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A Short History of Driving Simulation

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Abstract

The Problem. Driving is the most universal and ordinary task people perform every day as well as the most complex and dangerous. It requires a full range of sensory, perceptual, cognitive, and motor functions, all of which can be affected by a wide range of stressors and experience levels. The historical context here will provide appropriate perspective for simulating the driving experience. ***Role of Driving Simulators.*** Driving has measurable, real-world impacts and consequences for everyone, therefore methods are needed in order to safely quantify the driving experience. Experimental studies can always be conducted with on-road tests, however using a simulator is safer and more cost effective; provides for objective and repeatable measures of driver performance; allows for complete control of the driving environment (traffic, weather, etc.); and can be easily administrated in a laboratory setting. ***Key Results of Driving Simulator Studies.*** Since the earliest days of driving simulation, simulators have been used in a wide range of clinical studies in order to understand the driver, the vehicle, and the complex driving environment. From early studies that investigated traffic control devices and highway signage, to modern studies dealing with driver texting, cell phone use, and sedative hypnotic pharmaceutical compounds, driving simulation has been a leading research tool. The areas of human factors, medical research, vehicle dynamics, highway design, and more have all benefited from results obtained through driving simulation. ***Scenarios and Dependent Variables.*** One of the huge advantages for using driving simulation is the ability to create and repeat most conceivable driving situations, leading to documentation of how the driver performed. Within a simulator, all aspects of the driving environment can be controlled and specific tests or events that the driver navigates will lead to the collection of desired performance outcomes. Roadway environmental conditions such as weather, traffic patterns, and signal light timing can all be controlled and repeated over many trials. Anything within the simulated environment can be measured providing objective and repeatable measures that cannot be obtained during on-road testing. ***Platform Specificity and Equipment Limitations.*** Over the years driving simulators have come in all shapes and sizes with a variety of approaches used based on the technology available at the time. Depending on the needs of the researcher, simulators have ranged from a simple set of pedals that a driver reacted with when a light turned on, to entire facilities dedicated to creating the most realistic simulator by using actual car cabs strapped to moving platforms. Although driving simulation does not yet match the fidelity of real-world driving, depending on the questions being asked, there are, and have been for some time, numerous driving simulators that can answer each question in its own unique way.

2.1 Introduction

The history of driving simulation has been motivated by general advancements in technology, related to the various cueing systems including visual, auditory, and proprioceptive feedback, and the equations of motion or vehicle dynamics that translate driver control actions into vehicle motions. The history has also evolved from our knowledge of driver behavior and issues that we desire to address with simulation, including research, assessment, training, and demonstration. Early simulation involved analog electronics and driving scenarios based on physical models, simplified calligraphic (i.e., line-drawn) displays, or film and video. With the development of digital computers and computer graphics, simulators became more sophisticated. Now in the PC (personal computer) era, with the advent of extremely capable and affordable CPUs (central processing units) and GPUs (graphical processing units) the development of driving simulation has become primarily a matter of software improvements plus driver interface hardware advances for establishing face validity.

As a practical matter, driving simulation development started in the 1960s using analog computers, electronic circuits and various display technologies (Hutchinson, 1958; Sheridan, 1967; Rice, 1967; Sheridan, 1970; Weir & Wojcik, 1971; Kemmerer & Hulbert, 1975; Allen, Hogge, & Schwartz, 1977). The block diagram in Figure 2.1 (Web Figure 2.1 for color version) shows the functional elements of driving simulators that have steadily expanded and improved to this day. The simulation computer processing (SCP) block includes all computations required to indicate vehicle motion relative to the environment, including driver control actions, and aerodynamic and road surface inputs. The first driving simulators used electronic circuits and/or analog computers for this function. Over the past two decades these functions have been mainly mechanized using digital computers. The SCP block then provides inputs to the sensory feedback generation (SFG) block which produces sensory cueing commands or inputs to the sensory display device (SDD) block. SFG was originally provided by very custom devices needed to provide visual, auditory and proprioceptive cueing. In the past two decades these functions have been mechanized by PC level devices including graphical processing units (GPUs), audio processing units (APUs) and digital algorithms for proprioceptive cueing, including steering feel and motion base commands. The SDD functions have mainly been implemented with commercial devices such as video monitors and projectors, sound equipment, torque loaders and various types of electric and pneumatic motion platforms. Given displayed sensory cues, the human operator (driver) then senses this information and, based on training and experience, produces control inputs that are fed back to the SCP. In virtual reality (VR) applications using head-mounted displays (HMDs), which have proliferated in the past decade, head orientation must also be provided to the SCP.

Driving simulator development has been motivated and supported by advances in electronics, computers and various display technologies. Understanding of driver and vehicle behavior has also motivated simulation developments along with the derivation of measurement algorithms for quantifying driver behavior and system performance. These developments have been advancing for over four decades, and with current technology advancing as it is, driving simulation development and refinement should continue for the foreseeable future. Researchers concerned about the evolution of driving simulation have, in general, been motivated to achieve a valid representation of the driving environment. This

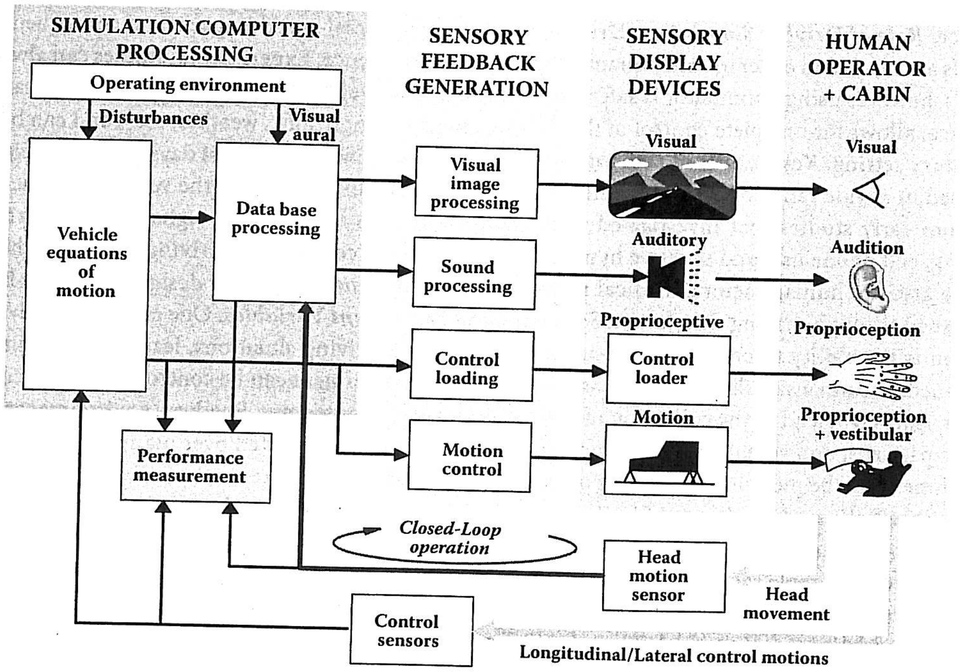


FIGURE 2.1 Functional elements of driving simulation.

