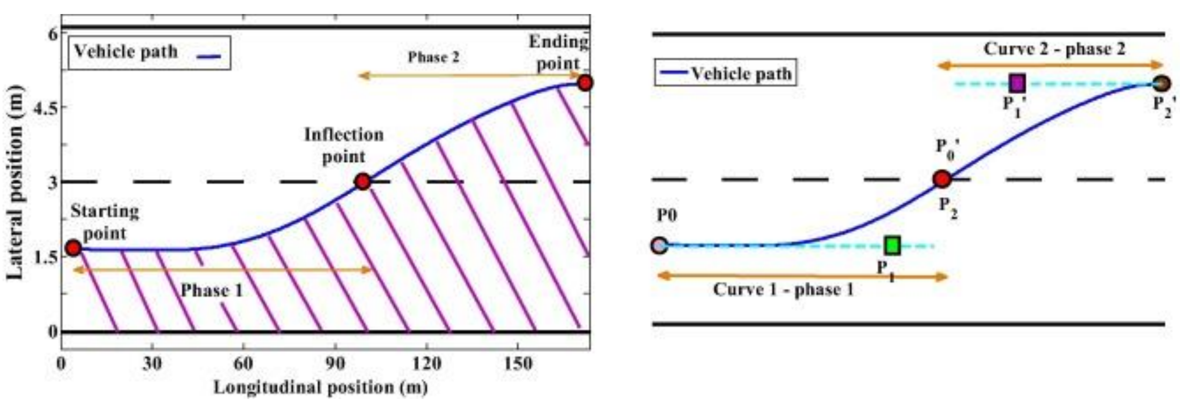

Figure 4 Phase one and two of lane changing by Tehran et al. [33]

In a driving simulator, time stamped data is collected at high frequency that includes the position vector of the vehicle. Along with this, other factors like velocity, steering wheel angle, and acceleration-deceleration data help to define lane-changing behavior in a simulated environment. To make comparisons between drivers, Naseri et al. suggested three parameters. The first parameter is the time interval between realizing a lane change is necessary, (utilizing verbal input from the driver,) to the start of the lane change. This parameter is indicative of the driver's patience. The second parameter is the time headway between the lead car and the experiment car right before the start of the lane changing movement, which indicates driver's caution. The third parameter is the longitudinal and lateral acceleration during the lane-changing maneuver, which is indicative of aggressiveness of the driver.[34]

Response to Traffic Control Devices

The effectiveness of a traffic control device is dependent on a wide variety of factors such as sight distance, illumination, weather conditions, surface condition, location of signage, geometric design, drivers' attitudes towards obeying the traffic control, and drivers' understanding and interpretation of signage. Studies examining how drivers are behaving towards a sign, or the effectiveness of how a sign or type of signs in controlling traffic can be hazardous if real-time experiments are performed. Simulator-based studies can provide opportunity to explore responses to traffic control devices in detail.[35] Traffic signs are of utmost importance, as they are designed to protect vulnerable groups. Even so, every year, hundreds of fatal crashes are caused by failure to obey road signs.[36] In a driving simulator based experiment design, well-thought-out placement of signs and signals must be programmed. Several performance indicators such as average speed, location of first braking/action point while approaching the sign, variance in acceleration, etc., can be correlated to sign following behavior.[35] Typically, if an experiment deals with the effectiveness of signs, a closed loop of simulated driving scenario is developed. An example of such design is provided in **Figure 5**, below.

