Driving Simulation to Study the Role of Different Sensory Cues in Operating an Agricultural Vehicle

By

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DRIVING SIMULATION TO STUDY THE ROLE OF DIFFERENT SENSORY CUES IN OPERATING AN AGRICULTURAL VEHICLE

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A Thesis/Practicum submitted to the faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirement of the degree

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ABSTRACT

Driving simulators provide unprecedented opportunities and advantages for driving research in terms of experimental control, flexibility, cost, and safety. Successful driving simulation, however, requires a good understanding of the mechanisms involved in the driver's perception and action. On the other hand, driving simulators can be used to study those same mechanisms.

A valid driving simulator must draw, from the human drivers, the same driving behavior that they would show in real world driving. In order to achieve this level of validity, an important requirement is that the simulated vehicle and environment should provide adequate sensory information (i.e., feedback) to the driver. Often this sensory feedback is primarily visual. However, depending on the driving task at hand, other forms of sensory feedback, such as motion and force feedback, can play important roles. The goal of this thesis is to investigate the role of different sensory cues in the operating of agricultural vehicles, which have significant differences with automobiles in virtually all major aspects.

A tractor driving simulator was developed to provide realistic visual feedback, yaw motion, and torque feedback on the steering wheel. The error of a GPS lightbar guidance system and the self-deviation of the tractor were measured in the field. The measurements were used to model the straight line driving of a tractor with a lightbar system and the model was implemented in the simulator.

Field tests and simulator experiments were carried out with experienced tractor drivers to investigate the role of motion and visual cues in common driving tasks associated with agricultural vehicles. Observations showed that drivers effectively use yaw motion feedback in steering the vehicle in parallel swathing mode. Steering effort

significantly increased and performance deteriorated when motion feedback was eliminated. Visual feedback from the outside field was not used by the drivers in parallel swathing mode. Visual cues, however, were essential for turning maneuvers. Experienced drivers did not have a proper understanding of the relationship between their steering input and the vehicle motion. They needed visual feedback to complete maneuvers that required more than one steering input.

Torque feedback on the steering wheel was shown to be effective when the operator was engaged in a monitoring task as well as the steering task. Certain torque feedback schemes resulted in improved performance levels for both steering and monitoring tasks and reduced steering effort. These included a torque feedback that tends to move the steering wheel to the center position and a torque feedback that is proportional to the projected driving error.

When the operator performed the steering and monitoring tasks simultaneously, auditory signals were effective in reducing the load on the visual channel and thereby increasing the operator performance. Auditory signals were not appropriate for communicating the information regarding the steering task. However, they were very effective when used for the monitoring task. When the information regarding the steering and monitoring tasks were communicated to the operator through visual and auditory channels respectively, highest performance levels for both tasks were achieved.

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1. GENERAL INTRODUCTION

Virtual reality systems and simulators of various types are products of advancements in several fields of science and technology, including computer software, computer hardware and psychology of human perception. They allow a user to interact with a computer simulated environment. Some simulators and virtual reality environments provide only a visual experience, while others provide additional sensory information such as sound or force feedback.

Driving simulators have been developed for different types of vehicles and have turned out to be very successful tools for training and research. They have provided researchers with unprecedented opportunities in terms of experimental control, flexibility and safety in driving research. Questions, however, have been raised regarding the validity of findings from the research that is conducted in a driving simulator.

An effort to address the issue of driving simulation validity requires an investigation of how a driver interacts with the vehicle and the environment in real world driving. To be an effective research tool, a driving simulator should elicit, from the driver, the same actions and responses that (s)he would show in real driving. A driver of a real vehicle perceives vehicle motions and the state of the vehicle with respect to the environment through a continuous flow of visual and non-visual information which (s)he receives. The non-visual information includes motion cues, haptic feedback, as well as auditory feedback. The driver decides and regulates his actions based on this information. Therefore, for a driving simulator to be a valid research tool, it should provide the driver with the same information that (s)he uses in real world driving.

The information that is actually used by a driver depends on the driving task being performed. This thesis will focus on agricultural vehicles and will investigate the role of different sensory cues in operating these vehicles. Driving of agricultural vehicles is markedly different from automobile driving. The tasks of the operator of an agricultural vehicle are very different that those of an automobile driver. Moreover, the dynamics of the tractor and working conditions such as forward speed, noise and vibration levels, and the environment in which the vehicle operates are significantly different. Yet, no study has been done on the importance of different sensory cues for driving these vehicles. By showing which sensory cues are effectively used by the operators of agricultural vehicles in performing their tasks, this study establishes the criteria for validity of driving simulation for agricultural vehicles. The results of this study can also be useful in other ways. For example, this information can be used for the modeling and analysis of the behavior of the operator of an agricultural vehicle.

Chapter 1 is the general introduction. Chapter 2 includes a detailed review of the driving simulation literature pertinent to the objectives of this thesis. Chapter 3 describes the development of a tractor driving simulator. Chapters 4 to 8 are presented in paper format, and the status of each paper is shown in Table 1.1. Chapter 4 describes the modeling of straight line driving (parallel swathing) for the tractor driving simulator. Chapters 5 and 6 describe the role of motion and visual cues in driving an agricultural vehicle. Chapter 7 investigates whether the force feedback on the steering wheel can provide useful information to the operator of an agricultural vehicle so that better driving performance can be achieved. Chapter 8 investigates how auditory cues can be used to improve the performance of the operator of an agricultural vehicle. The overall conclusions and recommendations are discussed in Chapter 9.

Table 1.1 Status of the manuscripts.

Chapter	*Status of the manuscript*	*Journal*
4	Submitted in October 2007; final acceptance for publication received in April 2008.	Applied Engineering in Agriculture
5	Submitted in February 2008	Biosystems Engineering
6	Submitted in February 2008	The Open Ergonomics Journal
7	Submitted in April 2008	Computers and Electronics in Agriculture
8	Published, Vol.14 (1): 71-78. January 2008.	Journal of Agricultural Safety and Health

2. REVIEW OF LITERATURE

2.1 History

A driving simulator is a system providing an intelligent and consistent multi-sensory environment for a driver to perceive and control the motions of a virtual vehicle. The driver sits in a cockpit which contains controls usually found in a real vehicle. The driver's commands determine the simulated vehicle motion on the basis of a vehicle dynamic model. Driving simulators are amongst the most successful achievements in the field of virtual reality. They integrate real-time computer-generated graphics with motion feedback, force feedback and acoustic display, to create a realistic driving simulation scenario for the user (Huang and Gau 2003).

The first flight simulators appeared in the 1930s and they were basically used for flight training applications. Because real flight is unsafe without sufficient training, from the earliest days different simulation schemes were used to allow new pilots to familiarize themselves with the instruments and controls in an airplane cockpit. Driving simulators, however, appeared for the first time in the 1970s when General Motors built a driving simulator for human-in-loop driving research (Gruening et al. 1998). The hardware, such as the motion bases, that had originally been developed for flight simulators were adapted and used by the developers of driving simulators (Stoner et al. 1997).

Recent advancements in computer hardware and software have made it possible to develop driving simulators with an acceptable degree of fidelity at a reasonably low cost. Current desktop computers can support the computational requirements of such driving simulators. These inexpensive computers, which can be clustered easily by a local area network, are capable of producing high fidelity graphics, as well as doing vehicle dynamics computations necessary for high-fidelity motion and force feedback (Kang et al. 2004; Allen et al. 1998). As a result, in recent years many researchers and research institutes started developing their own driving simulators using desktop computers as the computing engine. At the same time, extensive research has been completed on the psychology of human perception in driving. The findings of these studies have been extremely helpful to the development of driving simulators (Huang and Gau 2003).

Initially simulators were used for training purposes such as flight and army simulators. In these cases the simulator is an interactive system to enable training and acquisition of skills for either parts of a task or a complete mission. More recently, simulators have been extensively used for industrial research (Koutsopoulos et al. 1995) as well as for academic research, particularly on human driving behavior (Noyce et al. 2002). According to Noyce et al. (2002), at that time there were almost 40 high fidelity driving simulators in research institutes throughout the world. The range of research fields that use driving simulators is very broad and includes, but is not limited to, design and evaluation of roads and highways as well as vehicles (Kawamura et al. 2004), ergonomics and human factors (Rakauskas et al. 2004) and clinical research (George 2003). Driving simulators are not restricted to automobile simulators; a mobile crane simulator (Huang and Gau 2003), a bicycle simulator (Kwon et al. 2001), a motorcycle simulator (Ferrazzin et al. 1999), and driving simulators for construction equipment (Son et al. 2001) and agricultural vehicles (Wilkerson et al. 1993) are other examples.

2.2 Advantages of Driving Simulator Research

2.2.1 Experimental control

Experimental control is one of the greatest advantages of driving simulator research. Many extraneous variables that may affect the driver's behavior in the real world can be controlled in a driving simulator. These variables depend on the type of experiment being performed and may include environmental variables and the characteristics of the vehicle or the experimental protocol. As an example, for on-road experiments with an automobile, it is very difficult to repeat an experiment on the same road under the same traffic and environmental conditions. Driving simulators enable manipulation of independent variables while keeping other (extraneous) variables at a constant level for several experimental runs (Horiguchi and Suetomi 1995).

2.2.2 Efficiency, flexibility and expense

Simulator research is generally much more efficient than studies in the real world. Firstly, experiments require fewer participants and fewer experimental sessions (repetitions) as a consequence of the experimental control issues mentioned above. Simulator experiments need a lot less planning and preparation compared to real-world experiments which means significant savings of money and time. Shorter preparation time allows for more treatments to be presented to each participant; consequently, simulators are more beneficial for experiments with a repeated measures design (Godley 1999). Also, because of a more tightly controlled situation, all drivers are exposed to identical experimental scenarios. This reduces the unwanted variation between participants and therefore the number of participants needed to achieve the same level of confidence in statistical analysis will decrease (Nilsson 1993). Some studies such as the effect of modification of the vehicle characteristics or road conditions can be very expensive or impossible to perform in the real world, but might be possible to conduct more easily in a driving simulator (Horiguchi and Suetomi 1995).

2.2.3 Safety

Safety is another advantage of driving simulator research, which increases the experimenter's flexibility in terms of the range of topics that (s)he can study, while avoiding the risk of injury to the participants. Moreover, the driver's behavior during critical decision making situations can be studied using a driving simulator. For example, Wilkerson et al. (1993) developed a tractor driving simulator to study the tractor roll-over situation. Driving simulators are also extensively used in the simulation of situations which lead to an accident such as dangerous road conditions or drivers under influence of alcohol, and high fatigue or mental overload (Alexander et al. 2002). Obviously, such studies are very hazardous to try in the field or on the real road; however, all of these situations can be investigated safely using a driving simulator.

2.2.4 Evaluation of new technologies

New technologies can be evaluated using a simulator while they are still in the development phase or even when they are in a conceptual stage. Intelligent vehicle systems, such as anti-collision devices are an example of these technologies. These technologies can be tested for their usability, safety and customer acceptance in a driving simulator before they are installed in a real vehicle or mass produced (Nilsson 1993).

2.2.5 Ease of data collection

Modern simulators, along with the additional instruments that can be installed in them, allow the measurement of most, if not all, aspects of driver behavior with relative ease. Although many measurements are also possible using an instrumented vehicle, they are not always as easy or accurate as they are in driving simulators. As an example, it is difficult to measure the position of the vehicle with respect to the road edges in a real world driving experiment. This constraint significantly limits what can be learned about driver behavior. In a driving simulator many constraints of this kind do not exist. Monitoring equipment such as eye and head tracking equipment and the equipment for measuring physiological reactions of the human driver are easy to install and use in a driving simulator. It is not impossible to use these types of equipment in an instrumented vehicle, but it is not as easy (Horiguchi and Suetomi 1995).

2.3 Shortcomings of Driving Simulator Research

2.3.1 Physical limitations and realism

An important shortcoming of driving simulators is their inability to accurately render all of the sensory cues that a driver utilizes in real driving. These sensory cues, as will be discussed in later sections, include visual, vestibular, kinesthetic, haptic, and auditory cues. Although no simulator can completely represent all of the real-world cues, not all driving tasks simulated in a driving simulator require accurate reproduction of all sensory cues. In fact, there is still some uncertainty regarding the exact role of each of the sensory cues for different driving maneuvers (Kemeny and Panerai 2003). Fixed-base driving simulators do not provide motion cues (i.e., vestibular and kinesthetic cues), which could be a significant departure from reality. Motion-based driving simulators, on the other hand, only provide limited motion cues because of space limitations, and although sophisticated motion algorithms circumvent this problem to some degree, no driving simulator can fully duplicate real vehicle motions. Visual cues have their own limitations in terms of small field of view and limited, if any, depth cues (Nilsson 1993). These limitations will be discussed in more detail in the next sections.

2.3.2 Transport Delay and Realism in Simulators

Transport delay refers to the phenomenon whereby the response of a driving simulator or one of its subsystems falls behind the driver command. The delay referred to here is usually much larger than the tiny delays that exist in a real vehicle. There are three major sources of delay in the driving simulator: 1) the time needed to perform the vehicle dynamic computations, 2) the delay in generating/refreshing the visual scene, and 3) the delay in the motion and haptic systems (Kemeny 2001). The transport delays in a driving simulator are inevitable because of the time needed to detect an operator command input, compute the new state of the vehicle, and return (to the operator) the resulting changes in the state of the simulation in terms of the sensory feedback. This delay can be a serious problem for studies evaluating vehicle handling, but it is less important for investigations of normal driving situations. However, this delay may lead to performance decrement and simulator sickness of the operator (discussed later). Long delays also decrease the realism of the simulation (Nilsson 1993; Dagdelen et al. 2002).

A driving simulator consists of different subsystems such as motion and force feedback, visual and audio systems, vehicle model and other computations. All of these systems work together, to create the simulation. It is very important, not only to have small delay in any of these subsystems but also to synchronize these subsystems together (Johansson and Nordin 2002). Most of the studies on simulator delay have attempted to minimize the delays of the visual and motion systems independently (Mollenhauer 2004). However, according to the theories of simulator sickness such as the cue conflict theory, instead of considering motion and visuals delays as independent factors, one should try to coordinate the two systems together. Therefore, careful attention should be paid in the design of the simulator to minimize the transport delay and coordinate different subsystems. In particular, the coordination of the visual subsystem with motion and force feedback subsystems is essential for motion-based simulators (Dagdelen et al. 2002).

There is no agreement on a threshold for acceptable transport delays that ensure a real driving experience. Kemeny (1999) suggests a value of 50 ms and Johansson and Nordin (2002) suggest a range of 40-60 ms. For head-mounted display (HMD) applications, the allowable transport delay is lower (typically 20 ms) (Dagdelen et al. 2002). The maximum acceptable value of the delays, however, depends on many factors, most importantly on the driving task being performed. For example, according to Cunningham et al. (2001), a small delay of 40 ms significantly affects the subject's ability in some visual tasks. According to Kemeny (2001), larger delays can be tolerated in a motion-based simulator than in a fixed-base simulator.

The speed of many driving simulators is dictated by the slowest subsystems, which is usually the visual subsystem (Hawks 1995). A study by Frank et al. (1988) showed that visual delay is more important than motion delay and if a choice has to be made between the two, the priority should be given to minimizing the visual delay. Some of the driving simulator subsystems and components such as the audio subsystem have very loose requirements in terms of transport delays which are satisfied by almost all driving simulators (Allen et al. 1998).

The delay in the visual subsystem is considered to consist of two parts: image generation delay and frame rate time. Image generation delay is the time required to calculate the new scene and make the picture ready for presentation. The frame rate is the number of times the image generator draws the scene. If the frame rate is 50 Hz, the frame rate time will be 20 ms. In this case, the image generation delay must be shorter than 40 ms in order to satisfy the 40-60 ms limit mentioned before. Calculation of the vehicle dynamic models also takes time, and should be added to the above mentioned delays to obtain the total delay time (Johansson and Nordin 2002).

Studies have shown that the subjects in a driving simulator gradually adapt to delays even if they are as large as 430 ms (Cunningham et al. 2001). However, the larger the delay, the longer the adaptation time. In addition, after initial adaptation to a delayed simulation, removal of the delay will result in a decrease in driver performance (Cunningham et al. 2001). Adaptation to transport delay is part of the "simulator adaptation" topic discussed later.

2.3.3 Simulator Sickness

A potential problem with driving simulator research is simulator sickness. Simulator sickness is not identical to motion sickness (Nilsson 1993). Motion sickness only happens if the simulation includes motion, but simulator sickness can occur without motion. Moreover, simulator sickness is usually less severe. In addition to the causal factors of motion sickness, simulator sickness may also be caused by problems with the visual subsystem of the simulator and the interaction between visual and motion subsystems (Kennedy et al. 1992).

Symptoms of simulator sickness usually arise when the person is driving in the simulator, but may continue to exist or even start to appear after using the simulator. They can persist for more than six hours after the driving simulator experiment (Baltzley et al. 1989). Simulator sickness has several symptoms. In a well designed simulator, most subjects do not show any symptoms. Sufferers, however, may show several of the symptoms. Eyestrain and dizziness are the most common symptoms. For flight simulators, major symptoms during simulator exposure are nausea, drowsiness, general discomfort, pallor, headache, stomach awareness, disorientation, fatigue, and incapacitation (Godley 1999).

2.3.3.1 Causes of simulator sickness

The most widely believed theory regarding the cause of simulator sickness is the "cue conflict theory", which states that simulator sickness is caused by an inconsistency between two or more of a person's senses (Godley 1999). The two senses that are typically involved are the visual and the vestibular senses. In fixed-base simulators, cue conflict occurs because a person's eyes see the motion, but his/her vestibular system does not. In motion-based simulators, cue conflict happens if the visually perceived motion does not exactly match the motion sensed by the vestibular system (Kolasinski et al. 1995; Noyce et al. 2002). An alternative, but less widely accepted, theory on the cause of simulator sickness was proposed by Riccio and Stoffregen (1991). They suggest that simulator sickness is caused by postural instability, or ataxia, which is "a person's loss of full control of movements in their perception and action systems". They claim that postural instability both precedes symptoms of sickness, and is necessary to produce those symptoms. Others like Kennedy and Fowlkes (1992) argue that simulator sickness is polygenic, that is, no single factor or mechanism can be identified as its cause; rather, many factors are involved. The rate of simulator sickness is, however, highly dependent on three aspects: the driving simulator, the driving task involved, and the driver. These factors are discussed in more detail below.

2.3.3.1.1 Simulator Characteristics

Several factors associated with a simulator can cause simulator sickness. Simulators with a wider field of view, (i.e., projection systems that produce wider horizontal and vertical visual angles of the simulated scene) usually lead to higher risk of sickness (Duh et al. 2002). This factor will be discussed in more detail in the following sections. Another factor is the transport delay described earlier. As mentioned before, visual delays are more important than delays in the motion system. Also, synchronization between the visual system and the motion system is even more critical. If the visual scene is not synchronized and matched with the motion and force feedback, the driver performance will significantly deteriorate (Johansson and Nordin 2002). Motion-based simulators are more likely to cause simulator sickness than fixed-base simulators. This is because motion-based simulators can result in motion sickness as well as simulator sickness (Kolasinski et al. 1995). According to Johansson and Nordin (2002), motions with frequencies of around 0.2 Hz and accelerations above $0.2\,\mathrm{m/s^2}$ are responsible for motion sickness. However, this seems to be mainly a result of inaccuracies in rendering motion cues in that range. A literature review by Mollenhauer (2004) shows that motion cues, when they are accurate, have a great potential to reduce simulator sickness. In fixed- base driving simulators, there is a limit on how rapidly drivers can perform maneuvers before their behavior is affected by the lack of motion cues. Beyond this threshold, drivers will notice the lack of vestibular cues and rapid maneuvers become confusing (Nilsson 1993). Another important factor for simulator sickness is low update rate of visual scene. According to Mollenhauer (2004), the update rate of image generators in most driving simulators is far below the nervous system's ability to detect a change. This factor will always contribute to the lack of realism and possible simulator sickness. The situation is worse if the update rate is variable because it disables the human's nervous system adaptation.

2.3.3.1.2 Scenario Characteristics

The level of simulator sickness is also influenced by the type of driving task being performed. Experiments performed by Nilsson (1993) showed that the occurrence of sickness was typically associated with sharp bends and quick decelerations. In normal driving situations, however, simulator sickness rarely occurred. Other researchers have shown that long experimental sessions increase the probability of sickness (Godley 1999).

2.3.3.1.3 Driver Characteristics

People with more real driving experience are affected more often by simulator sickness than novice drivers (Godley 1999). This is probably because experienced drivers are more familiar with the dynamics of a real vehicle and more easily notice any cue mismatch in a simulator. Moreover, experienced drivers are more likely to use motion and haptic cues in real driving (Godley 1999). Such driving habits will help the experienced driver to more easily notice any difference between the real vehicle and the simulator. Lerman et al. (1993) found no relationship between the rate of sickness and the level of experience in a tank simulator. However, this finding may have been due to the slow nature of maneuvers involved. Because of human adaptation, the risk of simulator sickness will decrease as the subject gains experience in using a particular simulator (Kolasinski et al. 1995). Lerman et al. (1993) found that people with a history of motion sickness are more likely to show simulator sickness symptoms.

2.3.3.2 How to manage simulator sickness

Simulator sickness can be avoided to a large extent by considering the factors mentioned above. However, almost always some level of simulator sickness is expected. It is, therefore, important to manage the consequences that simulator sickness can have on driving research. The simplest way to tackle this problem is to identify the affected subjects and discard the data collected for those subjects (Godley 1999). The data from these subjects can be corrupted for two reasons. Firstly, the discomfort felt by the subject will distract the driver, so that (s)he does not concentrate on the task being studied. Secondly, participants may find ways to alleviate the discomfort. For example, they may decrease their speed or steering wheel activity to avoid or reduce simulator sickness (Kolasinski et al. 1995).

2.4 Simulator Adaptation

Driving involves simultaneous use of sensory, perceptual and cognitive capabilities and continuous interaction with the environment and the vehicle. As mentioned before, even the most sophisticated driving simulators have deviations from real driving. No driving simulator perfectly replicates the control characteristics of a real vehicle on an actual road. Resolution and scene detail in visual feedback is always lower in driving simulators than in the real world. It is critical that drivers quickly understand and adapt to the differences between the simulator and the real world. However, adaptation to such virtual environments is not always quick and perfect. Participants in simulator studies need sufficient time to learn the look and dynamic of the simulator before they display a realistic behavior (McGehee et al. 2004). According to Green (2005), at least 3 min are needed to adapt to a simulator. Experiments by McGehee et al. (2004) with 80 experienced drivers showed steering behavior became stable after 240 s (6 min) from the start of simulator driving.

2.5 Sensory Cues Used in Driving

The role of a good driving simulator is to simulate a real-world scenario in a way that it draws from the subjects responses that are similar to those expected under real-world conditions (Adler et al. 1993). However, sometimes tasks that are easily performed in real world driving (e.g. lane shift), become difficult to perform in a driving simulator (Nehaoua et al. 2005). This happens because the lack of sufficient sensory stimuli (such as haptic feedback) prevents the driver from controling the virtual vehicle. In order to drive a virtual vehicle, the driver needs sufficient information in the form of sensory cues that allows him to control the virtual car easily and efficiently (Kemeny and Panerai 2003). Therefore, the adequateness of a driving simulator depends on how effectively it translates the real-world situations and the way the elements of the real world that affect the driver's behavior are represented (Adler et al. 1993). Therefore, to achieve a good simulation, it is essential to have a good understanding of the sensory cues that are used in real world driving. Building realistic and effective driving simulators requires a large amount of engineering knowledge and a deep understanding of the perceptual processes involved in driving. In the following sections, the sensory cues used in driving are explained in detail.

2.5.1 Visual Perception

Vision is certainly the single most important sense used by human drivers. It is generally believed that more than 80%, or even more than 90%, of the information needed for driving is received through vision (Lee et al. 1998). Wallis et al. (2002) demonstrated that drivers rely on visual feedback even for performing a very simple steering task such as lane changing. In their experiments, when visual feedback was removed, drivers were unable to complete the lane changing maneuvers. They suggest that drivers follow a simple strategy of "turn and see" and have poor understanding of the relationship between steering wheel angle and vehicle response. Wilkie and Wann (2006) also emphasize the unique role of visual information in following a path with the vehicle. They suggest fixating points and optic flow (described later) as the control variables used by the human drivers.

Visual perception of self-motion (often referred to as 'vection') is provided by optic flow, which is defined as the perceived visual motion of the surrounding objects as the observer moves relative to them (Goldstein 1989). The importance of optic flow for the visual control of heading and navigation was recognized by Gibson (1950). He noticed that the visually perceived motion in the "optic array" surrounding the observer radially expanded out from a point located along the direction of his/her heading. He called this point "the focus of expansion" (FOE) and suggested that heading is estimated by identifying the location of this point. But the problem is in fact more complicated than what Gibson's analysis suggested. This is because the sensors of the visual system (i.e. the eyes) can move with respect to the body during self-motion. These eye movements (as well as head movements) are superimposed on body movements and generate the final visual motion on the retina. Therefore these motions are superimposed on the optic flow and the result is a retinal motion pattern that also includes translational and rotational components due to eye and head. Therefore, we have to distinguish "retinal flow" from optic flow. The human visual system uses retinal flow, not optic flow, for perceiving and estimating self-motion.

The question of whether the retinal flow alone allows the brain to estimate heading, or whether an additional 'extraretinal' signal is needed, has been controversial. A major problem in estimating self motion based solely on retinal flow is to separate the translational and rotational components. For simple linear movement without eye rotation, the FOE will be an indicator of heading. However, eye and/or head rotation produces additional image motion on the retina which changes the retinal-flow pattern and makes it different from the optic flow. Therefore, in this case FOE cannot be used to estimate the heading and a different strategy would be needed.

One of the theories suggested to answer the above question states that eye or eye–head rotations would generate non-visual (also called 'extraretinal') signals, including vestibular and proprioceptive signals and efferent copy (all described later), which help to clear this ambiguity. On the other hand, a second hypothesis suggests that retinal flow itself carries enough information and the brain can use that to separate translational and rotational components of motion (Lappe et al. 1999). Results of driving simulator research generally support the first theory (Kemeny 2000). Experiments carried out by Kemeny and Panerai (2003), for example, showed that extraretinal information has a crucial role in disambiguating the complex retinal flow patterns.

Human vision uses two mechanisms. This idea, proposed by Held (1970), describes two different kinds of visual information processing mechanisms that are associated with different parts of the brain. These two modes are the focal mode (also called the central mode) and the ambient mode (also called the peripheral mode). The focal mode is responsible for recognition and identification of objects while the ambient mode is responsible for spatial orientation, locomotion and posture (Duh et al. 2002). Experimental evidence generally indicates that stimulation of the peripheral area of the retina is more effective in conveying the perception of self-motion. Brandt et al. (1973) found that, when the central retina was stimulated, self-motion was not perceived but a strong self-rotation was perceived when the peripheral retina was stimulated. Hulk and Rempt (1983) found that the perception of self-motion was most frequently reported at angles of $50-60^{\circ}$ from the center of FOV. Howard and Heckmann (1989) reported that when a stimulus was presented in the peripheral visual field, the self-motion experienced by subjects was stronger than when it was presented in the central visual field.

Larger field-of-view angles will result in better motion perception in driving simulators. This is due to the increased stimulus of peripheral vision which has a greater influence on self-motion perception (Mollenhauer 2004). Velocity information can be obtained from the peripheral visual areas while positional information is obtained from the central areas of the visual scene (Macadam 2003). According to Kemeny (2001) a narrow field of view may result in an underestimation of forward speed, while a wide field of view usually results in correct or over-estimation of speed. It has also been shown that that narrow FOV causes underestimation of distances to objects in the scene (Paille et al. 2005). However, some research shows different results. Experiments by

Chatziastros et al. (1999), for example, showed that lateral lane control was not significantly affected by increasing FOV from 40 to 180° while in the same experiment changing road texture (which effectively resulted in different optic flow) improved accuracy in lateral lane control.

Therefore, wide field of view (FOV) can be a great asset to a driving simulator. Moreover, wide FOV and high resolution are necessary to provide the subject with a strong sense of realism (Seay et al. 2001). Wide FOV can even lead to higher task performance (Duh et al. 2002). On the other hand, wide FOV can increase the risk of simulator sickness (Lin et al. 2002). Seay et al. (2001) found that large FOV is one of the most important causes of both simulation realism and simulator sickness. Kappe et al. (1999) found that driver performance in a driving simulator was improved in a lane keeping task in the presence of side wind gusts as the FOV was increased to 150°. Mollenhauer (2004) suggests that optimum FOV depends on the driving task being performed and that for some tasks a FOV of 180° may be required. Most driving simulator literature suggest a FOV of approximately $120-140^\circ$ and 120° is regarded as the limit that leads to correct speed perception and estimation (Kemeny and Panerai 2003). It should be pointed out that human drivers do not always fully use the entire field of view that is available to them. Many factors including driver fatigue, age, sleepiness, driving speed, driving in low visibility conditions such as night driving, and long monotonous simulated driving will lead to deterioration of useful FOV (Roge et al. 2003; Panerai et al. 2001; Crundall et al. 1999).

Optic flow cannot give information about the absolute distance to an object, but it can be used to compare spatial distances and for time measurements relative to the objects in the scene (Kemeny and Panerai 2003). Because the speed of the driver and other objects in the environment determine the velocities in the optic flow, optic flow is the only visual mechanism by which a driver perceives speed. Some psychophysical studies have shown that human drivers can underestimate the speed when image contrast, texture or luminance is reduced. The same mechanism is responsible for speed underestimation in foggy weather or in night driving (Snowden et al. 1998).

In addition to wide FOV and low transport delay, effective visual feedback depends on several other factors. Some of these factors are described below:

2.5.1.1 Depth cues

One shortcoming of visual cues in driving simulators is the fact that three-dimensional coordinates of the simulated environment have to be converted into two-dimensional data. Therefore, the depth of the scene looks different from that of the real world. In other words, when the subject in a driving simulator focuses on the projected scene, the focal distance is different from the one in the real world. Unlike flight simulators, which provide a very long focal distance, driving simulators must provide a wide range of focal distances (Horiguchi and Suetomi 1995). Many driving maneuvers require high resolution depth cues (Stoner et al. 1997). Some techniques such as binocular computation with a stereoscopic display will generate better results but have their own drawbacks (Kemeny 1999).

2.5.1.2 Frame rate (update rate)

Low update rates will result in display flicker which can be a major cause of simulator sickness. Wide FOV and high luminance level will increase the risk of flicker perception (Mollenhauer 2004). According to Johansson and Nordin (2002), frame rate is more important than resolution particularly if the visual scene has lots of detail. Also, flicker perception frequency threshold is higher for peripheral vision. In other words, as the frame rate decreases, human subjects perceive flicker first in the peripheral area of the visual scene (Godley 1999). Depending on the application, an update rate of 30- 60 Hz has been suggested for an acceptable visual comfort (Kemeny 1999).

2.5.1.3 Resolution

Higher resolution permits higher visual scene detail and results in better realism. Some researchers have suggested that higher resolution improves depth perception and distance estimation especially if the field of view is narrow (Duh et al. 2002). The required resolution depends on several factors, such as the distance to the screen. The resolution of the human visual system is about 1 arcmin (equal to 0.0167°) (Mollenhauer 2004). This is equivalent to 60 pixels per degree. Therefore, for a screen 120° wide, this would translate into 7200 pixels. Considering the common driving simulator setup that uses three projectors, each part of the scene would need 2400 pixels. This is more than the resolution of current PC monitors (Green 2005). Side and rear views require much lower resolution (Johansson and Nordin 2002). Finally, some studies (e.g. Duh et al. 2002) have shown that high resolution increases the risk of simulator sickness.

2.5.1.4 Reference objects or frames

The ability to view the vehicle body (such as the vehicle hood, roof, and pillars) facilitates determination of vehicle heading and generally improves task performance and makes vehicle control easier. The human visual system derives its judgments about self motion by selecting some fixed objects. According to the "rest frame hypothesis", the human nervous system assumes one of the frames as stationary and all judgments about self-motion are made based on that frame. The term "independent visual background" (IVB) is used to describe such a frame. Parts of the simulated visual scene (e.g. clouds) can act as IVB (Prothero 1998).

2.5.1.5 Vertical FOV and eye height

The subject in a driving simulator should be in the appropriate location so that the visual scene as viewed by the subject in the simulator matches the scene viewed in the real world driving. Small errors can have negative effects and cause false cues and driver confusion (Mollenhauer 2004). Incorrect driver's eye height will result in wrong visual perception and cause biased observations, particularly of close distances (Kemeny and Panerai 2003). Also, for some applications, vertical field-of-view may be of a very high functional importance. For example, in truck driving a vertical FOV of more than 50° is needed (Kemeny 1999).

2.5.2 Vestibular Cues

As discussed before, the human is able to judge his/her direction of motion from retinal flow. As a matter of fact, a number of models for steering behavior are based solely on human visual perception (Wilkie and Wann 2005). However, experimental evidence suggests that there are other sources of information that make a strong contribution to human motion perception. Some studies have shown that human subjects can accurately estimate their self-motion in space in the absence of visual cues during simple movements such as moving on a straight line and rotations (Siegler et al. 2001). This is because there are additional sensory cues that are available to the human for motion perception. These cues are called extra-retinal cues and are usually believed to be three (Kemeny and Panerai 2003; Crowell et al. 1998):

- Vestibular cues: Inside the inner ear there are vestibular organs (otoliths and semi-circular canals) which inform us about the orientation and localization of our head and are responsible for the perception of linear and rotational motion.
- Proprioceptive cues: There are sensors in muscles, tendons, and joints that provide a cue on the position and orientation of the body and limbs. The term "kinesthetic cues" is usually used interchangeably with "proprioceptive cues".
- Efferent copy: Refers to the motor command that the brain sends to the eyes and the head to turn. The visual system uses this information to compensate for the effects of eye or head movement on the retinal flow.

