Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Driving Simulator Development and Performance Study

Examensarbete utfört i Fordonssystem
vid Tekniska högskolan i Linköping
av

Erik Juto

LiTH-ISY-EX--10/4293--SE

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Utveckling och utvärdering av personbilssimulator

Driving Simulator Development and Performance Study

Författare
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Sammanfattning
Abstract

The driving simulator is a vital tool for much of the research performed at the Swedish National Road and Transport Institute (VTI). Currently VTI posses three driving simulators, two high fidelity simulators developed and constructed by VTI, and a medium fidelity simulator from the German company Dr.-Ing. Reiner Foerst GmbH. The two high fidelity simulators run the same simulation software, developed at VTI. The medium fidelity simulator runs a proprietary simulation software.

At VTI there is a wish to integrate the medium fidelity Foerst Trainer simulator hardware into the VTI simulation software environment. This would increase research, development and maintanance flexibility and simulator availability since development and research could be performed on one additional simulator. An integration would lead to a homogenous software environment that also decreases development, maintanance and training costs.

To integrate the Foerst Trainer simulator and the VTI simulation software to communicate a program that translates and relays input and output between the two was developed. An assessment of the hardware-software integration was performed through an experiment where the high fidelity Simulator 3 and the medium fidelity Foerst Trainer simulator were compared. The experiment was designed to measure the participants driving performances and the perceived realism of the simulator.

The results of the experiment shows that there is suprisingly small differences between the simulators, but more research is needed for more conclusive results.

Nyckelord
Keywords

driving simulator, VTI, Foerst

Abstract

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Acknowledgments

Many people have been involved in making this thesis possible. In no particular order, I would like thank Anders Andersson, Albert Kircher, Laban Källgren and Björn Peters at VTI; and Erik Hellström at Linköpings Universitet for their supervision. A special thank you to Anders for your help with the software implementations before the experiment and to Björn for helping with the statistical analysis of the questionnaires.

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Contents

Chapter 1

Introduction

1.1 Background

The Swedish National Road and Transport Institute (VTI) is an independent and internationally recognized research institute that investigates many aspects of traffic related research. An important tool in the research is the driving simulators. They provide a cost-effective and safe way to perform traffic and vehicular research, such as traffic safety, vehicle dynamics, driving behaviors, and evaluation of new vehicle technology.

A driving simulator typically consists of a driver cabin, systems for audio and video feedback from the simulation, and motion system which provides force feedback from the simulation to the driver. The specific configuration of a simulator depends on its intended usage and development budget. A basic and cheap driving simulator can consist of a standard PC with a simulation software, for example a car racing game. A driving simulator can also be an advanced and expensive machine with a real car cabin, 360 degrees field of view, and force feedback from a motion base not only capable of pitching, rolling and shaking the car, but also exerting almost 1 g of force along the car's lateral and longitudinal axes, all controlled by a distributed computer system.

A driving simulator provides a controlled environment where experimental conditions can be reproduced and the data from the experiments are easily available. The simulator also provides a safe experimental environment where research that otherwise could be potentially dangerous, to the driver and other traffic, can be performed. Examples of such experiments are: Driving under the influence of alcohol or medication, very tired drivers, or traffic situations with intense sun glare.

VTI currently posses three driving simulators; Simulator 2, a high-fidelity heavy vehicle simulator; Simulator 3, a high-fidelity simulator mainly used to simulate passenger cars, but have the capability of heavy vehicle simulations and the Foerst Trainer simulator, a medium-fidelity car simulator. All simulators are located in Linköping, Sweden. A fourth simulator, Simulator 4, is currently under development and will be built at VTI in Göteborg, Sweden [1].

The Simulator 2 and Simulator 3 are of the same basic design. The motion system consists of a linear motion base for the simulation of lateral forces during shorter time periods. The motion base tilts the simulator cabin for simulation of additional lateral and longitudinal forces or forces acting on the vehicle during longer time periods. A vibration table simulates the contact with the road. Simulator 3's motion base also has the capability to turn the cabin 90 degrees so that the linear motion base simulates longitudinal forces. This gives a more accurate simulation of accelerating and braking forces. The driver sits in a real vehicle cabin in front of a projector screen providing the driver with a 120 degree forward view. Monitors in the rear view mirrors lets the driver see what happens behind the vehicle.