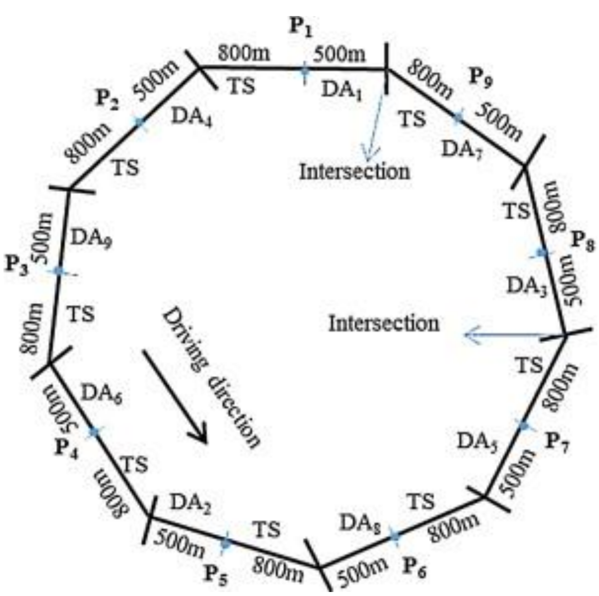

Figure 5 A closed test route example used by Zhao et. al 2015 [35]

Avoidance of Pedestrians

Providing the appropriate right-of-way for pedestrians is a key concern mostly in urban locations. In a signalized intersection with pedestrian lights, pedestrian movements are protected perpendicular to the direction of thru traffic. However, in left and right turn movements, and stop and yield controlled junctions, the driver's attributes play an important role in pedestrian avoidance. Studies have found positive correlation between the age and experience of drivers and number of pedestrian involved occurrences. Passing an intersection has been proven to require a large amount of information processing and cognitive workload, as it demands awareness and avoidance of vulnerable groups like pedestrians of bicyclists.[37] A study by Reynolds proposed studying a particular driver's approach through an analysis of steering behavior when pursuing a target or avoiding an obstacle.[38] Varying pedestrian trajectories in a simulator based environment can be another way analyzing predictive and cooperative behaviors of drivers.[39]

Driving Task: Navigation

Navigation while driving has less of a safety impact than control or guidance, and has more impact on the performance of the facility, with poor navigation causes delay, bottlenecks, and may indirectly lead to crashes.[2] Navigation skills include effective trip planning and route following. Although the impact to cognitive workload due to navigation is relatively low, it is not negligible.

Trip Planning

Studying trip-planning behavior is a complex task, as there is a large amount of variability due to different factors. For example, some drivers choose cost as the primary optimizer of a route, while some drivers choose time. Comfort, purpose of trip, personal driving experience, gender of driver, road type, facility type (number of intersections, distance between entry and exit ramps, etc.,) and cognitive limitations contribute to this decision.[40][41] In addition, dependency on different digital autonomous trip planning tools like GPS adds more complexity in quantifying trip planning behavior.[42]

Collecting data for this type of behavior is observational and subjective in nature. Multiple options of route oriented experimental design may be simpler way of studying this behavior in a simulator. Visual or auditory cues can be provided during or before starting the test run, informing the participant of features of roads that will come up as alternating options, and can be interpreted on a predetermined baseline. Interviewing drivers can be another way of doing this but that involves expertise in survey design in order to obtain fruitful data.[41]

Route Following

Route following or wayfinding involves a high cognitive workload in an unknown roadway. Driving through the route in the same way for several times gives drivers a habituation with the route and reduces load.[43] However, in an unknown situation, cognitive overload is common in route following attempts. Error in taking the correct turn, getting lost, and losing focus from other driving tasks are examples of faulty route following skills.[44]

Driving simulator studies regarding route following design either need external visual or vestibular cues commanding the driver to perform certain actions such as taking the third left or the second exit on a roundabout, mentioning a certain exit number beforehand, etc. More specific design includes the alteration of the driving scenario as done by Srinivasan and Jovanis by adding shapes to the visual interface and asking drivers to identify them while following a pre-directed route. Additionally, other vehicles and pedestrians performed abrupt movement on the display.[45]

DRIVING SIMULATION

The first simulators used in the United States date back to before the WWII, when flight simulators were used for training fighter pilots. The advantages of using a simulator were the same as today: it reduced cost and ensured the pilot's safety.[46] The crisis was similar as well about validity. A number of theories had been developed justifying that training skills on a simulator were transferable, and that the outcome was representative, but definitive validity remains elusive.[47] The first driving simulator to be used in highway safety research happened in the 1960s, but the visual technology at that time was far different than reality.[48] Today, through the power of computing and electronic displays, the validity of driving simulators in studying human behavior has significantly improved and they are now used routinely in conducting research.[46] Very recently, work to validate the use of simulators in speed and gap acceptance studies, CMF development and other different planning tools has been occurring.