Experiments by Crowell et al. (1998) showed that none of the above cues alone is sufficient to guarantee accurate perception of self-motion. In their study, some of the subjects needed all three cues. A number of studies have investigated the human's use of vestibular and proprioceptive signals during rotations. These studies generally indicate that for rotational motion, proprioceptive cues are often the dominant source of extraretinal information. On the other hand, vestibular cues are very important in some other types of tasks (Wilkie and Wann 2005). Vestibular information can also provide direct feedback for steering control. For example, Wann and Land (2000) found that on curved paths, the rate of change for the heading angle can be derived from either the visual cues or the vestibular cues. According to Macadam (2003), the exact role and importance of motion cues compared to visual cues depends on the driving task being performed. For example, during straight-line driving in crosswind conditions, it is expected that drivers increase their dependence on yaw motion and lateral acceleration caused by the wind disturbance. This will increase the driver's dependence on vestibular and kinesthetic, rather than visual feedback.

In real-world driving, the driver feels yaw, roll and lateral accelerations which are a result of his/her steering actions, pitch and longitudinal accelerations which are a result of braking and acceleration, and vertical acceleration due to road roughness (Horiguchi and Suetomi 1995). The driver feels these motions not only through vision, but also through motion cues. Fixed-base driving simulators do not provide these cues, resulting in a conflict between visual and vestibular systems. Not only is this one of the main causal factors of simulator sickness (Siegler et al. 2001), some studies suggest that correct estimation of self-motion based solely on visual cues is not possible.

Results of driving simulator research generally show a strong positive effect for motion cues (Mollenhauer 2004). Experiments by Siegler et al. (2001) showed that motion cues, even with limited amplitude, are used by the driver in performing driving tasks, provided that they are relevant to the task. Some researchers (Stoner et al. 1997) believe that providing even motion disturbance due to wind gusts and high frequency motion cues, which are mainly a result of road surface unevenness, is absolutely necessary. Others (Eskandarian et al. 2006) believe that for many studies and applications, such as in highway driving, motion cues are not necessary. There are certain driving maneuvers which cannot be simulated because they are beyond the abilities of most motion platforms (Kemeny 2001). This issue will be discussed in more detail later.

2.5.2.1 Motion cues and driver performance

Many studies have shown that longitudinal and lateral accelerations in a motion-based driving simulator significantly ease the control of the simulated vehicle (Nehaoua et al. 2005; Mollenhauer 2004). Some studies (Siegler et al. 2001) show that motion cues prevent subjects from performing unusual driver actions, which are observed in a fixed-base simulator. Experiments performed in motion-based driving simulators show that drivers take wider turns compared to the way they steer in a fixed-base driving simulator (Kemeny and Panerai 2003). In a series of experiments by Horiguchi and Suetomi (1995), they found that the addition of motion cues can affect driver reaction time, but the result depends on the magnitude of the accelerations involved. In their experiments, when the value of yaw acceleration was small (up to $9.0^{\circ}/s^2$), motion cues increased the driver reaction time but when the yaw acceleration was larger, motion cues resulted in quicker driver reaction.

Speed and lateral position on the road are the most studied variables in experiments on the role of motion cues in driving simulation. For example, Alm (1995, cited by Siegler et al. 2001) found that means of both of these variables did not change with the addition of motion cues to the simulation. However, the variability in lateral position was smaller when motion cues were added. In another study, Panerai et al. (2001) also found no significant difference in driving speed perception when motion cues were turned on or off in a car following task. One of the first experiments to evaluate the role of motion cueing in a driving simulator was conducted by Repa et al. (1982). They compared driver's performance (in terms of the lateral position and heading of the vehicle) in the presence of sudden crosswinds under four scenarios: 1) no motion cues, 2) roll motion cue only, 3) roll and yaw motion cues, and 4) roll, yaw and lateral acceleration motion cues. Results showed that the subjects could stabilize the vehicle better on the road when motion cues were present in several axes. They found that the vehicle heading with respect to the road depended on motion cues more significantly than did the lateral position of the vehicle on the road. Reymond et al. (1999) developed a new criterion based on the relationship between vehicle speed and maximum lateral acceleration in order to evaluate the effect of motion cues on driver's behavior. By asking their subjects to drive the same test track on the Renault dynamic simulator with or without motion cues, they found that lateral accelerations in a simulator have a significant and positive effect on the drivers' speed choice strategy when driving on curved roads. Siegler et al. (2001) found a significant effect for motion cues in a braking task. Because the difference between the fixed-base and motion-based scenarios was seen at the beginning of the braking action, they concluded that motion cues change the driver's internal model of the simulated vehicle. According to Advani and Hosman (2001), the effect of motion cues depends on the type of task; skill-based driving maneuvers are affected much more than knowledge-based behaviors. For example, motion cues are more important in stabilizing a vehicle against wind gust disturbances than in a lane changing maneuver.

2.5.2.2 Delays in the motion system

As discussed earlier, delay and accuracy of motion cues as well as visual cues are very important because the driver uses them to estimate the responses of the simulated vehicle. The effect of transport delays on driving simulator validity is not completely known yet (Kemeny 2001). However, it seems that their role is more important than the role of the magnitudes of the cues. In particular, the coordination of visual and vestibular cues is essential. However, due to technical limitations (i.e., computation time, communication delays, actuator performance limits), perfect synchronization is not possible (Dagdelen et al. 2002). Because of these limitations, some researchers have suggested that when motion and visual cues are both provided, less motion might be better (Mollenhauer 2004). Horiguchi and Suetomi (1995) suggest that the delay of the motion system to respond to steering actions must be shorter than delays in a real vehicle, which, according to them, is 100-150 ms. Experiments by Dagdelen et al. (2002), found that for large transport delays, drivers observed an inconsistency between their commands and the vehicle motion. This will affect the perceived realism, although the subjects might be able to maintain control of the vehicle.

2.5.2.3 Motion and simulator sickness

Mollenhauer (2004) has done a thorough review of the literature on the effect of motion cues on simulator sickness. As it was discussed in the section on simulator sickness, motion cues should normally decrease the risk and level of simulator sickness, because the motion cues decrease the conflict between visual and vestibular perception in a fixed-base driving simulator. The literature review by Mollenhauer, however, concludes that although motion cues generally improve driver performance, they do not guarantee that simulator sickness will be reduced. There are many studies (Lin et al. 2005) that show motion cues have reduced simulator sickness, but there are also many studies that do not show a similar result. There are many factors that determine the effect of motion cues on reducing simulator sickness. These include synchronization with the visual cues, tuning of the motion drive algorithms, transport delays, and the driving task. Overall, it can be said that there is great potential for accurate motion to reduce simulator sickness (Mollenhauer 2004).

Experiments by Slick et al. (2006) showed that in a motion-based driving simulator if there is simulator sickness, it becomes worse as the simulation session becomes longer.

In a fixed-based driving simulator, however, their subjects showed few or no changes in terms of simulator sickness rating.

2.5.2.4 Motion systems and algorithms and their limitations

Displacements and rotations of the head are measured by the vestibular systems. Vehicle motion is also detected by tactile receptors in the skin (i.e., proprioceptive or kinesthetic sensors). The detection thresholds for linear and angular accelerations are approximately $5\,\mathrm{cm/s^2}$ and $0.3\,^\circ/\mathrm{s}^2$ respectively, depending on the duration of motion (Reymond and Kemeny 2000). Rendering transient vehicle motions is therefore an important requirement to achieve an acceptable level of perceptual validity. It is not possible to directly render low-frequency accelerations within the limited displacement envelope of driving simulators. This is possible, however, by taking advantage of the perceptual ambiguity between steady linear acceleration and rotation of the body. This trick was initially used by developers of flight simulators and is often referred to as 'tilt coordination' (Reymond and Kemeny 2000). When visual cues are also present, a visual compensation will be needed. This will also be discussed in more detail below.

Exact simulation of accelerations observed in real driving is impossible to achieve in a driving simulator, regardless of the motion platform used. A simple example of a maneuver for which motion cues are not realizable in a driving simulator is long braking. A trick to overcome this constraint is to provide the illusion of inertial effect of a certain maneuver. This technique is based on knowledge of the human vestibular system. As mentioned before, the vestibular organs (receptive cells in the otoliths) allow us, by the detection of their inclination angle, to measure linear accelerations. Because of the equivalence between gravity and linear acceleration, vestibular organs can also measure head tilt. This fact is used by the designers of driving simulators to provide lateral and longitudinal accelerations in curve driving, acceleration or braking (Kemeny 1999). In other words, in the case of sustained accelerations, the illusion is produced by tilting the driver forward, backward or to the sides. Such tilt is interpreted by the driver's vestibular system as positive, negative or lateral acceleration depending on the direction of the tilt. In the case of transient accelerations, the platform is moved in the appropriate direction and is returned back to its neutral position very slowly when the acceleration is zero or constant (Nehaoua et al. 2005). Therefore, most motion-based simulators use a combination of filters, called washout filters, whose job can be summarized as follows: (Reymond and Kemeny 2000; Stoner et al. 1997)

- Remove the low frequency part of accelerations by high-pass filtering (this is performed to keep high frequency cues that are required for vehicle control, while eliminating the low frequency motions with large amplitude that produce sustained accelerations). Integrate the signal twice to obtain a position command which is sent to the actuators to move the platform
- Extract the low frequency horizontal accelerations by low-pass filtering. Use this to compute a tilt angle which is added to the output command (this is performed to provide low frequency cues that are lost due to filtering in the first step)
- Bring the platform back to its neutral position.

The last stage is often referred to as the washout step. This step is necessary to avoid saturation of the actuators. It is important that this step is performed at undetectable rates to avoid a false cue. In other words, returning of the motion platform to its neutral position should be done at accelerations and velocities that are below the human perception thresholds. Another technique that is widely used is "scaled cueing". The scaled cueing technique consists simply of multiplying the accelerations and velocities that are computed by the vehicle dynamic models by a constant number (with a magnitude of less than one). So with a scaling factor of 0.25 and a computed acceleration of $4\,^\circ/s^2$, the subject in the simulator is provided with $1\,^\circ/s^2$. Scaling allows representation of a wider range of acceleration inputs without going outside the limits of the motion hardware (Mollenhauer 2004). It has been shown that the human accepts a great deal of variation in the magnitude of the linear and rotational accelerations (Kemeny and Panerai 2003). Some authors even suggest that the use of scale factors of 0.2 and 0.6 in the implementation of motion cues are realistic, for the translational cues and tilt angle, respectively (Kemeny 2001). Groen et al. (2000) found that in flight simulators, pilots overestimate the motion of the platform relative to the visual motion and therefore motion downscaling is necessary. They suggest a scale factor of 0.2 and a bandwidth (for washout filter) of 0.73 rad/s for the translational cues and a gain of 0.6 for the tilt-coordination channel.

Therefore, motion control algorithms filter out low-frequency linear accelerations, which are provided by tilting the simulator cab or driver seat. During such displacements, the visual scene should remain stable with respect to the driver's visual reference frame, (i.e., the cab or the cockpit). Therefore, when the projection system is not attached to the motion platform, the image generator has to compensate for the cab motion by moving the driver's point of view by the displacement of the motion system. Although this compensation is necessary, it is accompanied by a delay. It is important to decrease this delay in order to maintain the coherence between the visual and motion cues (Dagdelen et al. 2002).

To render horizontal transient motion, usually linear actuators and rails are used. Such platforms operate at low frequencies. Therefore, additional platforms or vibration seats are needed to render the high frequency motions due to vehicle-road contact (Kemeny 1999). High frequency motions (with frequencies of up to 30 Hz) correspond to car body vibrations and are not a direct result of the driver commands which have much lower frequencies. Moreover, at high frequencies, the output of the motion actuators typically used in driving simulators decreases rapidly. Therefore these actuators are adequate for rendering only the motions that are due to driver actions (i.e., motions with frequencies below 3.0 Hz). High frequency vibrations may be realized with a special system, such as a vibration seat, to help the subjects to better estimate the vehicle speed or the road surface conditions (Reymond and Kemeny 2000; Kemeny 1999).

2.5.3 Auditory Cues

Generally, the use of auditory information as redundant cues is considered to be effective in improving the realism of the simulation. However, auditory cues are most effective under high workload conditions where they can supplement the visual information (Macadam 2003).

Some researchers (Stoner et al. 1997) have emphasized the importance of accurate, three dimensional auditory cues and suggested that they should distinctly represent tire, power train noise, wind and traffic (if any). Green (2005) suggests that vehicle sound levels can be increased above their real values to increase the sense of speed, if desired. According to Huang and Gau (2003), audio feedback is essential to 'immerse' the subject. Experiments performed by Fukuhara et al. (2002) tend to support this idea. In experiments by Panerai et al. (2001), subjects increased their forward speed when the auditory feedback was removed. Eskandarian et al. (2006) point out the effect of noise on driver fatigue. However, auditory cues are not essential for most driving tasks and there is no evidence that the lack of auditory cues reduces the driver's performance.

According to Macadam (2003) secondary cues (such as auditory or haptic cues), provide redundant/reinforcing information. They help the driver to confirm his/her decisions and to react more quickly. Speed perception and estimation, for example, is enhanced by auditory cues; that is, even though visual cues are used primarily, auditory and kinesthetic information will generally improve speed perception and estimation by the driver.

2.5.4 Haptic and kinesthetic cues

Force feedback was initially designed for many gaming and simulation applications in order to compensate for the limited or no motion. Green (2005) suggests that one way to compensate for the missing motion cues in a fixed-base driving simulator is to increase the steering torque to levels above that found in the real vehicles. Some recent studies on real vehicles and in driving simulators have shown that haptic feedback on the steering wheel significantly affects driving performance in terms of variables such as steering variance (Liu and Chang 1995), steering control and driver adaptation (Toffin et al. 2003). Results of a study by Steele and Gillespie (2001) indicate that the haptic steering wheel allows a significant reduction in visual demand and also improves path following performance. They suggest that force feedback on the steering wheel might be particularly useful for agricultural vehicles where the driver must simultaneously monitor an attached machine.

Because of their dependence on power steering systems, real vehicles have very little force on the steering wheel. Also, steering feedback heavily depends on the car brand and model. But none of these seem to affect most driving behaviors. Probably what is more important than the level of force or torque on the steering wheel is the behavior of the steering wheel. The ability of the steering wheel to return to the central position, for example, is essential for making correct turns (Drive Square 2001).

As explained before, the term "proprioception" refers to sense of the body's position, weight or motion developed in muscles, tendons, and joints. The term kinesthesia or "kinesthetic perception" has the same meaning. This cue includes some sense of motion perceived by legs and torso which are in contact with the seat. This cue is usually referred to as a "kinesthetic" cue and can be an important cue in some situations such as turning on curves. In driving simulator experiments by Van Erp (2004), kinesthetic cues significantly decreased driver workload and reaction time. Kinesthetic cues are also a good indicator of the magnitude of steering input (Allen et al. 2000; Macadam 2003). According to Siegler et al. (2001), kinesthetic cues are particularly necessary in cornering maneuvers because subjects in a fixed-base simulator complain about being 'lost' after a turn. Research by Faber et al. (1999) showed that the importance of the kinesthetic feedback depends on the predictability of the situation; if the visual information is sufficient for performing the maneuver, kinesthetic information will play a minor role, but if visual information is reduced, kinesthetic information will become more important.

It is difficult in many cases to identify the separate contribution of vestibular and kinesthetic sensory channels because most acceleration information is generally detected simultaneously by both channels. Even under significant rotation, when the vestibular cue is very strong, the rotation is also detected by kinesthetic mechanisms that the drivers use to locate themselves within the vehicle or simulator cab. The vestibular cues provide important information such as rotational velocity and acceleration and the sense of gravitational orientation or tilt angle. On the other hand, the kinesthetic sense has the advantage of being distributed throughout the human body. It also provides some velocity information through vibrations of the body and limb movements, as well as control force/torque sensations from the steering wheel and control pedals (Macadam 2003).

Addition of higher frequency vibration by using vibration transducers mounted on the driver's seat can be an efficient way to mask some of the conflicts between visual and vestibular cues (Mollenhauer 2004). Allen et al. (1998) suggest that if the simulator has a cab, automotive 'sound shakers' can be mounted on the body to provide an enhanced sense of road feel. Tsimhoni and Green (1999) used bass shakers for this purpose in their driving simulator. The high-frequency vibrations can be an important cue for the perception of vehicle speed (Kemeny and Panerai 2003). According to Green (2005), using a seat shaker and increasing the amplitude of the vibration as vehicle speed increases provides a good cue for speed.

2.6 Simulator Validity

There are two levels of validity for driving simulators: 1) Behavioral validity, or predictive validity, describes the correspondence between the simulator and the real world in terms of how the human driver behaves. 2) Physical validity, or fidelity, describes the physical correspondence between the simulator and the real world. This level of validity includes issues such as the dynamic models used in the implementation of the simulator and the simulator's layout and components (Godley 1999).

It is often assumed by people that validity at this second level (i.e., physical validity) also implies validity at the first level. Therefore, many simulator studies report the physical correspondence and do not analyze the behavioral validity. In reality, however, these two levels are not always related. For research and training applications, the behavioral validity is more important.

2.6.1 Physical validity (fidelity)

Researchers often explain physical validity by describing their driving simulator and mentioning its different features. The closer a simulator is to real driving in the way it looks, the way it is used and the way different sensory cues are generated, the greater the fidelity of the simulator. Therefore, a motion-based driving simulator has higher physical validity than a fixed-base simulator. Another criterion for measuring simulator fidelity is lack of simulator sickness. However, whether this measure is relevant and meaningful is debatable. Although fidelity of a driving simulator is a desired characteristic, often too much importance is attached to it. Although greater fidelity should always be sought, it should be remembered that ultimately no level of physical validity is useful for research purposes if behavioral validity is not achieved. It is important to note that a more sophisticated simulator (i.e., a simulator with higher fidelity) may not have higher behavioral validity than a less sophisticated one. In that case, it will not be more useful for behavioral research (Godley 1999).

2.6.2 Behavioral validity

Behavioral validity is an important consideration for any driving simulator used for training or research (Godley 1999). Blaauw (1982) suggests several ways for examining the behavioral validity of simulators. The first and most comprehensive method includes a comparison between driving in the simulator and in a real car, using identical task and conditions. If the numerical values from the simulator experiment and the real world experiment are identical, the simulator has absolute validity. On the other hand, if the differences found under various experimental conditions in the driving simulator are in the same directions as those in the real world driving experiment, then relative validity is established. One can examine both absolute validity and relative validity of a simulator. However, for a driving simulator to be an effective research tool, relative validity is necessary but absolute validity is not always required. This is because most research questions investigate the effect of different levels of some independent variable(s) or compare different scenarios. In other words, in most research projects the absolute numerical measurements are not very important. Commonly used variables used in simulator validation studies include driving speed, lateral position and steering behavior (Eskandarian et al. 2006)

Other validation methods suggested by Blaauw (1982) are less attractive. His second method is based on comparing physical and/or mental workload between the driving simulator scenario and real world driving. This comparison can be performed by measuring physiological variables, such as inter-heart beat variability. However, Blaauw admits himself that the knowledge of the relationship between physiological measures and driving performance is incomplete. The third technique involves subjective rating by simulator drivers. Eskandarian et al. (2006) believe that a thorough validation of a driving simulator should include both an objective evaluation and a subjective assessment (in the form of questionnaires filled by professional drivers or simulation experts). However, subjective evaluation alone is not sufficient. The last method suggested by Blaauw is based on transfer effects. However, this method is especially useful for examining the simulator's validity for training tasks, and probably not for other purposes such as research.

Different experiments using a particular driving simulator need different levels of validity (Kemeny and Panerai 2003). Avoiding collision with a car that suddenly enters the road while talking on a mobile phone requires a different set of simulator characteristics compared to monotonous night driving. Therefore, a simulator that is valid for certain driving experiments may not be valid for another experiment.

2.7 Summary of the literature review and the proposed objectives

Despite the problems such as transport delays, simulator sickness, and the difficulties with providing the motion cues, driving simulators are effective research tools. They are becoming increasingly more popular due to the unique advantages that they provide for driving research in terms of experimental control, flexibility, cost, and safety. Successful driving simulation, however, requires a good understanding of the mechanisms involved in the driver's perception and action. If the observations in a driving simulator are to be generalized to real world driving, the driving simulator must draw, from the human drivers, the same driving behavior that they would show in real world driving. This requires that the simulated vehicle and environment should interact with the simulator driver in the same way as the real vehicle and environment interact with the driver. This means that the simulated vehicle and environment should have the same appearance and dynamics, provide the same information (i.e., feedback) to the driver, and provide the same means for the driver to input commands.

The feedback from the vehicle and the environment to the driver is primarily visual. However, experimental evidence shows that in many driving tasks, human drivers use other forms of feedback information, including motion (vestibular and kinesthetic) feedback, haptic feedback, and auditory feedback. The extent to which the human driver depends on different sensory information is a function of many variables, the most important of which is the nature of the driving task at hand.

This thesis aims to investigate the role of different sensory cues in operating an agricultural vehicle. Compared to road vehicles, agricultural vehicles operate in different environments and under different driving conditions such as at very low forward speeds. They also have different dynamics. Furthermore, the nature of the tasks performed by the operators of agricultural vehicles is different from the tasks of an automobile driver. Therefore, because of the significant differences that exist in terms of the vehicle, the environment and the driving tasks involved, it is expected that the control behavior of the driver of an agricultural vehicle and his dependence on different sensory feedback should be different than those of an automobile driver.

As explained before, the knowledge of the role of different sensory cues in a driving task is essential for driving simulation. However, this information can be useful for many other purposes. On one hand, this information is very useful and necessary for studying and modeling driver behavior and performance. On the other hand, this information can be very useful for designers and engineers who are involved in the design and development of vehicles and in-vehicle technologies. Agricultural vehicles, specifically, are witnessing an array of new technologies in their cabs. A lot of additional information regarding the performance of the vehicle and the attached machinery is now available to the operator of agricultural vehicles. The additional information, which has so far been predominantly visual, increases the attentional demand on the operator. An optimal design of these technologies should cause minimal increase in the driver workload. Therefore, the designer of the human interface for these technologies would need to know how occupied different sensory channels of the operator are.

Therefore, the objectives of this thesis are as follows:

1- To develop a driving simulator for an agricultural vehicle that can accurately mimic the real world operation.

2- To study the role of visual and motion cues in driving an agricultural vehicle.

3- To investigate if other sensory channels, such as haptic and auditory channels, can be used to provide some information to the operator of an agricultural vehicle in order to improve his performance.

2.8 Experimental Procedure

Experiments were performed in the field with two tractors and 14 experienced tractor drivers. Ten of the drivers drove a John Deere 5425 tractor while 4 drivers drove a Massey Fergusson 5400 tractor. Each subject first performed a selected set of turns and maneuvers, described in the next chapters. Then, each subject drove in parallel swathing mode with the help of an Outback® S lightbar guidance system.

Simulator experiments were performed with 15 experienced drivers. Each driver drove in the simulator for 5 sessions:

1- Control session, in which all sensory feedback was provided.

2- A session with no motion feedback.

3- A session with no torque feedback on the steering wheel.

4- A session with no visual feedback from the field boundary.

5- A session with no visual feedback from the field surface.

In each session, the driver first performed the same maneuvers and turns as those in the field experiment. Then, the subject drove in parallel swathing mode with lightbar guidance for 15 minutes.

Because the number of treatments (experimental sessions) was 5, and the number of subjects was 15, a repeated Latin square experimental design was adopted to achieve a random assignment of experimental sessions to subjects. In each of the Chapters 5, 6, and 7, portions of the data from the simulator experiment that are relevant to the objectives of the chapter will be discussed and compared with the field experiments described above. More details on the experimental procedure will be provided in the corresponding chapters.

3. DEVELOPMENT OF A TRACTOR DRIVING SIMULATOR

3.1 Abstract

Driving simulators have been effectively used to research different aspects of automobile driving. This chapter describes the potential of using driving simulation for agricultural vehicles. After a short review of the main issues in driving simulation, differences between automobile driving and driving of agricultural vehicles are briefly described. Then, the chapter describes different parts of a simulator for tractor driving that has been developed. The tractor-driving simulator includes systems for providing visual, motion, steering force, and auditory feedback to the driver. The simulator has been found to be an effective tool for studying various aspects of the ergonomics of tractor-machine systems including agricultural guidance systems.

3.2 Introduction

Automobile driving simulators have been in use since the 1970s (Gruening et al. 1998). As research tools, they provide unique opportunities in terms of experimental control, flexibility, cost, and safety. Over the last decade, they have been used to research different aspects of automobile driving including human perception and control (Kemeny and Panerai 2003), human factors aspects of driving (Rakauskas et al. 2004), clinical research (George 2003), and the design of vehicles and roadways (Kawamura et al. 2004).

Driving simulators have also been developed for other vehicles such as construction vehicles (Son et al. 2001), cranes (Huang and Gau 2003), motorcycles (Ferrazzin et al. 1999), and bicycles (Kwon et al. 2001). Surprisingly, no driving simulators for agricultural vehicles have been described in the published literature in recent years. Dating back to 1993, Wilkerson et al. described a tractor simulator that simulated roll-overs. According to the technology available today, their simulator is now obsolete. Technological advancements in computer hardware and software in the last 15 years have opened new opportunities for developing high-fidelity driving simulators at relatively low cost, making driving simulators affordable to most researchers.

Tractors and other agricultural vehicles run most of the time at forward speeds that are less than 20 km/h. Moreover, they usually run at a constant speed. Also, tractors do not have a suspension system. Therefore, acceleration and deceleration (i.e., braking) and pitch and roll motions which may be significant in automobile driving are not important in tractor driving (Crolla 1983). The driver of a car depends on the visual information from the surrounding vehicles, road edges and other objects in the visual scene to perform his maneuvers while the driver of an agricultural vehicle drives in a different situation where such external objects do not exist. Moreover, most tractor driving is done in straight lines (referred to as parallel swathing) and, unlike automobile drivers, tractor drivers usually use a guidance system and spend a significant portion of their time looking at the guidance system for guidance information. The goal of the steering task in this case is to minimize the deviation of the tractor from a desired straight line to values well below 1m. Also, most of the time, the operator of an agricultural vehicle has to monitor the operation of an agricultural machine at the same time that he is steering the vehicle. Noise and vibration levels are higher in agricultural vehicles. Furthermore, drivers of agricultural vehicles usually drive continuously for much longer periods compared to automobile drivers and their tasks are more monotonous and boring.

This chapter describes the development of a tractor driving simulator. This simulator is located in the Agricultural Ergonomics Laboratory in the Department of Biosystems Engineering, University of Manitoba. The simulator described in this chapter, is the same simulator that will be referred to in the next chapters of this thesis.

3.3 Development of a simulator for tractor driving

The following sections describe the main features of the tractor driving simulator. Figure 3.1 shows a complete block diagram of the simulator and Fig. 3.2 shows the front view of the simulator. The operator station, constructed using a cab salvaged from an old Versatile tractor, was created to ensure a realistic environment for the driver.

3.3.1 Computers

The simulator has two desktop computers. The main computer runs the main code which is written in Visual Basic .NET. This code receives operator input commands from the steering wheel, a joystick, and several buttons and switches on the operator console in the simulator cab through a PCI-DIO96H and a PCI-DAS1002 data acquisition board (Measurement Computing Inc., Norton, MA). The computations that are performed by the code include the calculation of tractor motion, the random error of the lightbar guidance system, the random disturbance on the tractor, and the torque feedback on the steering wheel. The main computer communicates with a servomotor that is attached to the steering column and an AC motor that provides yaw motion feedback to the tractor cab via two RS-232 serial ports. The main computer also runs a lightbar in the tractor cab through the PCI boards mentioned before. The computed tractor velocities are sent to the second desktop computer which is responsible for generating the visual scene.

Figure 3.1 A complete block diagram of the tractor driving simulator.

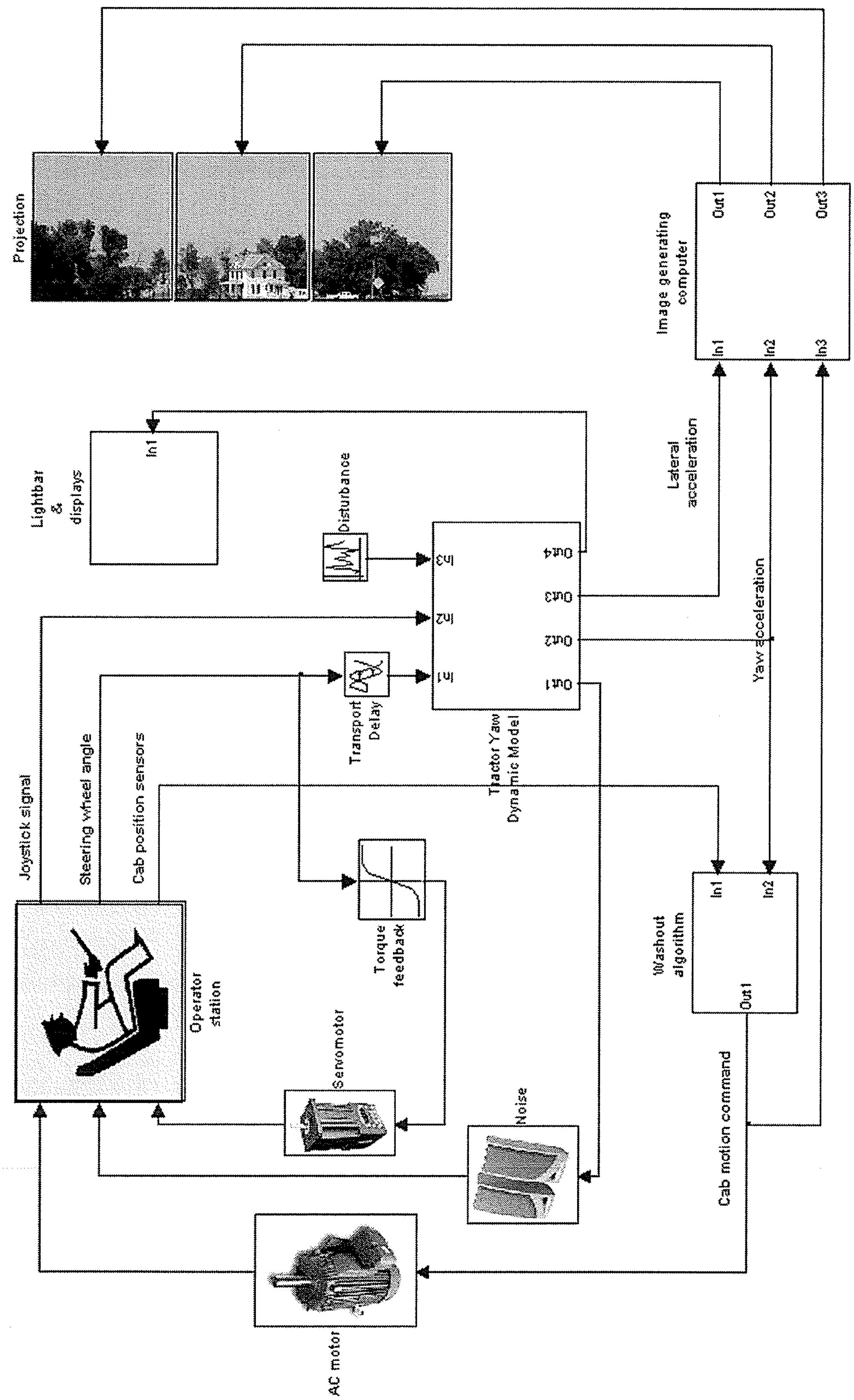
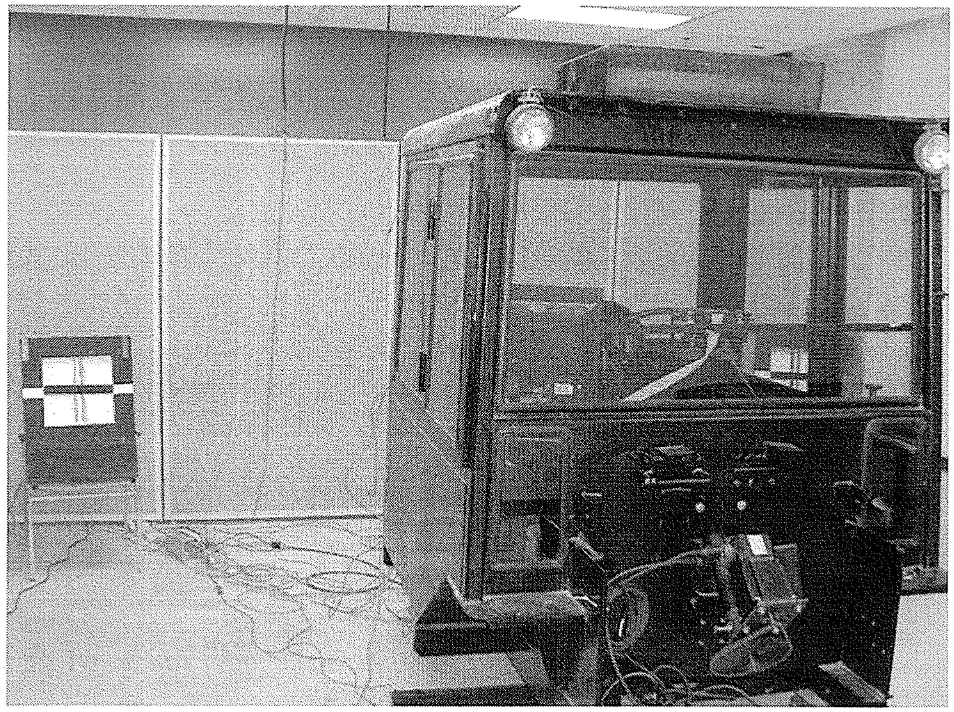


Figure 3.2 The front view of the driving simulator.