involves fidelity in sensory cueing, vehicle handling (response to control inputs) and in the task environment which can be considered as cognitive fidelity (for more detailed discussions of fidelity see in this book, chap. 7 by Greenberg & Blommer; chap. 8 by Andersen, and chap. 9 by Ranney). The task environment involves all aspects of the driving environment, including traffic control devices (signs, signals, roadway markings and other delineators), traffic, pedestrians and various roadside elements including cultural features and flora. Early simulators implemented steering and speed control tasks and sign recognition that could be accomplished with slides or film projection. The ability to create a complex task environment requiring cognitive skills such as situation awareness, hazard perception and decision-making has been more fully realized with digital graphics, which permit the creation of complex 3D (three dimensional) scenes with control of the spatial and temporal properties of scene elements.

The major elements of a typical driving simulator as summarized in Figure 2.1 include: cueing systems (visual, auditory, proprioceptive, and motion), vehicle dynamics, computers and electronics, cabs and controls, measurement algorithms and data processing and storage. Cueing systems involve stimulation of all driver sensory and perceptual systems. In each of the cueing systems (visual, auditory, proprioceptive and motion) the appropriate stimulus resulting from the driver's control inputs must be computed and then accurately displayed to the driver. Cues such as steering feel are a direct consequence of the driver's control response and resulting vehicle reaction. Motion cues are a function of the vehicle's dynamic response to driver control inputs, with additional independent inputs due to roadway (e.g., road crown) and aerodynamic (e.g., wind gust) disturbances. Visual and auditory cues can result from driver/vehicle responses, but also have significant independent inputs due to dynamic roadway elements (e.g., traffic, pedestrians, and traffic control devices) in the driving scenarios. Vehicle dynamics have developed somewhat independent of the real-time simulation community but have been significantly employed in driving simulation through the years. The remaining elements have developed primarily outside of the real-time simulation community and have been adapted for use in quantifying driver behavior and system performance. These developments will be discussed subsequently.

Several functional elements in Figure 2.1 have been important and even critical to driving simulation's historical development but may not be obvious to the casual observer. These include vehicle dynamics, control and presentation of driving scenarios (road profiles, traffic control devices, traffic and pedestrians and roadside objects), and sensors and measurement algorithms. Ground vehicle dynamics started with fairly good models in the 1950s, followed by significant developments in the 1980s and 90s, particularly of tire models that produce the maneuvering forces that are essential to determine vehicle stability.

The control and presentation of driving scenarios has developed steadily over the years and is still an active area of development (Green, 2007). Measurement algorithm development has been spurred on by a combination of the need for quantifying driver behavior and system performance, and the development of fundamental mathematical and computational algorithms that allow desired and appropriate processing of time histories and transient events. Because of the visual nature of driving, one key area of sensor and measurement development has been eye movements.

To a large degree driving is primarily a visual task, so developments of visual cueing have been of vital importance. Figure 2.2 (see insert or Web Figure 2.2 for color version) shows some visual display effects as driving simulator display systems have improved over the years. Early simulators had electronically generated calligraphic displays (Figure 2.2a), model boards with video presentations, or film, but the introduction of digital graphics provided a rather dramatic step forward that has carried us to the sophisticated graphics systems that we are familiar with today. Figures 2.2b–d illustrate the evolution of digital graphics from primitive low count flat-colored polygons, through shaded polygons, and into today's technology, which allows texturing of high count polygonal models. Along the way display technology has also improved with monitors and projectors displaying increasing color and pixel resolution, contrast ratio, and brightness range and levels. Auditory system displays have always been fairly sophisticated because of high fidelity sound equipment. Developments in sound synthesis and sound generation and control cards have improved greatly along with software for generating realistic sound effects. Video game technology has led the way for many visual and sound effects through a combination of both software and hardware. Proprioceptive feedback such as steering feel has been available with properly controlled torque

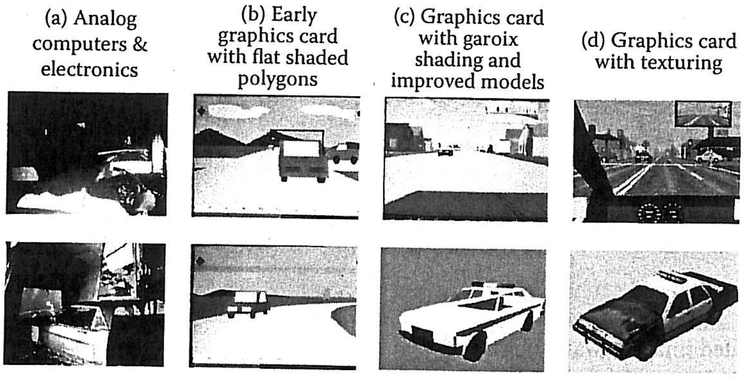


FIGURE 2.2 **(See color insert)** Evolution of driving simulators and PC graphics.

motors for the last couple of decades. Full motion systems have seen the most development, evolving to the current six degrees of freedom hexapod (Stewart Platform) systems with hydraulic and electrical actuators ("History of Video Games", n.d.) and for high-end facilities, the addition of horizontal motion tracks, (Garrott, Mazzae, & Goodman, 2006).

Historically, over the last four decades, developments in all of these areas have continually improved driving simulator capabilities. These developments have been applied to a full range of simulator configurations and applications, from large facilities to smaller setups; from research to testing and training of drivers. In the past, developments such as simulation computers and visual cueing systems were quite expensive and required significant equipment investment and thus tended to be implemented only in significant facilities. However, developments in the personal computer arena over the last decade have reduced the requisite computer hardware investment. The most significant outlay now resides in software development plus cabs and motion systems which still require significant hardware investment.