Simulator Sickness

Simulator sickness is a concern for simulator based research studies. Drivers are subjected to motion sickness due to the gap between real response and a simulated response of driving activities. In a minority of cases, drivers report headache, dry mouth, dizziness, and disorientation among their symptoms.[49] A post-experiment driver questionnaire is the most common method for collecting data about simulator sickness, and is standard practice.[50] Many studies have overcome simulator sickness by means of the advancement of simulation technology, but the key mitigation for participants is a practice run in the simulator that is not used for research results. A practice run time as low as 10 min and as high as 40 min is reported in literature.[51] However, experiment design should be as such that it could eliminate the results of drivers significantly prone to simulator sickness. Georgia Tech has prepared a simulator sickness protocol, which walks through researchers in detail through the causes and solutions regarding simulator sickness.[51]

STATE OF THE PRACTICE EQUIPMENT

Four sample driving simulators were chosen from the literature review based on their applicability in different branches of study (psychology, medicine, engineering, etc.) Simulators reviewed represent the current state of the practice in driving simulator research, and include the Virage simulator model VS300/VS500, the STISIM Drive, the Realtime Technologies Simulator, and the NADS MiniSim. The basis of comparison herein includes, but is not limited to, the capacity and features of each simulators, what type of questions each is best able to answer and their limitations as a research tool.

Virage Simulator Model VS300 and VS500

Virage VS300/VS500 is a quarter of a car based driving simulator with actual car components to provide a realistic feel of vehicle controls.[52] It is a fully immersive, portable driving simulator. The primary focus group for this simulator is drivers in training. Scenario development or customization is not as open to users as other simulators, but Virage provides additional support in order to develop customized scenarios. This simulator has a motion/vibration system. Both automatic and manual transmissions are available. The steering wheel is connected to an electrical load system that allows drivers to sense and feel surface friction of the road on steering during turning maneuvers. In addition, the motion/vibration system is capable of providing acceleration cues, engine vibration, and road texture feedback based on acting speed. Vibration sensitivity is attained by a compact three-axis platform with electric actuators. This simulator provides an 180˚ view with three monitors resolving a problem in visual discontinuity experienced in earlier models. The VS300 and VS500 differ in the sound system, which controls audio cues. The VS300 has frontal sound system whereas the VS500 provides surround sound. Both of these are included with a multifunction display that works as a control to set up scenarios and the driving environment. The VS500 has two additional screens in the location of blind spots on both sides to provide more realistic feel of driving.

Virage has been in the market since 2005. In 2011,the Federation of Canadian Municipalities presented a study in a sustainability conference emphasizing the importance of eco-drive training using Virage Simulators.[53] The University of Sunderland performed a study in 2012 on the role of driving simulators for training drivers and their contribution to fuel economy.[54] Virage itself is performing research. In 2016 Virage Simulation published an article on the benefits of driving simulator training and using their simulator for data collection.[55]

STISIM Drive

STISIM Drive was initially introduced for clinical and pharmaceutical research to study the effect of medication or fatigue, and eventually expanded to include highway safety aspects.[56] This simulator was developed over a course of 30 years and validated for different medical aspects, cognitive processes, and human factors evaluation. STISIM software has 140 built-in driving scenarios, and custom scenarios can be created. Significant performance measures of this simulator include crash counts, speeding behavior, reaction time, lane maintenance, driver compliance with traffic signals and signs, etc. Scenario Definition Language (SDL) is a programmable tool incorporated with the software to customize output according to needs of the research. The maximum field view varies from 60˚ to 135˚. The visual interface is interactive in terms of signal changes and conflicting vehicles. Both manual and automatic gear shifting are available with this simulator. The seat is adjustable. The lower end model has one display monitor and advanced models have three monitors. A motion sensor is not included with any of the packages. This simulator has sufficient tools for off-road training purposes.

