Simulators for Driving Safety Study – A Literature Review

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Abstract. Driving simulator is an important facility for driving safety study. This paper introduced three well-know large-scale moving-base driving simulators and two fixed-base simulators. Driving simulator has a broad range of applications of driving safety study, from driver's behavior study to vehicle device and technology study, the paper reviewed seven main research aspects including behavior study, driver education and training, transportation infrastructure, medicine and therapy, ergonomics, Intelligent Transportation System, and administrative method.

Keywords: Driving simulator; Driving safety; Moving-base; Fixed-base.

1 Introduction

Automobile driving simulator is a rather new application of computer technology compared to the flight simulator used in aerospace industry for almost fifty years. As the performance of computers has greatly improved, coupled with a drastic decrease in cost, it has made it possible for automotive industry to develop useful simulators of ground vehicles at a reasonable cost, relying instead on the use of actual vehicles for testing and development. In the early 1980s, the full-scale driving simulators developed by Daimler-Benz and the Swedish National Road and Transportation Research Institute (VTI) were of the most well-known in the world [1]. During the next 10 years, leading automobile manufacturers and research institutes like General Motors (GM), Ford, Mazda began to develop their own simulators one after another. At the end of 1993, National Highway Traffic Safety Administration (NHTSA, USA) developed the National Advanced Driving Simulator (NADS) in the University of Iowa, which cost more than 10 million dollars and was well-known as the largest simulator in the world. Today's driving simulators vary greatly for different applications, ranging from low-level inexpensive desktop-mounted systems with single-monitor display, to high-level expensive installations capable of replicating large amplitude driving motions with a moving base and detailed virtual driving environments[2].

The driving simulator has a broad range of applications from driver's behavior study to vehicle device technology study. Because it provides an environment that is both safe and replicable, driving simulator is ideal for driving safety study and driver

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training. The simulator can safely measure driver reaction to unsafe and even life-threatening situations [3]. Dutta et al. used a mid-level driving simulator to evaluate and optimize factors affecting understandability of various message signs [4]. Liu and Wen investigated the effects of two different display modes (head-up display (HUD) vs. head-down display (HDD)) on the driving performance and psychological workload ratings of drivers operating commercial vehicles in Taiwan [5]. Desktop driving simulators have also been used to investigate the situation awareness and workload in driving while using adaptive cruise control and cellular phones. By using driving simulators instead of driving on real roads, these studies eliminated the danger of accidents due to wrong operations or cellular phone distraction [2]. In addition, training of new drivers on a simulator eliminates the danger of wrong operations and allows the drivers to experience some designed dangerous situations. Simulators can be also used in carefully controlled experimental studies, in which the experimental variables are isolated from other factors that might influence driver performance [3]. For example, driving simulation is a useful way to evaluate road sign design. By measuring subjects' performance, one can quantitatively tell which design of road signs has the highest satisfaction and the best recognition and reaction of the testing drivers [6] [7].

The use of driving simulation for driving safety study is increasing with the reduction of simulator cost and the improvement of hardware/software technology. Software advances make it possible for researchers to design specific testing situations in a virtual environment. Nowadays, worldwide universities, research institutes and authorized organizations are using simulators in driving safety studies, just as NHTSA, VTI, University of Michigan Transportation Research Institute (UMTRI), University of Iowa, Monash University Accident Research Center (MUARC, Australia), and Institute for Transportation Studies in University of Leeds (UK). This paper will introduce several well-known large-scale simulators and other mid-level simulators, then review the use of simulators in driving safety studies.

2 Well-Known Simulators

Driving simulators are diversified from simple desktop fix-based one that costs only thousands dollars to large-scale moving-based one that costs up to millions of dollars. However, all of them can be well used for different purposes if technical parameters are well controlled.