2.2 Early History

Driving simulation was originally developed to avoid the cost of field studies, achieve more control over circumstances and measurements, and safely present hazardous conditions. In the second half of the twentieth century, simulation was being successfully applied to aeronautical, rail and maritime operations. Passenger car and truck simulators were being used in studies of the driver (e.g., impairment, visual search patterns, training, etc.), vehicle characteristics (handling qualities, accident avoidance, design, etc.), and the environment (e.g., visibility, roadway characteristics, and design, etc.). In the late 1970s simulator design had evolved into five key areas: Visual and auditory display generation, kinesthetic cues (motion and control feel), driving scenario programming, computational vehicle dynamics, and the vehicle cab including controls and instruments. Several summaries of early driving simulation have been prepared over the years (e.g., Hutchinson, 1958; Sheridan, 1967; Rice, 1967; Sheridan, 1970; Weir & Wojcik, 1971; Kemmerer & Hulbert, 1975; Allen et al., 1977; O'Hanlon, 1977; Tu, Wu, & Lee, 2004; Garrott et al., 2006; Green, 2007; "History of Video Games", n.d.). Figure 2.2a shows an early simulator that included a calligraphic display generator, video projector and analog computation (Allen et al., 1977).

In the 1970s there were at least 20 research driving simulators throughout the US and Europe including many small, part task devices used for training and licensing. In these early simulators display generation and computations were done with parallel electronic circuits and analog computers so that high image frame rates (basically video frame rates) could be maintained to produce displays with good dynamic characteristics (Donges, 1975), and video or graphics projection systems were used to present large size (45°–60° FOV) visual displays (Donges, 1975; Gilliland, 1973). Digital computer-generated imagery was being developed to provide complex visual fields for car driving (Gilliland, 1973; Michelson, Niemann, Olch, Smiley, & Ziedman, 1978), however, these efforts were limited by the relatively slow serial processing characteristics of digital machines, and the delay tended to be proportional to image complexity (update rates of 20 Hz or less and time delays of greater than 100 msec). Digital computational delays were understood to be a serious artifact in the dynamics of the operator's control task (Leslie, 1966), and later on compensation techniques were developed to offset this artifact (Ricard, Cyrus, Cox, Templeton, & Thompson, 1978).

The recognition of the consequences of computational delays was critical to simulation development, particularly as simulation components were evolving from analog electronics to digital computation. The general problem with time delays in human/machine systems was realized after its identification as a significant simulation artifact (Ricard et al., 1978; Hess, 1982; McFarland & Bunnell, 1990), and methods for measuring and compensating for visual delays were developed for driving simulation (Hogema, 1997). Computational delays are still an issue that must be considered with current technology for very complex 3D visual scenes, and must be dealt with carefully in order to avoid significant artifacts, such as Simulation Adaptation Syndrome (Rizzo, Sheffield, & Stierman, 2003). Compensation techniques involve various computational methods to provide anticipation or prediction into the display variables (e.g., Hogema, 1997).

Point light source or shadowgraph techniques provided an early alternate approach to display generation, but tended to be limited in their capability to reproduce photometric conditions (Shuttel, Schmacher, & Gatewood, 1971). This type of display implemented the roadway scene as a tinted Plexiglas model illuminated by the point light source with the image presented on a screen in front of the driver (see Green & Olson, 1989, for a description of a shadowgraph display). Model motion was controlled to represent the speed and heading of the simulated car. This approach was obviously limited by the difficulty of constructing and controlling large complex models.

Film-based motion picture simulators provided excellent detail, but were not truly interactive. Typically the driver's steering actions controlled the pan angle of one or more projectors which gave an impression of heading control, and speed was represented by varying the speed of the projector (Hutchinson, 1958). The detailed resolution of 35 mm film allowed the motion picture technique to present elements such as signs in great detail approaching real-world viewing conditions as shown in Table 2.1 (Templeton, n.d.; Computer Display Standard, n.d.). However, the arduous film production efforts were a serious drawback to this approach.

Scale models can represent complex geometric conditions including traffic and roadside objects. This approach was taken in simulation with a moving belt model with a closed circuit TV display (Weir & Wojcik, 1971). As shown in Figure 2.3 the model belt moved towards the video camera with belt speed representing the velocity of the vehicle and camera azimuth angle and lateral position representing vehicle heading and lateral position respectively. Vehicle dynamics were mechanized on an analog computer and could be set up to represent a range of vehicle characteristics, including articulated vehicles (i.e., trailer towing). However, this approach suffered from limited resolution, lighting, and depth of field. Large

TABLE 2.1 Resolution Capability of Various Media

Medium	Resolution
35 mm film	5300 × 4000
Human Eye (1 minute of visual arc)	30° HFOV = 1800 × 1350 arc minutes
	45° HFOV = 2700 × 2025 arc minutes
Typical Digital Display Resolutions	1024 × 768 (XGA)
	1280 × 768 (WXGA)
	1280 × 1024 (SXGA)
	1600 × 1200 (UXGA)
	1920 × 1080 (1080p HDTV)
	1920 × 1200 (WUXGA)
	2048 × 1536 (QXGA)
	2560 × 1600 (WQXGA)
	1920 × 1200 (WUXGA)

Source: Templeton, n.d.; Computer Display Standard, n.d.

terrain boards have been used in aeronautical simulators to provide scene complexity (Carlson, 2003), but these approaches are generally limited by the difficulty of constructing large, complex models, and the representation of environmental conditions (lighting and atmospheric effects). The transition to digital graphics generation ultimately supplanted the need for physical models.