In literature, the use of STISIM Drive exists from 2001 to 2017. In 2001, German researchers used this simulator for monitoring driver drowsiness and stress level.[57] A study from

2003 in Australia performed research on the inflated risk associated with older drivers in vehicle crashes.[58] In the Netherlands in 2011, the effect of alcohol impairment on highway driving was studied using STISIM Drive.[59] Very recently, the department of psychology of Macquarie University, Australia used this simulator to study the effects of anti-speeding advertisements on young drivers.[60] It is evident in the literature that this simulator is widely accepted in European and Australian research institutes and has displayed sufficient fidelity to evaluate human factors and generalized driving behavior under different circumstances. The capacity of this software to produce customized driving scenarios was not found in the literature.

Realtime Technologies Inc. (RTI) Simulator

The RTI simulator is also a fixed-base simulator. The greatest benefit of this simulator is the options for customizing animation and vehicular setup.[61] RTI's modular scalable interface design offers addition and subtraction of components as well as the creation of new driving scenarios from scratch. SimVista is RTI's scene and scenario control subsystem that allows the modification of scenarios in terms of weather condition, pedestrian volume, vehicle density on the road, etc. In addition, depth of view, color palette, and overall visual complexity are customizable according to scale. There is an emphasis on quality of graphics (60 Hz update rate) to ensure fully immersive experience for research participants. Assignment of behavior of pedestrian and conflicting vehicles can be done in this simulator. The physical set up options vary from half car to full SUV, with cost varying accordingly. Typically, an 180˚ front view is provided. No specification about the placement of rearview and side view mirrors was mentioned in the product details. Power steering is connected to vehicle dynamics that give the feel of turning movements, curves, and tire alignment. This simulator is motion-compatible with six degrees of freedom available for the low profile setup or three degrees of freedom supported by a motion base. This simulator is reported to provide fast and smooth motion cueing. A built-in audio system provides engine, transmission, and wind and tire noise.

NADS MiniSim Driving Simulator

National Advanced Driving Simulator (NADS) of the University of Iowa has three types of simulators: NADS-1, NADS-2 and NADS-miniSim.[62] The price and features of these three simulators are in the descending order of names mentioned. MiniSim was developed for research in the transportation field, clinical applications, and training purposes. Minisim seeks to transfer major features inherited from NADS-1, but at a lower cost. Like other simulators, this one also provides the facility to tailor according the needs of the research in terms of hardware and software. Variable set-up options range from a single monitor set up, to an actual vehicle. It has surround sound and a touch-screen operator console. Additional displays, a floor mounted gear selector, and an entertainment panel can be added to the package.

The visual features of MiniSim are similar to the NADS-1 and 2, as are the built-in driving scenarios. Driving environments include urban, sub-urban, rural- and interstate-highway areas. Traffic control devices such as signals and road signage are in compliance with current specifications from the Manual on Uniform Traffic Control Devices (MUTCD).[63] Different vehicle types and weather conditions are also available. Scenarios can be customized using a tool called Interactive Scenario Authoring Tool (ISAT) and all dynamic elements are editable.