The Foerst Trainer simulator is a commercial driving simulator developed by Dr.-Ing Reiner Foerst GmbH, Germany. The system runs a proprietary simulation software and consists of a basic driver cab, three 40 inch monitors, two channel audio system and a basic motion system that pitches and rolls the cab to simulate forces acting on the vehicle.

Simulator 2, Simulator 3, and in the future Simulator 4, run the same simulation software, developed at the VTI department of Vehicle Technology and Simulation. The modular design of the software allows one to substitute subsystems, both hardware and software, of the simulator with minimal changes to the rest of the simulator. Only the substituted sub-system's software need to be re-programmed, the rest of the simulation software is unaffected. Some of the advantages of running the same software on all the simulators are that all simulator can take benefit from improvements of the general software, smaller staff training costs and reuse of scenarios is very simple, at least from a technical point of view.

If the Foerst Trainer simulator is integrated into VTI's simulation software environment the utilization of all of the simulators can increase. The integration gives a homogeneous software environment allowing development and testing of VTI simulation software and scenarios on the Foerst simulator, thus increasing the time available for research in the other VTI simulators. An integration also eliminates the need of the extra training required for scenario development on multiple platforms, increases the ability of cross-simulator research and reusing of scenarios.

1.2 Objectives

This thesis work's objective is two folded. The first part is to integrate the Foerst Trainer simulator into VTI's simulation environment so that it's possible to run a simulation using the Foerst Trainer simulator hardware and the VTI simulation software. The second part is to compare the driving performance and perceived realism of Simulator 3 and the Foerst Trainer simulator.

1.3 Limitations

The main limitations of this thesis where time and budget. The software implementation time affected the time that was left for the performance study. Budget limitations restricted hardware purchases; only hardware that's available at VTI was used.

1.4 Related Work

In [2] the problem of driving simulator scenario portability is studied. The paper discusses the issues of replicating research and comparing performance variables measured during drives in different simulators due to differences in fidelity, cues, audio feedback and visual rendering.

Peters and Lidström propose a method for driving simulator fidelity assessment in [3]. The paper suggests that the fidelity should be measured through both objective and subjective measures, i.e. driving data and questionnaires. To get relevant driving data the authors propose several driving sub-tasks (called scenarios in this thesis) and measures to evaluate the drivers perception of the vehicle's position, speed, acceleration, vehicle control and the environment. The suggested subjective measures are questionnaires to measure the driver's perception of simulator realism and simulator sickness.

1.5 Thesis Structure

Chapter 2: The Simulator Systems. In this chapter the hardware and software of Simulator 3 and the Foerst Trainer simulator is presented.

Chapter 3: System Integration and Software Development. The work required to integrate the two simulators into the VTI-F simulator and to run the experiments is presented.

Chapter 4: Experiment - Method. A presentation of the experiments method, including participants, driving scenarios, questionnaires and measures.

Chapter 5: Experiment - Results. The results of the experiment are presented.

Chapter 6: Discussion. The system integration and the experiments are discussed. Future work and improvements are suggested.

Chapter 7: Conclusions. A conclusive summary of the thesis work.

1.6 Thesaurus

Following abbreviations and notations are used in this thesis work.

ANOVA	Analysis of variance
CAN	Controller-area network
Foerst GmbH	Dr.-Ing. Reiner Foerst GmbH
GUI	Graphical user interface
HID	(USB) Human interface device
I/O	Input/output
LCD	Liquid crystal display
MFC	Microsoft foundation class library
mmTTC	mean of minimum of TTC
NoCKO	Number of cones knocked over
PC	Personal computer
ScramNet	Shared common random access memory network
SDK	Software development kit
SDLP	Standard deviation of the lateral position of the car.
SDS	Standard deviation of speed
SSQ	Simulator sickness questionnaire
TARP	Translation and Relaying Program
TFT	Thin film transistor liquid crystal display
THWY	Time headway
TTC	Time to collision
UDP	User datagram protocol
USB	Universal serial bus
VTI	Swedish national road and transport research institute

Chapter 2

The Simulator Systems

The two simulator systems used in this thesis work, Simulator 3 and the Foerst Trainer simulator, are presented in this chapter. The simulators' hardware configurations is described in section 2.1 and the VTI simulation software, relevant in the scope of this thesis, is briefly described in section 2.2.