The image generating computer receives the computed tractor speeds from the main computer through a PCI-DIO48H data acquisition board (Measurement Computing Inc., Norton MA). It runs a 360° OpenGL simulation of an agricultural field under Visual C++ .Net. Two graphics cards (a GeForce 7800 GTx and a GeForce 6200 LE, NVIDIA Corporation, Santa Clara, CA) run three projectors to provide the visual feedback.

3.3.2 Dynamic model on the main computer

The tractor model that is used in the simulator was obtained through field experiments that we performed in the summer of 2006. Motion of a front-wheel steered vehicle in the horizontal plane is described in its simplest form by the following equation, referred to as the "bicycle model" (Wang 1993):

$$\begin{bmatrix} \dot{V}_y \\ \dot{\Omega}_z \end{bmatrix} = \begin{bmatrix} -\frac{2C_f + 2C_r}{mV_x} & -V_x + \frac{2bC_r - 2aC_f}{mV_x} \\ \frac{2bC_r - 2aC_f}{I_z V_x} & -\frac{2b^2 C_r + 2a^2 C_f}{I_z V_x} \end{bmatrix} \begin{bmatrix} V_y \\ \Omega_z \end{bmatrix} + \begin{bmatrix} \frac{2C_f}{m} \\ \frac{2aC_f}{I_z} \end{bmatrix} \delta_f \tag{3.1}$$

where: V_x , V_y : forward and lateral velocity of the vehicle at its center of mass, m/s

Ω_z : vehicle yaw velocity, rad/s

δ_f : steering angle, rad

I_z : vehicle yaw moment of inertia, kg.m^2

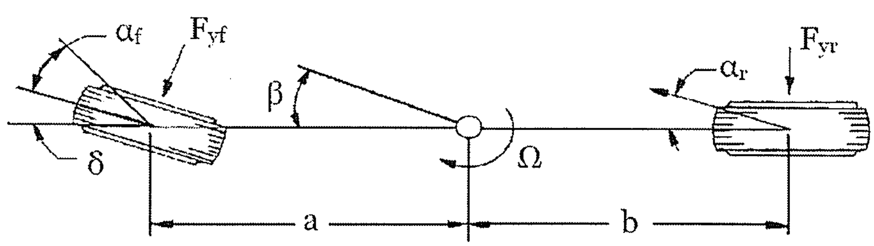
C_f , C_r : cornering stiffness of the front and rear tires respectively, N/rad

m : vehicle mass, kg

a, b : distance from the vehicle center of mass to the front and rear axles respectively, m

The rest of the parameters are shown in Fig. 3.3.

Figure 3.3 Bicycle model of vehicle motion in horizontal plane.



An improvement to the bicycle model can be made by modifying the way the force on the tires is calculated. The bicycle model assumes a linear relationship between the tire slip angle and the lateral force on the tire. However, theoretical modeling and experimental studies indicate a lag between a change in tire slip angle (α) and the corresponding change in tire lateral force (Pacejka 2002). This phenomenon is especially important when the vehicle forward speed is low, which is a characteristic of agricultural vehicles. This behavior is often simply characterized by a "relaxation length" which is defined as the distance a tire needs to rotate following a change in slip angle for it to develop 63% of its steady-state lateral force. Hou et al. (2003) express this relationship by the following equation for small slip angles.

$$\frac{\alpha(s)}{\alpha_{ss}} = \frac{1}{1 + l_y s} \tag{3.2}$$

where α_{ss} is the steady-state value of slip angle in rad, l_y is the tire relaxation length in m and s is the Laplace variable. The value of α_{ss} for front and rear tires is given by the following relations:

$$\alpha_f = \delta_f - \frac{a\Omega_z + V_y}{V_x} \qquad \alpha_r = \frac{b\Omega_z - V_y}{V_x} \tag{3.3}$$

Combining Eqs. 3.2 and 3.3 with Eq. 3.1 will result in the following equation:

$$\begin{bmatrix} \dot{V}_y \\ \dot{\Omega}_z \\ \dot{\alpha}_f \\ \dot{\alpha}_r \end{bmatrix} = \begin{bmatrix} 0 & -V_x & C_f/m & C_r/m \\ 0 & 0 & a.C_f/I_z & -b.C_r/I_z \\ -1/l_{yf} & -a/l_{yf} & -V_x/l_{yf} & 0 \\ -1/l_{yr} & b/l_{yr} & 0 & -V_x/l_{yr} \end{bmatrix} \begin{bmatrix} V_y \\ \Omega_z \\ \alpha_f \\ \alpha_r \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ V_x/l_{yf} \\ 0 \end{bmatrix} \delta_f \tag{3.4}$$

We conducted field experiments to investigate whether the bicycle model can accurately describe the plane motion of a tractor in the field and if the proposed modification will result in an improvement with respect to the bicycle model. A Massey Ferguson 150 tractor was used as the platform for field experiments. A linear string potentiometer (model P-80A, Ametek, Costa Mesa, CA) was used to measure the front wheel steer angle. Yaw rate of the tractor was measured using an ADXRS300 MEMS gyroscope (Analog Devices Inc.) The output from the potentiometer and the gyroscope were recorded by a data acquisition system (Omega OMB LogBook 300) mounted on the tractor fender. A Leica GPS1200 RTK system was used to record the exact location of the tractor in the field. The tractor was run on an agricultural soil at four different forward speeds (i.e., 2.8, 6.1, 10 and 13.7 km/h) and on a compacted soil at two different forward speeds (i.e., 6.1 and 10 km/h).

Figures 3.4 to 3.7 show how these two models were able to estimate the observed tractor motion. The data presented in these figures are from experiments with a forward speed of 6.1 km/h. Both models were able to predict the tractor motion quite accurately on both the soft agricultural soil and the compact soil when the steering input was slower than 0.4 Hz. When the steering input is faster than 0.4 Hz, however, the modified model (i.e., Eq. 4) was more accurate. The model accuracy was assessed by computing the Root Mean Square (RMS) of difference between the measurements and the model predictions using the following equation:

$$\mathrm{RMS} = \sqrt{\frac{\sum_{i=1}^{N}\left(y_{\text{measured}} - y_{\text{model}}\right)^2}{N}} \tag{3.5}$$

Using this equation, we find that, in Figs. 3.5 and 3.7, the RMS error of the predictions by the bicycle model is approximately 40% more than that of the improved model. However, as mentioned before, this improvement is only for steering inputs that are faster than 0.4 Hz. The steering angle data from several experiments in the driving simulator were analyzed to find how important these steering inputs are. Analysis shows that, on average, steering inputs with a frequency higher than 0.4 Hz comprise 20-25% of the steering input in terms of the signal energy.

Equation 3.4 is implemented in the simulator code using the Euler method with a step size of 0.02 s. As shown in Fig. 3.8, this method provides accurate results.

Figure 3.4 Comparison of the bicycle model and the improved model for tractor yaw rate estimation for slow maneuvers on an agricultural soil.

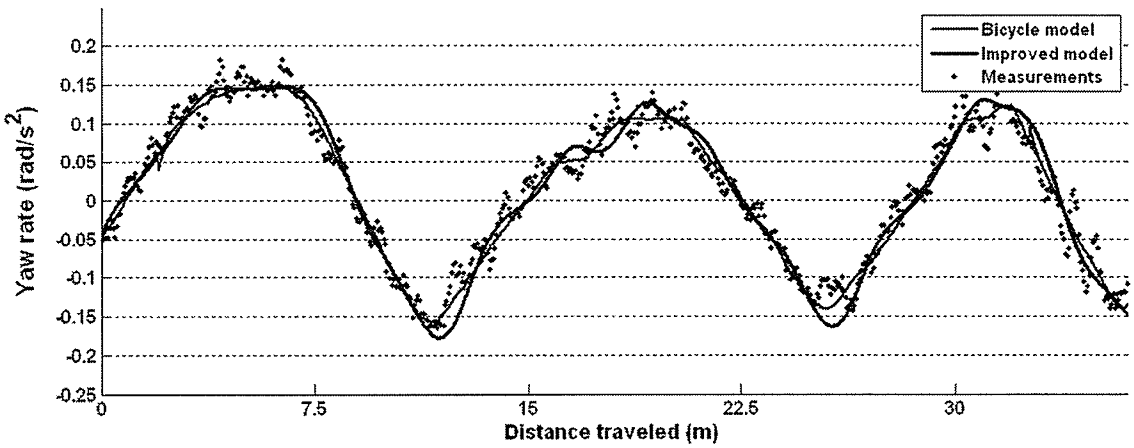


Figure 3.5 Comparison of the bicycle model and the improved model for tractor yaw rate estimation for quick maneuvers on an agricultural soil.

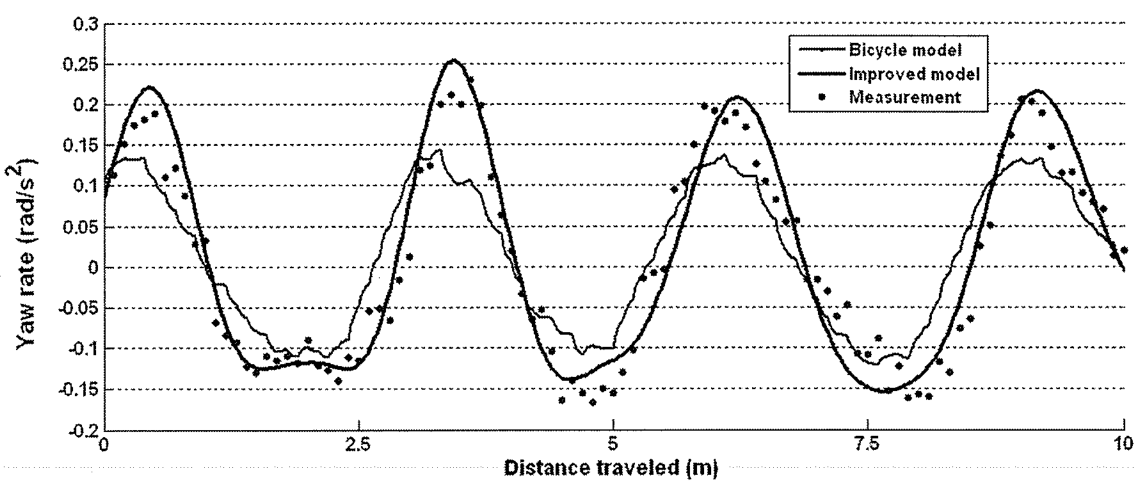


Figure 3.6 Comparison of the bicycle model and the improved model for slow maneuvers on a compacted surface (the two curves are not distinguishable since they are very close for all values).

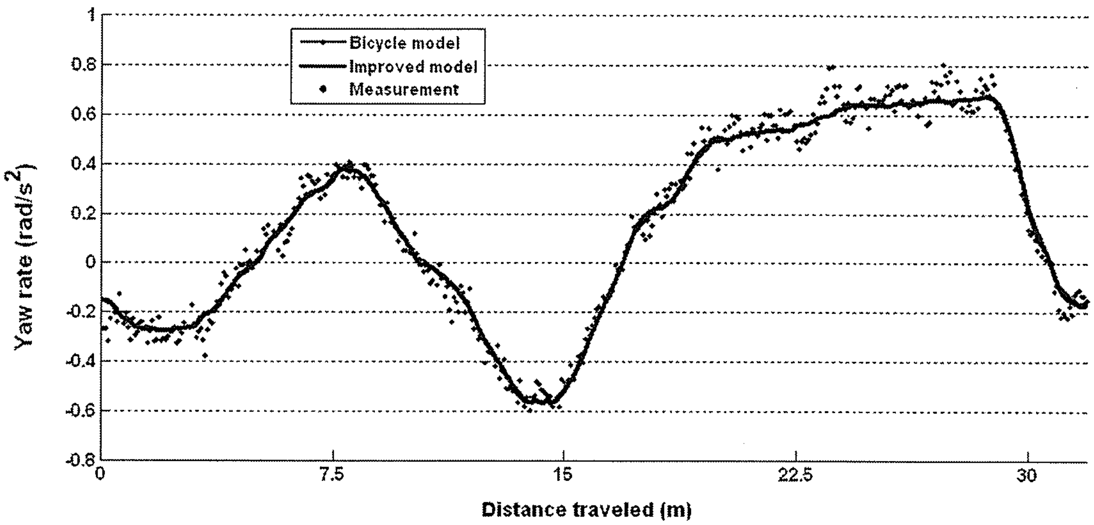


Figure 3.7 Comparison of the bicycle model and the improved model for quick maneuvers on a compacted surface.

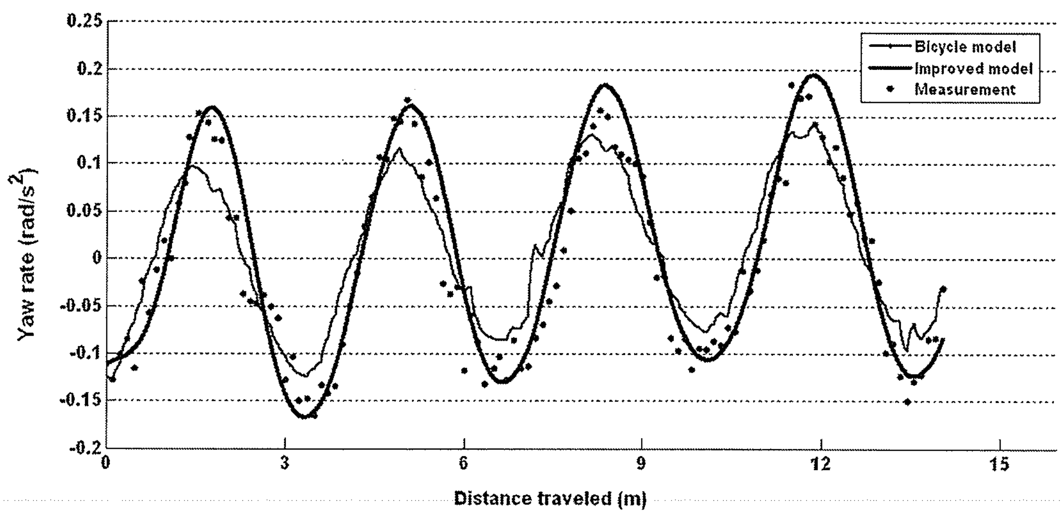
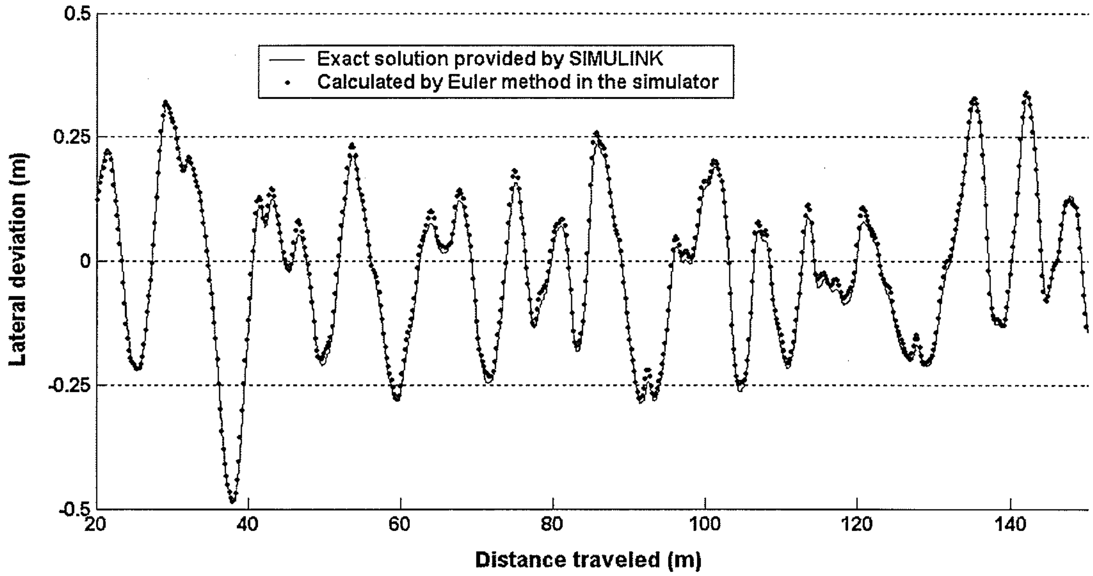


Figure 3.8 Accuracy of numerical solution of the tractor dynamics in the simulator.



3.3.3 Image generating subsystem

The image generating computer receives forward speed, lateral speed and yaw rate from the main computer and runs an OpenGL simulation of an agricultural field. Using three projectors, a forward FOV of approximately 65° and a vertical FOV of approximately 25° is achieved. The simulated visual scene is relatively simple; it employs 34 textures and consists of approximately 4000 polygons (mostly squares). The update rate, therefore, is not limited by the speed of the image generating code, rather by the speed of communication with the main computer. The overall update rate is approximately 80 Hz. The schematic in Fig. 3.9 shows how the visual scene is generated in the tractor-driving simulator. The field boundary consists of 32 textures, each covering 11.25° of the horizontal field of view. The field surface is generated by a single texture which is repeated in the x and y directions. The image-generating program receives computed vehicle motions from the main program and renders them in two steps:

1) Translational motions (i.e., in the x and y directions) are only applied to the field surface. In other words, the field boundary moves along with the driver's virtual position in the scene.

2) Rotational motion (i.e., the yaw rotation) is applied to the whole visual scene (i.e., both the field surface and the field boundary).

The resulting visual scene can be updated at a high rate by an average desktop computer with a good graphics card. Figure 3.10 shows a view of the visual scene when the simulator is running.

Figure 3.9 A schematic illustrating how the visual scene is simulated in the tractor-driving simulator.

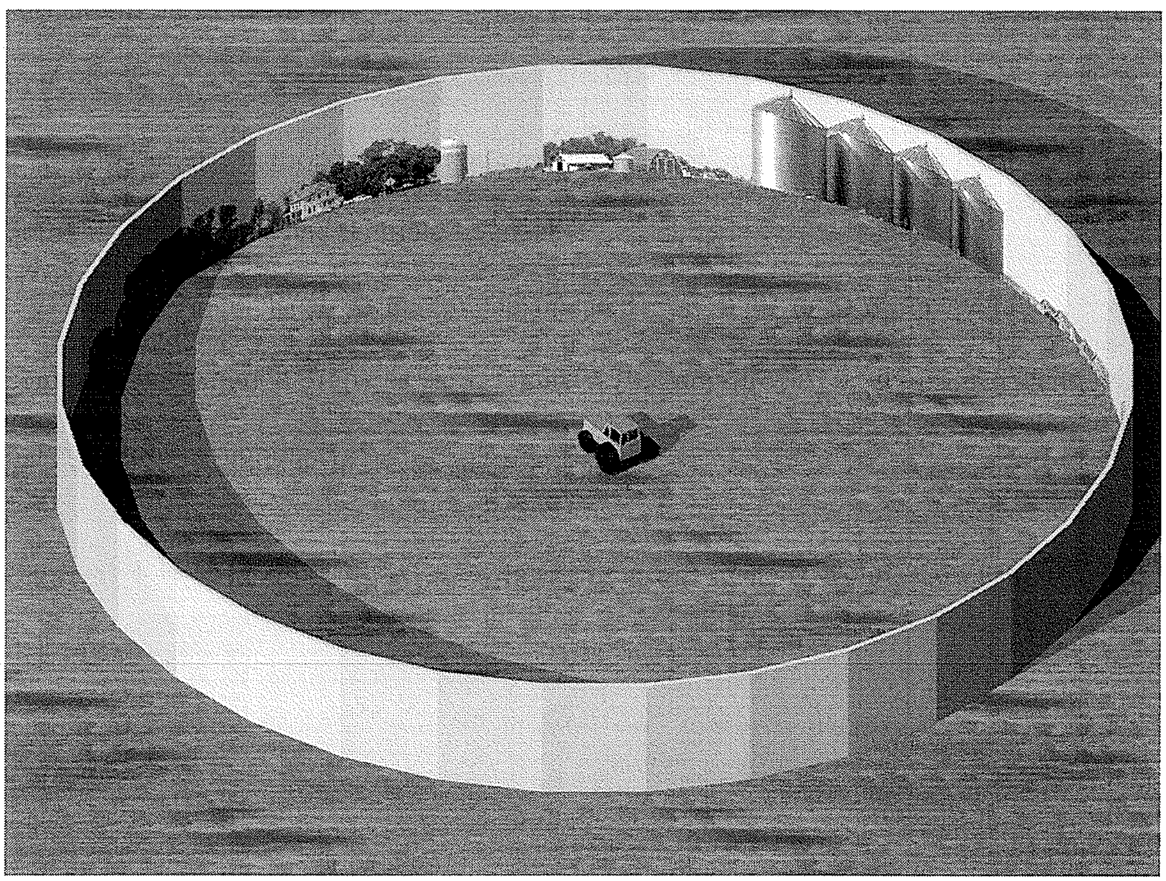
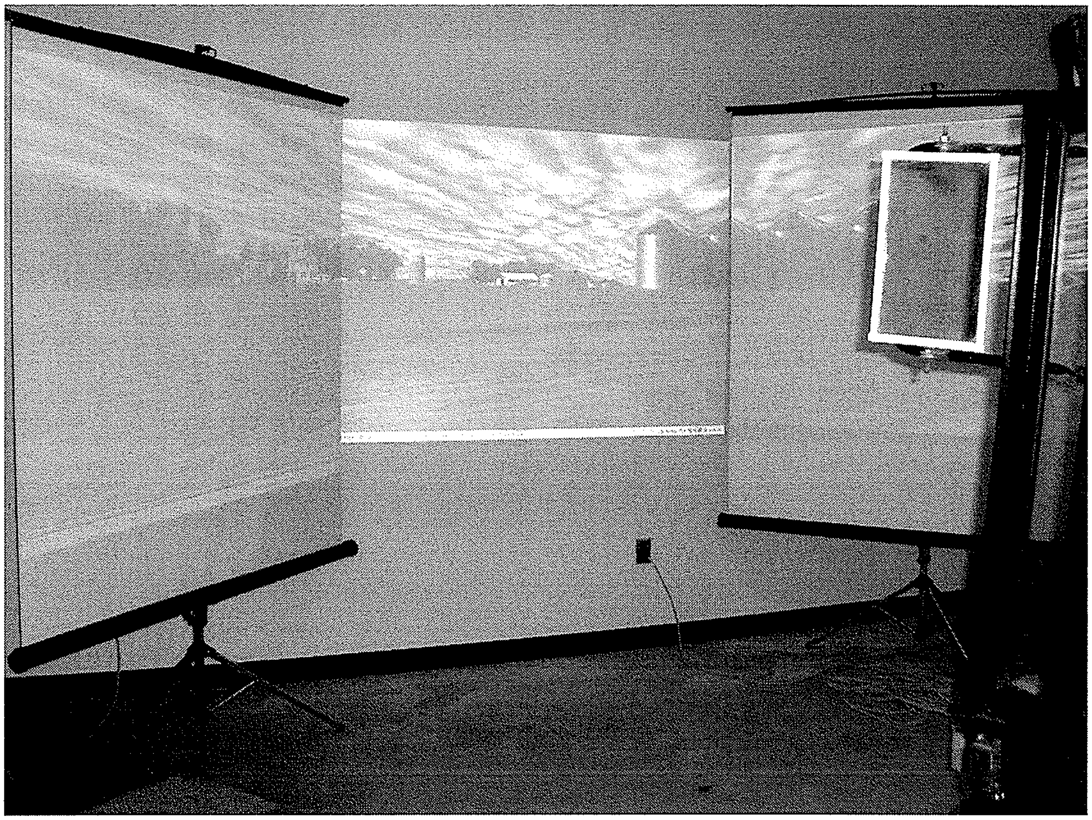


Figure 3.10 The simulated visual scene for the tractor driving simulator.



3.3.4 Steering wheel torque feedback

Steering wheel torque versus steering wheel angle data were collected on several tractors. The transducer used for this measurement consisted of a P-80A string potentiometer (Ametek Inc. CA) and an accurate torque sensor (TQ301 reaction torque sensor from Omega Engineering Inc., CT). Figure 3.11 shows these transducers and how they are used to perform the measurement. A sample of measurements is shown in Fig. 3.12 where dots show the envelope of angle-torque measurements and the lines with arrows indicate how the torque changes as the steering wheel is turned. Figure 3.13 shows the actual relationship between the steering wheel angle and the steering wheel torque as implemented in the simulator.

Figure 3.11 Steering wheel torque feedback measurement in a tractor.

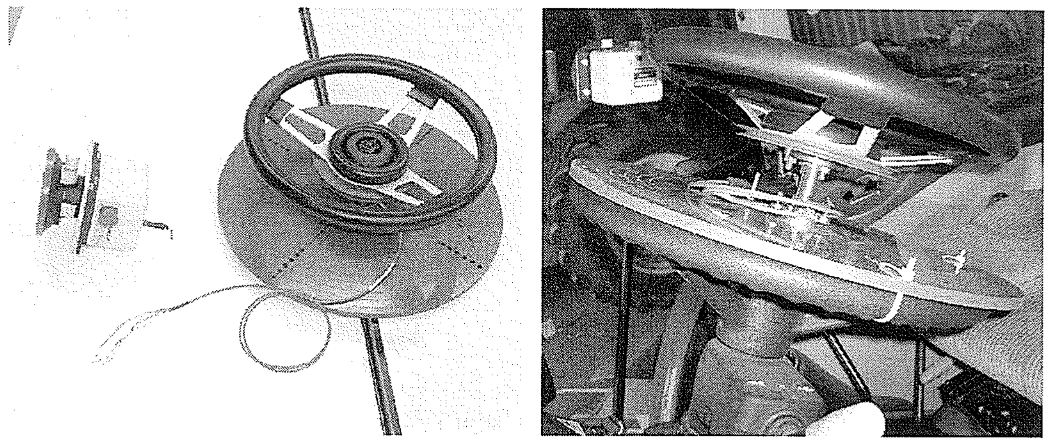


Figure 3.12 Torque feedback measured on the steering wheel of a tractor.

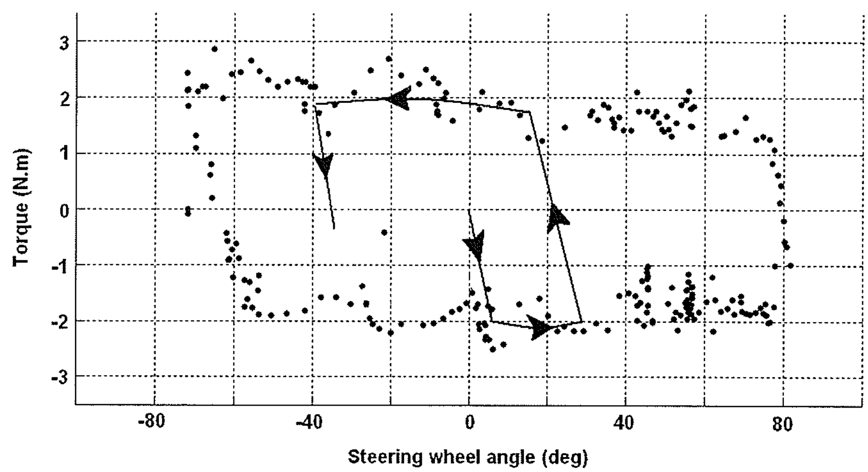
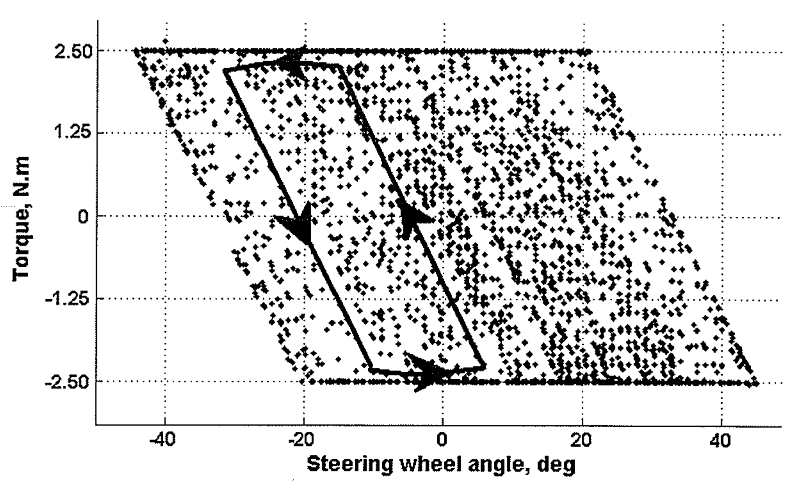
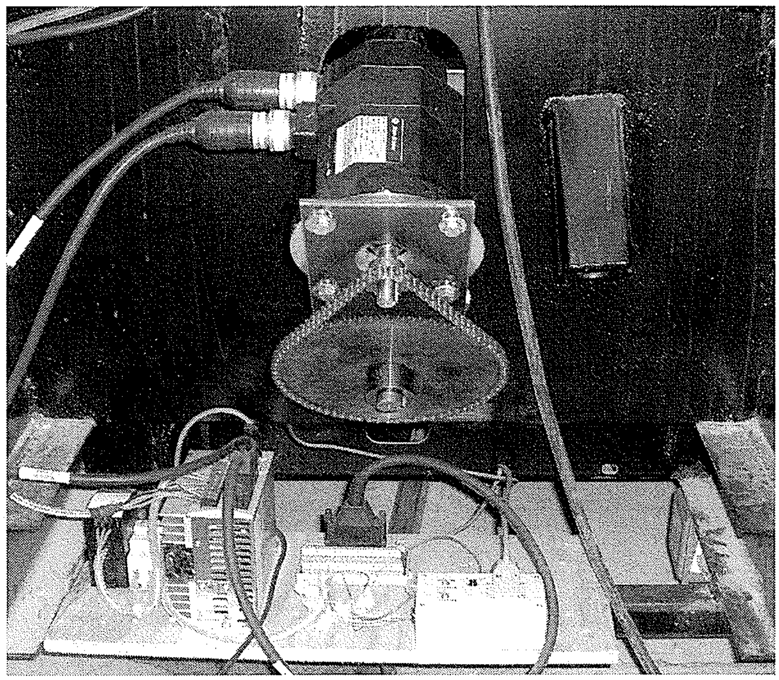


Figure 3.13 Steering wheel torque-angle relationship implemented in the simulator.



The torque feedback on the steering wheel of the simulator is applied by an Allen Bradley AC servo motor controlled by an Ultra 3000i drive (Rockwell Automation, Milwaukee, WI). The servomotor is attached to the steering column of the simulator using a chain and sprocket mechanism (Fig. 3.14).

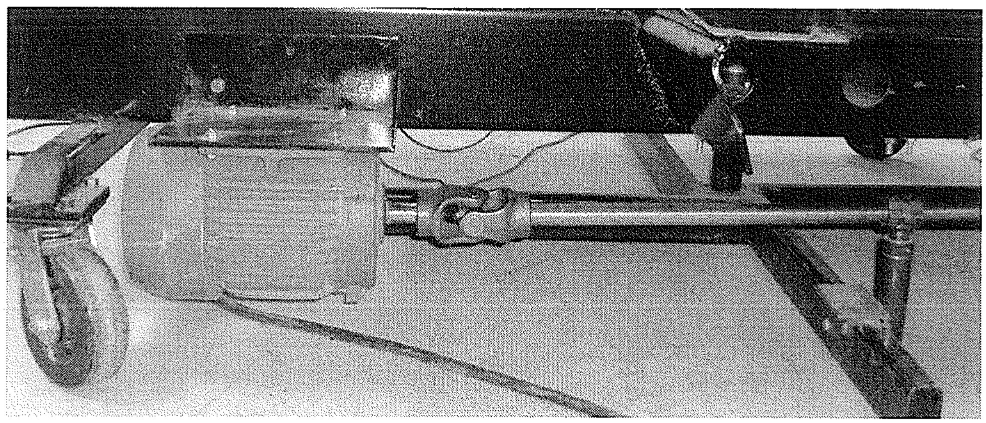
Figure 3.14 Servomotor mechanism on the steering column of the simulator.



3.3.5 Motion system

Because we are concerned about the motion of the tractor in the horizontal plane and because the forward speed is assumed constant for most of the driving tasks, only two motion components are present: yaw motion and lateral motion. From the driver's perspective, yaw motion is much more important than the lateral motion, particularly for driving on a straight line (Weir and McRuer 1968). Therefore, only yaw motion is provided. For this purpose, a screw mechanism had been previously built by the technicians of the Department of Biosystems Engineering at the University of Manitoba. A 1-hp single phase Toshiba AC motor is used to drive this mechanism (Fig. 3.15). The motor has a variable-frequency drive (a Toshiba VF-S7 Industrial Inverter) which is connected to the main computer through a serial port and is controlled by the main program. The rotation of the cab is sensed by an array of seven optical sensors which tell the main computer when the cab is at the center position or when it rotates by 4, 8, and 12° to each side. The main computer read the optical sensor outputs through the PCI-DAS1002 data acquisition board.

Figure 3.15 Electric motor used to generate yaw motion for the simulator.



This setup is capable of providing approximately 30° of yaw motion to the cab (15° to each side from the center position). This range is almost sufficient for the straight line driving scenario. Therefore, a scaling factor of 0.5 is used but no filtering is performed and the yaw motion can be rendered directly.

For driving tasks that involve turns and other maneuvers which are beyond the range of the simulator motion system, motion filtering and scaling is necessary. This is performed in the following three steps:

1. The computed yaw acceleration is high-pass filtered using an FIR filter with a cut-off frequency of 0.73 rad/s. An FIR filter was chosen because IIR filters are nonlinear phase and more appropriate for offline data filtering. On the other hand, FIR filters are

exactly linear phase and always stable. The only drawback with FIR filters compared with IIR filters is that they require a much higher order to achieve the same filtering specifications. Consequently, the delay that they introduce into the system is much longer than that of a similar IIR filter. For an FIR filter of order N, the group delay is N/2 (Oppenheim and Schafer 1975). In other words, all signal samples are delayed by N/2 samples. Therefore, it is essential to choose an order as small as possible. It was decided to use an FIR filter of order 20. Because the computations are performed with a frequency of 50 Hz, an FIR filter of order 20 will introduce a delay of 200 ms which is probably the largest acceptable delay.