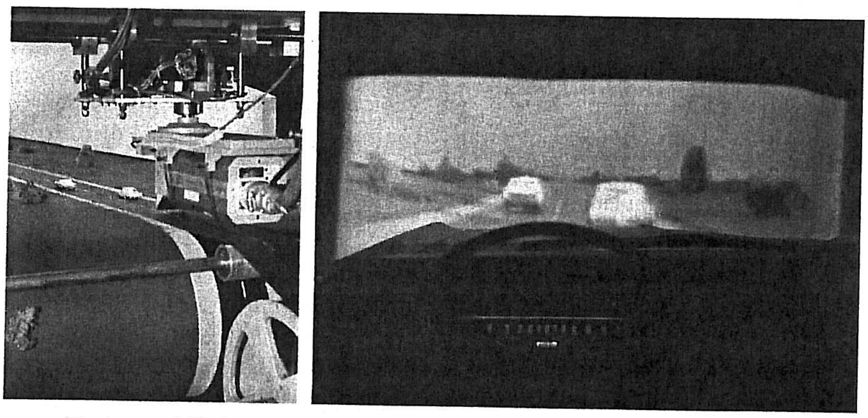
The transition from analog to digital processing was accomplished in stages as more simulation elements were converted. For example, studies of driver decision-making have been accomplished with analog computer vehicle dynamics, analog electronics for generating roadway elements, and a paper tape programmer run at vehicle speed for controlling tasks and events in the driving scenario (Allen, Hogge, & Schwartz, 1975). With the availability of capable PC graphics cards, all digital versions of driving simulation were produced (Allen, Stein, Aponso, Rosenthal, & Hogue, 1990). The development and application of driving simulation has proliferated since with increased capability of PC-based CPUs and GPUs.

2.3 Cueing Systems

Cueing system developments for simulation have definitely benefited from technical progress in the graphics and audio industries. Visual feedback in driving simulation is the most compelling cueing system, and developments of display devices and graphics rendering have historically been the prime drivers of development (Allen et al., 2000). Visually rich cueing displays were originally presented by film projection (Kemmerer & Hulbert, 1975), with a transition to CRT (cathode ray tube) and video displays as these technologies developed and matured.

Digital 3D graphics development has been ongoing for the last four decades (e.g., Carlson, 2003). Much of the early work was too computationally intensive for real-time simulator applications. Real-time graphics were first produced on specialized and expensive display generators and workstations. More recently graphics cards and graphics processing units (GPUs) for desktop computer systems have made extremely fast, real-time, photorealistic graphics rendering available at reasonable costs (Crow, 2004; NVIDIA Corporation, n.d.). Display resolution has been an issue historically because of the rendering of traffic control devices, particularly roadway signs (see Chrysler & Nelson, this book, chap. 36 for a more detailed discussion). Table 2.1 summarizes display resolutions, based on the capabilities of the eye and various display media. Digital displays are just now getting up to the basic capability of the human eye for reasonable fields of view and are still far below the resolution of 35 mm film. Furthermore, high resolution display devices are still quite expensive.

Driving simulation started off in the 1970s with analog electronics, and various display concepts. An early concept with calligraphic displays and projectors is shown in Figure 2.2a (Allen et al., 1977). Processing delays were not an issue with the early analog electronics approach, but subsequently became a problem with early digital computers and computer graphics systems. Processing delays of more than 100 msec were found to be a problem with the human operator (Allen & DiMarco, 1984), and digital processors and visual image generators were developed that minimized this problem.



Moving model belt — Driver's video view

FIGURE 2.3 Video display system with model belt.

It wasn't long after the original IBM PCs were introduced that more capable graphics cards were developed for the PC bus. Some interesting historical background can be found on the Web regarding the development of computer graphics, including PC bus display adapters (e.g., the history by Carlson, 2003). Single chip GPUs started with the Texas Instruments Graphics Architecture (TIGA) ("TMS34010," n.d.), then readily began to evolve with the introduction of the 3DFX standard and have continued with current NVIDIA, ATI and Intel chips ("Graphics Processing Unit," n.d.). Current GPUs offer an impressive array of photorealistic effects that are made available through the user-programmable shading capabilities of the graphics chip ("Unified Shader Model," n.d.).

Audio cueing has been historically advanced by the audio entertainment industry and home audio equipment has long given more than adequate resolution for simulator aural cueing displays (Audio Engineering Society, 1999). More recently the digital recording and reproduction of music has provided a convenient standard for simulation sound systems. Computer standards for sound such as .wav files have resulted in adequate aural resolution for driving simulation. Editing software for digital sound files has emerged more recently, and the availability of digital sound libraries has proliferated. Although audiophiles complain about digital resolution and "warmth", there does not seem to be any reason to go beyond current digital music standards and 3D sound cueing (Audio Engineering Society, a list of standards, n.d.). Three dimensional sound is quite appropriate for the driving simulation environment, providing necessary spatial cueing (for example, a car horn during an ill-advised lane change) as well as to simulate effects of relative motion (Doppler effect). Digital sound production has recently made the simulation of 3D auditory effects practical, and surround sound electronics and displays have made this approach cost-effective.

Proprioceptive cueing includes the feel in the steering system, pedals and gear shifting. Active steering feel has traditionally been provided by torque motors and simulation of the elements such as tires, suspension and steering system, which contribute to steering torque as a function of the important maneuvering conditions (Norman, 1984). Steering feel is fairly critical to the driver's sense of vehicle handling (Adams & Topping, 2001), and this research has made a significant contribution to simulation steering feel fidelity (Brocker, 2006).

A wide variety of whole body motion concepts have been tried with driving simulation, with Stewart (1965/1966) as an early example. The motivation for motion cueing has been both to improve the realism and validity of the simulator experience, and to minimize simulator sickness effects. The development of motion systems for driving simulators has generally been based on motion cueing ideas developed for aircraft simulation. Aircrafts make coordinated turns, so that motion cues are primarily angular rates. Four-wheeled ground vehicles impart significant lateral and longitudinal accelerations, and for reasonable speeds yaw rate is a near threshold cue compared with lateral acceleration. This is because lateral acceleration is a function of longitudinal velocity squared, while yaw rate is only a linear function of velocity.

Lackner and DiZio (2005), in a review of contributions to spatial orientation, note that while the vestibular contributions to body orientation have long been recognized, the more recent contributions of proprioceptive and somatosensory signals have also proved to be significant in relation to specific force cueing. For lateral maneuvers such as lane changes, Grant, Artz, Blommer, Cathey and Greenberg (2002) found that classical motion cueing parameter sets which reduced roll errors at the expense of lateral acceleration errors resulted in higher perceived fidelity. Higher gains, which lead to large errors in the shape of both the roll and lateral motions, also resulted in the lowest subjective fidelity.