2.1 Hardware

2.1.1 Simulator 3

In 2004 the Simulator 3 was taken in use after several years of development. The simulator consists of an vehicle cabin mounted on top of a motion system. Simulator 3 is mainly used as a passenger car simulator, but the cabin can be exchanged to suit simulations of lorries, busses or trains. In front of the cabin an arched projection screen provides the forward view. An illustration of Simulator 3 can be found in figure 2.1.

The Simulator 3 motion system consists of a motion base and a vibration table. The motion base simulates forces acting on the vehicle by tilting the cabin and through linear motion along the lateral or longitudinal axis of the vehicle. The tilting and translating actions of the motion base supplement each other, the tilting motion best simulates forces that are constant or changes with low frequency, the translation is best suited to simulate forces that changes with a high frequency [4]. If an experiment requires more realistic acceleration and braking forces than lateral forces, the cabin can be rotated so that the linear motion base provides longitudinal forces instead of lateral. The vibration table is responsible of providing small high frequency translations, rotations and vibrations of the cabin. The arrows in figure 2.1 shows possible movements of the simulator motion system and table 2.1 shows the motion system specifications.

The visual system of Simulator 3 consists of three projectors, an arched projection screen providing the driver with a 120 degree forward view and three small TFT monitors, mounted in the rear view mirrors, provides the driver with rear view. The audio is supplied by an 8 channel audio system.

Motion base	Tilting motion	Pitch angle: -9 to +14 degrees
		Roll angle: ±24 degrees
	Linear motion	Maximum amplitude: ±3.75 m
		Maximum velocity:±4.0 m/s
		Maximum acceleration: ±0.8 g
Vibration table		Vertical movement: ±6.0 cm
		Longitudinal movement: ± 6.0 cm
		Roll angle: ±6 degrees
		Pitch angle: ±3 degrees

Table 2.1: Simulator 3 motion system specifications.

The computer cluster that is responsible for the simulation in the Simulator 3 consists of standard PCs running either Windows XP or the GNU/Linux distribution OpenSUSE. The computers have specific tasks, such as rendering a graphics channel, controlling the motion system or synthesizing audio. The computers are connected to the simulation kernel via ethernet, CAN-busses and ScramNet. See figure 2.3 for an schematic view of the system architecture.

2.1.2 The Foerst Trainer Simulator

The Foerst simulator is a commercial driving simulator developed for driver training by the German company Dr.-Ing Reiner Foerst GmbH. The simulator was acquired by VTI when participating in a research project funded by the EU. The Foerst Trainer simulator consists of a basic car cockpit mock up, a simple motion system, three 40 inch TFT monitors and an audio system [5].

The simulator cockpit consists of parts from a Ford Focus. All controls required for driving a car are available, i.e. steering wheel, pedals, dashboard, etc. The pedals are spring loaded for a realistic resistance in the pedals, and the steering wheel have a constant base resistance when the simulator is switched on.

The motion system of the Foerst Trainer simulator is a simple motion base capable of pitching and rolling the cab ±6 degrees to simulate longitudinal and lateral forces [5].

The video system consists of three 40 inch widescreen LCD-monitors. The monitors are responsible for showing the forward view, the rear view mirrors and the parts of the car body that's visible from the driver seat. The audio system supplies 2-channel audio to a 5.1 surround sound system.

The Foerst simulator utilizes one computer for rendering software, audio and motion cues. The computer is a standard PC, with a rather powerful, two channel, graphics card. A video splitter is used to split up one of the two channels so that three monitors can be used.

Figure 2.2 shows a picture of a Foerst Trainer simulator running the Foerst simulation software.