2. The electric motor accepts velocity commands. Therefore, the filtered yaw acceleration from the previous step is integrated to obtain the yaw rate. Then, the computed yaw rate is scaled down. Following Groen et al. (2000), a scaling factor of 0.2 is used.

3. When the computed yaw rate from step 2 is zero, the cab is moved very slowly towards the center (neutral) position. This is done at a yaw velocity of $0.15^\circ/\mathrm{s}$.

3.3.6 Noise and vibration

Noise and vibration levels are usually higher in tractors compared to automobiles. Depending on the type of experiments that are to be conducted in the simulator, noise and vibration may or may not be important (Mollenhauer 2004). Pre-recorded tractor noise can be played in the simulator cab and filtered in real time based on tractor forward speed and the engine speed. High-frequency vibrations (with frequencies of up to 30 Hz) are of low amplitude and can be produced by vibration transducers (also called bass shakers) that can be mounted on the driver seat or the body of the simulator (Allen et al. 1998).

Vibrations in the range of 2-10 Hz are of large amplitude and are difficult to produce. This range of frequencies, however, is important because it has the most significant effect on operator comfort (Matsumoto and Griffin 2005). Systems that are built to produce vehicle motion due to the driver steering are not capable of generating vehicle vibrations because the output of the corresponding actuators saturate at frequencies above 3 Hz. Therefore, specific actuators are needed to produce vibrations in the range of 2-10 Hz. Shaking the operator seat might be the only option. The tractor-driving simulator does not currently include any system for creating vibration.

3.4 Example application of the tractor driving simulator

3.4.1. Tasks completed by an operator using a lightbar guidance system

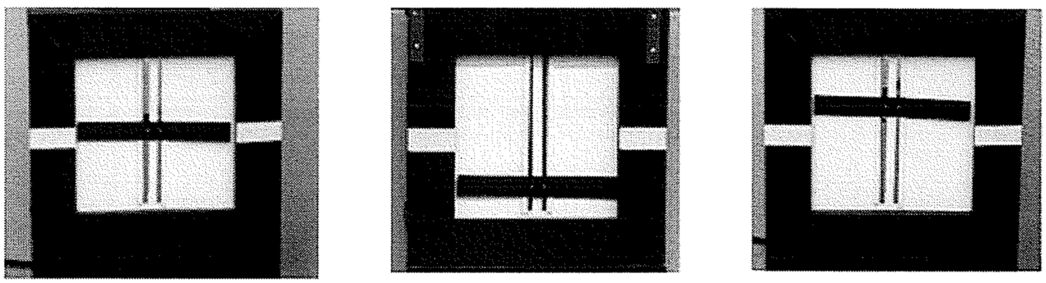
The tractor-driving simulator has been used to research agricultural guidance systems from a human factors perspective. Agricultural guidance systems have changed significantly over a short period of time (Wilson 2000). During the past decade, there has been a rapid influx of ideas based on global positioning system (GPS) technology, beginning with 'lightbar' navigation aids (that presented supplemental navigation information for the driver) and now auto-steer systems (that make steering corrections for the driver). This rapid change in technology has significantly changed the role to be played by the human operator of the agricultural vehicle. Human factors principles are needed to understand how best to utilize the capabilities of the human operator in these new human-machine systems. The following sections describe modifications that were made to the simulator to undertake this research.

To be able to incorporate appropriate features in the simulator, it was first necessary to study the task of operating an agricultural vehicle. Typical task analysis methodologies were used to identify the most common sub-tasks associated with operating an agricultural vehicle. A self-propelled agricultural sprayer was selected because, at the time, GPS technology was most commonly used during spraying operations. Details of the task analysis procedure and results can be found in Young (2003). A summary of the outcome of the task analysis is as follows: operators use the GPS lightbar as the main source of information for steering the sprayer. Most drivers also used an aiming point, which is an object on the horizon or in the field toward which they drove. Operators allocated anywhere from 10-50% of their time to controlling the sprayer booms. They also scanned other displays in the sprayer cab. These included i) a mapping system, which shows a bird's-eye view of the field with the tractor's position in the field and the places where the spraying has been performed, and ii) an application display, which provides such information as the field area covered, forward speed, and the amount of solution in the sprayer tank.

3.4.2 Features added to the tractor-driving simulator

A lightbar was built using 23 LEDs; there were three green LEDs in the centre with 10 red LEDs on each side. A multi-function joystick control was added to the right of the operator's seat. A task similar to boom height control was created. A display containing a moving bar (Fig. 3.16) was located in the line of sight for an operator looking to the end of a 30 m boom. When the bar is centered, no control action is required. If the bar is above or below centre, the operator must use a button on the joystick to move the bar back to centre. Only one press of the correct button is required. In each display, the bar moves from centre independently and is returned to centre by the operator. Each display operated independently of the other. Time between the last return and the next movement can be specified by the experimenter.

Figure 3.16 The displays used to mimic the monitoring function. The desired state is for the black bar to be in the centered position (left). If the black bar is in either the down position (middle) or the up position (right), appropriate control action must be taken by the operator.



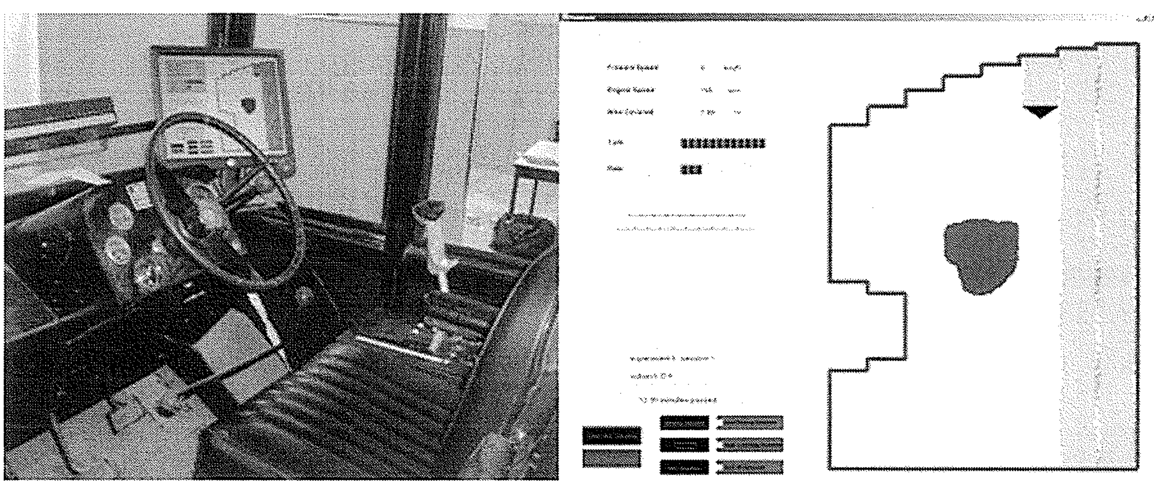
A 'field mapping and application' display was developed (Fig. 3.17). The main computer code of the simulator, which is run by the main computer (Fig. 3.1), is in Visual Basic .NET. The field mapping and application display is presented to the subject in the simulator by an LCD monitor that is connected to the monitor of the main computer using a video splitter. An array of buttons and switches are mounted on the operator console and are intended to imitate controls for turning on or off different sections of the boom or the pump in the sprayer tank. The display reflects the states of these switches in a suitable graphical or textual way.

3.5 Conclusion

Driving simulators provide unique advantages for research in many areas including driver behaviour. Efforts of engineers and psychologists and advancements in computer hardware and software have provided sufficient knowledge and adequate tools for developing relatively inexpensive driving simulators that can be used for research. This chapter described a tractor-driving simulator that has been developed, noting key differences that exist with automobile-driving simulators. The tractor-driving simulator developed at the University of Manitoba currently includes systems for providing visual, motion, steering force, and auditory feedback to drivers. A system for subjecting the driver to vibration has not yet been realized.

To enable the tractor-driving simulator to be used to research the ergonomics of GPS guidance systems, several controls and displays were added to the simulator to reflect the task of operating a self-propelled agricultural sprayer. It is anticipated that the simulator can be used in future research to study the role of the human operator in semi-automated and fully-automated tractor-machine systems.

Figure 3.17 The field mapping and application display as it appears on the main form of the simulator code (right) and in the simulator cab (left).



4. MODELING OF STRAIGHT-LINE DRIVING WITH A GUIDANCE AID FOR A TRACTOR-DRIVING SIMULATOR

4.1 Summary

Minor steering corrections are necessary to keep a tractor moving in a straight line. If the factors that cause such steering corrections are not considered in the implementation of a driving simulator, the task of straight-line driving will be both unrealistic and too simple. The objective of this study was to develop and validate a model, for simulation of parallel swathing in a tractor-driving simulator, which accounts for both guidance system error and tractor self-deviation. Guidance system error and tractor self-deviation were both measured by an RTK GPS system. Fourier analysis was used to determine the energy spectrum in high, medium, and low-frequency regions. Complex sinusoids which had similar energy distributions to those obtained from field measurements were proposed for both guidance system error and tractor self-deviation. To validate the straight-line driving model, root mean square (RMS) and frequency composition of lateral deviation of the vehicle were determined for both the tractor-driving simulator and several real systems consisting of a tractor, driver, and lightbar guidance device. Six subjects participated in the simulator study. On average, the RMS of lateral deviation was 33 cm. The energy distribution was 32% in the high-frequency region, 39% in the medium-frequency region, and 29% in the low-frequency region. Field experiments with a single driver with seven distinct lightbar guidance systems yielded an average RMS of lateral deviation of 15 cm. The energy distribution was 27% in the high-frequency region, 41% in the medium-frequency region, and 32% in the low-frequency region. Field experiments with seven drivers using a single lightbar guidance

device yielded an average RMS of lateral deviation of 30 cm. The energy distribution was 30% in the high-frequency region, 40% in the medium-frequency region, and 30% in the low-frequency region. Field experiments showed close agreement with simulator experiments in terms of the frequency composition of the lateral deviations.

4.2 Introduction

Driving simulators date back to the 1970s when General Motors developed one of the first driving simulators (Gruening et al. 1998). Today, driving simulators are being used as effective research tools in several areas including vehicle system development and human factors studies. They enable researchers to reproduce real driving situations in a safe and easily controllable environment (Lee et al. 1998). Rapid increases in the computational power and graphic capabilities of desktop computers over the last decade have enabled researchers to build high fidelity driving simulators at reasonably low cost. Although driving simulators have been extensively used in the automotive industry for many years, only a small number of driving simulators have been developed for agricultural vehicles; the work by Wilkerson et al. (1993) is one of the few examples.

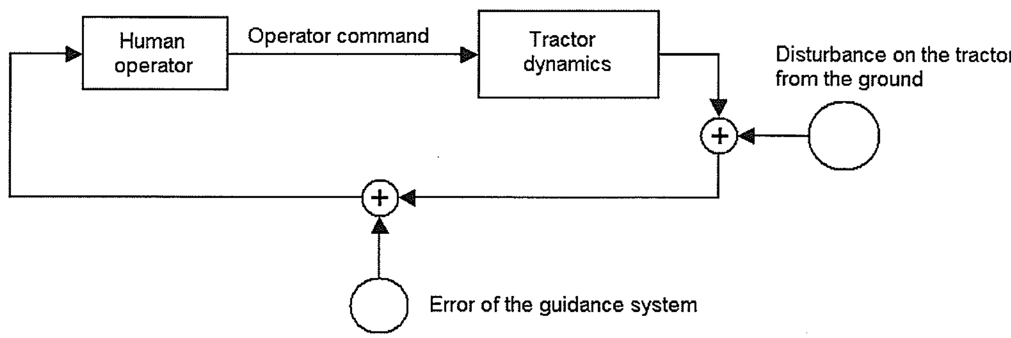
Most field operations are performed in parallel swathing mode which consists of driving the agricultural vehicle along a series of parallel paths to cover the entire field. Although the desired path might be a straight line, the driver has to constantly make steering adjustments to keep the tractor on target due to unevenness of the field surface and imperfections in both the vehicle and the guidance system. A good tractor-driving simulator must provide a realistic replication of straight-line driving. For straight-line driving on a simulator to be realistic, the simulator must account for the factors that contribute to deviations of the tractor from the desired straight line. The nature of these factors must be described in mathematical terms.

In some ways, automobiles are similar to tractors because imperfections that contribute to lateral deviations exist in both systems. Standard Deviation of Lateral Lane Deviations (SDLLD) has been used to compare the performance of automobile-driving simulators to actual automobile driving (Allen et al., 1994). It is common for SDLLD to be smaller for simulator driving than for automobile driving, possibly because automobile-driving simulators do not consider the minor imperfections that exist in real driving conditions (Green, 2005). To prevent this problem, Green (2005) suggested introducing some disturbance to cause the simulated vehicle to deviate from the straight path.

Despite the similarities between a tractor and an automobile, the nature of disturbances is quite different due to different driving surfaces and forward speeds. Furthermore, tractor operators often use a guidance system to achieve higher straight-line driving accuracy. The interaction between the driver, the tractor, and the guidance system in straight-line driving can be illustrated by a simplified block diagram (Fig. 4.1). Motion of the tractor is a superposition of the movements due to steering commands and the disturbance from the ground surface. The guidance system has its own error. Proper simulation of the straight line driving requires an understanding of both the disturbances on both the vehicle and the guidance system error.

The objective of this study was to develop and validate a model for simulation of parallel swathing in a tractor-driving simulator that accounts for both guidance system error and tractor self-deviation.

Figure 4.1 Block diagram representation of driving in parallel swathing mode.



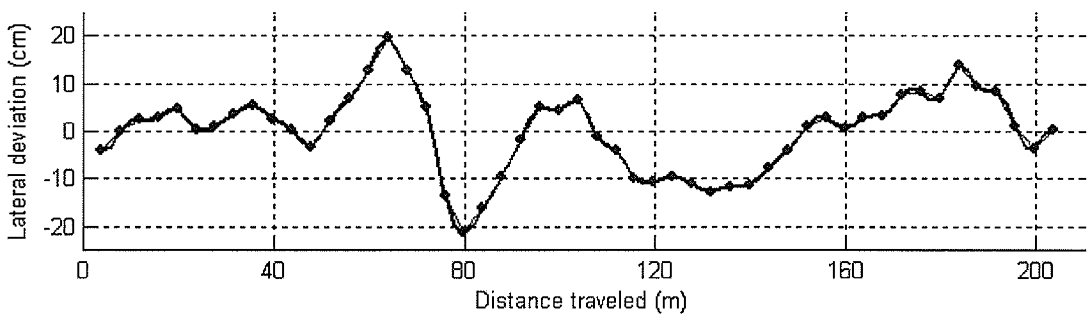
4.3 Procedure for Model Development and Validation

The first step in developing the straight-line driving model was to determine mathematical descriptions of guidance system error and tractor self-deviation. After modifying the code of the tractor-driving simulator, experiments were completed with the simulator. Root mean square (RMS) and frequency composition of lateral deviation of the vehicle were determined. Field experiments were also completed using tractors driven through agricultural fields in response to guidance information provided by lightbar navigation devices. RMS and frequency composition of lateral deviation of the vehicle were determined. Comparison of the data obtained with actual vehicles to the data obtained with the tractor-driving simulator was used to determine the validity of the straight-line driving model.

4.4 Data Analysis Procedures

The raw data collected in this study was position data of either the real vehicle or the simulated vehicle. These position data were analyzed by first calculating the deviation from the desired straight line (i.e., cross track error) for each pass. Then, Fourier analysis was performed to obtain the frequency composition of these deviations. Discrete Fourier analysis requires data points to be equally-spaced. Because this was not the case for the data, a spline curve was first fitted to the data points. The number of pieces of the spline was increased until the spline passed through all data points, eliminating fitting error. Figure 4.2 shows an example of the error data and the fitted spline curve.

Figure 4.2 A sample plot of the error of the lightbar guidance system (solid circles) and a spline curve fitted to these points.



Next, a continuous-time Fourier transform was applied to the spline curve y(x) (Oppenheim et al., 1997):

$$Y(j\omega) = \int_{-\infty}^{+\infty} y(x)\, e^{-j\omega x}\, dx \tag{4.1}$$

where:

x = distance along the path

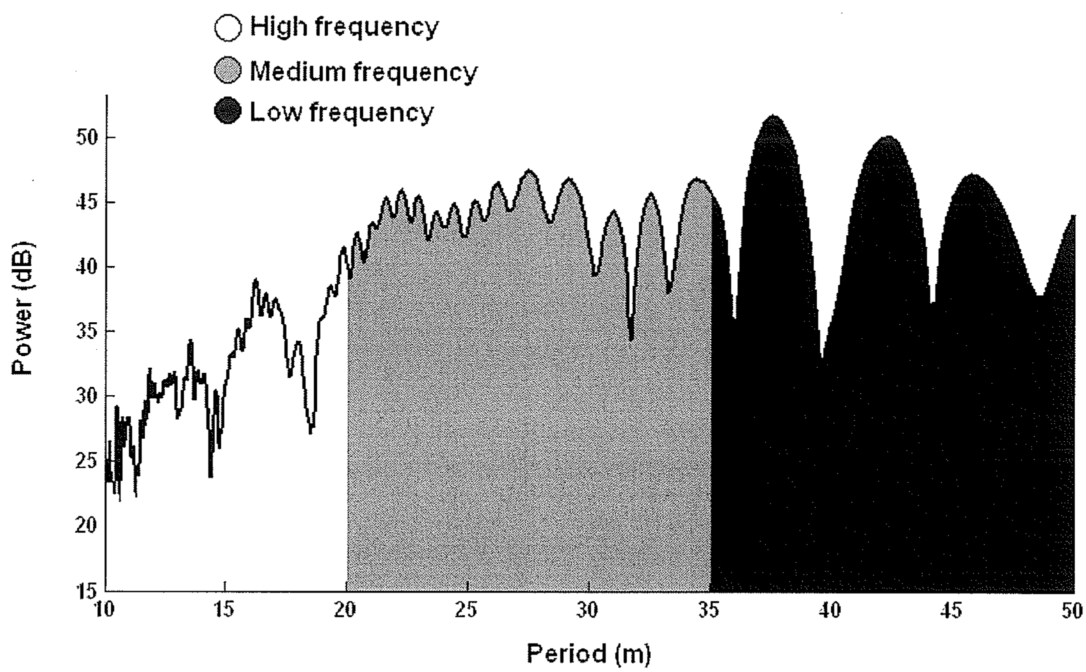
y(x) = driving error at position x

$Y(j\omega)$ = value of Fourier transform for frequency equal to ω

ω = frequency, here ω is 'positional frequency'; since x is distance (m), the dimension of ω is 1/distance (i.e., L^{-1}).

An example of the resulting spectrum is shown in Fig. 4.3.

Figure 4.3 A sample spectrum of the error of the guidance system.



The horizontal axis is in the period, T, instead of the frequency, ω, because it is easier to interpret. In fact, T is twice the distance traveled during each excursion for the specific harmonic. T is in units of m, and is related to ω through the following equation:

$$T = \frac{2\pi}{\omega} \tag{4.2}$$

The spectrum was divided into three parts:

- T= 10 to 20 m, the high-frequency region
- T= 20 to 35 m, the medium-frequency region
- T= 35 to 50 m, the low-frequency region

Because data were recorded at 4-5 m intervals along the path, the computation of the spectrum for periods smaller than 10 m was not possible based on Nyquist criterion. Also, because of limited length of each pass (less than 200 m in most cases), computation of the frequency spectrum was not valid for periods larger than 50 m. These are the reasons for choosing the frequency ranges.

The energy of the power spectrum for the range of frequencies ω_1 to ω_2 can be computed using the following equation:

$$\text{energy} = \frac{1}{2\pi} \int_{\omega_1}^{\omega_2} \left|Y(j\omega)\right|^2 d\omega \tag{4.3}$$

For each pass, energy of the spectrum in each of the three regions was computed. Then, the energy in each of the three regions was divided by the total energy in the spectrum to obtain the normalized values (in percentage) for each of the three regions.

4.5 Error of a Lightbar Guidance System

This experiment was performed to evaluate the error of a lightbar guidance system. Although this error will be dependent upon the specific characteristics of the lightbar guidance device, a thorough characterization of the error of all lightbar guidance devices is beyond the scope of this research. The decision was made to investigate the error of one commercial system - the Outback® S (Hemisphere GPS, Calgary, Alberta, Canada) – because of its availability.

This experiment was performed in a parking lot on the campus of the University of Manitoba, Canada; a Leica GPS1200 RTK (Leica Geosystems, St. Gallen, Switzerland) system was used to provide accurate measurements. The antenna of the lightbar guidance system was placed close to the RTK GPS antenna on a small, four-wheeled cart. The lightbar was also placed on the cart. Parallel-swathing runs were performed by manually guiding the cart according to the lightbar signal. Because the cart was easily maneuverable and tests were performed at low speed (approximately 0.3 m/s), it was possible to achieve zero error on the lightbar for most of the duration of the test. Once the error shown on the lightbar was not zero, data logging was stopped until the lightbar error was re-zeroed (i.e., by adjusting the position of the cart). Consequently, the experiment produced a set of RTK data points showing the trajectory of the lightbar antenna when the lightbar indicated no lateral error.

The root mean square (RMS) of error of the lightbar system was approximately 14 cm. Fourier analysis showed that, on average, 23% of energy of the spectrum was in the high-frequency region, 38% in the medium frequency region, and 36% in the low-frequency region of the spectrum. The mathematical function to be added to the tractor-driving simulator to represent guidance system error (Fig. 4.1) should have similar characteristics.

The literature on human tracking control suggests that a sum of three or more sinusoids with different frequencies is perceived as random to human operators (Jagacinski and Flach, 2002). Therefore, it is sufficient for this function to be a summation of three or more sinusoids. The third condition is that the RMS of the function values should be approximately 14 cm. The following mathematical function, for example, satisfies these three requirements.

$$y(x)=9.6\sin(0.42x)+12.3\sin(0.25x)+12\sin(0.16x) \qquad (4.4)$$

where:

$y(x)$ = the cross-track error of the lightbar guidance system (cm)

x = distance traveled (m).

4.6 Disturbance due to Tractor Self-deviation

This experiment was conducted to develop an insight into the nature of the disturbance on a tractor moving in a straight line. Once again, a comprehensive examination of this phenomenon is beyond the scope of this study. Rather, the goal was to gain some general knowledge about this phenomenon by studying a specific case. Therefore, only one tractor was used. The tractor, a John Deere 5425, was driven on both loose and compacted agricultural soil. John Deere 5425 is a four wheel drive tractor with 3057 kg weight and 60 kW engine power. No steering adjustments were made by the operator so the deviations were due to tractor self-deviation. Forward speed was constant at 6 km/h. The same RTK GPS system as in the previous experiment was used and provided a measurement accuracy of less than 2.5 cm.

After some distance, perhaps 30 m, the tractor will deviate a large amount from the straight line. Such deviations are not of interest in this study because the tractor driver does not allow such large deviations when operating agricultural machines. The small deviations that occur over short distances more accurately reflect the tractor self-deviations expected in a field setting. Therefore, in this experiment, exact tractor position was recorded every 1.2 m. Data were analyzed using the procedures described above, except different definitions of high, medium, and low-frequency regions were selected as follows:

- T= 2.5 to 5 m, the high-frequency region
- T= 5 to 10 m, the medium-frequency region
- T= 10 to 15 m, the low-frequency region

Because the goal was to investigate the self-deviation of a tractor over short travel distances, the data collected were segmented into small portions each representing a travel distance of approximately 30 m. The RMS of tractor deviation was approximately 6 cm. Fourier analysis showed that 41% of energy of the spectrum was due to high frequencies, 36% due to medium frequencies, and 23% due to low frequencies. Following the same rationale as presented in the previous section, the following equation will be adequate to model tractor self-deviation in the tractor-driving simulator:

$$y(x)=4.5\sin(1.6x)+4.2\sin(0.8x)+3.4\sin(0.5x) \tag{4.5}$$

where:

$y(x)$ = self-deviation of tractor (cm)

x = distance traveled (m).

4.7 Performance of the Straight-line Driving Model

The tractor-driving simulator used in this study is located in the Agricultural Ergonomics Laboratory in the Department of Biosystems Engineering, University of Manitoba. It is a fixed-base simulator (Fig. 4.4) that provides visual feedback with a horizontal field-of-view of 65° and torque feedback on the steering wheel. The flowchart shown in Fig. 4.5 illustrates how straight-line driving happens in the tractor-driving simulator. Modifications were made to the code of the tractor-driving simulator to incorporate both guidance system error and tractor self-deviation.

An experiment was conducted using the tractor-driving simulator. Seven subjects participated in the simulator experiments. Subjects were all students at the University of Manitoba and none of them were experienced tractor drivers. Therefore, each subject was

Figure 4.4 View of the front of the driving simulator (left) and a schematic showing the setup of the visual display during operation (right).

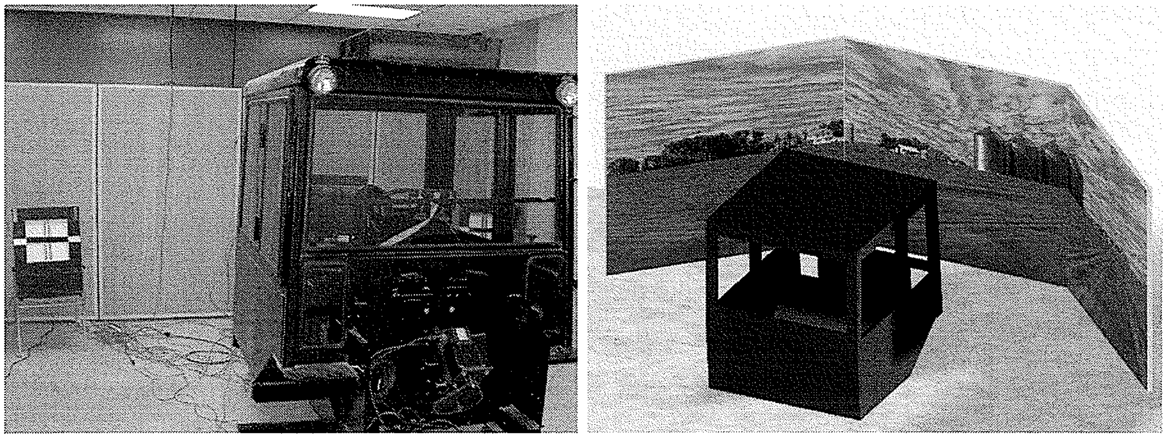
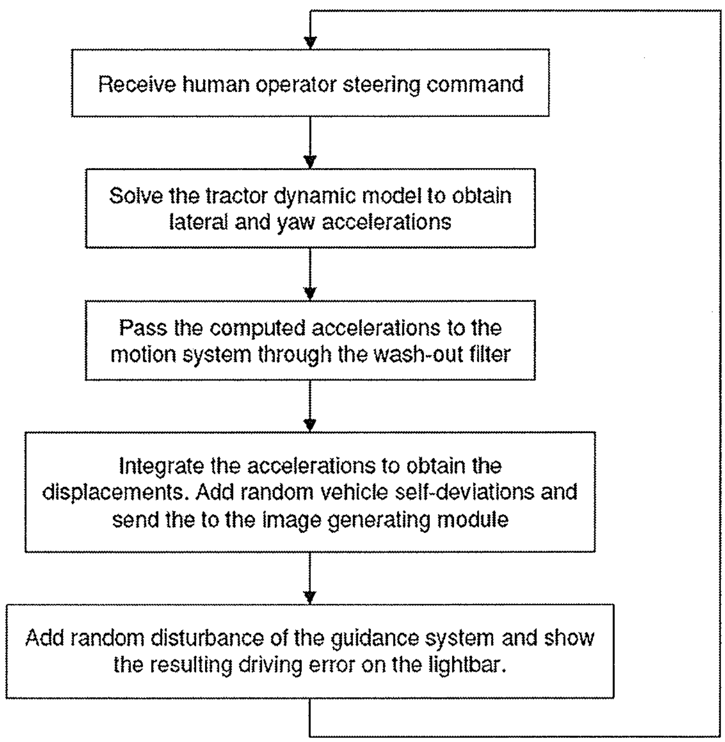


Figure 4.5 Flowchart illustrating the operation loop of the simulator.



given enough time to become familiar with the tractor-driving simulator and the experimental task of driving in parallel swathing mode with guidance information provided by a lightbar guidance system. Each subject then drove in the simulator for 12 min. Forward speed was constant at 8 km/h. The exact position of the simulated tractor was recorded. Data were analyzed using the procedures previously described.

On average, 29% of energy of the spectrum was in the high-frequency region, 39% was in the medium-frequency region, and 32% was in the low-frequency region (Table 4.1). There was no statistically significant difference in the frequency composition of lateral deviations between drivers. The RMS of driving error was 33 cm.

Table 4.1 RMS of lateral deviation and energy of high, medium, and low-frequency regions of the spectrum observed during simulator experiments.

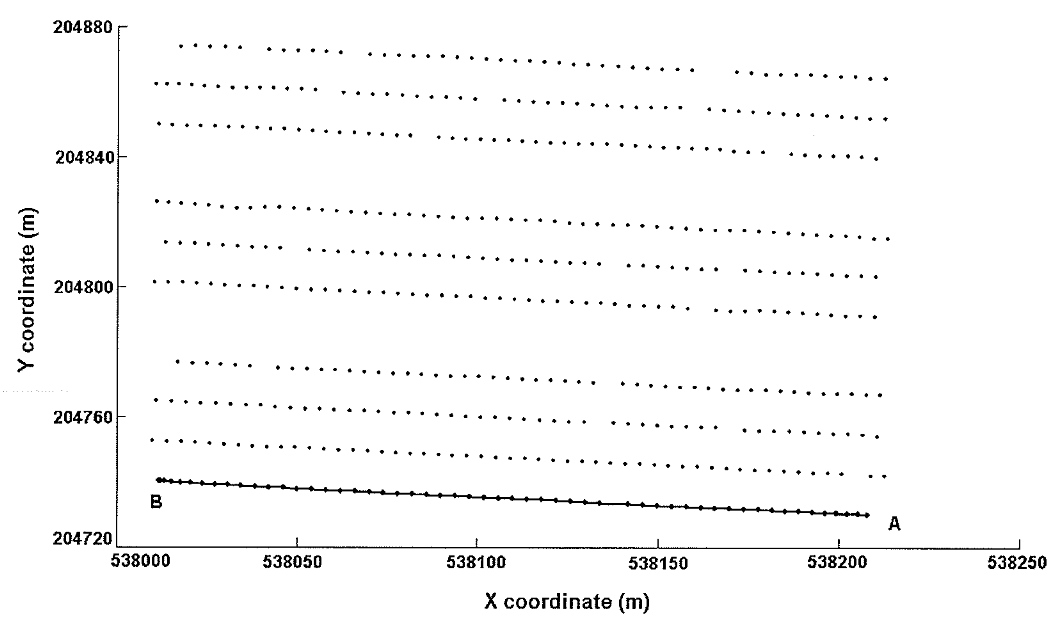
Driver	RMS of lateral deviations (cm)	Energy of high-frequency region of spectrum (%)	Energy of medium-frequency region of spectrum (%)	Energy of low-frequency region of spectrum (%)
1	31	28	43	29
2	30	32	41	27
3	36	25	43	31
4	31	31	43	26
5	36	27	33	40
6	34	28	32	40

4.8 Field Validation of the Straight-line Driving Model

To validate the straight-line driving model, field data were collected for comparison with the data collected using the tractor-driving simulator. Two sets of data were used in the validation process. The first set of data comes from an experiment completed in an 8-ha wheat field in central Ohio in 2001. Seven different lightbar guidance systems; Cultiva, John Deere, Midtech, Outback, Raven, Satloc, and Trimble, were used for parallel swathing. Guidance systems were randomly selected and the same driver and tractor (John Deere 4640) were used for all tests. To determine the exact location of the tractor in the field, a RTK GPS was used (Trimble 4800 rover unit and Trimble 4600 base station). The driver had minimal experience using lightbar systems prior to the experiment and the forward speed was 8 km/h. A detailed description of the experiment is available in Ehsani et al. (2002).

Figure 4.6 shows a sample of the data after removing data points from the headland turns. Small dots indicate the exact position of the tractor in the State Plane Coordinate System. Line A-B is the first pass, after which the driver made several parallel passes using guidance information provided by a lightbar guidance system. For each pass, an analysis identical to that described previously was performed to calculate the frequency composition of lateral deviations of the tractor from the straight line.

Figure 4.6 An example of driving path data provided by RTK-DGPS measurement of tractor location.



On average, 27% of the energy of the spectrum was in the high-frequency region, 41% in the medium-frequency region, and 32% in the low-frequency region (Table 4.2). Analysis of variance was completed to examine the effect of the guidance system using a Tukey's test with α=0.05. Statistically significant differences were observed in the frequency composition of lateral deviations between the seven guidance systems (Table 4.2).