Haycock and Grant (2007) have shown that both acceleration and jerk (i.e., the derivative of acceleration) contribute significantly to the perceived strength of motion. In a number of experimental cases, the subjective measure of motion strength was larger for a lower level of acceleration when the jerk was larger by a sufficient amount. This suggests that increased levels of jerk in a simulator could lead to an impression of excessive simulator motion, or that scaled down accelerations could be augmented with additional motion jerk. More recent examples of motion systems are given in Nordmark, Jansson, Lidstrom and Palmkvist (1986), Drosdol and Panik (1985), and Greenberg, Artz and Cathey (2003) with the ultimate example being the National Advance Driving Simulator described in Allen et al. (2000). The most universal approach to motion cueing has been through use of the Stewart platform or so-called hexapod. A good summary of the history of the Stewart platform and the development of appropriate cueing algorithms is described in some detail in Tu et al. (2004). In addition to hardware, good cueing algorithms are critical to obtaining the appropriate motion feel, and considerable discussion has been devoted to this issue in the literature (Grant et al., 2002; Haycock & Grant, 2007; Nordmark et al., 1986; Drosdol & Panik, 1985; Greenberg et al., 2003; Romano, 2003a; Zywiol & Romano, 2003). Key issues in motion cueing algorithms have to do with artifacts that the driver perceives as not corresponding to visually perceived or control-induced motions, including washouts and proclivities of motion actuators such as turnaround bumps (i.e., when an actuator changes motion direction it momentarily sticks at the zero velocity position).

2.4 Vehicle Dynamics

Vehicle dynamics define the response of the vehicle to driver control inputs and external disturbances (road, aerodynamic). The perceived handling of the simulated vehicle and even steering feel depend on the modeling of the vehicle dynamics. There are various vehicle dynamics effects that are important from the driver's perception including speed sensitivity, understeer, maneuvering limits (lateral and longitudinal acceleration) and torque feedback to the steering system. Modeling and analysis of vehicle dynamics has been developed extensively over the years based on an increasingly good understanding of ground vehicle handling and stability. Developments have also been motivated by the needs of driving simulation for handling fidelity and limit performance maneuvering (tire saturation effects).

One of the first comprehensive vehicle dynamics models was developed by Segel (1956/1957) at Calspan. Subsequent modeling was carried forward by Weir, Shortwell and Johnson (1967), and Ellis (1969). A significant amount of analysis of early linear models was carried out in the frequency domain (i.e., Laplace and Fourier transforms: Spiegel, 1965). This is particularly insightful for understanding dynamic modes and stability properties (Ellis, 1969). The understanding of limit performance handling, and stability in particular, requires a nonlinear tire model (Allen, Rosenthal, & Chrstos, 1997; Pacejka & Bakker, 1993) which generally must be analyzed in the time domain. The first significant analysis effort of nonlinear computer simulation modeling was carried out at Bendix for NHTSA (Hartz, 1972). More recently, computer simulation modeling has been advanced significantly by the multibody modeling approach (Sayers, 1999; Romano, 2003b; Heydinger, Salaani, Garrott, & Grygier, 2002). However, multibody modeling tends to require a significant number of parameters to define detailed vehicle characteristics, and solution procedures require significant computing resources and lengthy computational times which can limit simulation fidelity. The validation of complex vehicle dynamics models has been addressed in order to ensure model fidelity (Heydinger et al., 2002; Allen, Chrstos, Howe, Klyde, & Rosenthal, 2002). Simplified nonlinear vehicle dynamics models (VDMs) have been developed to minimize the parameter specification and computational load (Allen et al., 1990).

As driving simulation has become more sophisticated, particularly with the addition of motion cueing, detailed vehicle dynamics models have become more important in providing the driver with appropriate cueing. Motion cueing will impart acceleration cues to the driver, so acceleration response to maneuvering is a key aspect of the VDM. The driver also feels a torque response in the steering wheel that is a function of vehicle maneuvering, tire characteristics, caster and steering system compliance, and the VDM must properly model these characteristics. Auditory cueing can give tire screeching sounds due to the amount of force saturation that is involved, which is a function of lateral and longitudinal acceleration. Auditory cues such as tire screeching have typically derived from recordings to minimize the computational load, even in critical applications such as auto industry NVH (noise, vibration, harshness) (Blommer & Greenberg, 2003). VDM characteristics affect visual cueing due to angular rates and velocities, but details of the VDM will not typically be displayed very sensitively in the visual display. (Additional discussion of vehicle dynamics models and their validation can be found in this book, chap. 11 by Schwarz.)

2.5 Driving Tasks and Scenarios

The basis for driving simulator research, training and clinical applications resides in the development of scenarios that produce the desired independent and dependent variables of interest. The independent variables include the tasks and events relevant to the driver behavior of interest, and the dependent variables consist of measures of this behavior and the related system performance. Various processes have evolved for specifying complex tasks and driving scenarios as the computational capability of simulation has evolved.

Task and scenario development is essential to real-time driving simulator applications. Scenarios create the visual, auditory and proprioceptive environments that are important for the face validity of the driving simulator, and provide for relevant situations which are critical to various driving applications. In research on driver behavior, the scenario must contain elements that stimulate relevant behavior. For training, the scenarios must promote the repeated use of critical skills in a variety of situations that will advance the learning process and make the driver proficient and safe. For driver assessment and prototype testing, relevant performance measures must be available and keyed to the scenario situations so that the driver's behavior can be properly quantified.

Task and scenario development are important for defining a range of elements found in the driving environment, including roadway geometry (e.g., horizontal and vertical curvature, intersections and traffic circles), TCDs (traffic control devices, including signals, signs and markings), interactive traffic and pedestrians, and roadside objects such as buildings and flora). Control of the timing of traffic, pedestrian movements, and signals is also important in order to present critical hazards to drivers. These capabilities have generally expanded as simulator capability has advanced, and these developments have, in fact, significantly improved the utility of driving simulation over the years.

Driving simulator tasks and scenarios have been developed to measure, train and assess driver competence in relation to tasks that are critical to performance and safety. The driver must exert behavioral skills in dealing with the complexity of the roadway environment. These skills, which include the perceptual, psychomotor and cognitive functions required in vehicle navigation, guidance and control, must be applied competently to maintain system safety and performance. Task and scenario design and programming have developed historically along with technological advancements in simulation. The earliest film and physical model-based simulations were limited in their ability to represent tasks and scenarios other than vehicle control and sign recognition (Kemmerer & Hulbert, 1975). These approaches basically gave a fixed scenario that could only be changed by re-filming or re-doing the model database.