2.1 NADS at the University of Iowa (USA) [8]

The National Advanced Driving Simulator (NADS) is the most sophisticated research driving simulator in the world. Developed by the NHTSA, and located at the University of Iowa's Oakdale Research Park, the NADS offers high-fidelity, real-time driving simulation. It consists of a large dome in which entire cars and the cabs of trucks and buses can be mounted. The vehicle cabs are equipped electronically and mechanically using instrumentation specific to their make and model. At the same time, the motion system, on which the dome is mounted, will provide 400 square meters of horizontal and longitudinal travel and nearly 360 degrees of rotation in either direction. The effect will be that the driver will feel acceleration, braking and steering cues as if he or she were actually driving a real car, truck or bus. Fig. 1 shows the configuration of the NADS.

Fig. 1. The NADS at University of Iowa

As a national leading simulator, the NADS was charged with many kinds of research projects and contributed a lot of valuable publications. They are focused on five research areas: a) driver distraction relating to wireless voice communication devices; b) driver behavior including young driver risk, driver validation and driver reaction to thread separation scenarios; c) drugs and driver impairment including vision validation test and pharmaceutical project; d) advanced vehicle system including electronic stability control, evaluating lane change collisions, safety vehicles using adaptive interface technology, agricultural virtual proving ground, and Crash Avoidance Metrics Partnership (CAMP); f) advanced simulation including visual database development, advanced simulator research consulting, and software support.

2.2 Simulator III at VTI (Sweden) [9]

Simulator III at the VTI was introduced in April 2004, after several years of intensive development work. Simulator III is built around a real vehicle chassis and a sophisticated motion system, which enables fast acceleration. The surroundings are simulated and displayed to the driver via three main screens and three rear view mirrors. Under the chassis is a vibration table to simulate contact with the road surface, providing a more realistic driving experience. The driving dynamics are also very advanced and on the forefront of what can be done with current technology. Together this creates a unique simulator that provides an extremely realistic experience. Because of the modular construction, the various subsystems can be adapted to suit the needs of each individual research project. The driving simulator can be fully adapted for private cars and trucks by means of a chassis interchange system. In the future, it will also be possible to use it to simulate rail traffic.

Fig. 2. Simulator III at the VTI, left-side is the appearance of simulator outside the dome, mid-side is the system control center, right-side is the view inside dome

The application of Simulator III was broad from studies concerning driver behavior, the human-machine interface and the effects of tiredness and drugs to projects concerning environmental issues, road and landscape design, tunnel design, the reactions of the body, drivers with reduced functionality and new subsystems in vehicles. The effects of noise and vibrations on driver performance are examples of other areas that may be studied using the simulator. One exciting area is how the new technology influences driving, for example the use of mobile telephones. VTI has performed this type of test in the simulator, which would have been impossible in a real traffic environment for safety reasons. Recently, the simulator has also been used for the planning of the Northern and Southern Link Roads in Stockholm, for example, in order to determine the positioning of road signs and for reasons of aesthetic design.

2.3 Other Moving-Base Simulators

Except the large-scale simulators with extendable motion area as NADS and VTI, most of other moving-base simulators were not so expensive and area consuming, although they are still much more costly and complex compared with fixed-base simulators. Many research institutes developed such kind of simulators, for example, Institute of Industrial Science in the University of Tokyo, driving simulator in VIVW at Würzburg University in Germany, National Institute of Advanced Industrial Science and Technology (Japan), and DaimlerChrysler Research Center. Fig. 3 is the simulator developed at the University of Tokyo. It was developed for human, vehicle and traffic research. It is equipped with a 360-degree omni-directional image generation system, 6 DOF motion platform with turn table and flexible layout cabin. A macroscopic and microscopic traffic simulation system is embedded into the driving simulator. That is called KAKUMO. KAKUMO can generate virtual traffic in the simulator scenario in real time, with up to 100 surrounding vehicles created and controlled independently [10].