Table 4.2 RMS of lateral deviation and energy of high, medium, and low-frequency regions of the spectrum observed during field experiments; a single driver used seven different GPS lightbar systems. Different superscripts within the same column indicate statistically significant differences

Guidance System	RMS of lateral deviations (cm)	Energy of high-frequency region of spectrum (%)	Energy of medium-frequency region of spectrum (%)	Energy of low-frequency region of spectrum (%)
1	11^{a}	$28^{a,b,c}$	$39^{a,b}$	$33^{a,b,c}$
2	11^{a}	33^{c}	$39^{a,b}$	28^{a}
3	$13^{a,b}$	$25^{a,b}$	47^{c}	$28^{a,b}$
4	$14^{a,b,c}$	$22^{a,}$	$43^{a,b,c}$	35^{c}
5	$17^{b,c}$	$25^{a,b}$	$40^{a,b,c}$	35^{c}
6	18^{c}	$25^{a,b}$	$41^{a,b,c}$	$32^{a,b,c}$
7	19^{c}	$29^{b,c}$	38^{a}	$33^{a,b,c}$

Additional data for validation of the model were collected in an agricultural field in Manitoba, Canada in the summer of 2007. Seven drivers drove a John Deere 5425 tractor using an Outback S® lightbar system in parallel swathing mode. Although all of the drivers were experienced in driving tractors, none of them had previously used a lightbar guidance system. Therefore, they were given some training time to become familiar with the guidance system. Furthermore, during actual tests, they were instructed to choose a comfortable forward speed. A Leica GPS1200 RTK system was used to record the exact tractor path.

Mean values for each driver are shown in Table 4.3. Averaging the data from all drivers shows that 30% of energy of the spectrum was in the high-frequency region, 40% in the medium frequency region, and 30% in the low-frequency region. Statistical analysis showed no significant differences between the results for different drivers ($\alpha = 0.05$).

As mentioned before, lateral deviations of a vehicle from the desired straight line, as characterized by RMS and frequency composition of these values, were used to assess the validity of the proposed model for straight-line driving in a tractor-driving simulator. The RMS of lateral deviations is expected to depend on the driver's skill in guiding the tractor, whereas frequency composition of the deviations has a direct relation with the frequency of steering adjustments by the driver and is a good indicator of the task difficulty. Table 4.4 shows the results of the analysis of variance which is used to compare the results from the simulator experiment to the two sets of field experiments.

Table 4.3 RMS of lateral deviation and energy of high, medium, and low-frequency regions of the spectrum observed during field experiments; seven different drivers used a single GPS lightbar system. Different superscripts within the same column indicate statistically significant differences.

Driver	RMS of lateral deviations (cm)	Energy of high-frequency portion of spectrum (%)	Energy of medium-frequency portion of spectrum (%)	Energy of low-frequency portion of spectrum (%)
1	$32^{a,b}$	33^{a}	39^{a}	28^{a}
2	34^{a}	21^{a}	46^{a}	33^{a}
3	36^{a}	32^{a}	40^{a}	28^{a}
4	$28^{a,b}$	30^{a}	42^{a}	28^{a}
5	$26^{a,b}$	32^{a}	33^{a}	35^{a}
6	20^{b}	30^{a}	37^{a}	33^{a}
7	36^{a}	29^{a}	43^{a}	28^{a}

Table 4.4 Comparison of the results obtained from the simulator experiment and the two field experiments. Different superscripts within the same column indicate statistically significant differences.

Experiment	RMS of lateral deviations (cm)	Energy of high-frequency portion of spectrum (%)	Energy of medium-frequency portion of spectrum (%)	Energy of low-frequency portion of spectrum (%)
Simulator	33^{a}	28^{a}	39^{a}	32^{a}
Field 1	15^{b}	27^{a}	41^{a}	32^{a}
Field 2	30^{a}	30^{a}	40^{a}	30^{a}

The results show close agreement of the simulator results with field observations in terms of the frequency composition of lateral deviations. The RMS of the lateral deviations was statistically the same for the simulator experiment and the second field experiment whereas the first field experiment produced a lower RMS value. We believe this was because the single driver used in the first field experiment was highly experienced. Based on the agreement in frequency composition of lateral deviations of the tractor between the simulator and field experiments, it can be said that the proposed model works well.

4.9 Conclusion

The objective of this study was to develop and validate a model of straight-line driving with a tractor for application in a tractor-driving simulator. Error of a typical lightbar guidance system and self-deviation of a typical tractor were measured to provide representative data for development of the model. The lateral deviations of a tractor during parallel swathing can be characterized by RMS and frequency composition of the deviations. These two values were used as criteria to compare performance of the modified tractor-driving simulator with field data. Field experiments showed close agreement with simulator experiments in terms of the frequency composition of the lateral deviations. The results of this study show that frequency-domain characterization of error of the guidance system and tractor self-deviation can be used to simulate straight-line driving in a tractor-driving simulator with adequate fidelity.

5. ROLE OF MOTION CUES IN STRAIGHT LINE DRIVING OF AN AGRICULTURAL VEHICLE

5.1 Summary

Driving simulators open new opportunities for research in a wide range of areas including human factors and ergonomics. The main concern regarding driving simulator research is the validity of the results. Therefore, one would like to know which sensory cues are used by the human driver. This study investigates the effect of motion cues in straight-line driving of a tractor. Field experiments were conducted in which experienced tractor drivers drove a tractor in parallel swathing mode with the help of a lightbar guidance system. Driving simulator experiments were then performed in which experienced tractor drivers drove in two sessions: in one session motion cues were provided whereas in the other session motion cues were not delivered. Analysis showed that in the absence of motion cues, the drivers significantly increase their control activity and their performance deteriorates. It is also shown that drivers are unable to respond to the full range of disturbances on the tractor and the guidance system and that they automatically reduce the open-loop crossover frequency by reducing their gain, in order to avoid high tracking errors. In the presence of motion cues, drivers adopted a more relaxed driving style by reducing their gain and lead time constant. Using a multiloop feedback scheme it is shown that if the driver uses both tractor lateral deviation and yaw rate as feedback variables, he/she can drive the tractor with no lag or lead equalization.

5.2 Introduction

The first driving simulators were developed in the 1970s (Gruening et al., 1998) and since that time they have been used for research, training, and other purposes such as vehicle and roadway design (Rakauskas et al., 2004; George, 2003). Driving simulators provide safe and easily controlled experimental conditions in which an experiment can be run many times with the same or arbitrarily modified experimental variables at a much lower cost compared to real road or field tests. Questions, however, arise regarding the validity of driving simulator research. For driving simulator research to be valuable, the driving simulator must replicate the real world conditions to an acceptable degree. Driving simulator validity is defined at two levels: 1) physical validity (or fidelity of the driving simulator) refers to the correspondence of the components, layout, and dynamics of the simulator with the real vehicle, whereas 2) behavioral validity (or predictive validity) describes how close the simulator is to the real world scenario in the way the human driver behaves (Godley, 1999). In other words, a driving simulator has behavioral validity if it elicits from the driver responses and behaviors which are close to the ones that he/she would have shown under real world conditions. For research purposes the behavioral validity is of foremost importance. No research has been reported on the conditions and requirements for validity of tractor driving simulation.

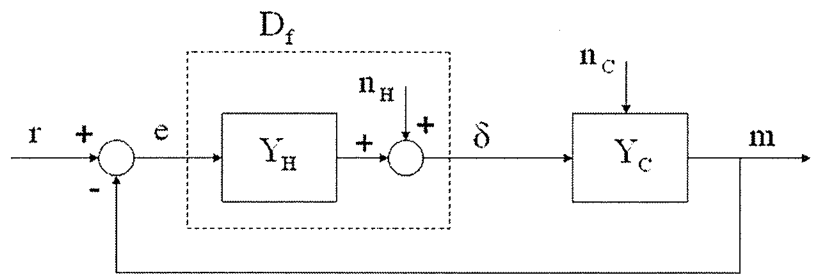
The sensory cues used by the driver to accomplish a driving task may include visual, vestibular, proprioceptive, haptic, and auditory cues. Vestibular cues are sensed by vestibular organs in the inner ear and tell us about the position and orientation of our head and, therefore, help us to perceive linear and rotational motions. Proprioceptive cues inform us about the relative position and motion of our body parts and originate from sensors (proprioceptors) which are chiefly found in muscles, tendons, and joints (Schmidt & Lee, 1999). Vestibular and proprioceptive cues together are called motion cues. The importance of each of these cues depends on the driving task being performed. Although some experiments have shown that human drivers are able to perform certain maneuvers based solely on visual information, other experiments have demonstrated significant influence of the other types of sensory cues (e.g. Siegler et al., 2001). Motion cues, particularly, have been shown to be essential to many driving tasks while haptic and auditory cues often have less importance (Macadam, 2003).

Although there has been much research on sensory cue requirements for flight simulators and automobile driving simulators (Kemeny and Panerai, 2003), there has been no such research reported for agricultural vehicles. This is despite the fact that driving of an agricultural vehicle has significant differences with automobile driving and involves a different pattern of sensory cues. For example, visual cues such as road edges and surrounding vehicles that are present in automobile driving are not found in the setting of tractor driving. Also, the motion cues in tractor driving are different because tractors have different dynamics, travel at much lower speeds, and are usually driven in a straight line. The goal of this study, therefore, was to investigate the role of motion cues in driving an agricultural vehicle in parallel swathing mode.

5.3 Theory of manual control

This section discusses the theory of manual control relevant to the task that is being studied in this paper. Straight line driving of an agricultural vehicle with a lightbar guidance system is a tracking task and, more specifically, falls in the category of compensatory manual control tasks. As shown in the block diagram representation of Fig. 5.1, in compensatory manual control tasks the only input to the driver is the error, or the difference between system response and the reference (ideal) response. The task is therefore to minimize the instantaneous error, e, without direct reference to the response, m, of the controlled element (Jagacinski and Flach, 2002).

Figure 5.1 Compensatory control task of human operator (Jagacinski & Flach 2002).



In Fig. 5.1 the human operator, D_f, is shown in what is usually called a "describing function representation". In this representation, the control actions of the human operator consist of two parts. The first part, usually represented by a linear transfer function, Y_H, includes that portion of human output which is correlated with his/her input. The second part, n_H, is called remnant and includes the portion of human output that cannot be obtained from his/her input by a linear operation. Remnant, n_H, is usually quantified by its power spectral density. Y_C is the controlled element and n_C is any possible disturbance acting on it. The output, m, of the controlled element is subtracted from the reference input, r, and the difference, e, is presented to the operator by a display.

The theory of human compensatory control was developed and published by McRuer and his colleagues based on extensive experimental data (McRuer & Weir, 1969). The most important result of their studies is known as the crossover model of human operator:

$$Y_H . Y_C = \frac{\omega_c e^{-j\omega\tau_c}}{j\omega} \tag{5.1}$$

The model suggests that for different controlled element dynamics, Y_C, the human operator adjusts his/her control dynamics, Y_H, so that the combined open-loop gain $|Y_H.Y_C|$ decreases with frequency with a slope of -20 db/decade. This is the characteristic of a good servomechanism, resulting in good performance of the closed-loop system (Sheridan & Ferrell, 1974) and is the consequence of the human operator's adaptive change in his/her control strategy. For example, if the controlled element dynamic is a simple gain, $Y_C = K$, the human operator will choose an integration control strategy, $Y_H = K/s$, or if the controlled element is an acceleration control, $Y_C = K/s^2$, the human operator will choose a lead or derivative strategy, $Y_H = Ks$. ω_c is the crossover frequency (frequency at which $|Y_H.Y_C| = 1$) and $\exp(-j\omega\tau_e)$ represents the delays in Y_H and Y_C. The value of the crossover frequency can be accurately estimated using the following equation:

$$\omega_c = \omega_{c0} + 0.18\,\omega_{BWr} \qquad (5.2)$$

where ω_{BWr} is the bandwidth of the reference command, r, and ω_{c0} is the crossover frequency adopted by the human operator when the bandwidth of r approaches zero. Values of ω_{c0} were estimated by McRuer and his colleagues for different controlled element dynamics; for lateral control of most vehicles, and at steering frequencies not too high, this value is approximately 3 rad/s (McRuer & Krendel, 1974).

McRuer's experiments also showed that for a wide range of control element dynamics, Y_C, and forcing functions, r, the human operator's control can be satisfactorily described by a model of the following form:

$$Y_H(j\omega) = \left[\frac{\exp(-j\omega\tau_H)}{T_N j\omega + 1}\right]\left[\frac{K(T_L j\omega + 1)}{T_I j\omega + 1}\right] \tag{5.3}$$

The first term on the right of Eq. 5.3 represents the inherent limitations of the human operator and includes the reaction delay, τ_H, and a first order lag, inherent in the neuromuscular system, with time constant T_N. The second term includes a gain, K, as well as a lead term and a lag term with time constants T_L and T_I, respectively, and represents the human operator's equalization. The human operator adjusts these three parameters to satisfy some performance criterion such as the minimization of root-mean-square (RMS) of error (e in Fig. 5.1).

5.4 Materials and methods

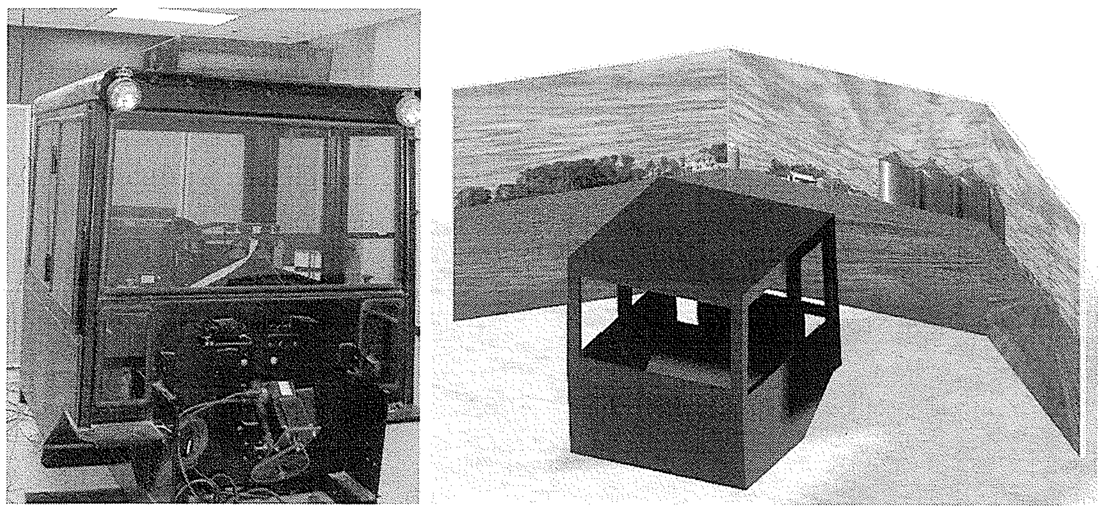
5.4.1 Field experiment

Experiments were conducted in the summer of 2007 in field plots on the campus of the University of Manitoba, Canada. Seven experienced tractor drivers participated in this experiment. A John Deere tractor (model 5425, 81 hp) with an Outback S® lightbar guidance system was used. Because some of the drivers had never used this system before, each driver was given some time to drive using the lightbar as the source of guidance information until he became familiar with the system. Then each driver drove seven or eight passes along the field. The drivers were instructed to choose a comfortable forward speed; all drivers chose a forward speed of 6-8 km/h. An RTK GPS system (Leica GPS1200) was used to record the exact position of the tractor. The measurement accuracy of the RTK system was 2.5 cm or better for most of the duration of the experiment. Because the RMS of lateral deviations measured by the RTK system was 30 cm or larger on average, the measurement error from the RTK system was ignored.

5.4.2 Simulator experiment

The tractor-driving simulator used in this study is located in the Agricultural Ergonomics Laboratory in the Department of Biosystems Engineering, University of Manitoba. The simulator provides visual feedback with a horizontal field-of-view of 65° and torque feedback on the steering wheel (Fig. 5.2).

Figure 5.2 Front view of the driving simulator (left) and a schematic showing the setup of the visual display and the simulator cab during operation (right).

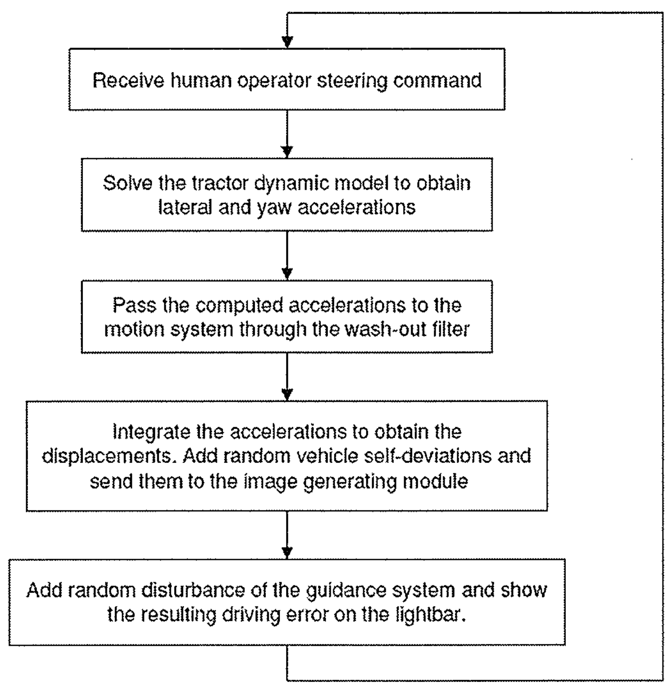


Reconsidering Fig. 5.1, simulation of straight line driving in the simulator requires knowledge of the tractor dynamics, Y_C, disturbance on the tractor, n_C, and the reference command, r. In the case of straight line driving, the reference input equals zero for an ideal guidance system. Real guidance systems, however, are not perfect and, therefore, the reference input, r, is the random error in the guidance system. The model of tractor dynamics is the one described in Chapter 3, i.e. Eq. 3.4. As a transfer function from steer angle in radians, δ, to tractor lateral deviation in meters, m, this model can be expressed as follows:

$$Y_C(s) = \frac{m(s)}{\delta(s)} = \frac{5.57s^2 + 82.4s + 212}{s^4 + 20.9s^3 + 99.1s^2} \qquad (5.4)$$

Field measurements were performed on a single tractor and a single lightbar guidance system to estimate the disturbance on the tractor, n_C, and the error of the guidance system, r, and the results were implemented in the driving simulator. A flowchart representation of the simulation of straight-line driving in the driving simulator is provided in Fig. 5.3.

Figure 5.3 A flowchart representation of the simulation of straight line driving in the tractor driving simulator.



Validity of the driving simulator for straight line driving has already been established by in Chapter 4. n_C and r were quantified by computing their RMS and power spectrum. For the simulator experiments explained in this paper, each of these two signals was approximated by a sum of ten harmonically independent sinusoids. Table 5.1 shows the magnitude and frequency of each of these harmonics for a forward speed of 8 km/h used in this experiment. Signal r has a bandwidth 0.045 Hz-0.221 Hz and RMS of 14 cm while signal n_C has a bandwidth 0.150Hz-0.890Hz and RMS of 6 cm.

Table 5.1 Magnitude and frequency of sinusoids used to represent the disturbance on the tractor, n_C, and the error of the lightbar guidance system, r.

n_C		r	
Magnitude, cm	**Frequency, Hz**	**Magnitude, cm**	**Frequency, Hz**
2.7	0.150	5.7	0.045
2.7	0.201	5.7	0.063
2.9	0.277	4.9	0.081
2.9	0.351	4.9	0.100
2.9	0.432	4.9	0.119
2.4	0.511	2.9	0.138
2.4	0.601	2.9	0.159
2.4	0.683	2.9	0.177
2.4	0.787	2.9	0.197
2.4	0.890	2.9	0.221

Tractors are usually operated at a constant forward speed. They also do not have a suspension system. Therefore, acceleration and deceleration (braking) and pitch and roll motions which are very common in driving cars are insignificant in tractor driving (Crolla, 1983). The tractor driving simulator used in this study provides only yaw motion.

An electric motor and a screw mechanism are used to turn the whole cab around an axis that approximately passes through the driver's seat.

Fifteen experienced tractor drivers participated in the driving simulator experiments. The subjects were male and 20 to 61 years old (average 48 years). Each subject completed two sessions. In one session the motion cue was used while in the other session the motion cue was not used. Subjects were randomly assigned to complete either the session with the motion cue or the session without the motion cue first; eight of the subjects completed the session with motion cue first whereas seven subjects completed the session without the motion cue first. Each session was 15 min long. During the simulator experiments, the following data were recorded and saved with a frequency of 20 Hz by the main computer: position of tractor in the x and y directions and its heading, steering wheel angle and the values of signals n_C and r.

5.5 Data analysis

RTK GPS data from the field experiment provided the exact location of the tractor during parallel swathing. The position of the tractor was also recorded in simulator experiments. Therefore, we were able to calculate the RMS of driving error, i.e. deviation from the desired path, for field and simulator experiments. Also, the same data were analyzed to find the frequency composition of lateral deviations of the tractor from the straight line. This was done by first computing the Fourier transform:

$$Y(j\omega) = \int_{-\infty}^{+\infty} y(x) e^{-j\omega x} dx \qquad (5.5)$$

where:

x = distance along the path

$y(x)$ = driving error at position x

$Y(j\omega)$ = value of Fourier transform for frequency equal to ω

ω = frequency, here ω is 'positional frequency'; since x is distance (m), the dimension of ω is 1/distance.

The spectrum obtained in this way was divided into three parts:

T= 10 to 20 m, the high-frequency region

T= 20 to 35 m, the medium-frequency region

T= 35 to 50 m, the low-frequency region

Where $T=2\pi/\omega$ is the period. The energy in each part of the spectrum was calculated using the following equation:

$$\text{energy} = \frac{1}{2\pi}\int_{\omega_1}^{\omega_2} \left|Y(j\omega)\right|^2 d\omega \qquad (5.6)$$

The energy in each portion was then divided by the sum of the energy of all three portions to obtain the normalized values in percentage.

The record of steering wheel angle from the driving simulator experiment was also analyzed in order to obtain the number of steering wheel reversals and the RMS of steering wheel angle. These values are measures of control activity of the driver. A small number of steering wheel reversals and/or low RMS of steering wheel position indicate more relaxed steering or less effort exerted by the driver.

As mentioned before, all of the signals δ, e, m, r, and n_C in Fig. 5.1 were recorded in the simulator experiment. Therefore, we were able to use system identification techniques to estimate the value of the parameters of the human operator model presented in Eq. 5.3. System Identification procedures in Matlab were used for this purpose.

5.6 Results and discussion

Table 5.2 shows a summary of the results from the field experiment. There are some significant differences between drivers in terms of both the RMS of lateral deviations and their frequency compositions. However, it is reasonable to compute the averages for all seven drivers. On average, RMS of lateral deviations was 30 cm, and the amount of energy in the low, medium and high-frequency portions of the spectrum were 30, 40, and 30%, respectively.

Table 5.2 Results of field experiments. Different superscripts in the same column indicate statistically significant differences.

Driver	RMS of lateral deviations, cm	Energy of high-frequency portion of spectrum, %	Energy of medium-frequency portion of spectrum, %	Energy of low-frequency portion of spectrum, %
1	32[a,b]	33[a]	39[a]	28[a]
2	34[a]	21[a]	46[a]	33[a]
3	36[a]	32[a]	40[a]	28[a]
4	28[a,b]	30[a]	42[a]	28[a]
5	26[a,b]	32[a]	33[a]	35[a]
6	20[b]	30[a]	37[a]	33[a]
7	36[a]	29[a]	43[a]	28[a]
Average	30	30	40	30

Table 5.3 shows a summary of the results from the two simulator experiments. The values shown in this table are the averages for all 15 subjects.

Table 5.3 Results of the simulator experiments showing the averages for all 15 subjects.

	Simulator exp. with motion	Simulator exp. without motion
RMS of lateral deviations, cm	35	39
Energy of high-freq. portion of spectrum, %	26	28
Energy of med.-freq. portion of spectrum, %	40	42
Energy of low-freq. portion of spectrum, %	33	30
Steering wheel reversals per minute	22	21
RMS of steering wheel position, degree	13	19

As mentioned before, each simulator experiment was 15 min long. The data were divided into one-minute pieces and the calculations were performed for each piece separately to check for possible changes with time. For many of the subjects and many of the sessions, the calculated values were significantly different for the first one or two minutes of the experiment. For a small number of cases the adaptation time was as long as 4 min. Therefore, it was decided to remove the first 5 min of data for each experiment and the values shown in Table 5.3 are the averages for the last 10 min.

The most significant trend observed from Table 5.3 is the significant decrease in RMS of steering wheel angle between the experiment with motion cues and the one without motion cues which is an indication of decrease in driver control activity.

Analysis of variance shows that the observed difference is statistically significant (Pr(>F)=0.004). This suggests that drivers did in fact make use of motion cues and changed their control strategy in the presence of these cues.

It is interesting to note that the number of steering wheel reversals per minute, which is another indicator of driver control activity, was statistically the same under the two scenarios. This number was on average 22 for the experiment when motion cues where present and 21 for the experiment with no motion cues. Intra-subject differences were small for the number of steering wheel reversals per minute. Although the control activity of the driver, in terms of the RMS of steering wheel angle, substantially decreased when motion cues were used, the performance did not deteriorate. In fact, the RMS of lateral deviations, which can be considered as a measure of performance, was 35 cm for the case when motion cues were provided and 39 cm when the motion cues were not provided. However, this difference was not statistically significant (Pr(>F)=0.10). Frequency composition of lateral deviations also changed slightly between the two experiments; when motion cues were provided, low frequency changes increased whereas medium and high frequency changes decreased in proportion. However, none of these changes were statistically significant.

For subjects 1 to 7 who participated in the field experiment as well as the simulator experiments, it was possible to compare the results of the field experiment with those from the two simulator experiments. The values that were computable for the field experiment included RMS and frequency composition of lateral deviations. Analysis of variance was performed to compare these values between the field experiment, the simulator experiment with motion cue, and the simulator experiment without motion cue

(Table 5.4). There were no differences in terms of frequency composition of lateral deviations between field experiments and either of the simulator experiments. In terms of RMS of lateral deviations, however, there was a significant difference between the field experiment and the simulator experiment without motion cues (Pr(>F)=0.043).

Table 5.4 Comparison of field experiment results with the results of the driving simulator experiments for subjects 1 to 7. Different superscripts within the same column indicate significantly different means.

Subject	RMS of lat. Dev., cm	Energy of low-freq. portion of spectrum, %	Energy of med-freq. portion of spectrum, %	Energy of high-freq. portion of spectrum, %
Field experiment	30[a]	30[a]	40[a]	30[a]
Sim. experiment with motion cues	34[a]	33[a]	40[a]	27[a]
Sim. experiment w/o motion cues	39[b]	33[a]	39[a]	28[a]

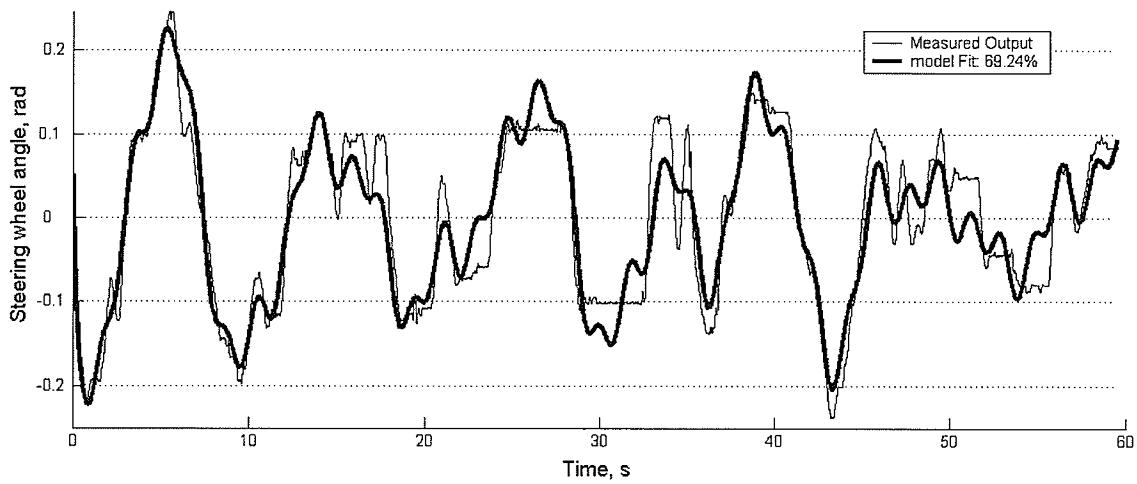
System identification using a prediction error method (Ljung, 1987) was used to identify the parameters of Eq. 5.3. The input to the driver is the error, e, in meters and the output from the driver is the steer angle of the front wheel. The tractor steering system for the driving simulator has been modeled by a constant gain equal to 0.5 from steering wheel angle to front wheel steer angle after some measurements on a Massey Ferguson 150 tractor. Because direct implementation of the delay term, τ_H, in the greybox model was not possible, identification was performed for a range of τ_H from 0 to 2 s in 5 ms intervals and the value of τ_H that provided the best fit was selected. Similar to the previous analysis, the data were divided into one-minute pieces and analysis was performed on each piece separately. Tests of stationarity such as those suggested by Bendat and Piersol (1986) showed that one-minute-long pieces of the collected data were stationary. Similar to the measures previously described, the identified parameters were usually significantly different for the first couple of minutes of each simulator experiment. Therefore, the first 5 min of data for each experiment were ignored. Table 5.5 shows the average values, for the last 10 min, of the identified parameters for each of the two experimental conditions as well as the analysis of variance results.

Table 5.5 Values of parameters of driver model obtained through system identification. Different superscripts in the same column show significantly different values.

Experimental condition	K	T_L	T_N	T_I	τ_H	Degree of fit, %
With motion cues	0.12^a	1.16^a	0.07^a	0.36^a	0.43^a	69^a
Without motion cues	0.16^b	2.40^b	0.09^a	0.40^a	0.40^a	66^a

The degree of fit was 62 to 75% which is at an acceptable level (Sheridan and Ferrell, 1974). This is the degree of fit of the model to the data that was used to obtain the model. When the identified model for 1 min of the test was validated against data from the next 1 min, it showed 1-10% decrease in fit which is rational considering the random nature of the disturbance inputs and possible changes in the degree of attention of the subject to the task during the experiment. Fig. 5.4 shows a sample of measured driver output (steering wheel angle) and the model output.

Figure 5.4 Measured steering wheel angle and the prediction by the identified model.



As can be seen from Table 5.5, when motion cues were present, the subjects showed a significantly smaller gain and a smaller time lead constant. These are indicative of a more relaxed driving style (Chen and Ulsoy, 2006). Values of the first order time lag constant and neuromuscular time constant are very small. They have break frequencies at approximately 2.5 and 12 Hz, respectively. Since the steering inputs from the driver barely exceed 1 Hz, these two terms do not have a significant effect. Especially the neuromuscular lag term can be easily ignored as long as slow and medium steering angle inputs are concerned. The values of the reaction time found for both experiments are larger than the values reported by other researchers. According to Sheridan and Ferrell, for example, this value is between 0.12 and 0.20 s. The large delay values computed here are partly due to the delays in the simulator systems. The delay in the motion system was measured by installing a gyroscope on the simulator and recording the steering wheel position and simulator cab motion by a data acquisition system; the estimated value for this delay was 75 ms. We expect the visual cue delay and lightbar reaction time to be much smaller than 75 ms for our driving simulator. Even considering a delay of 75 ms, the identified value for the reaction time is still larger than the values found in the literature. On the other hand, the values identified for the neuromuscular lag time, T_N are smaller than the values reported by others which is approximately 0.2. It is possible that the identification computations have automatically included the neuromuscular lag into the reaction time delay. In other words, the model suggested by the identification is of the following form:

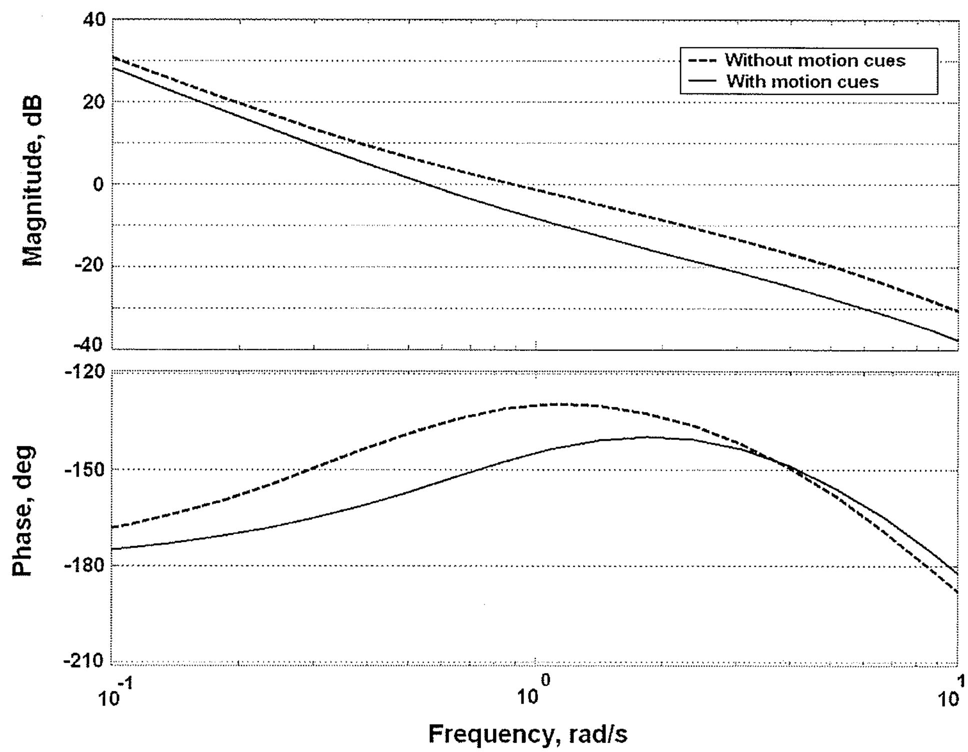
$$Y_H(j\omega) = \left[\frac{K(T_L j\omega + 1)}{T_I j\omega + 1}\right] e^{-j\omega(\tau_H + T_N)} \tag{5.7}$$

which is suggested by some researchers (e.g. McRuer & Krendel, 1974) and the values represented as τ_H in Table 5.5 are in fact $\tau_H + T_N$.