The earliest efforts with programmable events and signs allowed for more flexibility in task and scenario specification (Lum & Roberts, 1983; Alicandri, 1994). With the addition of significant digital computational power, procedural methods for designing scenarios and visual databases were developed for making driving simulators more easily programmable and adaptable (Allen, Rosenthal, Aponso, & Park, 2003). Significant attention has been devoted to the development and application of procedural methods in recent years (Kaussner, Mark, Krueger, & Noltemeier, 2002; van Wolffelaar, Bayarri, & Coma, 1999). Procedural methods allow scenarios to be defined with script-based languages rather than in 3D database modeling programs, with the simulator assembling and drawing the 3D database. Databases for real-time simulation with 3D digital graphics systems were traditionally developed in graphics programs as composite 3D models. This approach requires extensive effort and experience with graphics modeling programs. Procedural methods have allowed scenarios to be developed more easily and have permitted scripting control of the spatial and temporal variables of task elements. (Park, Rosenthal, & Aponso, 2004. For a more detailed discussion see Kearney & Grechkin, this book, chap. 6.)

2.6 Performance Measurement

Performance measurement is a critical aspect of driving simulation, allowing for objective quantification of both driver and system behaviors. Performance measurement has evolved along with simulator development, motivated by the desire to better quantify specific driving behaviors and the driver/vehicle/environment system. Early driving simulators collected data with pen recorders and magnetic tape recorders. Most data processing was done offline. The sophistication of performance measurement has progressed quite dramatically with the advênt of digital computation which has allowed for a range of statistical metrics and time series analysis of input/output algorithms.

Simple global measures were first implemented, including accidents, tickets, speed limit exceedances, lane and speed deviations, turn indicator usage, and so forth. This category has also included various measures of driver steering, throttle and brake control actions and associated vehicle responses including body axis accelerations and velocities (Sheridan, 1970; Weir & Wojcik, 1971; Kemmerer & Hulbert, 1975; Allen et al., 1977). These measures have been collected during entire simulator runs, and were subdivided into sections of driving scenarios where road geometry, vehicle and pedestrian interactions, traffic control devices and other task demands made them particularly relevant as the ability to program driving scenarios became more mature. Various algorithms were applied to these measures including distributions and moments (e.g., mean and standard deviation), power spectra, and more modern procedures such as wavelet analysis (Thompson, Klyde, & Brenner, 2001), which can quantify time variations in driver behavior. (For an additional discussion of independent variables in driving simulators see in this book, chap. 15 by McGwin, and chap. 17 by Brookhuis & de Waard; for a discussion of recent surrogate methods, see Angell, this book, chap. 10; and for a discussion of qualitative measures, see Moeckli, this book, chap. 23.)

With increasing computational capability in driving simulators more powerful measurement paradigms were employed where independent variables were more closely controlled and measurement algorithms quantified the relationship between dependent variables (i.e., driver response) and independent variables. For example, time series analysis methods have been used to quantify the relationship between driver response and road curvature, aerodynamic disturbances, and lead vehicle velocity changes (Allen & McRuer, 1977; Marcotte et al., 2005). These methods allowed for the analysis of driver time delay in responding to stimulus inputs, and the correlation of driver response to the stimulus input (additional discussion can be found in this book, chap. 21 by Boyle). With advancing capability in programming driving scenarios, driver response has also been quantified for more discrete and transient stimuli such as a traffic signals or conflicts with vehicles and pedestrians. These situations covered steering and/or speed control responses, and were analyzed in terms of driver decision-making and response time (Stein & Allen, 1986).

The measurement of human operator behavior, including driving, has been pursued for more that half a century, and is rooted in the general problem of modeling the human operator (Young, 1973; Sheridan & Ferrell, 1974). The early work dealt with the stable feedback control of vehicle dynamics in general, and a special conference, the Annual Conference on Manual Control, was held for over two decades and was devoted to the behavior and modeling of the human operator (Bekey & Biddle, 1967; Miller, 1970). Figure 2.4 generally illustrates the driving task and its three key components: driver, vehicle and environment. This conceptual model portrays several issues associated with modeling and measuring the performance of the driving task. The driver controls a vehicle, and this feedback process must be stable in a closed loop sense. Theories of linear feedback control have been applied to this problem, and a range of models have been proposed for its quantification (McRuer, 1980) that deal with stability either structurally, such as classical stability analysis (Weir & McRuer, 1973; Allen, 1982), or algorithmically, with procedures such as optimal control (MacAdam, 1981; Kleinman, Baron, & Levison, 1971; Thompson & McRuer, 1988). These two approaches raise the general issue of the computational procedures that are used in driver measurement, which have involved classical time series analysis and modern techniques such as wavelets (Thomspon et al., 2001). Higher level characteristics have been ascribed to the human operator (Goodstein, Andersen, & Olsen, 1988; Pew & Mavor, 1998), and cognitive functions such as risk perception, decision-making, and situation awareness are strongly factored into the driver's reaction to environmental inputs such as traffic, traffic control devices, and hazards in general.

Generally, driver models and measurements have been broadly categorized according to their control, guidance and navigation functions. Control concerns psychomotor functions that stabilize the vehicle path and speed against various aerodynamic and road disturbances. Guidance involves perceptual and psychomotor functions coordinated to follow delineated pathways, adhere to implied speed profiles, interact with traffic and avoid hazards. Navigation involves higher level cognitive functions applied to path and route selection and decisions regarding higher level

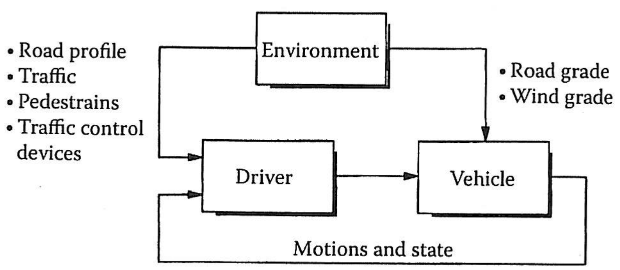


FIGURE 2.4 Performance measurement: driver, vehicle and system.

traffic interactions (e.g., avoiding congestion). Models have been developed that allow for the driver to respond to disturbances and commands in the driving environment (Allen & McRuer, 1979). These models have characterized the driver operating in so-called compensatory and pursuit modes. The compensatory mode relates to nulling out errors such as lane or speed deviations. Pursuit behavior arises when the human can perceive commands independently of errors, for example road curvature (McRuer, Allen, Weir, & Klein, 1977). Drivers will also respond to perceived vehicle motions and steering torque, which speaks to the importance of these cueing variables and accounting for them in the measurement process. Through vestibular and proprioceptive feedbacks the human operator can also respond to vehicle motions and control system forces which may be important in limit performance maneuvering (Young, 1973). (For more detailed discussions of driver models see in this book, chap. 42 by Salvucci, and chap. 43 by Flach, Jagacinski, Smith, & McKenna.)