2.4 Fixed-Base Simulators

Though fixed-base simulator is not as fabulous as the advanced moving-base one, its low cost and convenience makes it more popular in driving related research and training. In recent years, traffic safety issues got more and more attention both in academic area and administrative organizations, consequently, a great deal of universities and institutes purchased or developed driving simulators. However, due to limited resources, most of researchers could not afford such sophisticated moving-base one, then, fixed-base simulators become the better choice. On the other hand, despite continuous improvement in driving simulation techniques and equipment capabilities over the years, subjects in a driving simulator still interact with a simplified environment and perceive less as compared to real-world driving [8]. That is to say, although the fidelity of moving-base is attractive, whether human's behavior can be established better is not sure. Therefore, fixed-base simulators are also reliable and adoptable for human factors research.

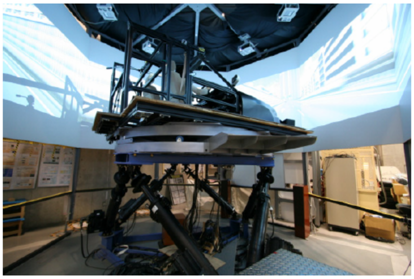

Fig. 3. The Universal Driving Simulator in the University of Tokyo

Fig. 4. Globalsim Simulator at UMTRI

GlobalSim Simulator at UMTRI (USA) [11]. University of Michigan Transportation Research Institute (UMTRI) is a world-leading research institute in traffic safety area. GlobalSim DriveSafety Research Simulator is their primary simulator used for studies of in-vehicle devices (navigation systems, cell phones), driver workload, the effects of health on driving (e.g., Alzheimer's disease, driver age), and other topics.

The driving simulator has a full size vehicle cab with a touch screen center console, a computer-controlled, projected LCD speedometer/tachometer cluster, operating foot controls, and torque motor to provide realistic force feedback. The in-cab sounds are generated by software and presented by a 10-speaker system from a Nissan Altima, supplemented by a 4-speaker system for road sounds. To provide realism, the cab has limited vertical vibration, and for use in warning systems, a haptic feedback seat. Road scenes are projected on 3 forward screens almost 16 feet from the driver (120 degree field of view) and a rear channel 12 feet away (40 degree field of view). Each channel has a resolution of 1024x768 and updates at 60 Hz. Scenes are currently daytime only, though bad weather (fog, rain, snow) can be simulated. Traffic is programmable, either following the general rules of the road or as scripted. The vehicle dynamics can be changed. Driver and vehicle performance (steering wheel angle, speed, lane position, etc.) are recorded at up to 30 Hz by the main simulator computer. In addition, driver actions (their face, hands, the instrument panel feet and foot controls) and parts of the road scene can be recorded by an 8-camera video system onto a quad split image. Control is achieved using 8x4 and 16x16 video switchers, and a 12x4 audio mixer.

3 Driving Safety Study

As an important approach for driving safety study, driving simulators have been used by many researchers for a variety of studies. Table 1 shows the research issues of driving safety study using simulators. Some typical research literatures are reviewed in the following sub-sections.

Table 1. Driving safety study using driving simulators

Number	Aspects of study	Study issues
1	Driver behavior study	
		- Influence of distraction or impairment (cellular phone use, fatigue, etc.)
		- Driving performance or behavior measurement (gap acceptance, lane change, speeding, passing vehicles, etc.)
		- Characteristic of young drivers (risk taking, drinking)
		- Collision
2	Education and training	
		- Novice driver training
		- Accident avoidance training
		- Education of holding safe views in driving
3	Design and evaluation of transportation infrastructures	
		- Traffic sign system
		- Road markings, road-block, speed Hump and other infra on road
		- Road surfaces, tunnel, bridge
4	Medicine and therapy application	
		- Drugs and alcohol
		- Clinical Trials Support
		- Crash Biomechanics
5	Ergonomics and cognitive study	
		- Visual and auditory obstacle in driving
		- Haptic feedback on simulator
		- Motion sickness
		- Old drivers
6	Intelligent Transportation System (ITS) study	
		- Adaptive Cruise Control system
		- Head-Up Display and Head-Down Display
		- Collision and accident warning system
		- Other new in-vehicle technologies
7	Administrative method evaluation	
		- Design and evaluation of the new policies
		- Urban and rural traffic environment