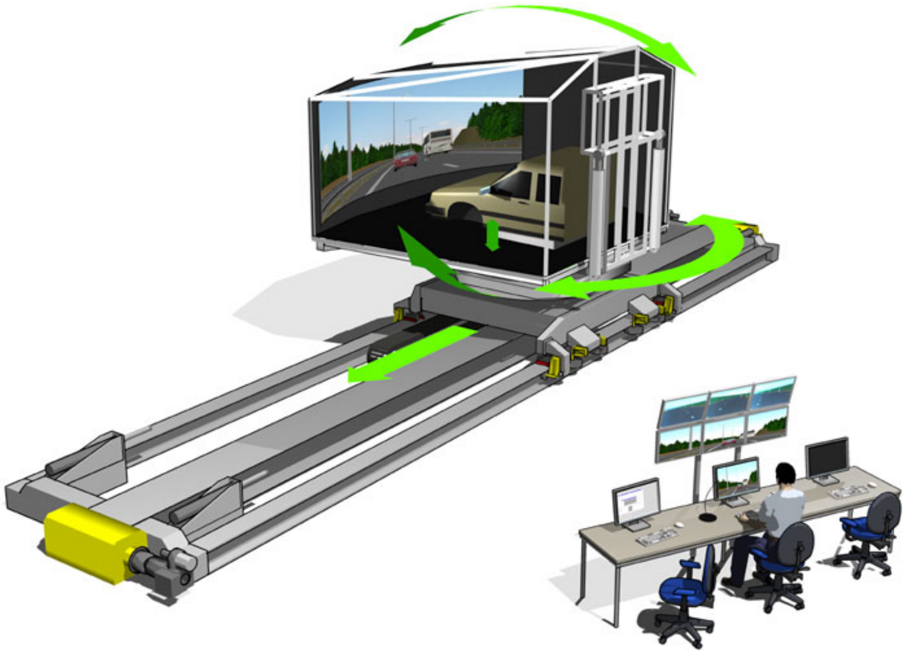


Figure 2.1: The illustration shows the Simulator 3, consisting of motion base, cabin and operator console. The arrows shows possible movement of the Simulator 3 cabin. Illustration: ARIOM reklambyrå.

Figure 2.2: Photo of the Foerst Trainer simulator. Photo: Dr.-Ing Foerst GmbH.

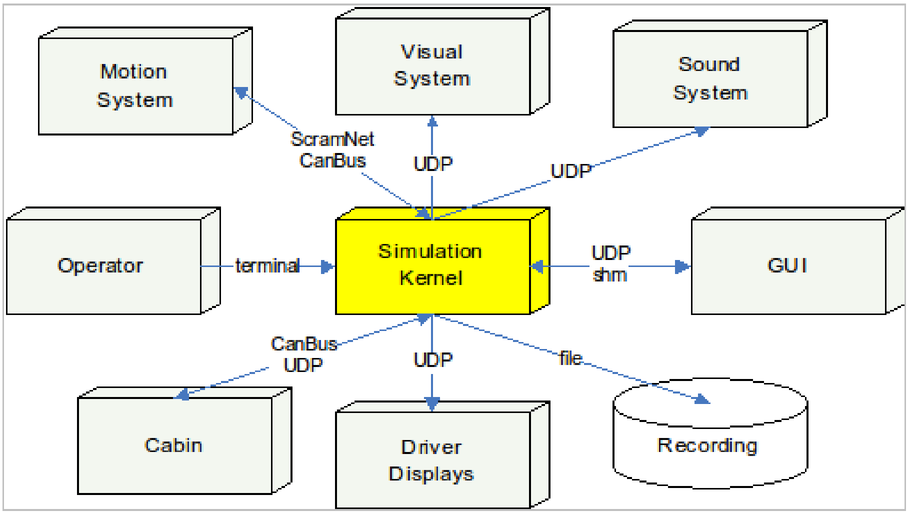


Figure 2.3: VTI Simulation system architecture [6].

2.2 VTI Simulation Software

The VTI simulation software run on a distributed computer system. The computers are standard PC's with Windows XP, or the OpenSUSE operating system. The software consists of a several programs, each responsible for different parts of the simulation. The core of the simulation software is the simulation kernel. It handles simulation calculations and data routing. Other parts of the simulation software sends data and/or receives data from the kernel to be able to perform it's task, such as displaying graphics, playing sound or controlling the motion system. See figure 2.3 for a schematic view of the system architecture.

Parts of the VTI simulation software relevant to the objectives of this thesis is described below in section 2.2.1 - 2.2.4.

Unless stated otherwise information in this section, and sub-sections, is collected from [6].