A wide range of research has been performed using the MiniSim driving simulator as a tool. Starting from the addition of advanced safety features like haptic seat or tactile alert systems, to driving under the influence, to general driving behavior and drivers' attention studies, many studies were performed using this simulator. [64]–[67]

CONCLUSIONS AND RECOMMENDATIONS

The literature suggests that studying driving behavior has relative validation, but still lacks in providing tactile and vestibular cues. Simulator sickness is also a confounding factor in determining a true representation of driving behavior. Overall, use of driving simulators in driver behavior studies is cost-effective and safe, which has led to the increase in the use of driving simulators in transportation engineering, psychology, medicine, and other fields. Crash and safety studies are currently one of the weakest areas of simulator based study. However, researchers are increasingly finding it to be an appropriate training tool, which with current developments, it is expected to be a valid and applicable planning tool soon. In medical sciences, the evaluation of driving performance after drug use, or during cognitive function decaying diseases like Alzheimer's or Parkinson's disease, a driving simulator is a trusted tool. Age, gender, geographic bias-based psychological studies have been proven to be valid using a driving simulator. Near-term increases in technology are likely to improve the ability of driving simulators to model real-world conditions, and the use of this safe and cost-effective research tool is likely to increase greatly.

REFERENCES

[1] "Federal Highway Administration Table DL-22 (Highway Statistics 2014)," 2015. [Online]. Available: https://www.fhwa.dot.gov/policyinformation/statistics/2014/dl22.cfm. [Accessed: 01-Jan-2017].

[2] *A Policy on Geometric Design of Highways and Streets*. Washington D.C.: American Association of State Highway and Transportation Officials, 2011.

[3] D. Davenne, R. Lericollais, P. Sagaspe, J. Taillard, A. Gauthier, S. Espi??, and P. Philip, "Reliability of simulator driving tool for evaluation of sleepiness, fatigue and driving performance," *Accid. Anal. Prev.*, vol. 45, pp. 677–682, 2012.

[4] D. L. Fisher, M. Rizzo, J. K. Caird, and J. D. Lee, *Handbook of Driving Simulation for Engineering, Medicine and Psychology*. Taylor & Francis, 2011.

[5] J. Suh, K. Yi, J. Jung, K. Lee, H. Chong, and B. Ko, "Design and evaluation of a model predictive vehicle control algorithm for automated driving using a vehicle traffic simulator," *Control Eng. Pract.*, vol. 51, pp. 92–107, 2016.

[6] J. L. Harbluk and Y. I. Noy, "The Impact of Cognitive Distraction on Driver Visual Behaviour and Vehicle Control," 2002.

[7] R. R. Mourant and T. H. Rockwell, "Strategies of Visual Search by Novice and Experienced Drivers," *Hum. Factors*, vol. 14, no. 4, pp. 325–335, 1972.

[8] P. A. Hancock, L. Simmons, L. Hashemi, H. Howarth, and T. Ranney, "Reply to Comments on 'The Effects of In-Vehicle Distraction on Driver Response During a Crucial Driving Maneuver,'" *Transp. Hum. Factors*, vol. 1, no. 4, pp. 295–309, 1999.

[9] A. Kemeny and F. Panerai, "Evaluating perception in driving next term simulation experiments," *Trends Cogn. Sci.*, vol. 7, no. 1, pp. 31–37, 2003.

[10] G. Underwood, D. Crundall, and P. Chapman, "Driving simulator validation with hazard perception," *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 14, no. 6, pp. 435–446, 2011.

[11] W. W. Wierwille, J. G. Casali, and B. S. Repa, "Driver steering reaction time to abrupt-onset crosswinds, as measured in a moving-base driving simulator.," *Hum. Factors*, vol. 25, no. 1, pp. 103–116, 1983.

[12] N. Oliver and A. Pentland P, "Graphical models for driver behavior recognition in a smartcar," in *IEEE Intelligent vehicles Symposium*, 2000, pp. 7–12.

[13] S. GODLEY, B. FILDES, T. TRIGGS, and L. Brown, "PERCEPTUAL COUNTERMEASURES: EXPERIMENTAL RESEARCH," 1999.

[14] J. Törnros, "Driving behavior in a real and a simulated road tunnel - a validation study," *Accid. Anal. Prev.*, vol. 30, no. 4, pp. 497–503, 1998.

[15] S. T. Godley, T. J. Triggs, and B. N. Fildes, "Driving simulator validation for speed research," 2002.