3.1 Driving Behavior Studies

Influence of Distraction or Impairment. Since conducting impaired driving test is risky on real road, many researchers have turned to use virtual driving simulation as the main approach. Wittmann et al. (2006) used driving simulation approach for evaluating the effects of visual display position on driving performance. To determine the relative safety of onboard display positions while driving, participants performed a lane-keeping task in a driving simulator. Concurrently, they reacted to a light by pushing the brake pedal. A secondary task was projected onto a display at one of the seven different locations in the cockpit. Behavioral data, eye movements, and subjective rating scales showed that the manipulation of display information during driving disturbed drivers' performance exponentially as a function of distance between the line of sight to the outside primary task and the onboard display position. Vertical eccentricity had a greater detrimental effect than horizontal distance. Under a certain condition with a high secondary task load, reaction time of pushing the brake to the outside stimulus nearly doubled with a diagonal eccentricity of 351 as compared to lower eccentricities. Subjective workload measures complement the behavioral data of clear detrimental effects with eccentricities of at least 351 [12]. Sung et al. (2005) used driving simulation for studying effects of oxygen concentrations on driver fatigue [13].

There are still lots of studies that investigate the influence of cellular phone use while driving in a simulator [14] [15]. These studies aim to understand how serious the distraction is due to cellular phone use. Simulator system can collect detailed driving performance data (e.g. gas control, brake control, steering, speed selection, etc.) and conduct quantitative study afterwards. The similarity of these studies is that both tests involve higher driving risks due to increased mental workload or impairment. It is needed to note that this kind of experiments can not be easily conducted in real driving condition due to risk concerns. So in this condition, driving simulation becomes a useful approach for this kind of performance measurement when there is risk effect.

Driving Performance or Behavior Measurement. Another kind of study using driving simulation is driving performance measurement. Real condition driving is difficult to track driver's operations while a simulator allows convenient collection of every operation data. For example, Salvucci, & Liu (2002) explored the time course of lane changing, including driver's control and eye movement behavior, using a fixed-base, medium-fidelity driving simulator and 11 participants. In the experiment, drivers were required to navigate a simulated multi-lane highway environment. Then the driver data were segmented into standardized units of time to facilitate an analysis of behavior before, during, and after a lane change. Results of this analysis showed that (1) drivers produced the expected sine-wave steering pattern except for a longer and flatter second peak as they straightened the vehicle; (2) drivers decelerated slightly before a pass lane change, accelerated soon after the lane change, and maintained the higher speed up until the onset of the return lane change; (3) drivers had their turn signals on only 50% of the time at lane-change onset, reaching a 90% rate only 1.5-2 s after onset; (4) drivers shifted their primary visual focus from the start lane to the destination lane immediately after the onset of the lane change. These results show that using simulators is an effective way of operation data collection. However, on the other hand, the result (1) also indicates that the steering behavior for driving in a simulated environment may have difference from driving a real vehicle. This implies that driving simulator fidelity or validity could be a research problem in order to make use of the measured data. If the validity is low, then the measured data is meaningless [16].

Young Driver's Risk Taking. Driving simulator is an ideal instrument to do experiments that was risky on real road. Leung (2005) conducted a single-blind randomized study with young and mature drivers to assess how age, combined with a modest dose of alcohol, influenced performance on a driving simulator. The driving tasks included detecting the presence of a vehicle on the horizon as quickly as possible, estimating the point on the road that an approaching vehicle would have passed by the participants' vehicle (time-to-collision) and overtaking another vehicle against a steady stream of oncoming traffic [17].