2.2.1 Framework

The VTI simulation kernel is built upon a software framework developed at VTI. The framework is developed in C++ and utilizes third-party libraries and frameworks such as Boost, OpenDrive and Qt. The framework provides a unified code base for all simulators of VTI. Figure 2.4 shows an illustration of the kernel architecture.

The framework has two central classes, the singleton `Router` class, and the abstract base class `SimObject`. The `Router` handles data routing between objects inherited from the `SimObject` base class. An class derived from a `SimObject` inherits its functionality to send and receive `Interactions` to and from other `SimObject` derived classes.

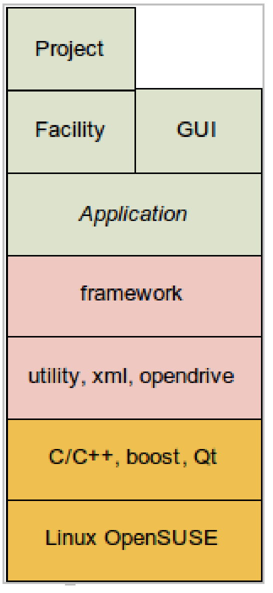


Figure 2.4: VTI Simulation kernel architecture [6].

An `Interaction` is basically a message containing a recipient and a message. The `Interaction` is sent from the sender object via the `Router` to the recipient.

2.2.2 Scenarios

The following definition of *scenario* is used in this thesis:

Scenario: The complete set of events[1] and interactions controlling the complete simulation experience from the start to the end of a driving task, see section 4.2 for a description of the scenarios.

The scenarios is controlled by actions from a scenario module. Actions can be triggered either manually by the operator or automatically by a measurement in the simulated environment, such as vehicle position or speed. An example of possible actions is the starting of an event or repositioning of the simulated vehicle.

2.2.3 Interfaces

The software interfaces provides a specification of methods that allows separate modules of the simulator software exchange data in a well specified manner. A software module can easily be exchanged, and a new module integrated with the simulation software by implementing the suiting interface.

Interfaces that is relevant in the scope of this thesis is:

[1]Events are detailed specifications of situations in a scenario. An event is a state machine that changes state when a specified trigger, e.g. speed, lane position, et.c. is set. Triggers are set by the simulated vehicle's state.

The facility interface: Specifies the methods required to let the simulator kernel/motion system exchange data.

The cabin interface: Specifies the methods of the simulator kernel/cabin communication.

The driver interface: Specifies the methods of the driver/cabin communication.

2.2.4 Other Software

Visual is the software responsible for rendering the graphical output of the simulation. The software is developed at VTI and is used both in Simulator 2 and Simulator 3.

PCLjudsystem is an audio software developed at VTI. PCLjudsystem models the different driving sounds using, for example the engine speed to model the engine sound.

Chapter 3

System Integration and Software Development

This chapter presents the work that was made for an integration of the Foerst simulator hardware and the VTI simulation software. In section 3.1 a brief description is given on system details considered before settling for a solution. Sections 3.2-3.4 gives an description of the software development needed to integrate the Foerst Trainer simulator into the VTI simulation environment. The scenarios is presented in 4.2 and software developed especially for the experiment is presented in section 3.5.

3.1 Background

On the original configuration of the Foerst simulator the hardware sends I/O to the Windows XP simulation computer through a USB cable. The USB interface is a virtual serial port on top of which a filter driver has been implemented. The filter driver makes the Foerst simulator hardware to appear as several USB HID's on the connected computer. The HID's are accessible through a SDK supplied by Dr.-Ing. Foerst GmbH, DirectX or by using Microsoft Windows built-in HID drivers.

The desired solution was to connect the Foerst simulator USB directly to the GNU/Linux computer running the VTI simulation kernel. The simulator was detected as a virtual serial device on the GNU/Linux computer, but the lack of GNU/Linux drivers made the HID programming approach unaccessible. Communication over the virtual serial port was examined and a successful connection was made. The serial communication approach was however discarded after a call to Dr.-Ing Foerst GmbH regarding the protocol of the communication since it appeared to time consuming to complete within the time limits of this thesis work.