Through the years there has been a trend in performance measures to switch from focusing on more driver-centered behavior (e.g., control activity, transfer functions, psychophysiological responses) to a more system-related performance involving safety and reaction to the driving environment. This trend has been influenced to a certain degree by the advancement of scenario design and control which have allowed more hazard-related events to be presented to the driver, and the desire to quantify safety in this context. Measurement is also somewhat specific to the application being addressed. For example, drowsiness and fatigue studies will typically focus on uneventful driving (Thiffault & Bergeron, 2003, see also Matthews, Saxby, Funke, Emo, & Desmond, this book, chap. 29), while training and assessment applications will focus more on situational awareness (e.g., see also Gugerty, this book, chap. 19) and how the driver responds to hazardous driving conditions (De Winter, Wieringa, Kuipers, Mulder, & Mulder, 2007; Johnson, Van der Loos, Burgar, Shor, & Leifer, 2001). When a range of measures are obtained, there have also been efforts to develop composite measures of performance using multivariate analysis approaches (Allen, Park, Cook, & Fiorentino, 2007; De Winter, 2009).

2.7 Simulator Sickness

Simulator sickness (SS) and its etiology have been a source of concern from the earliest days of simulator development and application (Reason, 1978; Casali & Frank, 1988). Much of the early work and concern revolved around aeronautical simulators, but driving simulators have also demonstrated similar issues (Rizzo et al., 2003). One issue that distinguishes driving simulation from aeronautical simulation is the same issue that impacts on motion cueing algorithms, that is, that aircraft mainly make coordinated turns while ground vehicle turns can induce large specific forces. In fact, as discussed under motion cueing above, specific forces dominate at high speeds, so the stimulation of drivers during maneuvering is much different than the stimulation of pilots. One historical rationale for improving simulator fidelity has been to minimize SS. This has led to efforts to improve cueing fidelity in visual and motion systems on many occasions, but with minimal success. Questionnaires have been developed to quantify the effects of SS (Kennedy, Lane, Berbaum, & Lilienthal, 1993). SS has been related to various simulator design configurations (Draper, Viirre, Furness, & Gawron, 2001; Roe, Brown, & Watson, 2007), and to environmental conditions (Rizzo et al., 2003). SS rates under various conditions have been quantified in some simulators (Park et al., 2004). It would appear that with proper care in simulator design and with attention to the environment SS rates can be minimized, although the details of these specifications are still not well understood. (For a more detailed treatment see in this book, chap. 8 by Andersen, and chap. 14 by Stoner, Fisher, & Mollenhauer.)

2.8 Fidelity and Validity

Fidelity and validity are continuing concerns for all driving simulation applications. Fidelity relates to the sensory experience in driving simulators. Face validity is concerned with the subjective impression of the physical layout of the simulator (controls, displays and cabin surround). More general validity relates to the suitability of the simulation for its intended applications. In research applications the simulator should provide measures of driver behavior (e.g., psychomotor, cognitive) and system performance (e.g., speed and lane deviations) that are consistent with real-world behavior (see also Ranney, this book, chap. 9). For assessment applications (e.g., driver capability, licensing) the question is how well does a simulator relate to driver performance in the real world (see also Mullen, Charlton, Devlin, & Bédard, this book, chap. 13)? For training applications, the question is how well the trained behavior transfers to the real world (e.g., fewer crashes; see also Pollatsek, Vlakveld, Kappé, Pradhan, & Fisher, this book, chap. 30)?

Simulation validity is multidimensional, and can relate to behavioral and physical dimensions (Jamson, 1999) as well as to the perceived sensation of the subjective experience and objective performance (Fildes, Godley, Triggs, & Jarvis, 1997; Wade & Hammond, 1998). Leonard and Wierwille (1975) have set down a validation methodology that generally follows good experimental design (see also Ouimet, Duffy, Simons-Morton, Brown, & Fisher, this book, chap. 24). Simulator validity must also be considered task-dependent (Kaptein, Theeuwes, & Van Der Horst, 1996). An early approach for validating simulation followed the typical psychological measurement assessment validity theory (American Psychological Association, 1954; Tiffin & McCormick, 1965). However, this approach has been criticized as a validity assessment (Ebel, 1961), as, more specifically, it relates to simulation (McCoy, 1963).

In general, validation procedures relate to simulation features or applications of interest which should be clearly stated in any such effort. For example, simulator speed profiles have been validated against data from real-world road tests for highway engineering studies (Bella, 2005). Furthermore, in decision-making research, driver stopping decisions at signal lights show reasonable similarities to real world observational data (Allen, Rosenthal, & Aponso, 2005). There are also issues associated with the driving task and driver motivation in the simulator versus the real world that can significantly affect driver behavior and system performance (Allen et al., 2005).

The Figure 2.1 block diagram illustrates the components of a simulation that factor into fidelity and validity. As discussed previously, the major elements of a typical driving simulator include: Cueing systems (visual, auditory, proprioceptive, and motion), vehicle dynamics, computers and electronics, cabs and controls, measurement algorithms and data processing and storage. Cueing systems involve stimulation of all driver sensory and perceptual systems. In each of the cueing systems (visual, auditory, proprioceptive and motion) the appropriate stimulus resulting from the driver's control inputs must be computed and then accurately displayed to the driver. Cues such as steering feel are a direct consequence of the driver's control response and the resulting vehicle reaction. Motion cues are a function of the vehicle's dynamic response to the driver control inputs, with additional independent inputs due to roadway (e.g., road crown) and aerodynamic (e.g., wind gust) disturbances.