3.2 Design and Evaluation of Transportation Infrastructures

Traffic Sign System. Driving simulation is a useful method for traffic sign design and evaluation. By conducting evaluation in a virtual environment and allowing drivers drive in that simulator, it helps evaluate and optimize the sign in very early stage, accordingly reduces cost and improves design quality and usability. In a study conducted by Upchurch et al. (2002), the design and placement of exit sign of Boston Central Artery-Tunnel (Interstate 93) through downtown Boston was simulated and evaluated. Before the study, reconstruction of the Central Artery is needed to improve traffic operations by reducing the number of exits and entrances on Interstate 93 from the current 27 exits and entrances (two-directional total) over 3 mi to 14. Yet, the reduction of the exit signs may cause drivers-especially unfamiliar drivers to have difficulty obtaining guidance information for their exit. This can lead to driver frustration and a reduction in safety caused by abrupt lane changing and other maneuvers. To address these problems with improved sign design and placement, a study using a driving simulator was undertaken. A computer-generated roadway through the tunnel was developed to replicate the tunnel geometry (including horizontal and vertical curvature and ceiling height) and sign placement. Test subjects drove through the simulated tunnel to evaluate the developed signing alternatives [6].

3.3 Intelligent Transportation System Study

Adaptive Cruise Control Systems (ACCs). In contrast with the rapid developed new technology in automobile industry, driver's adaptation seems always far more behind. Hence, use of driving simulators to measure and evaluate the new in-vehicle devices is a wise choice for manufactures avoiding inconvenience in factual application. Hoedemaeker (1998) has conducted a study aimed at assessment of driver behavior in new technology at that time, particularly Adaptive Cruise Control Systems (ACCs). In this study, benefits and drawbacks of Adaptive Cruise Control Systems (ACCs) were assessed by having participants drive in a simulator. The four groups of participants taking part differed on reported driving styles concerning Speed (driving fast) and Focus (the ability to ignore distractions), and drove in ways which were consistent with these opinions. The results show behavioral adaptation with an ACC in terms of higher speed, smaller minimum time headway and larger brake force. Driving style group made little difference to these behavioral adaptations. Most drivers evaluated the ACC system very positively, but the undesirable behavioral adaptations observed should encourage caution about the potential safety of such systems [18].

3.4 Administrative Method Evaluation

Driving simulation has also been used for traffic administration measurement. In the study conducted by Uzzell and Muckle (2005), the change of driving behavior was observed in driving simulation. By testing different engineering solutions for “quiet lanes”program, different driving behaviors and effectiveness were observed and evaluated. The background of the study: The growth in motorized traffic on rural lanes in the UK has increased the dangers of, and dissuades people from, walking, cycling or horse riding on roads in the countryside. A UK Government initiative, “Quiet Lanes”, aims to address this contra-sustainability development and make rural lanes safe and attractive for non-motorized users. Although traffic calming measures have been employed in urban areas, their translation into more environmentally sensitive rural areas has been problematic, largely on aesthetic grounds as they often have an urban appearance. Innovative solutions are necessary to reduce traffic speed but it would be prudent to assess experimentally the likely effectiveness and acceptability of any new measures before they are built. This paper discusses the use of simulated environments by means of manipulated color photographs to predict changes in driving behavior associated with changing road environments. It was found that respondents were able to differentiate between the different simulated engineering solutions and their suggested driving behavior accurately reflected that associated with road use under similar conditions elsewhere [19].

4 Conclusions

Using driving simulator is becoming a more and more important approach for driving safety study due to its advantages, such as safety, low cost, repeatability and controllability for experiment. Due to the rapid progress of computer technology, a lot of advanced driving simulators were developed for improving transportation research, such as the NADS and VTI. Meanwhile, many research institutes who are professional on transportation and accidents study support the development of simulators and road safety powerfully, such as the NHTSA, UMTRI and MUARC. It can be predicted that more and more people will share the benefits from driving simulators with the technological upgrading of high-level simulators, and wide spread of mid-level or low-level simulators.

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