The only feasible solution was to use a Windows XP computer as a relay. The relay computer communicates with the Foerst Trainer simulator over USB and relays data, via a local network, to the GNU/Linux computer that runs the VTI simulation kernel. However, communication over a network will introduce some time lag. The simulation demands that the software may not delay execution more than 5 ms, or else the driver might notice the latency. Due to this real-time demand; the time delays of the network communication were investigated. A simple client and echo-server was implemented using the Python programming language. The client started a clock, sent a string of characters to the server and the server echoed the string back to the client. When the string was received the clock was stopped. Both the UDP and the TCP/IP protocols were evaluated. Surprisingly, the UDP communication was slower than the TCP/IP[1], see figure 3.1 and table 3.1. Even though the UDP protocol was slower it was decided to be used since the VTI simulation kernel uses UDP as the standard protocol when communicating over network.

The latency introduced by the network in a relay solution, as described above, was considered to be tolerable, as the simulation deadline of 5 ms could be met. The implementation is presented in section 3.2, and a schematic view of the resulting system can be seen in figure 3.2.

		64 bytes		1023 bytes	
	Unit	UDP	TCP/IP	UDP	TCP/IP
Mean Latency	ms	0.75	0.48	2.50	2.51
Minimum Latency	ms	0.47	0.44	2.42	2.38
Maximum Latency	ms	18.30	1.35	27.40	19.00
Standard Deviation	ms	0.59	0.08	0.37	0.61

Table 3.1: Network latency data. The table shows the results of the latency tests with different packet sizes, 64 and 1023 bytes, and the two different network communication protocols, UDP and TCP/IP.

3.2 Translation and Relaying Program

To be able to use the Foerst Trainer simulator hardware with the VTI simulation framework it must be possible to send data between the two different systems. Also, the data representation on the two system differ, therefore a translation between the two data formats is needed.

A program, Translation and Relaying Program (TARP), responsible for data translation and relaying, was developed using Microsoft Visual C++, Microsoft Foundation Classes (MFC) and the Foerst Software Development Kit (SDK). The program receives data from the Foerst simulator, translate and relays it to the simulation kernel, and vice versa.

The data translation is in most cases a straight forward typecast. The Foerst SDK uses several different data types to represent the data sent to and from

[1]UDP is supposed to have lower latency than TCP/IP. The UDP protocol have minimal overhead as it is connectionless and have no error checking mechanisms [7].

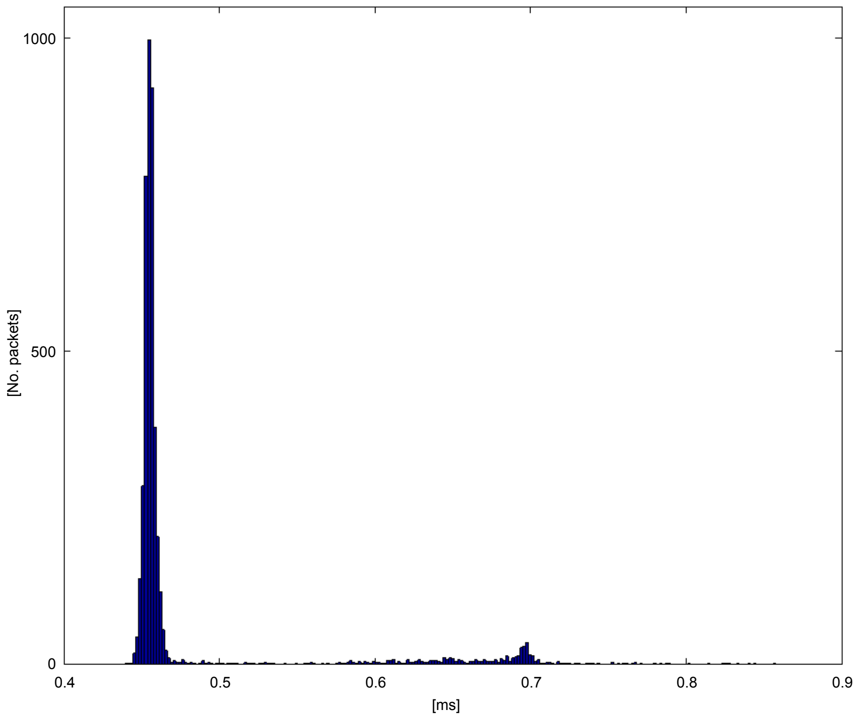


Figure 3.1: Histogram of the network latency. This histogram shows the latency of the TCP/IP protocol, 5000 packets, 64 bytes each. The latency of the other tests (see table 3.1) had the same principal shape with most packets in the lower time span and a few packets with higher latency.

the simulator. The data types is Microsoft specific such as `WORD`, `DWORD`, `BYTE`, etc. These are actually type definitions derived from ordinary C++ data types[7], `unsigned short`, `unsigned long`, `unsigned char`, etc. The VTI Simulation software exclusively uses `floats` in the cabin to simulation kernel communication.