Open-loop frequency response of the human plus controlled element can be obtained by combining the tractor dynamic model with the model obtained for the human operator or by direct frequency response estimation through spectral analysis. For the second approach, signal e in Fig. 5.1 should be considered as input and the output of the Y_C block, without addition of n_C, should be considered as the output. Fig. 5.5 shows a typical bode plot for a single driver for the experiments with and without motion cues.

An interesting observation from Fig. 5.5 is the low value of the crossover frequency. This value is 0.85 rad/s for the experiment without motion cues and 0.55 rad/s for the experiment with motion cues; both of these values are much smaller than the value suggested by Eq. 5.2. As mentioned previously, for lateral control of the tractor which is modeled by Eq. 5.4, ω_{C0} is 3 rad/s. The bandwidth ω_{BWr} in our experiment is in fact the bandwidth of the sum of signals r and n_C which according to Table 5.1 is 5.6 rad/s. Therefore, the crossover frequency predicted by Eq. 5.2 is 4 rad/s. However, Eq. 5.2 is valid only when the bandwidth of the reference command and disturbances, ω_{BWr}, is well below the predicted crossover frequency. When ω_{BWr} becomes close to the crossover frequency predicted by Eq. 5.2, the human operator suddenly acts to significantly decrease the crossover frequency by reducing his gain, K.

Figure 5.5 Open-loop Bode plot for the human plus tractor model combination.



This phenomenon is called the crossover regression (Hess, 1997) and is exactly what has happened in our study. For a nonhuman controller, such a decrease in the crossover frequency would result in a significant increase in the tracking error, e. However, in the case of a human controller this phenomenon will result in lower tracking errors than if crossover regression does not happen. The reason for this has to do with the human remnant, n_H. It can be shown that the remnant power is proportional to the square of tracking error or its power (McRuer & Weir, 1969). Therefore, if crossover regression does not happen, an increase in remnant power, due to bandwidth ω_{BWr}, would result in a substantial increase in tracking error. In other words, with very high ω_{BWr}, the human operator ignores the high frequencies by lowering his gain and so the open-loop crossover frequency. This is the strategy that human operators automatically adopt because responding to high frequency commands and disturbances would introduce so much remnant that will, in effect, have a negative impact on performance.

As mentioned before, a complete representation of the human operator describing function should also include quantification of the remnant, n_H. Figure 5.6 shows graphs of remnant power spectral density for the last 5 min of both simulator experiments. Graphs show the power spectral density for each subject as well as the average of all 15 drivers. The graphs show a slightly higher power spectral density for the experiment with no motion cues which is consistent with the general rule that remnant is higher when the driver adopts a larger lead (McRuer & Weir, 1969). The following approximations can be made for the average power spectral densities:

$$\begin{array}{ll} \text{with motion cues} & \mathrm{PSD}(\omega) = -0.0027\,\omega^3 + 0.012\,\omega^2 - 0.019\,\omega + 0.0094 \\ \text{without motion cues} & \mathrm{PSD}(\omega) = -0.00076\,\omega^3 + 0.0044\,\omega^2 - 0.0079\,\omega + 0.0046 \end{array} \tag{5.8}$$

If the driver effectively uses motion cues to estimate the state of the vehicle, the block diagram representation of Fig. 5.1 is inadequate because it shows only the feedback of the final vehicle output (i.e., its lateral deviation). Weir and McRuer (1968) investigated possible feedback loops that can be used by the human driver and the preferable multiloop control schemes from a control and guidance standpoint. In general, the most difficult part of the modeling is to identify which sensory feedback the driver is using in a particular task. In the case of our study it can be said that in addition to the lateral deviation information which is received visually through the lightbar, the driver perceives the yaw rate of the vehicle through vestibular cues and uses that as an additional feedback of the state of the vehicle. Vehicle heading would be a better feedback variable because it requires less equalization from the driver but it cannot be obtained directly from motion cues. Acceleration, on the other hand, is not a good feedback variable because it is too sensitive to driver gain variations (Weir & McRuer, 1968). Therefore, the block diagram representation of Fig. 5.7 is suggested for driver's control of the simulated vehicle in the presence of motion cues.

Figure 5.6 Power spectral density of driver remnant signal for driving simulator experiments with motion cues (left) and without motion cues (right). The thick curve shows the approximate average of all fifteen subjects.

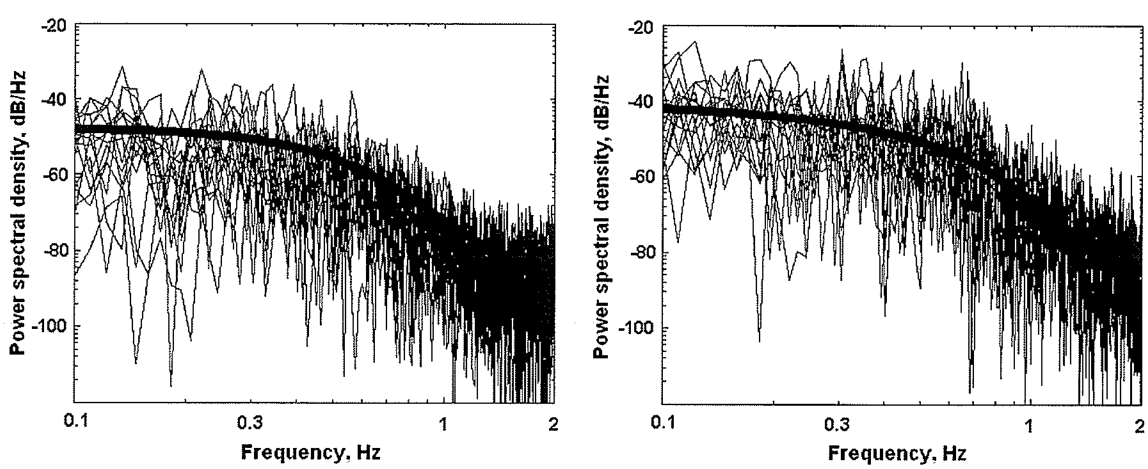
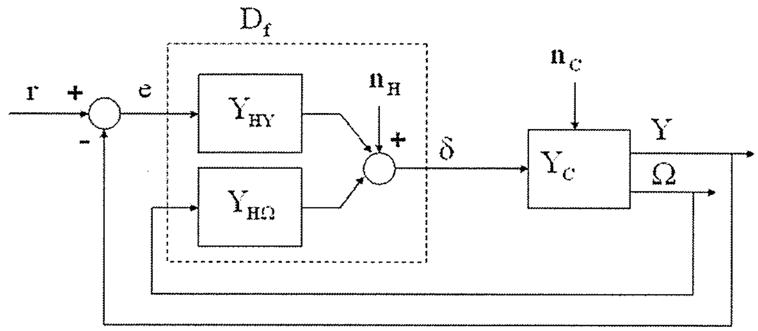


Figure 5.7 Block diagram representation for multiloop control of the vehicle.



Driver equalization for the inner loops is in general in the form of Eq. 5.3 discussed before. Actual interaction between human and the controlled element happens in the inner loop and therefore the human delay (consisting of neuromuscular delay) is considered in that loop only (Hess, 1997). The human control in the outer loops is considered to consist of only simple gains. Therefore, the following forms were considered for the two human compensations.

$$Y_{HY} = K_Y \qquad Y_{H\Omega} = \left[\frac{K_\Omega\left(T_{L\Omega} j\omega + 1\right)}{T_{I\Omega} j\omega + 1}\right] e^{-j\omega\tau_\Omega} \tag{5.9}$$

System identification techniques and records of the signals e, Y, and Ω in the simulator experiment with motion cue were used to estimate the values of the parameters in Eq. 5.9. Separate identification of both transfer functions is possible due to the presence of two input signals, r and n_C, with different bandwidths (Stapleford et al., 1967). Table 5.6 shows the average of these values. The values of $T_{L\Omega}$ and $T_{I\Omega}$ are very small. Therefore, driver compensation in the inner loop can be considered to approximately consist only of a gain and a delay term. This means that the driver needs to act on both heading rate and lateral deviation without any equalization. Effective use of motion cues to estimate yaw rate would therefore result in lower workload on the driver.

Table 5.6 Estimated values for the parameters of Eq. 5.9.

Parameter	K_Y	K_Ω	$T_{L\Omega}$	$T_{I\Omega}$	τ_Ω	**Degree of fit, %**
Identified value	0.09	1.1	0.16	0.06	0.30	70

5.7 Conclusion

The goal of this experiment was to determine the effect of motion cues in driving an agricultural vehicle on straight lines. The results show a significant decrease in control activity and an improvement in performance in the presence of motion cues. The results suggest that the best way to drive in parallel swathing mode with a lightbar guidance system is to use yaw motion of the tractor as an additional cue and to try to null errors with small steering wheel angle inputs. This would result in a more relaxed driving and improved performance. A bad strategy would be to respond to the error shown on the lightbar with large steering inputs.

6. ROLE OF VISUAL CUES IN DRIVING AN AGRICULTURAL VEHICLE

6.1 Summary

Driving is an interactive process in which the driver receives information regarding the state of the vehicle and the environment in which the vehicle is moving through visual, motion, haptic and auditory cues. The driver needs this information for successful guidance or navigation of the vehicle. A good understanding of this process requires knowledge of the sensory cues used by the driver in performing different driving tasks. This knowledge is also necessary in the development of driving simulators which are emerging as useful research tools. The goal of this research was to test whether drivers of agricultural vehicles use visual cues when performing common driving tasks such as parallel swathing and simple turning maneuvers. Experiments were performed using a tractor in the field and using a tractor driving simulator in the laboratory. The results show that most drivers only follow the guidance system and do not depend on visual information from the environment in straight line driving with a guidance system. Approximately 33% of the subjects in our experiment, however, used an aiming cue on the field boundary, when available. Visual cues played a significant role in maneuvers which included more than one phase of steering input. Drivers were able to successfully complete those maneuvers that consisted of only one phase of steering input, such as turns, even when complete visual cues were not provided. However, maneuvers which required multiple phases of steering input could not be completed when the visual information was incomplete. It can be concluded that drivers require visual feedback to complete steering maneuvers requiring multiple phases of steering input.

6.2 Introduction

It is generally believed, and has been shown by some experiments, that visual cues are the single most important cues in automobile driving (Wilkie and Wann, 2005). Although the exact contribution of the visual cues to the driver's perception is not clear (Sivak, 1996), it is known that in the absence of visual cues, drivers are unable to perform some basic driving tasks (Kemeny and Panerai, 2003). Other sensory cues (i.e., vestibular, proprioceptive, haptic, and auditory cues) have less importance and generally provide redundant information to reinforce the visually perceived information (Macadam, 2003). Recently, driving simulators have raised new questions and opened new research opportunities in this area. On one hand, successful driving simulation requires a good understanding of the human visual perception and the characteristics of the visual information that the driver needs to perform different driving tasks. On the other hand, driving simulators provide unique opportunities to research the same questions in a safe and easily controllable environment.

Although there has been extensive research on the role of visual cues in automobile driving, no similar research has been reported for agricultural vehicles. This is despite the significant differences that exist between the two types of vehicles and the driving tasks involved: agricultural vehicles have different dynamics and operate at lower speeds in straight lines through fields (called parallel swathing). Moreover, the source of visual information in automobile driving is different than the source in driving an agricultural vehicle; in automobile driving, visual information is derived from road edges and features or objects in the visual scene (i.e., other vehicles on the road) that do not exist in driving an agricultural vehicle in a field. Driving of an agricultural vehicle consists mostly of parallel swathing and simple maneuvers such as turns of various angles. The goal of this study was, therefore, to see whether drivers of agricultural vehicles use visual cues in performing these tasks and whether a driving simulator for these vehicles should include visual cues.

6.3 Materials and Methods

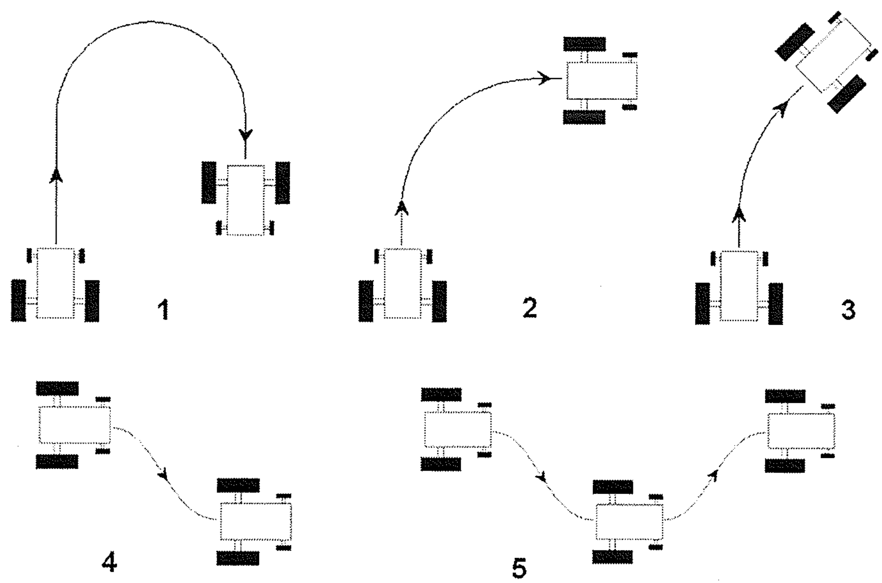
6.3.1 Field experiments

Field experiments were performed in the summer of 2007 in southern Manitoba, Canada. Ten experienced tractor drivers participated in the experiments. The experiments consisted of two parts: 1) parallel swathing with a lightbar guidance system, and 2) performing a selected number of turning maneuvers. A John Deere 5425 tractor was used in the field experiments.

In the parallel swathing experiments, an Outback S® lightbar guidance system was used to provide information to the operator to enable the tractor to be driven in a straight line. Because some of the drivers had never used this system before, each driver was given some time to drive using the lightbar until he became familiar with the system. Then each driver drove seven or eight passes along the field. The exact position of the tractor was recorded using an RTK GPS system (Leica GPS1200). The measurement accuracy of the RTK system was 2.5 cm or better for most of the duration of the experiment. Since the lateral deviations of the tractor from the straight line measured by the RTK system were 30 cm or larger on average, the measurement error of the RTK system was ignored.

In the second experiment, each driver was asked to perform a selected number of maneuvers (Fig. 6.1). The maneuvers included turns of 45, 90, and 180° to both the left and the right and two maneuvers which resembled single and double lane changes on a road. A printed copy of Fig. 6.1 was shown to the driver and he was asked to perform the maneuvers. The same RTK GPS system was used to record the exact position of the tractor.

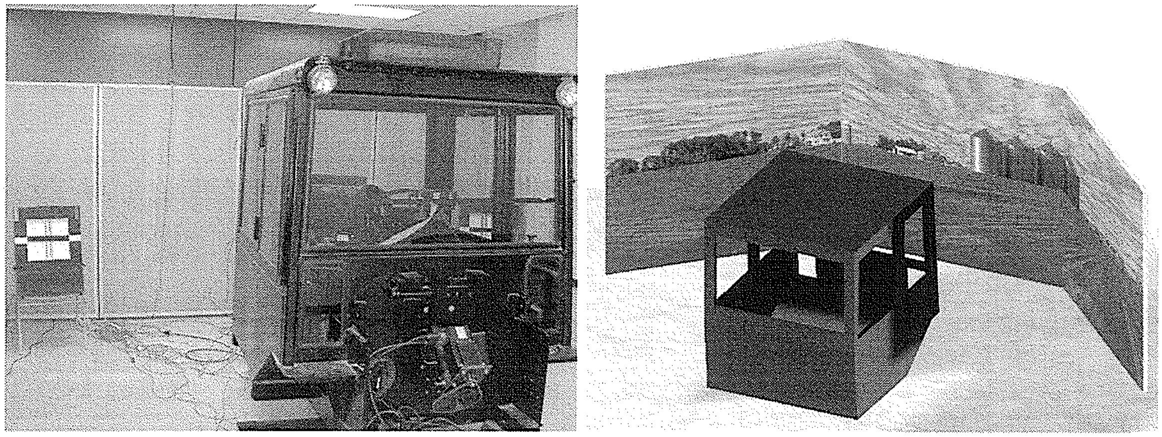
Figure 6.1 Maneuvers that were performed in the field and simulator experiments.



6.3.2 Simulator experiments

Simulator experiments were performed using a tractor driving simulator located in the Department of Biosystems Engineering, University of Manitoba. This is a moving-base simulator which uses three projectors to provide a forward field of view of approximately 65° (Fig. 6.2). The simulator also provides realistic torque feedback on the steering wheel. Fifteen experienced tractor drivers, including the ten drivers who participated in the field experiments, participated in the simulator experiments.

Figure 6.2 The front view of the simulator (left) and a schematic representation of the simulator and the visual display during operation (right).



The type of driving tasks performed in the simulator experiments were the same as those performed in the field experiments explained previously. The experiment consisted of three sessions: 1) full visual information was provided (referred to as SE1), 2) visual information only from the simulated field boundary was provided (referred to as SE2), and 3) visual information only from the simulated field surface was provided (referred to as SE3). Figure 6.3 shows part of the simulated visual scene during each of these sessions. In each of the three sessions, the driver first drove in parallel swathing mode for 15 min. Then the driver was asked to perform steering maneuvers identical to those performed in the field experiments. Images of the maneuvers were shown to the driver on an LCD monitor inside the simulator cab. Exact location of the simulated tractor and steering wheel angle were recorded by the main computer at a rate of 20 Hz.

6.3.3 Data analysis

A record of the tractor location obtained from the RTK GPS system in the field experiment was used to calculate the deviation of the tractor from the straight line. Root-mean-square (RMS) of lateral deviations was calculated. Fourier transform of lateral tractor deviations was then computed using the following formula:

$$Y(j\omega)=\int_{-\infty}^{+\infty} y(x)\, e^{-j\omega x}\, dx \tag{6.1}$$

where y(x) is the tractor lateral deviation. Using this transform, the energy of the signal for different frequency ranges can be obtained from the following equation (Oppenheim et al. 1997):

$$\text{energy} = \frac{1}{2\pi}\int_{\omega_1}^{\omega_2} \left|Y(j\omega)\right|^2 d\omega \tag{6.2}$$

We computed the energy for three frequency regions:

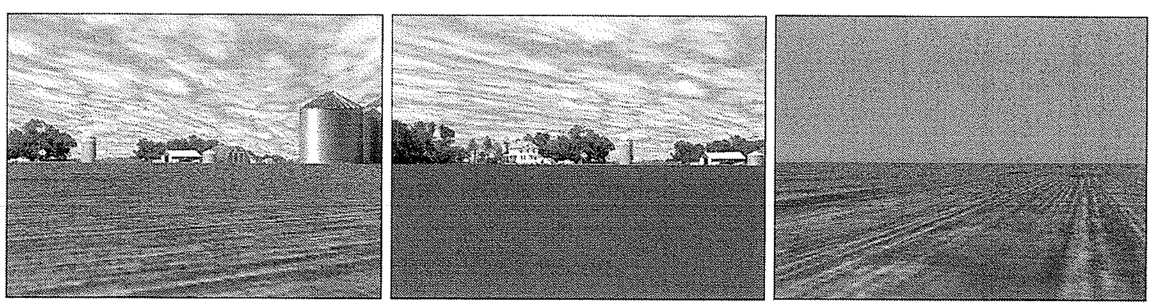
T= 8 to 16 m, the high-frequency region

T= 16 to 32 m, the medium-frequency region

T= 32 to 45 m, the low-frequency region

where $T = 2\pi/\omega$ is the period. The energy in each of these regions was then divided by the total energy to obtain the fraction, expressed in percentage, of energy of the lateral deviations in each frequency band.

Figure 6.3 Snap shots from the simulated visual scene in the three driving simulator experiments: SE1 (left), SE2 (center), and SE3 (right).



The same procedure was followed using the position data collected using the simulator. In addition, the RMS of the steering wheel angle was also computed for the simulator experiments to obtain a measure of the control activity of the driver.

6.4 Results and Discussion

6.4.1 Straight line driving

Table 6.1 shows the RMS of the lateral deviations and their frequency composition averaged for all drivers (10 drivers in the field experiment and 15 drivers in the simulator experiments). The numbers in Table 6.1 show that, on average, the results are very close for the field experiment with the three simulator experiments. Analysis of variance did not show any significant differences between any of the experiments and in terms of any of the four parameters.

Table 6.1 Summary of the results from straight-line driving experiments in the field and simulator.

Experiment	RMS of lateral deviations (m)	Energy of high-freq. portion of spectrum (%)	Energy of med.-freq. portion of spectrum (%)	Energy of low-freq. portion of spectrum (%)
Field (n=10)	0.32	30	40	31
SE1 (n=15)	0.35	29	43	29
SE2 (n=15)	0.35	29	42	30
SE3 (n=15)	0.34	31	42	27

Because there were no observable differences between the three sets of simulator experiments (when varying levels of visual information were provided to the driver), these results suggest that drivers do not require visual information from the field surface or boundary when performing straight line driving with a guidance system.

For one-third of the drivers (5 of 15), however, there is evidence that visual cues do play a role during straight-line driving. These drivers significantly increased their control activity, which is reflected by higher RMS of steering wheel angle, when field boundary cues were eliminated (experiment SE3). Table 6.2 shows the results of the three simulator experiments for five subjects in terms of the RMS of driving error (a measure of task performance) and the RMS of steering wheel angle (a measure of driver effort). In experiment SE3, when the field boundary was removed from the visual scene, the RMS of steering wheel angle was 20 to 130% (61% on average) larger than in experiments SE1 and SE2. Analysis of variance showed that the RMS of steering wheel angle in experiment SE3 is significantly different from experiments SE1 and SE2 (Pr(>F)=0.026). It is a common practice for drivers of agricultural vehicles to use an object on the field boundary as an aiming cue when driving in parallel swathing mode. This is particularly true when they do not use a guidance system. However, it is likely that even when a guidance system, such as a GPS lightbar system, is used, the driver does not spend all of his time looking at the guidance system and still uses an aiming cue as an extra source of guidance information. Our results tend to support this hypothesis for this select group (one-third) of the drivers. For these drivers, the use of an aiming cue on the field boundary (i.e., experiments SE1 and SE2) resulted in smaller steering movements which is an indication of a more relaxed driving style. As can be seen from the table, the RMS of lateral deviations of the tractor was lower for experiment SE3 compared to experiments SE1 and SE2. Although this difference was not statistically significant (Pr(>F)=0.50), it indicates that lateral deviations from the desired straight line increase when using an aiming cue on the field boundary instead of fully concentrating on the guidance system.

Table 6.2 The results of the simulator experiments for five subjects that seem to change their control strategy in straight line driving depending on the visual cues.

	SE1		SE2		SE3	
Subject	**RMS of lateral deviations (m)**	**RMS of steering wheel angle (°)**	**RMS of lateral deviations (m)**	**RMS of steering wheel angle (°)**	**RMS of lateral deviations (m)**	**RMS of steering wheel angle (°)**
1	0.40	10	0.39	15	0.42	23
2	0.41	18	0.45	15	0.30	26
3	0.38	12	0.37	10	0.28	18
4	0.25	7	0.30	10	0.26	12
5	0.40	17	0.25	12	0.32	22
Avg.	**0.37**	**13**	**0.35**	**12**	**0.32**	**20**

6.4.2 Turning maneuvers

Field experiments showed that drivers were able to perform all of the steering maneuvers shown in Fig. 6.1 with acceptable accuracy. Figure 6.4 shows examples of how the drivers performed maneuvers 1 and 5. The error in performing each of the maneuvers was quantified in terms of the difference between the observed final tractor heading and the desired heading for that maneuver. For maneuvers 1 to 5, the error averaged across all drivers was 5, 7, 5, 10, and 12° respectively. Table 6.3 shows this error for field experiments and for the simulator experiments.

Figure 6.4 Typical tractor trajectories as the tractor operator performed maneuvers 1 and 5 in the field.

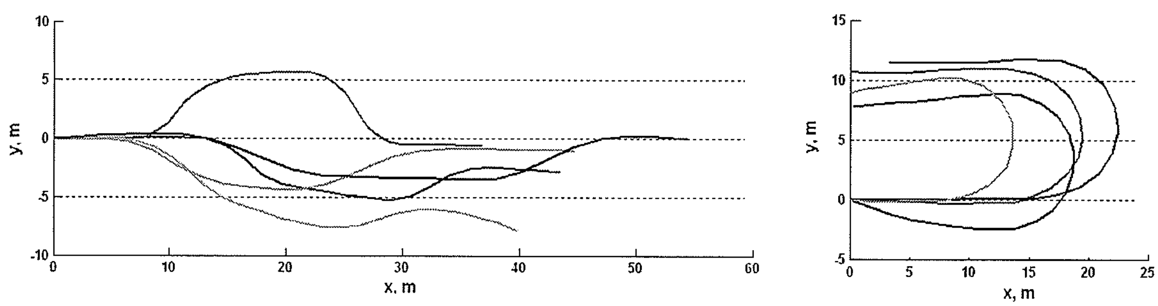


Table 6.3 Error in the final tractor heading for maneuvers 1 to 5, averaged across all drivers.

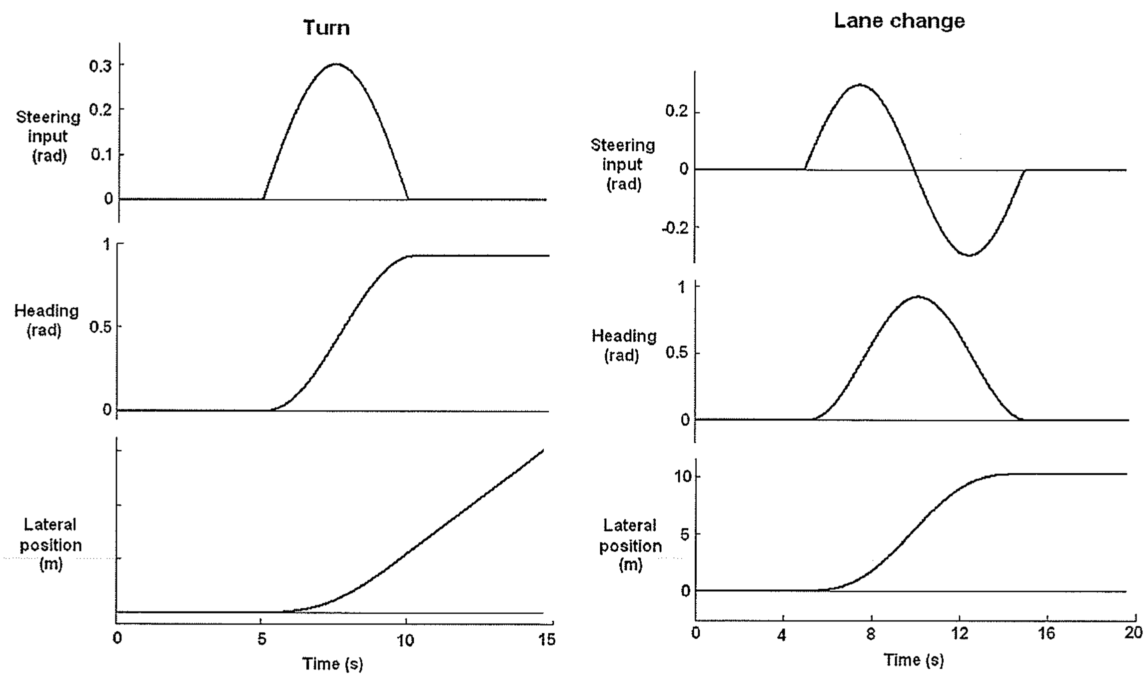
Experiment	Mnvr. 1	Mnvr. 2	Mnvr. 3	Mnvr. 4	Mnvr. 5
Field (n=10)	5	7	5	10	12
SE1 (n=15)	10	6	5	15	17
SE2 (n=15)	58	38	24	33	43
SE3 (n=15)	16	15	12	11	20

In the first simulator experiment (SE1), the drivers were able to perform the assigned maneuvers with acceptable accuracy although the average errors in the final heading were slightly higher than for the field experiment: 10, 6, 5, 15, and 17° respectively for maneuvers 1 to 5.

In the second simulator experiment (SE2), the drivers performed maneuvers 1, 2, and 3 with much larger errors (58, 38, and 24° for maneuvers 1, 2, and 3) and most of them were unable to perform maneuvers 4 and 5. For maneuver 4, for example, drivers produced steering wheel inputs that were needed for a turn. To understand the difference, it is instructive to consider Fig. 6.5 which shows the steering wheel movements required for both a simple turn and for maneuver 4. Heading angle and lateral deviations shown in this figure were computed using the tractor dynamic model used in the tractor driving simulator which can be represented by the following transfer functions (Eq. 3.4):

$$\frac{\psi(s)}{\delta(s)}=\frac{6.47(s+14.8)}{s(s+13.6)(s+7.31)}, \qquad \frac{Y(s)}{\psi(s)}=\frac{0.86(s+11.5)(s+3.33)}{s(s+14.8)} \tag{6.3}$$

Figure 6.5 Steering wheel inputs necessary to perform a simple turn and a lane change.



where:

δ: steering angle input (steer angle of the front wheel of the tractor), rad

ψ: tractor heading, rad

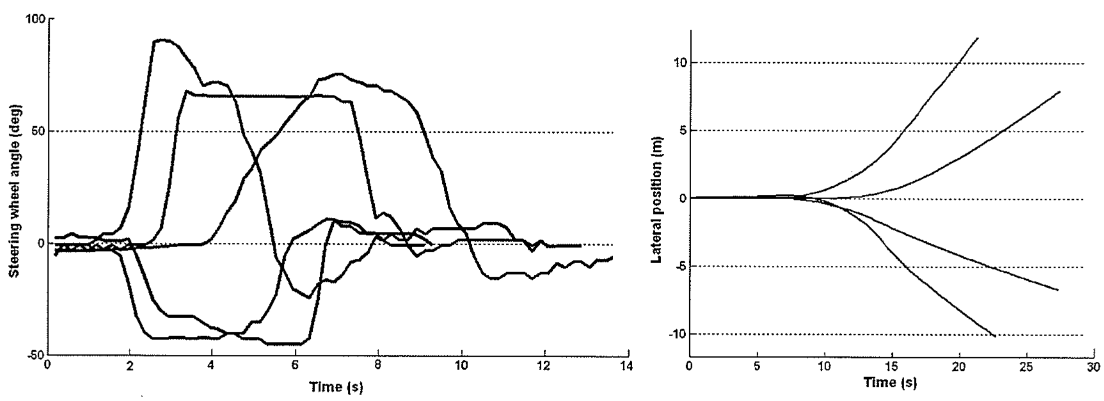
Y: tractor lateral deviation, m

The steering inputs in Fig. 6.5 are sine waves, but the exact shape of this input is immaterial. As can be seen from this figure, for a simple turn to the left, for example, the driver should turn the steering wheel to the left and then back to the center. For a maneuver similar to maneuver 4, however, the driver must repeat the same steering wheel movement in the opposite direction to make the total change in the tractor heading equal to zero. In fact for a zero change in the final heading, the net area under the steering wheel angle curve (the upper right curve in Fig. 6.5) should be zero. However, in experiment SE2, all but one of the drivers performed only the first part of the steering wheel movement (i.e., they effectively made a turn instead of a lane change maneuver). Figure 6.6 shows examples of the drivers' performance for maneuver 4.

As can be seen from Fig. 6.6, the second phase of steering wheel movement is either very small or completely ignored. Therefore, according to Fig. 6.5, the steering wheel movement generated by the driver is representative of the steering wheel input required for a turn. This is confirmed by the trajectory of the tractor, also shown in Fig. 6.6.

Wallis et al. (2002) asked several experienced automobile drivers to perform a lane change maneuver on a steering wheel in the absence of any visual cues. None of the participants performed the right steering wheel movements. In fact, in their experiment, similar to our observations in experiment SE2, the participants performed only the first phase of the steering wheel movement necessary for the lane change, effectively making a turn instead of a lane change. Observations from experiment SE2 show that in the absence of visual cues from field surface, drivers are able to complete one-step maneuvers such as turns, but when the maneuver includes two or more steps (maneuvers 4 and 5) the drivers do not initiate the second part of the steering movements. Since motion and haptic cues were provided in our experiments, it can be said that motion and haptic cues do not replace the visual cues for these maneuvers. Also, it should be noted that in this experiment (SE2), drivers were able to see the field boundary. Therefore, we might be able to conclude that the drivers use visual cues from the field surface for this maneuver. However, this conclusion might be wrong because of the limited field of view of the simulator, which was 65°. It is possible that with a wide field of view the driver would do a better job of performing the steering maneuvers.

Figure 6.6 Steering wheel angle and lateral deviation of the tractor in experiment SE2 as the drivers performed the maneuver 4 in Fig. 6.1.



In experiment SE3, the drivers were able to perform those maneuvers that consisted of only one steering step (i.e., maneuvers 1, 2, and 3). The errors in the final tractor heading were slightly higher than, but comparable with, those of experiment SE1 and the field experiment. The average of the errors were 16, 15, and 12° for maneuvers 1 to 3.

However, for maneuvers 4 and 5, a small number of the drivers performed incorrect steering inputs quite similar to the ones that were observed in experiment SE2. In other words, for maneuver 4, drivers performed only the first phase of the required steering input and ignored the second phase, therefore, effectively making a simple turn. This happened for 3 drivers only; 12 drivers performed the second phase of steering input. As mentioned before, only one driver made the right steering input in experiment SE2.

These results, therefore, clearly indicate that drivers of an agricultural vehicle need visual cues to perform maneuvers as simple as maneuvers 4 and 5. They do not know what steering inputs are required for such simple maneuvers. Full visual cues, from both the field surface and the field boundary are required to ensure drivers are able to navigate the tractor.