[16] B. Cahlon, "Safe solution of a car-following problem," *J. Math. Anal. Appl.*, vol. 81, no. 1, pp. 134–155, 1981.

[17] J. Lee, J. Choi, K. Yi, M. Shin, and B. Ko, "Lane-keeping assistance control algorithm using differential braking to prevent unintended lane departures," *Control Eng. Pract.*, vol. 23, no. 1, pp. 1–13, 2014.

[18] A. Azizan, M. Fard, M. F. Azari, and R. Jazar, "Effects of vibration on occupant driving performance under simulated driving conditions," *Appl. Ergon.*, vol. 60, pp. 348–355,

2017.
[19] H. Farah, E. Yechiam, S. Bekhor, T. Toledo, and A. Polus, “Association of risk proneness in overtaking maneuvers with impaired decision making,” *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 11, no. 5, pp. 313–323, 2008.
[20] E. Muhrer and M. Vollrath, “Expectations while car following-The consequences for driving behaviour in a simulated driving task,” *Accid. Anal. Prev.*, vol. 42, no. 6, pp. 2158–2164, 2010.
[21] F. P. da Silva, J. A. Santos, and A. Meireles, “Road Accident: Driver Behaviour, Learning and Driving Task,” *Procedia - Soc. Behav. Sci.*, vol. 162, no. Panam, pp. 300–309, 2014.
[22] B. Bragg and P. Finn, “YOUNG DRIVER RISK-TAKING RESEARCH: TECHNICAL REPORT OF EXPERIMENTAL STUDY,” 1982.
[23] M. A. Recarte and L. M. Nunes, “Mental workload while driving: effects on visual search, discrimination, and decision making.,” *J. Exp. Psychol. Appl.*, vol. 9, no. 2, pp. 119–37, 2003.
[24] J. M. Jenkins and L. R. Rilett, “Application of distributed traffic simulation for passing behavior study,” in *Transportation Research Record*, 2004, no. 1899, pp. 11–18.
[25] H. Bar-Gera and D. Shinar, “The tendency of drivers to pass other vehicles,” *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 8, no. 6, pp. 429–439, 2005.
[26] M. Yanagihara, N. Uno, and T. Nakamura, “Latent Class Analysis for Driving Behavior on Merging Section,” *Transp. Res. Procedia*, vol. 6, pp. 259–271, 2015.
[27] I. A. Ntousakis, I. K. Nikolos, and M. Papageorgiou, “Optimal vehicle trajectory planning in the context of cooperative merging on highways,” *Transp. Res. Part C Emerg. Technol.*, vol. 71, pp. 464–488, 2016.
[28] J. A. Davis, S. R. Farrah, and A. C. Wilkie, “Selective growth of Staphylococcus aureus from flushed dairy manure wastewater using acriflavine-supplemented mannitol salt agar,” *Lett. Appl. Microbiol.*, vol. 42, no. 6, pp. 606–611, 2006.
[29] L. Domenichini, F. La Torre, V. Branzi, and A. Nocentini, “Speed behaviour in work zone crossovers. A driving simulator study,” *Accid. Anal. Prev.*, vol. 98, pp. 10–24, 2017.
[30] P. G. Gipps, “A MODEL FOR THE STRUCTURE OF LANE-CHANGING DECISIONS,” *Transp. Res. Part B Methodol.*, pp. 403–414, 1986.
[31] PTV, “VISSIM 5.30-05 User Manual,” 2011.
[32] P. Green, B. Lin, and T. Bagian, “Driver workload as a function of road geometry: A pilot experiment,” *Ann Arbor*, vol. 1001, no. 48, p. 109, 1994.
[33] D. Sadeghi Tehran, A. Nahvi, M. Hajirasouli, H. Naseri, K. Lotfi, and M. Niknejad, “Effects of stimulant and opiate drugs on driver behavior during lane change in a driving simulator,” *Travel Behav. Soc.*, vol. 4, pp. 69–78, 2016.
[34] H. Naseri, A. Nahvi, and F. Salimi Naneh Karan, “A new psychological methodology for modeling real-time car following maneuvers,” Hong Kong Society for Transportation Studies, 2015.
[35] X. Zhao, J. Li, H. Ding, G. Zhang, and J. Rong, “A generic approach for examining the effectiveness of traffic control devices in school zones,” *Accid. Anal. Prev.*, vol. 82, pp. 134–142, 2015.
[36] F. Baratian-Ghorghi and H. Zhou, “Traffic control devices for deterring wrong-way driving: historical evolution and current practice,” *J. Traffic Transp. Eng. (English Ed.*, pp. 1–10, 2017.
[37] R. Matsumi, P. Raksincharoensak, and M. Nagai, *Autonomous braking control system for*