A simple code example of a data conversion can be seen below. The VTI simulation kernel expects the clutch pedal to deliver a value between 0 and 1, where 1 equals a fully depressed pedal. The Foerst SDK delivers the clutch pedal position as a value between 0 and 255, where 255 is fully depressed.

```
// Convert clutch pedal position from Foerst to kernel format
float clutch_pedal_to_kernel = (float)clutch_pedal_foerst/255;
```

In the case of the accelerator pedal a typecast was not sufficient. The accelerator pedal was very sensitive in the top position. A simple function was implemented to give the pedal a bit of play. A sketch of the function can be seen

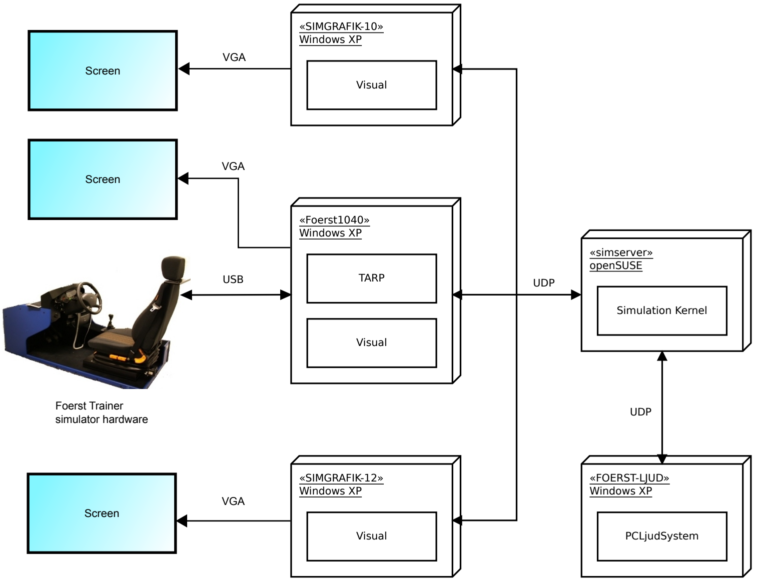


Figure 3.2: Illustration of the VTI-F simulator. The computers are drawn like boxes with a «computer name», operating system and which programs they execute.

in figure 3.3. The implemented function gave the accelerator pedal a more natural feeling.

When the Foerst simulator hardware sends output, the data is received by the device driver. The driver notifies the TARP, through Window messages, that data has been received. As soon the data has been loaded into the TARP, it is translated and sent to the VTI simulation kernel through a UDP network socket.

When data is received from the simulation kernel the receiving network socket's member function `OnReceive` is called by the MFC framework. The `OnReceive` member collects the data received, converts it to the correct data types and temporarily stores the data. When the TARP receives a `WM_TIMER` message, the stored data is sent to the Foerst simulator. The `WM_TIMER` message is emitted once every 15 ms.[2] Figure 3.4 shows a state diagram of the TARP.

3.3 Audio and Video

The audio system of Simulator 3 is an 8 channel system and the computer available for this thesis only had a 2 channel audio card. The audio software PCLjudsystem (see section 2.2.4) was therefore modified to play 2 channel audio. The two channels playing engine sound was kept and the remaining six audio channels were

[2]The timer's period was based on empirical testing. See section 6.1.1 for a more detailed explanation of the timer period.

Figure 3.3: Sketch of the implemented accelerator pedal function

removed. The removed channels contained the audio of road noise, rain and other sound effects.

The video program, Visual, was used almost unmodified. The only modification was a removal of data printouts that disturbed the visual impression of the simulation in the Foerst simulator hardware. In Simulator 3 the printouts is in the video feed, but it is projected out of the driver's view.

Visual was configured so that the drivers eyes and horizon were at the same height and so that the graphic distortion is minimized when shown over the seam of two monitors.