6.5 Conclusion

Most drivers did not use visual cues from the outside world when driving in straight lines with a guidance system. Approximately 30% of the drivers in our simulator experiments used an aiming cue at the field boundary as a source of guidance information in addition to the lightbar guidance system, resulting in significantly lower steering activity. Visual cues are also needed by the driver of an agricultural vehicle for performing maneuvers which consist of two or more steering inputs. Any model proposed for the behavior of a driver of an agricultural vehicle should, therefore, include the use of visual cues. For straight line driving with a guidance system, this contribution should probably appear as a feedback loop that can be closed or open, depending on whether the driver actually uses visual cues. For performing maneuvers, the driver model should explicitly show that the driver needs visual feedback to start a new steering input.

The results of this study also emphasize the essential role of visual cues in driving simulation for agricultural vehicles. The drivers in our study used optic flow from the field surface and aiming cues on the field boundary for the driving tasks considered; a driving simulator for an agricultural vehicle must include these features.

7. TORQUE FEEDBACK ON THE STEERING WHEEL OF AGRICULTURAL VEHICLES

7.1 Abstract

The torque feedback on the steering wheel of automobiles, also known as "road feel", is important in some driving situations. New electronic and electro-hydraulic steering systems remove the mechanical connection between the road wheel and the steering wheel, but make it possible for the designer to provide any desired torque feedback to the driver. This study was performed to investigate whether the operation of agricultural vehicles can be made easier by the nature of the torque feedback on the steering wheel. For operators of agricultural vehicles, this feedback can be particularly important when they simultaneously monitor the operation of an attached machine. Experiments were performed in the field and in a tractor-driving simulator in which experienced tractor drivers drove in parallel swathing mode with the help of a GPS lightbar. Torque feedback on a real tractors' steering wheel was measured and implemented in the simulator. Also, in different tractor simulator runs, torque feedback on the steering wheel was computed based on steering wheel angle, the lateral force on the ground wheel, and the projected driving error. Analysis showed that when steering is the only task, the behavior and performance of the operator does not significantly change if the torque feedback is removed. However, when the operator has to perform a monitoring task as well, the performance of the operator was significantly improved by providing a torque feedback that was a function of the projected driving error. Also, when the feedback torque is a function of steering wheel angle, tending to move the steering wheel towards zero

steering angle position, the operator achieved a higher performance, presumably by reducing unnecessary steering inputs.

7.2 Introduction

Studies with automobiles and automobile driving simulators have shown that the force feedback on the steering wheel helps the driver to complete certain driving tasks better than when there is no force on the steering wheel (Steele and Gillespie 2001; Toffin et al. 2003). Some of these studies (i.e., Liu and Chang 1995) take one step further and conclude that the force on the steering wheel is a function of the contact forces between the tires and the ground and some vehicle dynamic variables such as lateral acceleration and therefore includes some "information" for the driver. Setright (1999) dismisses this idea as a "myth" because, he believes, the force on the steering wheel is corrupted by so many irrelevant forces from the steering system and other sources that what someone feels on the steering wheel is almost certainly not the tire self-aligning torque developed at the contact area with the ground. With hydraulic and steer-by-wire steering systems, the steering wheel is mechanically disconnected from the steered wheels, leaving the force on the steering wheel to depend only on the design of the steering system. Because of their many advantages, steer-by-wire systems are expected to appear on agricultural vehicles in the near future (van der Kamp 2002). Many of the features of this type of steering system, including the steering feel, can be programmed as desired. This has been a subject of extensive research in recent years and different control strategies for force feedback on the steering wheel have been suggested. Side force on the road wheel (Amberkar et al. 2004), tire slip angle (Nagiri et al. 1994), yaw rate of the vehicle (McCann 2000) and king pin angle (van der Kamp 2002) are among the variables that have been suggested to be used to compute the force feedback on the steering wheel.

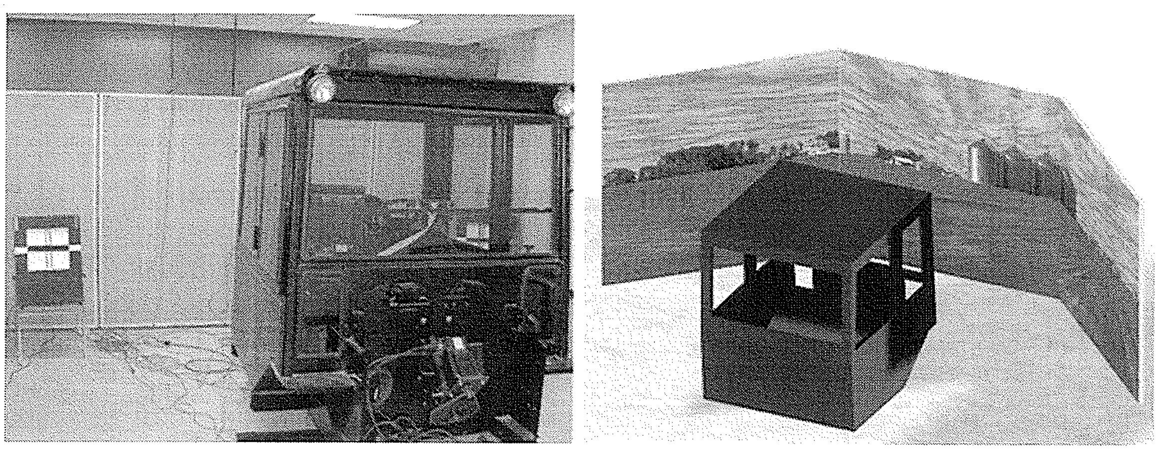
This paper addresses the issue of steering feel for agricultural vehicles and investigates whether the force on the steering wheel can help the operator of these vehicles by providing a cue regarding the state of the vehicle. Driving of agricultural vehicles in the field does not involve some of the difficult automobile driving maneuvers for which torque feedback on the steering wheel has shown to be important. However, most often operating of an agricultural vehicle also includes monitoring the operation of an attached machine. The driver has to frequently switch his visual attention from the steering task to the monitoring of the attached machine. Therefore, other cues such as motion cues or the force on the steering wheel can serve as "extraretinal" cues for the driver's steering task when (s)he is monitoring the attached machine. Force feedback on the steering wheel is particularly attractive because of the stimulus-response compatibility principle (Sheridan and Ferrell 1974). According to this concept, if the effectors of the response (i.e., the operator's hand in steering) also act as the information receptors, the reaction time and error rates will decrease. Therefore, if the force on the steering wheel facilitates quick and correct operator response, it is expected not only to achieve higher steering performance, but also to have better performance in a secondary task because less attentional resources would be needed for the steering task, leaving more resources for the secondary task. The objective of this study, therefore, was to examine whether force feedback on the steering wheel can help the operator of an agricultural vehicle in the completion of steering and monitoring tasks. Specifically, two objectives were considered: 1) to investigate whether the lack of torque on the steering wheel would affect the operator's steering performance, and 2) to determine the optimum torque feedback scheme during a dual-task scenario (i.e., steering and monitoring).

7.3 Effect of zero steering torque on steering performance

7.3.1 Experimental methodology for steering task

The objective of the first set of experiments was to investigate whether the lack of torque on the steering wheel would affect the operator's steering performance. Data were collected from two sources: a John Deere 5425 tractor and a tractor-driving simulator (Fig. 7.1).

Figure 7.1 The front view of the tractor driving simulator and a schematic showing the simulated visual scene during simulator operation.



The simulator provided visual feedback with a horizontal field of view of 65°, motion feedback, and force feedback on the steering wheel. The motion of the tractor in the horizontal plane is calculated in the simulator using:

$$
\begin{bmatrix} \dot{V}_y \\ \dot{\Omega}_z \\ \dot{\alpha}_f \\ \dot{\alpha}_r \end{bmatrix} = \begin{bmatrix} 0 & -V_x & C_f/m & C_r/m \\ 0 & 0 & a.C_f/I_z & -b.C_r/I_z \\ -1/l_{yf} & -a/l_{yf} & -V_x/l_{yf} & 0 \\ -1/l_{yr} & b/l_{yr} & 0 & -V_x/l_{yr} \end{bmatrix} \begin{bmatrix} V_y \\ \Omega_z \\ \alpha_f \\ \alpha_r \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ V_x/l_{yf} \\ 0 \end{bmatrix} \delta_f \tag{7.1}
$$

where

V_x and V_y : forward and lateral velocity of the tractor (m/s)

Ω_z : tractor yaw velocity (rad/s)

α_f : front tire slip angle (rad)

α_r : rear tire slip angle (rad)

δ_f : front wheel steer angle (rad)

The rest of the variables are the tractor parameters as described in Chapter 3.

Ten experienced tractor drivers drove a John Deere 5425 tractor making parallel passes using an Outback S® lightbar guidance system to provide guidance information. A Leica GPS1200 RTK system was used to record the exact tractor location. The measurements from the RTK system were used to calculate the root-mean-square (RMS) of lateral deviation from the desired straight line (i.e., the driving error). Since the accuracy of the RTK system for most of the duration of the experiment was 2.5 cm or better, the error in RTK measurements was ignored.

Fifteen experienced tractor drivers (including the ten who drove the John Deere 5425 tractor) then performed simulated parallel swathing using the tractor-driving simulator as the vehicle. After a short training session to become familiar with the simulator, each subject completed two sessions, each 15 min in duration. In one session, there was no torque on the steering wheel. The only sources of resistance on the steering wheel were the friction and inertia of the steering wheel and column which were both negligible. In the other session, the simulator was programmed to have torque feedback similar in nature to the torque feedback measured on real tractors (described in the next section of the paper). The order of sessions was randomly assigned to each subject. Steering wheel angle and lateral deviation of the simulated tractor from the straight line were recorded and saved on the simulator computer. RMS of steering wheel angle and RMS of driving error were calculated to provide assessments of control activity and steering performance, respectively.

7.3.2 Steering performance

Table 7.1 summarizes the results of this experiment. In terms of RMS of driving error, analysis of variance showed that there was no statistically significant difference between the simulator experiments and the field experiment (Pr (>F) = 0.15). In terms of the control activity (evaluated by the RMS of steering wheel angle), there was no significant difference between the two scenarios in the simulator experiment (Pr (>F) = 0.12). The results of this experiment suggest that, when the driver is only responsible for the steering task, neither steering behavior nor driving performance changes when the steering torque is removed.

7.4 Optimum torque feedback scheme for dual-task condition

7.4.1 Torque feedback schemes compared

The objective of this experiment was to determine the optimum torque feedback scheme for an agricultural tractor based on performance during a dual-task condition (i.e., steering and rear-monitoring). Five different torque feedback schemes were compared.

Table 7.1 RMS of driving error and RMS of steering wheel angle for experiments with and without steering torque.

Experimental vehicle	RMS of driving error	RMS of steering wheel angle
John Deere 5425 (n=10)	32[a]	Not measured
Simulator with torque feedback (n=15)	35[a]	13[a]
Simulator with no torque feedback (n=15)	36[a]	16[a]

i) Zero torque feedback (TF-Z): The only resistance was the inertia of the steering wheel and steering column. This represents a hydraulic or steer-by-wire system with no torque feedback on the steering wheel.

ii) Torque feedback similar to a real tractor (TF-R): To measure the torque on the steering wheel of a tractor, a P-80A string potentiometer (Ametek Inc., CA) and a torque transducer (TQ301 reaction torque sensor from Omega Engineering Inc., CT) were used in a configuration shown in Fig. 7.2.

The measurements were performed on several tractors of various sizes. Figure 7.3 shows a sample of the measurements from a John Deere 5425 tractor. Small dots show the boundary of the measurements and the arrowed lines show how the torque changes as a function of steering wheel angle. The graph shows a large hysteresis effect and no distinct center position for the steering wheel. In other words, if the driver removes his hands from the steering wheel, the steering wheel will not return to the zero-angle position. Values of maximum torque were obtained for several tractors (Table 7.2).

Similar trends were observed for all tractors. Based on the measured values, the torque-angle relationship shown in Fig. 7.4 was implemented in the simulator.

Figure 7.2 Transducers used to measure steering wheel torque and angle (left) and their attachment to an actual steering wheel inside a tractor cab (right).

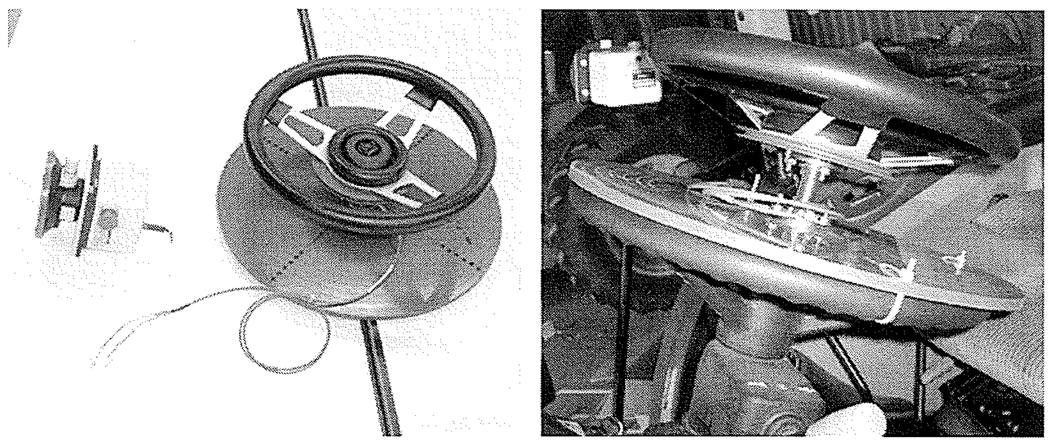
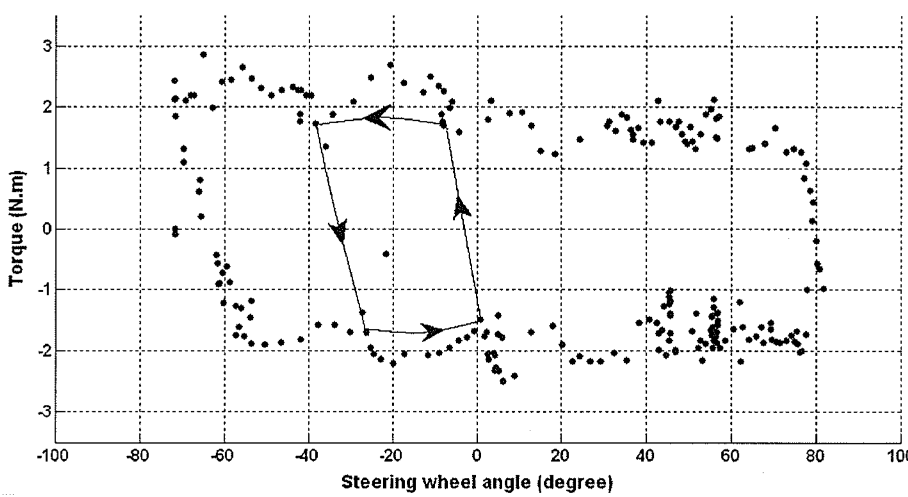


Figure 7.3 Sample measurement of steering wheel torque versus steering wheel angle.

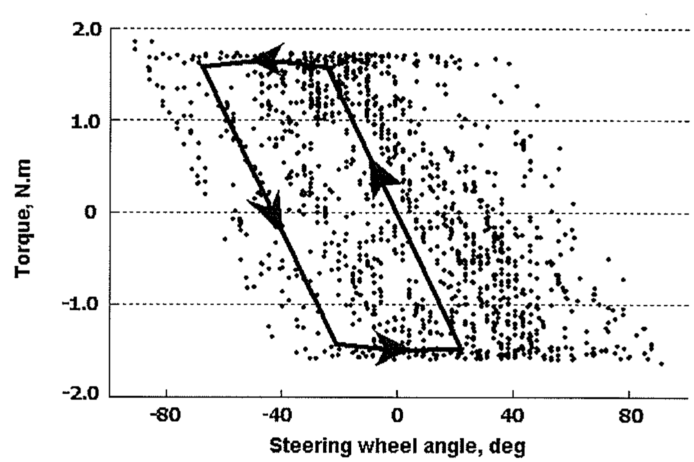


The maximum torque measured on real tractors was in the range of 1-2 N.m. However, most studies on steer-by-wire systems use higher torque values, usually in the range of 3-6 N.m (Jang et al. 2003; Segawa et al. 2004). Therefore, it was decided that for the next three torque feedback schemes, the maximum torque would be 2.5-4 N.m.

Table 7.2 Maximum steering wheel torque on several tractors.

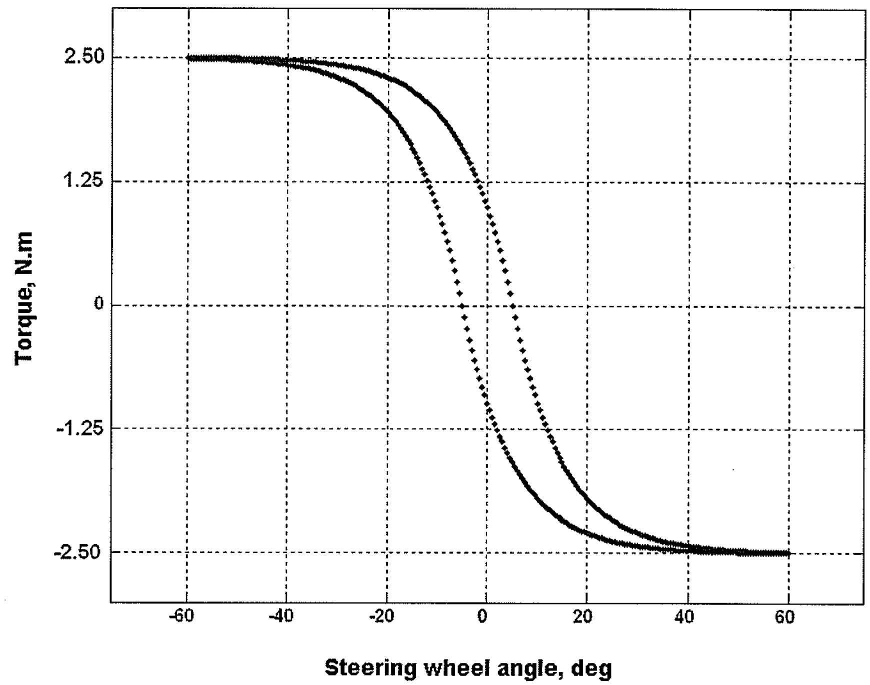
Tractor model	Max. torque (N.m)
John Deere 5425	2.0
John Deere 7520	1.6
Caterpillar MT765	1.5
Massey Ferguson 150	6.5
Ford/New Holland 8670	1.2

Figure 7.4 Steering wheel angle-torque relationship implemented in the tractor-driving



iii) Exponential torque feedback (TF-E): Exponential torque feedback is displayed graphically in Fig. 7.5. With this scenario, the steering wheel will tend to return to the zero-angle position when released and the torque on the steering wheel is proportional to the steering wheel angle. Therefore, unlike the measurements on real tractors, the torque on the steering wheel provides the driver with information regarding the magnitude of the steering wheel angle.

Figure 7.5 The envelope of the steering wheel torque feedback with exponential rise and small hysteresis.

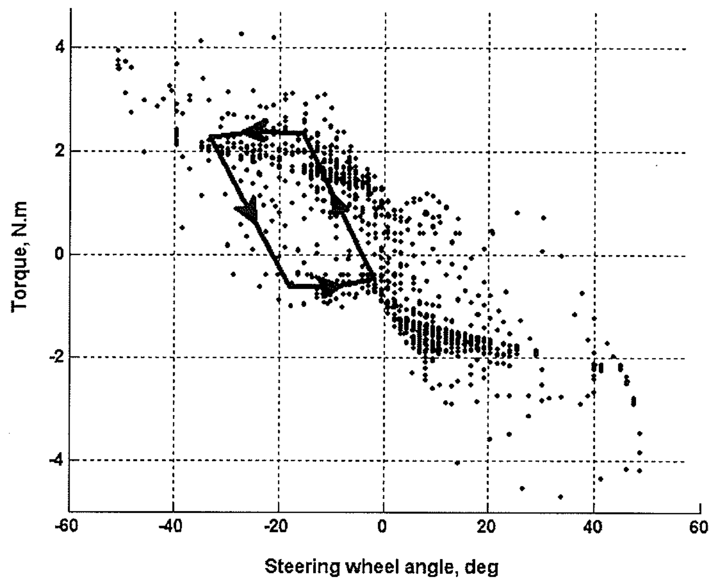


iv) Torque feedback proportional to the lateral force on the steered wheel from the ground (TF-PLF): Amberkar et al. (2004) suggested that the torque feedback for a steer-by-wire system should be proportional to the lateral force on the steered wheel caused by the ground. They suggest that one should preserve the steering wheel angle-torque relationship and increase the torque based on the force on the ground wheel. This is because using the force on the ground wheel alone to compute the torque feedback on the steering wheel will not result in a desirable phase relationship between the steering wheel angle and torque. The lateral force on the front wheel is:

$$F_{yf} = C_f \cdot \left(\delta_f - \frac{a\Omega_z + V_y}{V_x} \right) \quad (7.2)$$

where the term in the brackets is equal to the tire slip angle, α_f. Fig. 7.6 shows a sample of steering wheel angle-torque plot for this case.

Figure 7.6 The steering wheel angle-torque plot with the torque value increased by the value of the side force on the ground wheel.



v) Torque feedback proportional to the lateral deviation at a look-ahead distance (TF-PLD): The final scheme represents a situation where shared control between human and the machine exists. The goal of the steering task in straight line driving (parallel swathing) is to minimize the lateral deviation from the desired straight line. The driver tries to zero the lateral deviation (i.e., driving error) at a suitable look-ahead distance. In this torque feedback scheme, the lateral deviation from the desired straight line is computed at an appropriate distance ahead of the current tractor position, assuming that the steering wheel angle remains as it is at the moment. The torque on the steering wheel will be proportional to this deviation and in the direction of the desired steering correction. If the driver takes his hands off the steering wheel, the feedback torque will tend to turn the steering wheel so that the projected lateral deviation at the chosen look-ahead distance is zero. The appropriate look-ahead distance depends on the forward speed, dynamics of the vehicle, and driver skill and attention (Weir and McRuer 1968). Following the suggestions made by Weir and McRuer, a look-ahead distance of 8 m was chosen.

7.4.2 Experimental methodology for optimum torque feedback

As mentioned previously, the objective of this experiment was to evaluate different steering wheel torque feedback schemes in the presence of a dual-task workload. The tractor-driving simulator was used to conduct the experiment. The main difference between this experiment and the simulator experiment described earlier in the paper was the addition of a secondary task to simulate the monitoring of an attached machine. The secondary task included monitoring of two identical displays located behind and to the side (one to the left and one to the right) of the simulator (Fig. 7.1). Each display consisted of a small horizontal bar that moved vertically away from a center position after a random delay had passed. Once the bar moves from the center position, the subject in the simulator presses the proper button on a joystick to move it back to the center. The bar moves again after another delay time. The shorter the delay times, the more attention the subject has to pay to the secondary task. The performance in the secondary task is assessed by the reaction time, defined as the time between when the bar starts moving away from the center position until the time when the operator presses the correct joystick button.

Eight experienced tractor drivers participated in this experiment, using each of the five torque feedback strategies. Each subject completed five sessions. Each session was 15 min long. Prior to each session, the torque feedback strategy was explained to the subject. During the first 5 min of each session, the delay for the secondary displays was randomly varied between 15 and 30 s. This relatively long delay made the secondary task easy, allowing the subject time to focus on the steering task to learn the new torque feedback scheme. In the remaining 10 min, the delay was randomly selected between 5 and 15 s, making the monitoring task more demanding. Only the data from the last 10 min of each session were used for analysis. The analysis included computation of the RMS of lateral deviation (i.e., driving error) as a measure of performance in the steering task, RMS of the steering wheel angle as a measure of steering activity, and the average reaction time (to the secondary displays) as a measure of performance in the monitoring task.

7.4.3 Optimum torque feedback

Table 7.3 shows the summary of the results obtained in this experiment. The values in the table are the averages for all drivers. In terms of performance in the steering task, there was no difference between zero torque feedback (TF-Z), torque feedback based on measurements on real tractors (TF-R), and torque feedback proportional to lateral force on the steered wheel (TF-PLF). The driving error for these experiments is larger than the errors observed in the previous simulator experiment due to the addition of the monitoring task which prevents the driver from focusing full attention on steering. As expected, the last torque feedback scheme (TF-PLD), in which the torque feedback was in the direction of the desired steering correction, resulted in the best steering performance. Exponential torque feedback (TF-E) also resulted in relatively low driving error and also in the lowest steering activity. In terms of steering activity, the largest RMS of steering angle was observed when no torque feedback (TF-Z) was delivered.

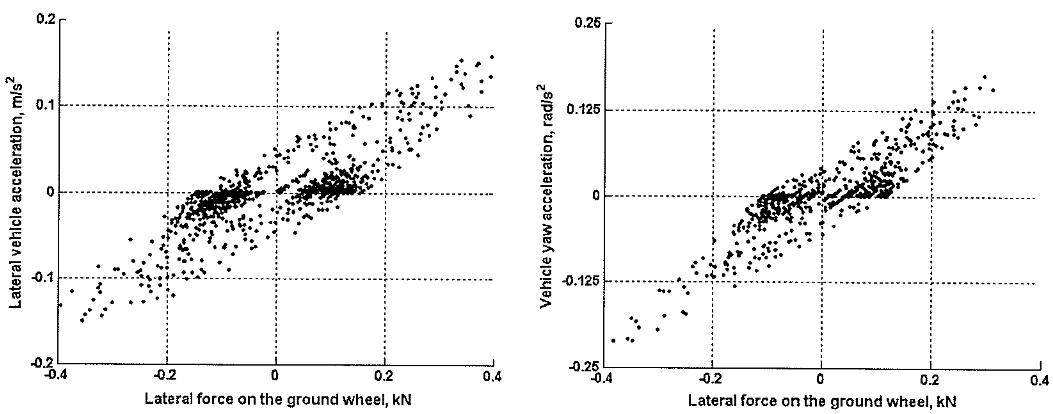
The between-subject differences in reaction time to the monitoring task were large. However, analysis of variance showed that the reaction time was lowest when the torque feedback was proportional to the projected lateral deviation at the look-ahead distance (TF-PLD). Exponential torque feedback (TF-E) also resulted in relatively small reaction times, significantly shorter than the reaction time when no torque feedback is provided (TF-Z).

Table 7.3 Average driving error, steering wheel angle, and reaction time for each of the five torque feedback schemes. Different superscripts in a column indicate significantly different numbers.

Torque feedback scheme	RMS driving error	RMS steering wheel angle	Reaction time for the monitoring task
TF-Z	47^{a}	18^{a}	3.8^{a}
TF-R	$52^{a,b}$	14^{b}	$3.1^{a,b,c}$
TF-E	$39^{b,c}$	6.0^{c}	$2.4^{b,c}$
TF-PLF	$44^{a,b}$	10^{b}	$3.3^{a,b}$
TF-PLD	31^{c}	13^{b}	1.8^{c}

The results show that enhancing the torque feedback on the steering wheel by the force on the ground wheel (TF-PLF) would not result in a significant improvement in the performance of the operator of an agricultural vehicle in the simultaneous task of steering the vehicle in parallel swathing mode and monitoring of the attached equipment. Driving in parallel swathing mode involves small steering angles, resulting in a relatively linear relation between the lateral force on the ground wheel and the lateral and yaw accelerations (Fig. 7.7). Therefore, a steering wheel torque feedback scheme based on lateral or yaw acceleration of the vehicle, suggested by some researchers (Segawa et al. 2000), would not be effective either.

Figure 7.7 Sample plots of lateral and yaw acceleration as a function of the side force on the front (steered) wheel of the tractor in straight line driving.



The exponential torque feedback scheme (TF-E) resulted in the lowest steering activity and good performance in steering and monitoring tasks. As mentioned before, the torque feedback tends to move the steering wheel towards the center position, thereby showing the center position of the steering wheel to the operator. It seems that the operators maintained a small steering wheel angle when monitoring the secondary displays. In fact, in many compensatory steering tasks, such as driving on a straight line in the presence of a disturbance, a good strategy is to keep the steering angle as small as possible; large steering inputs will result in an exponential growth in deviations (Hess 1997).

When the torque feedback indicated the direction of the desired steering correction (TF-PLD), the driving error was minimal. In this scheme the operator received a cue regarding the desired steering correction even when he was not looking at the GPS lightbar. Therefore, more attention could be paid to the secondary task, resulting in the lowest reaction time, too. However, it should be noted that if the information regarding the desired steering correction is available, the steering task can be automated. In other words, the operator can take his hands off the steering wheel and the feedback torque will move the steering wheel to the desired direction, provided that the system is stable. Our experiment represents the shared control between the operator and the automation, wherein the operator can follow or override the desire of the automation.

7.5 Conclusions

The first experiment showed that, when steering is the only task, the performance and behavior of the operator does not change when torque feedback is removed. This does not necessarily mean that torque feedback cannot be useful for this task, because no additional torque feedback schemes were examined. However, this conclusion is important for driving simulation of agricultural vehicles. From this standpoint, it can be concluded that torque feedback on the steering wheel is not necessary for a tractor driving simulator to mimic real tractor driving in parallel swathing mode.

The second experiment showed that torque feedback on the steering wheel can help the operator to perform steering and monitoring tasks with higher performance and less effort. The best results were observed when the torque indicated the future driving error (TF-PLD). This scheme can be improved by choosing an optimum look-ahead distance and optimizing the control of the feedback torque. A simple scheme that showed the zero steering angle position (TF-E) to the driver was also very effective. Unlike the former feedback strategy, this scheme can be easily implemented on real tractors with an inexpensive mechanical option such as a spring system.

8. APPLICATION OF AUDITORY SIGNALS TO THE OPERATION OF AN AGRICULTURAL VEHICLE: RESULTS OF PILOT TESTING

8.1 Summary

The operation of agricultural vehicles is a multitask activity that requires proper distribution of attentional resources. Human factors theories suggest that proper utilization of the operator's sensory capacities under such conditions can improve the operator's performance and reduce the operator's workload. Using a tractor driving simulator, this study investigated whether auditory cues can be used to improve performance of the operator of an agricultural vehicle. Steering of a vehicle was simulated in visual mode (where driving error was shown to the subject using a lightbar) and in auditory mode (where a pair of speakers were used to convey the driving error direction and/or magnitude). A secondary task was also introduced in order to simulate the monitoring of an attached machine. This task included monitoring of two identical displays, which were placed behind the simulator, and responding to them, when needed, using a joystick. This task was also implemented in auditory mode (in which a beep signaled the subject to push the proper button when a response was needed) and in visual mode (in which there was no beep and visual monitoring of the displays was necessary). Two levels of difficulty of the monitoring task were used. Deviation of the simulated vehicle from a desired straight line was used as the measure of performance in the steering task, and reaction time to the displays was used as the measure of performance in the monitoring task. Results of the experiments showed that steering performance was significantly better when steering was a visual task (driving errors were 40% to 60% of the driving errors in auditory mode), although subjective evaluations showed that

auditory steering could be easier, depending on the implementation. Performance in the monitoring task was significantly better for auditory implementation (reaction time was approximately 6 times shorter), and this result was strongly supported by subjective ratings. The majority of the subjects preferred the combination of visual mode for the steering task and auditory mode for the monitoring task.

8.2 Introduction

Vision is the fundamental sense for humans, and it is known that humans depend on the visual sense for 80% or more of external information (Takao et al., 2002). This has led to an underdevelopment of auditory and haptic feedback in the design of human-machine interfaces. In particular, we are not taking advantage of the powerful properties of sound as a carrier of certain forms of information (Søråsen, 2004).

Human information processing ability is limited by finite attentional resources (Wickens, 1992). The multiple resources model (Wickens, 1992) states that humans do not have a single supply of homogeneous attentional resources, but several different capacities with resource properties. These resources are distributed and shared among tasks as needed. As a task becomes more difficult, it requires a larger part of the available resources and consequently limits the resources available to other simultaneous tasks. However, different tasks may compete for different categories of resources. Therefore, when two tasks use different groups of resources, they can time-share the resources, but two tasks using similar resources are more likely to interfere with one another (Wickens, 2002). The multiple resources model identifies processing resources along three dimensions: processing codes, processing modalities, and processing stages. The more the different tasks share common resources along each of these dimensions, the greater the risk of task interference becomes. For example, two tasks demanding visual perception will interfere with each other more than if one of the two tasks requires visual perception and the other requires auditory perception. Therefore, it is assumed that as workload in the visual modality increases, providing additional information through the auditory channel will result in a better sharing of attentional resources and consequently in higher performance and lower workload (Belz, 1997).

Sound arouses attention and conveys information even if the subject does not pay attention to the signal. Furthermore, hearing is an omnidirectional sense, in that auditory signals capture the attention of the operator regardless of gaze direction. These interesting properties along with other advantages of auditory displays, such as their lower cost compared to visual displays (Stokes and Wickens, 1988), makes auditory displays an interesting option for certain applications. Important applications of auditory signals include alarms and warnings in industrial systems and processes and in airplane cockpits. In computer technology, they are used to enhance the user interface of computer games, operating systems, and other software. Several new areas have opened recently; examples include using auditory signals to manage and direct the operator's visual attention under high visual workload conditions and vehicle telematics. Wickens and Seppelt (2002) identified 18 research publications examining auditory versus visual delivery of in-vehicle task information to the driver, focusing on the secondary tasks introduced by new in-vehicle technologies. The results of their review strongly support the use of auditory displays, especially when the secondary task information is not relevant to the driving task.

Operation of agricultural vehicles is a multitask job. The two main tasks of the operator are (1) steering the vehicle and (2) monitoring and controlling the operation of a machine, whether self-propelled or tractor mounted. The operator has to divide his attention between the two tasks to maintain good overall performance. This is not always an easy task; for example, if the forward speed is high, the operator has to concentrate his visual attention on guidance and ignore machine performance (Chisholm et al., 1992). With the introduction and development of new technologies, such as precision agriculture, these tasks have become more accurate and less physically difficult, but they have also become more diverse and mentally demanding since there is more information for the operator to absorb. Careful consideration of human factors issues is necessary to enable optimum use of these technologies by the operator over extended periods of work and under difficult working conditions, such as glare, working at night, and high noise and vibration. Surprisingly, there has been little research in this area. The objective of this study was to compare operator performance (both steering and monitoring) when information is provided to the operator of a simulated agricultural vehicle using either visual or auditory cues.