pedestrian collision avoidance by using potential field, vol. 7, no. PART 1. IFAC, 2013.
[38] C. W. Reynolds, "Steering behaviors for autonomous characters," *Game Dev. Conf.*, pp. 763–782, 1999.
[39] J. Buisson, S. Galland, N. Gaud, M. Gonçalves, and A. Koukam, "Real-time collision avoidance for pedestrian and bicyclist simulation: A smooth and predictive approach," *Procedia Comput. Sci.*, vol. 19, pp. 815–820, 2013.
[40] M. A. Abdel-Aty, R. Kitamura, and P. P. Jovanis, "Using stated preference data for studying the effect of advanced traffic information on drivers' route choice," *Transp. Res. Part C Emerg. Technol.*, vol. 5, no. 1, pp. 39–50, 1997.
[41] R. P. Payyanadan, M. Gibson, E. K. Chiou, M. Ghazizadeh, and J. D. Lee, "Contextual design for driving: Developing a trip-planning tool for older adults," *Transp. Res. Part F Traffic Psychol. Behav.*, 2016.
[42] T. Liebig, N. Piatkowski, C. Bockermann, and K. Morik, "Dynamic route planning with real-time traffic predictions," *Inf. Syst.*, vol. 64, pp. 258–265, 2015.
[43] R. R. Mourant, T. H. Rockwell, and N. J. Rackoff, "Driver's eye movements and visual workload," *Highw. Res. Rec. Drivers Driv.*, vol. 292, pp. 1–10, 1969.
[44] E. Y. Uc, M. Rizzo, S. W. Anderson, Q. Shi, and J. D. Dawson, "Driver route-following and safety errors in early Alzheimer disease," *Neurology*, vol. 63, no. 5, pp. 832–837, 2004.
[45] R. Srinivasan and P. P. Jovanis, "Effect of selected in-vehicle route guidance systems on driver reaction times.," *Hum. Factors*, vol. 39, no. 2, pp. 200–15, 1997.
[46] E. Blana, "a Survey of Driving Research Simulators Around the World," *Inst. Transp. Stud. Univ. Leeds, Work. Pap. 481*, vol. 110, pp. 115–122, 2009.
[47] G. D. Logan, "Toward an instance theory of automatization.," *Psychol. Rev.*, vol. 95, no. 4, pp. 492–527, 1988.
[48] K. M. Roberts, "FHWA HIGHWAY DRIVING SIMULATOR," *Fed. Highw. Adm. (public roads)*, vol. 44(3), 1980.
[49] J. O. Brooks, R. R. Goodenough, M. C. Crisler, N. D. Klein, R. L. Alley, B. L. Koon, W. C. Logan, J. H. Ogle, R. A. Tyrrell, and R. F. Wills, "Simulator sickness during driving simulation studies," *Accid. Anal. Prev.*, vol. 42, no. 3, pp. 788–796, 2010.
[50] J. E. Domeyer, N. D. Cassavaugh, and R. W. Backs, "The use of adaptation to reduce simulator sickness in driving assessment and research," *Accid. Anal. Prev.*, vol. 53, no. April 2013, pp. 127–132, 2013.
[51] T. M. Gable and B. N. Walker, "Georgia Tech Simulator Sickness Screening Protocol: GTSSSP Tech Report-v4-BNW," 2013.
[52] "SIMULATORS AND SIMULATION-BASED SOLUTIONS FOR DRIVER TRANING, EVALUATION, RESEARCH AND REHABILITATION," *Virage Simulation Web Page*. [Online]. Available: http://viragesimulation.com/.
[53] M. Rimini-doering, D. Manstetten, T. Altmueller, U. Ladstaetter, M. Mahler, and R. B. Gmbh, "Monitoring driver drowsiness and stress in a driving simulator," in *Proceedings of First Internation Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*, 2001, pp. 58–63.
[54] V. BC and P. Hirsch, "Driving Simulator-based Ecodrive Training," *Sustain. Communities Conf. Trade Show*, 2011.
[55] P. Hirsch and R. Quimper, "EVIDENCE OF MULTIPLE BENEFITS FROM DRIVING SIMULATOR TRAINING," *Virage Simul. Artic.*, 2016.