There are three methods in general for validating simulator characteristics. First, if there is some absolute criterion for validating simulator components such as display resolution, then the characteristics can be measured. A second validation method involves comparing simulation measurements with results obtained in real vehicles under controlled experimental conditions, e.g., validating a component such as vehicle dynamics (Allen et al., 2002) or validating driver/vehicle performance (Jamson, 1999; Bella, 2005). A third method, which might be considered the highest form of validation, involves the comparison of simulator behavior with real-world results obtained under uncontrolled observational conditions. In this third case, if combined operator/vehicle behavior is being validated, operators are presumably performing under real-world conditions with appropriate motivation, for example, with regards to driver performance (Bella, 2009; Allen et al., 2005), or transfer of training for training simulators (Blaiwes, Puig, & Regan, 1973; Rose, Evans, & Wheaton, 1987).

As has been pointed out in the past (Allen, Mitchell, Stein, & Hogue, 1991), it is not possible to completely validate a simulator with one set of experiments or measures. For example, a simulation that is validated for speed production (Bella, 2005) may not have adequate resolution for sign reading and therefore would not be useful in evaluating the recognition distance of signs. Another example might be a fixed-base simulation that is useful for presenting complex scenarios requiring situation awareness and decision-making, but is not suitable for evaluating control actions because of the lack of motion cues (Siegler, Reymond, Kemeny, & Berthoz, 2001). Clearly, establishing the fidelity and validity of driving simulation is a multidimensional problem, and much work is required to establish the fidelity and validity of each of the simulator components summarized in Figure 2.1.

There are some efforts at more formal procedures for the verification and validation of modeling and simulation. Sargent (1998) describes different approaches for various validation techniques including data validity, and also notes that there is no specific set of tests to determine which techniques or procedures should be used. Balci (1997) describes a more prescribed approach, and addresses the life cycle of applying verification and validation to modeling and simulation projects, but notes the difficulty of formally applying these procedures. Balci deals primarily with accuracy and certification that a model of simulation is acceptable for use for a specific purpose. As simulations are applied to training and assessment, the question of accuracy will become more and more important. In this regard some efforts are being concentrated on the verification and validation of data bases submitted to regulatory authorities (Clinical Data Interchange Standards Consortium, Data Standards Team, 2005).

2.9 The Future

The future of driving simulation will generally be influenced by a combination of improvements in cueing systems and computational capacity along with a better understanding of how the driver reacts to the driving environment. Visual cueing will benefit from ongoing advancements in GPU development (Wilson, 2007; Gschwind, n.d.) software for creating a wide range of visual effects (Lankes, Strobl, & Huesmann, 2008; Williams, Chou, & Wallick, 2005; Ellis & Chalmers, 2005) and display devices that will improve resolution, contrast and brightness. These improvements should lead to better night and inclement weather scenes, and generally cover a wider range of the important visual variables such as brightness, contrast, resolution and field of view. Improvements in GPU and CPU capability will allow for increased visual complexity in scenes that will make them more photorealistic and also provide for more complex road and traffic environments which will be important for training and assessment. There is also the possibility of binocular displays (Law, 2009) that might enhance the rendering of close traffic conditions.

Sound cueing will most likely continue to take advantage of commercial PC computer-based solutions (Heitbrink & Cable, 2007). Motion cueing will advance with ongoing developments in motion base hardware and cueing algorithms (Colombet et al., 2008; Brünger-Koch, Briest, & Vollrath, 2006). A key issue here will be to minimize artifacts that are not consistent with visual inputs and control actions. Because of the participant safety problem, effective motion systems will typically impose facility requirements that increase initial purchase, maintenance and logistics costs. Hardware cost will also be a consideration here as larger, more costly motion platforms also provide more capability.

In the future, driving simulator applications will expand beyond research and development to more applied uses. Software will extend the capabilities of driving scenarios and performance measurement, and will permit a wide variety of simulator training and assessment applications. For new simulator applications the key will be user interfaces that make the simulator convenient to use for clinicians. Software development will allow training and assessment applications to be more directly suited to operators and participants (Parkes, 2003; Akinwuntan et al., 2005). New applications will develop, such as simulator assessment of highway designs and traffic engineering problems (Bella, 2009, Qiao, Lin, & Yu, 2007). Regarding software development for highway design simulation, an open standard has been proposed for roadway descriptions (Dupuis & Grezlikowski, 2006). Given low cost desktop simulators, it is possible that highway and traffic engineers will be able to routinely visualize and assess their designs before investing significantly in real-world facilities. A key issue here will be the capability of importing road design CAD models into simulator rendering systems, and a convenient means for adding relevant traffic control devices (signals, signs, markings and delineators). These efforts are under active consideration by the US Transportation Research Board Visualization in Transportation committee (Transportation Research Board, n.d.). (For related discussions of the future of driving simulation, see in this book, chap. 4 by Hancock & Sheridan; chap. 34 by Granda, Davis, Inman, & Molino, and chap. 39 by Manore & Papelis.)

Key Points

- Development has taken place in a significant number of simulator components including the rendering and display of sensory cues, the development and production of driving scenarios, and the measurement of driver behavior and driver/vehicle system performance.
- Hardware development outside of the simulation field has had a significant impact on simulator development and advancements, including motion cueing systems, computer processing units (CPUs), and graphical processing units (GPUs).
- The ultimate capability of simulators, given adequate hardware, depends on the software that controls the creation of the driving environment and the rendering of sensory cueing.
- Through software advancements, the ability to specify and control elements of the driving environment has increased dramatically over the years. These elements include roadway profiles, roadway traffic, roadside structures, flora and fauna, and traffic control devices including signs, signals, markings, and other delineation elements.
- Display resolution is still a limiting issue for tasks such as reading signs. It remains a practical challenge to achieve the limits of visual resolution (i.e., one minute of visual arc).

Keywords: Driving Scenarios, Fidelity and Validity, Performance Measurement, Sensory Cueing, Simulator Sickness

Web Resources

The *Handbook* web site contains supplemental material for the chapter, including color versions of Figure 2.1 and Figure 2.2.

Web Figure 2.1: Functional elements of driving simulation (color version of print Figure 2.1).

Web Figure 2.2: Evolution of driving simulators and PC Graphics (color version of Figure 2.2).

Key Readings

Akinwuntan, A. E., De Weerdt, W., Feys, H., De Vooght, F., Devos, H., Baten, G., et al. (2007). Training of driving-related attentional performance after stroke using a driving simulator. *Proceedings of the fourth international driving symposium on human factors in driver assessment, training and vehicle design* (pp. 112–118). University of Iowa, Iowa City.

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