8.3 Materials and Methods

8.3.1 Apparatus

The experiments were performed in a tractor driving simulator. The simulator included a steering wheel for directional control of the simulated tractor, which was the primary task. A joystick with two rocker switches was used for the secondary task, which required monitoring of two identical displays located to the left and the right and behind the simulator cab. Primary and secondary tasks are explained in more detail in the following subsections. For the second set of experiments, realistic visual feedback with a horizontal field of view of 40° and torque feedback on the steering wheel were provided to increase the realism of the simulation.

8.3.2 Primary (Steering) Task

The primary task was driving the simulated tractor along a straight line. In order to provide a realistic duplication of the real-field situation, the simulated vehicle was constantly deviated from the straight line and the subject had to make proper steering adjustments to nullify the deviation. This intentional departure of the simulated tractor from the straight line was done using a spline forcing function that had been developed based on field experiments. The driving error was shown to the subject either visually (using a lightbar) or aurally (using two speakers). In the visual mode, a lightbar, consisting of a horizontal arrangement of 23 LEDs, was placed in front of the subject, close to the windshield (as shown in Fig. 8.1). The three center LEDs were green, and the other LEDs, ten on each side, were red. At any time, three LEDs were on. If the simulated vehicle deviated to the left, for example, three LEDs on the left side of the lightbar were illuminated. The location of the LEDs that were on indicated the error magnitude: the closer they were to the center of the lightbar, the smaller the error. If the three center LEDs were on, the error was almost zero. The smallest error that could be shown on the lightbar (when the first red LED went on) was 4 cm.

In the auditory mode, driving error information was provided using two speakers that were placed inside the simulator cab, approximately 0.8 m in front of the subject and 1.2 m apart from each other. If the deviation of the simulated vehicle was to the left, a beep was played only through the left speaker, and vice versa. The implementation, however, was not the same in the first and second experiments. In the first experiment, a beep was used to tell the subject if the driving error had passed a threshold of 10 cm. If the driving error was more than 10 cm to the right, for example, the beep was played through the right speaker. The volume of the beep was constant. In the second experiment, the volume of the beep indicated the magnitude of the deviation: the larger the deviation, the higher the volume. A total of five discrete volume levels were used to indicate if the error has passed five thresholds, namely 5, 12.5, 20, 27.5, and 37.5 cm. In both experiments, the beep was 200 ms in duration and, if the driving error was greater than the lowest threshold (10 cm in the first experiments and 5 cm in the second experiments), the beep was repeated at 1 s intervals. The subjects were allowed to adjust the volume by turning the speaker knob.

It needs to be mentioned that it is almost impossible to remove the use of visual cues in a steering task. Therefore, even when steering information is presented in an auditory mode, the driver will look ahead and will probably utilize visual cues in doing the task. Thus, the present study represents a stringent test of the extent to which auditory information may facilitate driving performance.

8.3.3 Secondary (Monitoring) Task

The first set of experiments included only steering; a secondary task was added in the second set of experiments. The secondary task included monitoring two identical displays located behind and to the left and right of the simulator cab. The simulator is shown in Fig. 8.1, and a schematic showing a floor plan of the experimental setup is shown in Fig. 8.2. Each of these two displays consisted of a level bar that moved vertically away from a center position at random and on a delay sequence. This delay was randomly selected by the main computer, which controlled the simulation within a range that could be specified in the beginning of each session.

Figure 8.1 A front view of the simulator, showing also the displays (right) and the interior of the simulator cab, showing the lightbar and joystick (left).

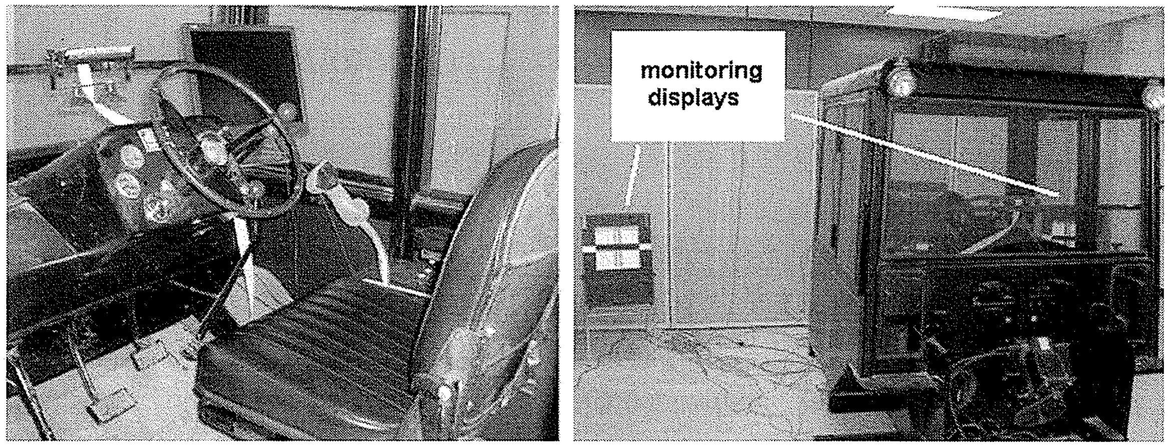
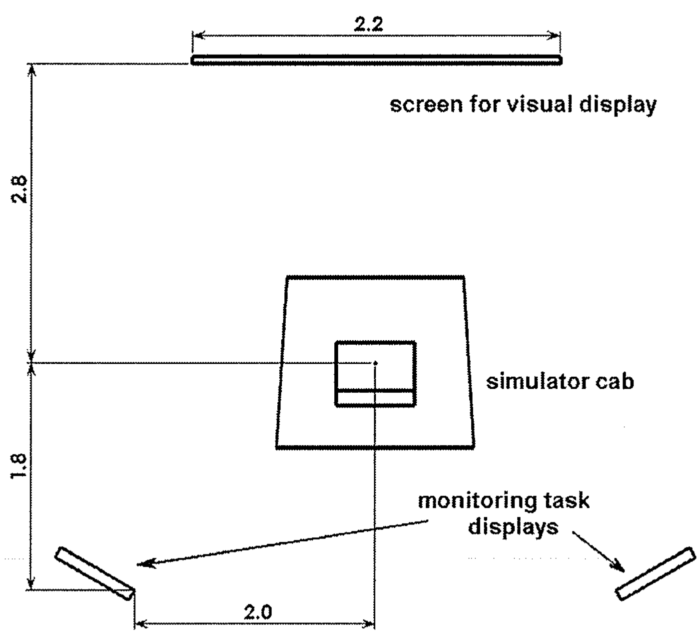


Figure 8.2 Floor plan of the experimental setup (dimensions are in m).



It was decided to have two levels of monitoring task difficulty. For the "difficult" monitoring task condition, the delay was randomly selected between 5 and 15 s; for the "easy" monitoring task condition, it was selected randomly between 15 and 45 s. When the level bar in a display moved from its centered position, the subject had to re-center the bar by simply pressing one of the two rocker switches on the joystick. Similar to the steering task, the monitoring task was realized in both visual and auditory modes. In the visual mode, the subject had to frequently monitor the displays, by looking back to see them, to make sure that the bars were centered. In the auditory mode, once the level bar started moving from its centered position, a beep was played to notify the subject; therefore, the subject did not need to visually monitor the displays. If the subject did not respond by pressing the proper switch on the joystick, the beep was repeated after approximately 3 s and the repetition continued until the subject pressed the proper joystick switch. Similar to the steering task, the auditory cues for the monitoring task were played only through the proper speaker (i.e., if the left display needed a correction, the beep was played only through the left speaker). The beep used for the monitoring task was of 200 ms duration. Incidentally, the beep that was used for the primary (steering) task was different from the one used for the secondary (monitoring) task, and all subjects could distinguish between them very easily.

8.3.4 Experiment 1

8.3.4.1 Subjects

Eleven subjects, eight female and three male, drove the simulator. The number of subjects was chosen based on the previous research found in the literature. For example, McBride and Ntuen (1997) used eight subjects to investigate the effect of multimodal display aids on performance, and Pierno et al. (2005) used the same number of subjects to study aurally and visually guided target acquisition in a virtual environment. Subjects were undergraduate students of the University of Manitoba, and none of them had experience driving an agricultural vehicle. Average age of the subjects was 22 years.

8.3.4.2 Experimental Design

Each subject drove the simulator in two sessions; each session was of 10 min duration. The only task was steering, which was simulated in visual mode for one session and in auditory mode for the other session. Subjects randomly completed the visual steering first or the auditory steering first. Each subject was provided with an oral description of the task and a short demonstration in the beginning of each session. They were also given some time to drive the simulator before each session so that they could understand the task completely. After the completion of both sessions, the subject was asked about his subjective evaluation of the two scenarios. In addition to these subjective ratings, driving error for each subject was recorded by the computer running the driving simulator.

8.3.5 Experiment 2

8.3.5.1 Subjects

Eight subjects, six male and two female, with an average age of 26 years participated. Subjects were students of the University of Manitoba, and only one of them had previous experience operating an agricultural vehicle.

8.3.5.2 Experimental Design

Both steering and monitoring tasks were included in this experiment. The combination of two steering task modes (visual and auditory), two monitoring task modes (visual and auditory), and two levels of monitoring task difficulty generated eight different scenarios. Each subject completed all of the scenarios in 5 min sessions. In order to eliminate the effects of fatigue and learning, the order of presentation of different scenarios was randomly varied between subjects. Before starting the actual experiments, the subject was given an oral description and a demonstration. The subjects were also given some time to drive the simulator until they felt confident that they understood the tasks. The subjects were also given time to rest briefly between sessions if they wished. Steering wheel angle and driving error data were collected by the main computer at a frequency of 30 Hz. The reaction time of the subject to the secondary displays was also recorded by the computer. Reaction time was defined as the time between when the level bar on the display started moving until the moment the subject pushed the proper switch on the joystick. After completing all of the experimental sessions, the subject was asked to complete a short subjective evaluation form; they were asked which of the implementation modes (visual or auditory) they found easier for the steering task and for the monitoring task and which of the four possible combinations of task modalities they preferred for doing the two tasks simultaneously.

8.4 Results and Discussion

8.4.1 Experiment 1

An analysis of variance showed that subjects had significantly better steering performance in the visual mode. The average of root mean square (RMS) of driving error was 19.1 cm (standard deviation equal to 4.0 cm), which was significantly lower [Pr(>F) < 0.01] than the average driving error in auditory mode which was equal to 47.9 cm (standard deviation equal to 15.3 cm). On the other hand, all but one of the subjects reported that the auditory mode was easier.

8.4.2 Experiment 2

An analysis of variance was completed to examine the effect of task modality on RMS of driving error using Tukey's test with $\alpha = 0.05$. Table 8.1 shows a summary of the results. In this analysis, for each of the four scenarios, both levels of secondary task difficulty were considered together. The results of the analysis indicate a significant role of the steering task modality on driving error. Subjects were able to perform the visual steering task with significantly lower error compared to the same task in auditory mode. When the steering task was auditory, the modality of the monitoring task did not have a significant effect on the performance in steering. However, when the steering task was visual, performance was higher when the monitoring task was auditory compared to when the monitoring task was also visual [Pr(>F) < 0.01].

During the time between the first set of experiments and the second set of experiments, fundamental modifications to the driving simulator were completed. Therefore, the driving error values from the two sets of experiments cannot be compared. However, it can be seen that in the first set of experiments the driving error in auditory mode was 2.5 times the driving error in visual mode, while this ratio was approximately 1.75 in the second set of experiments. This improvement can be attributed to a better implementation of the auditory steering task in the second set of experiments; using different volume levels, we were able not only to convey the magnitude of the driving error but also to decrease the driving error threshold for an auditory signal delivery from 10 to 5 cm.

Table 8.1 Results of analysis of variance to determine the effects of steering and monitoring task modalities on steering task performance and monitoring task performance. Different superscripts within the first row indicate significantly different means.

Scenario	Both tasks visual	Primary task visual, secondary task auditory	Primary task auditory, secondary task visual	Both tasks auditory
RMS driving error (cm)	46.8^{a*}	36.7^{b}	74.0^{c}	75.8^{c}
Reaction time (second)	4.9^{a**}	0.89^{b}	6.3^{a}	0.98^{b}

* (Pr (>F) <0.01)
** (Pr (>F) <0.01)

Considering all four scenarios together, the level of difficulty of the monitoring task did not have a significant effect on the performance in the steering task. In addition, considering each of the scenarios separately, statistical analysis showed that there was no significant effect on steering task performance of the two monitoring task difficulty levels used in this study.

In implementing the steering task in auditory mode, we tried to design a task that has almost the same level of difficulty as the corresponding visual task. Subjective ratings showed that three (out of eight) subjects found the auditory mode of steering easier. This is a good indication that the two implementations had similar difficulty levels. As mentioned before, we used five different volume levels to convey five levels of driving error (from 5 cm to larger than 37.5 cm); it does not seem feasible to come up with a much better implementation. Therefore, we assume that, based on the resolution, range, and frequency requirements, the driving error information is more appropriately conveyed using a visual display.

A similar analysis was performed to investigate the effect of task modalities on reaction time to displays, which was a measure of performance in the monitoring task. Table 8.1 shows a summary of the results of the analysis of variance. The values shown in table 8.1 are the averages of two experiments with two levels of monitoring task difficulty. The results indicate a significant role of the monitoring task modality on performance (as measured by reaction time); reaction times are much shorter when the monitoring task is auditory. The modality of the steering task did not seem to have any significant effect on the performance in the monitoring task, however, the best performance was achieved when the primary task was visual and the secondary task was auditory. This is interesting because the highest performance for the steering task was also observed in this scenario. This result is also in complete agreement with the subjective evaluations. Seven, out of eight, subjects rated this combination as the best combination of steering and monitoring task implementations. Even two of the subjects who rated auditory steering easier preferred a combination of visual steering and auditory monitoring.

Regarding monitoring task difficulty, analysis showed no effect of task difficulty on performance under any of the four task modality combinations, although, on average, the reaction time was shorter (the performance was better) under the easy monitoring task condition. This difference, however, was not statistically significant [Pr(>F) < 0.66].

Our simulator did not provide realistic noise. Although noise has been traditionally common in agricultural vehicles, modern agricultural tractors have sound-proofed cabs, which strongly attenuate the external noise. Therefore, it does not appear that this limitation undermines the validity of our results. In fact, in some situations, tractor drivers use the sounds of the attached machine as indicators of its performance. For example, in forage harvesting, these sounds help in monitoring machine loading and malfunctions (Talamo et al., 1984). While operating in modern tractor cabs, drivers have to leave the cab door open in order to be able to hear these sounds, thereby nullifying the noise-attenuating design of modern cabs. By using auditory signals inside the cab, however, the noise protection of modern cabs can be utilized.

8.5 Conclusion

Auditory implementation of the steering task resulted in lower performance levels, but application of auditory cues for the monitoring task resulted in a significant improvement in performance and also received positive subjective assessments. It relieved the operator from constant visual monitoring of rear displays, and it significantly decreased the response time. Although the steering performance was lower for auditory steering, subjective evaluations of auditory steering were promising; when the threshold was 10 cm, 90% of subjects found auditory steering easier. Under extended periods of work, the operator might develop eye fatigue and prefer to switch to auditory steering if possible. The reduction of driving performance due to fatigue might be much higher than the difference observed between auditory and visual modes in this study. Our experiments were unable to show this effect because the experimental sessions were short. Simulated or real-field experiments can be performed to see how often the operator will switch between visual and auditory steering modes.

9. GENERAL CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The major findings of this thesis are:

1. Driving of an agricultural vehicle in parallel swathing mode with a guidance system can be implemented in a driving simulator by modeling the error of the guidance system and self-deviation of the vehicle. The models can be very simple, such as the sum of several non-harmonic sinusoids, as long as the models have spectral characteristics that are close to the real phenomena.

2. Yaw motion cue is essential to the straight line driving of an agricultural vehicle. Experienced drivers effectively use this cue, resulting in lower steering activity and a relaxed driving style without losing performance. It is not possible for the operators to respond to the full range of disturbances on the tractor and the guidance system and they automatically reduce the open-loop crossover frequency by reducing their gain in order to avoid excessive driving errors. Yaw motion feedback helps the driver to apply this strategy more effectively. When yaw motion cues are available, the driver produces smaller steering angles, reducing the amount of unnecessary steering inputs. If the operator effectively uses the yaw motion feedback and the lateral deviation information from the lightbar, (s)he can perform the steering task without any lead or lag equalization. The best way to drive in parallel swathing mode with a lightbar guidance system is to use yaw motion of the tractor as an additional cue and to try to null errors with small steering wheel angle inputs. This would result in relaxed driving and

improved performance. A poor strategy would be to respond to the error shown on the lightbar with large steering inputs.

3. Operators of agricultural vehicles do not have a proper understanding of the relationship between the steering input and vehicle response. In performing maneuvers that include more than one steering input, such as lane-change-type maneuvers, they require visual feedback to perform the proper steering input. In parallel swathing mode, however, most drivers do not use feedback from the visual scene and depend only on the information from the guidance system.

4. Torque feedback on the steering wheel can be an effective cue for agricultural vehicle operators. This thesis showed the positive effect of some torque feedback schemes when the operator steered the vehicle and was also engaged in a simultaneous monitoring task. A particularly effective feedback strategy is one that tends to return the steering wheel to the center position. This scheme resulted in higher performance in steering and monitoring tasks and considerable reduction in the steering effort of the operator. The optimum scheme is wherein torque feedback on the steering wheel is in the direction of the desired steering input. This scheme provides shared control between the human and the automation and results in the best performance in steering and monitoring tasks.

5. Auditory cues can be effectively used to increase the performance of the operator of an agricultural vehicle. When driving in parallel swathing mode, the information regarding the steering task, (i.e., the driving error) is best communicated through a visual display such as the lightbar. Providing this information through auditory cues resulted in a higher subjective rating, but lower

performance. On the other hand, using auditory signals to provide the information regarding the monitoring task resulted in significant improvements in operator performance and high subjective rating.

9.2 Recommendations

1. The operators of agricultural vehicles work for extended hours. The resulting fatigue will probably change the behavior of the operator. Studies should be performed to investigate this phenomenon. Auditory cues, for example, may be especially useful in that situation and their role needs to be reevaluated.

2. Vibrations in agricultural vehicles can be significant. High vibration levels can change the driver's behavior. For example, vibration might interfere with the driver's use of motion cues. Therefore, the role of motion cues in the presence of vibrations should be reassessed.

3. In this study, the field experiments were performed with a tractor that pulled no machine or equipment. When the tractor pulls an attached machine, the steering behavior of the tractor changes and guiding the tractor usually becomes more difficult. This can be considered and investigated in future research.

4. It is required to study the effect of other motion cues such as the lateral acceleration.

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Appendix A

Description of the contents of the accompanying CD

The thesis comes with a CD which contains the following:

1. The data that is used in this thesis. All data is in Microsoft Excel (i.e., .xls) format. The data includes the RTK GPS data that was collected in the field, the driving simulator data, and some measurements on tractors such as the steering wheel torque feedback and measurements that were used to study tractor yaw dynamics in Chapter 3.

The computer code for the driving simulator. This includes the main code and the code that generates the visual scene. The two codes are included in their original format with all supporting files as well as in simple text format with the software-generated code removed.

Appendix B

SIMULATOR SICKNESS

As mentioned in Chapter 2, simulator sickness can be a major issue in driving simulation. It was mentioned that the main theory of simulator sickness is based on the conflict between human sensory channels. Motion cues, particularly, have shown to be of significant effect in certain experiments. However, research on the effect of motion cues on simulator sickness has produced inconsistent results; in some driving scenarios motion cues have had a mitigating effect (Lin et al. 2005), while in other studies they have made simulator sickness more severe (Mollenhauer 2004). This chapter describes the observations on simulator sickness in the tractor driving simulator.

Fifteen experienced tractor drivers participated in the study. Each subject drove in the tractor driving simulator in parallel swathing mode for two sessions, each 15 min in duration. In one session yaw motion was provided, while in the other session the simulator cab was not moved. Each subject was randomly assigned to perform the session with motion feedback or the session without motion feedback first. In order to assess the role of motion cues on simulator sickness, the experiment was stopped after 5, 10, and 15 min from the start of each session and the subject was asked to fill the Simulator Sickness Questionnaire (SSQ). SSQ was developed by Kennedy and his colleagues in 1993 and, ever since, it has been the standard instrument for evaluating simulator sickness in flight and driving simulators (Kennedy et al. 1993). The questionnaire was also administered before each session began in order to assess the pre-exposure sickness level. The SSQ can be used to calculate three subscale sickness scores and a total score (TS). The subscale scores include Oculomotor (O), Disorientation (D), and Nausea (N) scores and are designed so that they can be helpful in understanding the nature of the causal factors of simulator sickness in a specific driving simulator.

Kennedy et al. (1993) also provide the results of extensive measurements on 10 flight simulators that can be used to compare with new measurements from any flight or driving simulator. According to Kennedy et al., if the value of a given subscale score for a new simulator is within the range of the upper three or four simulators (from the 10 simulators that they used in their study), that can be regarded as an indication that the simulator is not well designed or that it is not functioning properly and a close examination of the simulator is required.

Figure B.1 shows the value of the total sickness score for each subject. Table B.1 shows the average of the three subscale scores and the total score for all drivers for the two driving simulator experiments. Also, the average value and the fourth highest value from the 10 driving simulators studied by Kennedy et al. are included in the table.

Figure B.1 Total sickness scores for the individual drivers.

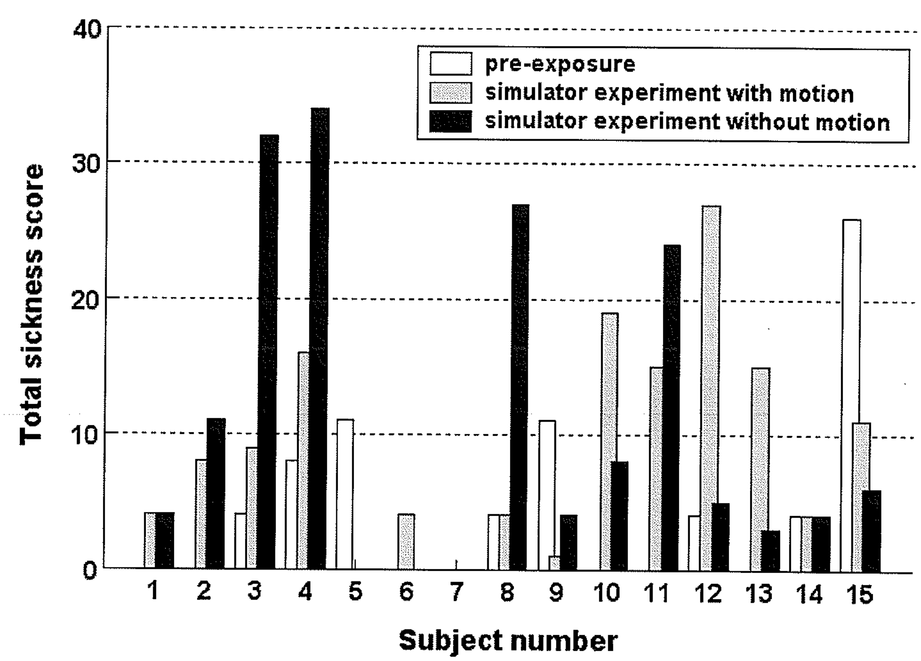


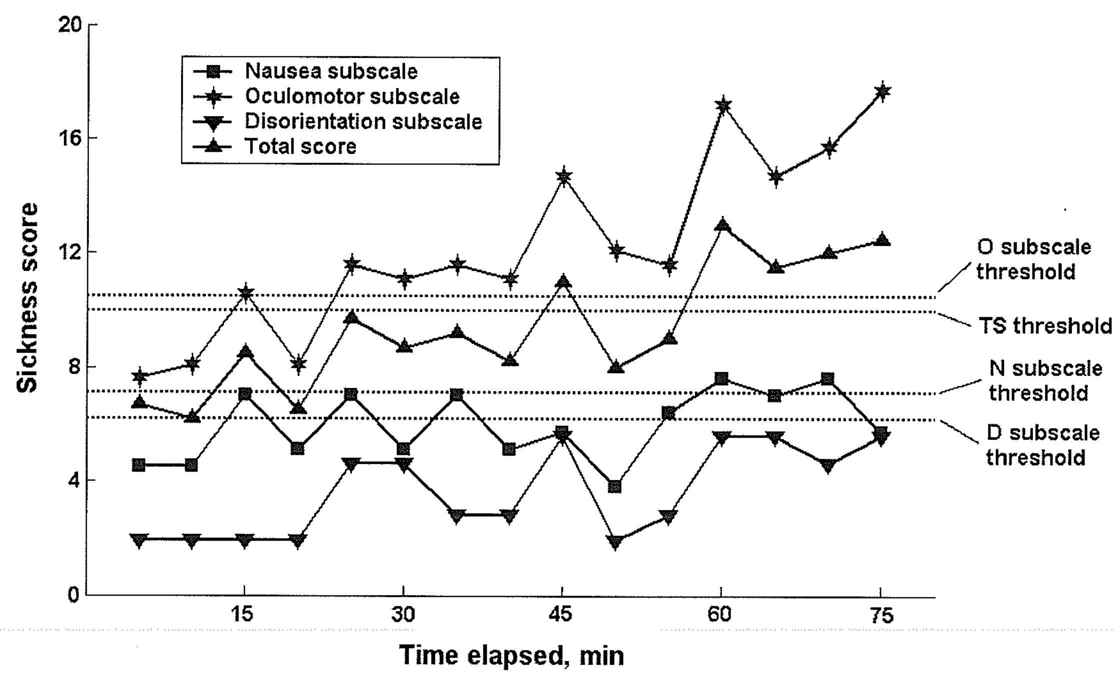
Table B.1 Subscale and total sickness scores from the tractor driving simulator and the reference values.

	N	*O*	*D*	*TS*
Pre-exposure	3.2	6.6	0.9	4.7
Tractor simulator with motion cue	5.3	12.3	3.4	9.0
Tractor simulator without motion cue	6.1	14.1	4.9	10.7
Average values from Kennedy et. (1993)	7.7	10.6	6.4	9.8
Fourth highest score from Kennedy et. (1993)	7.1	10.5	6.2	10.0

Following the suggestion made by Kennedy et al., the values calculated for the tractor driving simulator can be compared to the last row in table B.1. For total sickness score, this comparison shows that without motion cues, the TS in the tractor driving simulator barely exceeds the threshold. When yaw motion was provided, it is slightly below the threshold. Considering the subscale scores for both tractor driving simulator experiments, the Nausea (N) and Disorientation (D) subscale scores are well below the acceptable threshold while the Oculomotor (O) subscale scores exceed the threshold. Therefore, it is most likely that relatively high values of total sickness score in the tractor driving simulator are entirely due to the visual perception (Kennedy et al. 1993). As it was shown in Chapter 6, most drivers do not use visual feedback from the visual scene in parallel swathing. Therefore, the major cause of simulator sickness must be eyestrain due to extended focus on the lightbar.

It is also very likely that long driving simulator sessions contribute to high sickness scores. This consideration is particularly important for tractor driving simulators because tractor drivers usually work for extended hours. To test this hypothesis, data from fifteen subjects who drove in the simulator for 75 min were analyzed. The SSQ was completed every 5 min from the beginning of the experiment. Figure B.2 shows the change in simulator sickness scores as a function of time. While N and D subscale scores remained below or slightly above their corresponding threshold for the entire duration of the experiment, the O subscale score exceeded the corresponding threshold 25 min after the start of the experiment. The total sickness score had an almost acceptable value until 1 h from the start of the experiment. Therefore, unless the cause of observed sickness is identified and resolved, the simulator sessions should be no longer than 25 min.

Figure B.2 Change in simulator sickness as a function of the time elapsed from the start of simulator session.



Appendix C

Subject consent forms

1. Consent form for field and simulator experiments in Chapters 4 to 7 and Chapter 9.

Sensory Cues in Driving an Agricultural Vehicle

*** The consent for will be printed on the Department of Biosystems Engineering letterhead. ***

Research Objective

These set of experiments are part of the doctoral thesis of Davood Karimi, the primary investigator. Flight simulators and automobile driving simulators have been used for research and training for a couple of decades. Driving simulators provide a safe method to study driver and vehicle parameters in tightly controlled experiments. Experimental control is achieved much easier in driving simulators than in road tests, flexibility and efficiency of experiments are much higher and data collection is a lot easier. These and other advantages make driving simulators the best choice for driver-vehicle studies. In the Department of Biosystems Engineering at The University of Manitoba a tractor driving simulator has been developed. This simulator is a medium-level PC-based driving simulators that provides visual, haptic, auditory and motion cues and simulates the driving of a tractor and monitoring of an attached machine. The first goal of this project is to validate this simulator by comparing driving behavior in the field and in the simulator. The second goal is to study simulator sickness in this simulator.

Research Procedure

Experiment will have two parts.

i) field experiments: in the first part, you will drive a tractor for about 40 minutes. The driving maneuvers include driving on parallel lines (called parallel swathing) and doing some simple maneuvers such as simple turns. As you are performing these maneuvers, the exact tractor trajectory is recorded using a precise RTK GPS system.

ii) simulator experiments: later, you will participate in a set of experiments in a tractor driving simulator in the Department of Biosystems Engineering at The University of Manitoba. You will drive for 3 hours (9 sessions, 20 minutes each). Similar to the field experiments, you will perform simple maneuvers such as driving on straight lines and simple maneuvers. During these simulator experiments, simulated tractor trajectory will be recorded by computers that control the simulator. Every five minutes during these experiments, you will be asked to complete a Simulator Sickness Questionnaire to evaluate the degree of simulator sickness experienced by you.

If possible, the experiments will be performed during working hours (8:30 till 16:30). However, if the tractor and/or the participant are not available during working hours, the experiments can be performed after 16:30. The experiments with each of the participants will be completed in a single day unless the participant wants to postpone part of the experiment for another day. If weather conditions allow, all of the experiments will be completed in one week.

Risk
Field experiments will include simple driving maneuvers in the field. Maneuvers that you will be asked to perform are simple maneuvers that you do in your day-to-day work and no more risk that those simple maneuvers. Because of your familiarity with tractors, there is no risk involved in these experiments. Simulator experiments will be conducted in the lab and will be free of any risk except for a risk of simulator sickness. In some parts of the laboratory experiments we will be investigating the role of some simulator parameters in simulator sickness. It is expected that some of the subjects will show one or more of the typical symptoms of simulator sickness such as eyestrain, dizziness, or stomach awareness. However, based on the published literature in this field, most subjects either do not show any of the symptoms or they show only very mild signs such as slight eyestrain, sweating or dizziness. Vomiting, for example, has been reported for less than 1% of the participants.

Instruments
During field experiments, the tractor trajectory will be recorded by an RTK GPS system.

Assurance of Confidentiality
Your name will never be used with reference to this research. Only the principal investigator, Davood Karimi, and his advisor, Dr. Danny Mann, will have access to the information collected. The data will be stored in the research lab of Dr. Danny Mann until it has been entered into the computer. Once entered into the computer, it will be coded (i.e., subjects will not be identified by name). The original data (including the questionnaires) will be kept until completion of Davood Karimi's Ph.D. thesis and publication of the research results or December 31, 2009, whichever comes sooner. The data will be saved on PC hard drives for analysis; the PC is password protected and can be accessed only by the main investigator. At least one backup copy of the data will be saved on CDs to ensure safety. The data collected in these experiments will be used in the Ph.D. thesis of Davood Karimi. They may be used in manuscripts written for presentation in conferences and/or publication in scientific journals. Finally, after the period mentioned above, the data will be removed from the hard drives and the backup copies will be destroyed.

Availability of Research Results
The project is part of the research that will be described in my Ph.D. thesis. Preliminary findings will be available in the form of a summary sheet by the end of August 2007.

☐ Check the box to the left if you would like to receive a summary of the research. Please provide your e-mail address so that I can contact you when it is ready.

____

Remuneration

You will receive an honorarium of $25 for participating in the field experiments and $60 for participating in the simulator experiments.

Assurance of Voluntary Participation
Your participation in this research is voluntary. If at any time you wish to withdraw from the project, you may do so without consequence. Participation in this experiment is not part of the requirements of your work; your refusal to participate in this experiment will have no effect, whatsoever, on your work conditions.

Human Subject Research Ethics Approval
This research has received approval by the Education/Nursing Research Ethics Board (ENREB). Any complaint regarding a procedure may be reported to either the Human Ethics Secretariat (474-7122) or the Head of Biosystems Engineering (474-9819).

If you have any questions or concerns, please contact the primary investigator, Davood Karimi, or his advisor, Dr. Danny Mann:

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My signature indicates that I have read and understand the above conditions. I hereby give my consent for, and agree to participate in, this research project.

Name:______________________________ Date: ________________________

Witnessed by: ______________________ Date: __________________________

2. Consent form for simulator experiments of Chapter 8.

AUDITORY COGNITION
CONSENT FORM

I, ________________________________ agree to participate in this experiment.
(Please print your name legibly)

Please initial all statements with which you agree.

1. I have been provided with a description of the experiment. __________

2. I understand that all information collected through my participation in the experiment will be kept in strict confidence. __________

3. I understand that the information collected through this experiment may be published and/or presented at academic conferences. __________

4. I understand that in exchange for my participation in the experiment I will be compensated monetarily. __________

5. I understand that my participation is entirely voluntary and that I am free to withdraw at any time from the experiment. __________

__________________ (Date)

__________________________ (Participant signature in ink)

__________________ (Date)

__________________________ (Researcher signature in ink as witness)