[56] "STISIM Drive(R)-DT Software," *STISIM Drive*. [Online]. Available: http://stisimdrive.com/driver-training/stisim-drive-dt-software/.

[57] M. Rimini-Doering, D. Manstetten, T. Altmueller, U. Ladstaetter, and M. Mahler, "Monitoring Driver Drowsiness and Stress in a Driving Simulator," *Proc. Int. Driv. Symp. Hum. Factors Driv. Assessment, Train. Veh. Des. Aspen, Color. August 14-17, 2001*, 2001.

[58] H. C. Lee, A. H. Lee, D. Cameron, and C. Li-tsang, "Using a driving simulator to identify older drivers at inflated risk of motor vehicle crashes," vol. 34, pp. 453–459, 2003.

[59] M. A. J. Mets, E. Kuipers, L. M. De Senerpont Domis, M. Leenders, B. Olivier, and J. C. Verster, "Effects of alcohol on highway driving in the STISIM driving simulator," *Hum. Psychopharmacol.*, vol. 26, no. 6, pp. 434–439, 2011.

[60] B. R. C. Plant, J. D. Irwin, and E. Chekaluk, "The effects of anti-speeding advertisements on the simulated driving behaviour of young drivers," *Accid. Anal. Prev.*, vol. 100, pp. 65–74, 2017.

[61] "On-Road Simulators," *Realtime Technologies Inc.* [Online]. Available: http://www.simcreator.com/simulators/onroadsim.htm.

[62] NADS, "The Power of World's most Advanced Driving Simulator," *University of IOWA*. [Online]. Available: http://www.nads-sc.uiowa.edu/minisim/.

[63] FHWA, "The Manual on Uniform Traffic Control Devices (MUTCD)," 2009.

[64] A. Telpaz, B. Rhindress, I. Zelman, and O. Tsimhoni, "Haptic Seat for Automated Driving : Preparing the Driver to Take Control Effectively," in *Proceedings of the 7th International Conference on Automotive User Interfaces and Interactive Vehicular Applications*, 2015, pp. 23–30.

[65] J. L. Harbluk, P. C. Burns, S. Hernandez, J. Tam, and V. Glazduri, "Detection response tasks: Using remote, headmounted and tactile signals to assess cognitive demand while driving," in *Proceedings of the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*, 2013, pp. 78–84.

[66] G. Kay, O. Ahmad, T. Brown, and A. Veit, "Comparison of the MiniSim and STISIM Driving Simulators for the Detection of Impairment: An Alcohol Validation Study," in *PROCEEDINGS of the Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design*, 2013, pp. 191–197.

[67] Y. Peng, L. Boyle, M. Ghazizadeh, and J. Lee, "Factors affecting glance behavior when interacting with in-vehicle devices: Implications from a simulator study," in *The Seventh International Driving Symposium on Human Factors in Driver Assessment, Training, and Vehicle Design 474*, 2013, pp. 474–480.