3.4 Implemented Interfaces

In this section a short presentation of the implemented interfaces is made. The description will be general and in the context of the communication between the Foerst simulator and the simulator kernel. Implementation details will be held to a minimum.

The cabin interface is actually split up into two parts. One interface handles input to the cabin and one handles output. The output interface only needed to send speedometer and tachometer values to the Foerst simulator. The output interface also can receive an `Interaction` from the GUI application (see section 3.5.1) used to control the simulation. The `Interaction` sets the speedometer and tachometer to zero, so that the speed estimation scenario (see 4.2.2) could be performed.

The input interface receives data from the Foerst simulator, via the TARP. The received data is:

- pedal positions
- gear number

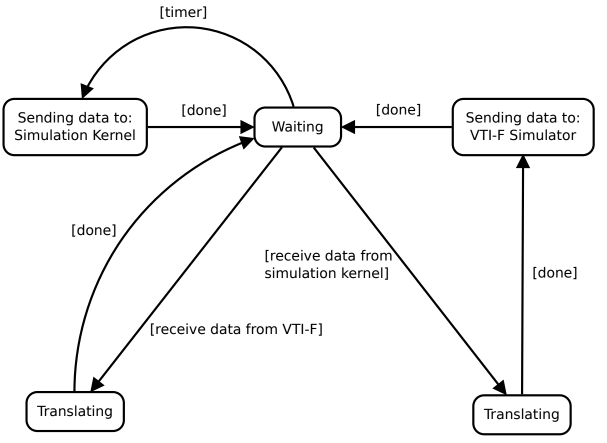


Figure 3.4: State diagram of the TARP. The figure shows the states of the program and the events that trigger a state change. When receiving data from the VTI-F simulator the data is buffered. The buffered data is sent to the simulation kernel on a `WM_TIMER` window message.

- steering wheel angle
- turn indicator

When the data is received it is sent through the input interface where it undergoes integrity checks and type casts and conversions. The data is then sent to the vehicle model which provides output for the next time step of the simulation.

The driver interfaces was not changed as the functionality of the supplied code was sufficient.

No facility interface was implemented[3] and the Foerst simulator was used as a fixed base simulator during the experiments.

3.5 Experiment Preparations

After the system integration was completed software for the experiments still was needed. The software implemented for the experiments is briefly presented in this section.

3.5.1 GUI Application

The GUI application is used by the test leader to select driving scenario, control scenario specific settings and set markers in the data. The GUI application was implemented using the Qt framework and was based on software developed at VTI for similar tasks.

[3]When the simulator software is started with a “no motion system” switch; the simulator kernel use an empty facility interface.

3.5.2 Scenarios

The driving scenarios were implemented in an existing scenario module called Demo2008. The scenarios were implemented so that they matched the demands from the experiment. See section 4.2 for a description of the scenarios.

3.6 Summary

The implemented TARP and kernel interfaces allowed the Foerst Trainer simulator to communicate with the VTI simulation kernel. Figure 3.2 shows the a schematic sketch over the resulting system, from here on called the VTI-F simulator. The implemented GUI application and scenarios allowed the performance evaluation, through experiments, to start.

Chapter 4

Experiment - Method

After the software implementation, described in chapter 3, the simulators were able to run the same software and scenarios. A simulator experiment was planned and conducted with the objective to determine if there were any differences between the two simulators in terms of driving performance and perceived realism.

The simulator experiment was designed to get objective as well as subjective measures of the driver's performance and experience of the simulator. The experiment included five scenarios that were driven by all participants. Driving scenarios and questionnaires were taken from [3].

The Simulator 3 drives took place in June of 2009, and the VTI-F simulator drives in September of 2009.

4.1 Design

The design of the experiment was a between-group design with two groups of five persons each. One group drove all scenarios in the VTI-F simulator and one group drove in Simulator 3.

4.1.1 Hypothesis

The hypothesis to be tested was that there should be no differences between Simulator 3 and the VTI-F simulator.

4.2 Scenarios

The rationale and description of included driving scenarios is presented in this section. The scenarios did not include any other traffic except for a lead vehicle in the car following scenario, see 4.2.3.

4.2.1 Lateral Positioning

Rationale: Measure driver perception and control of the vehicle's lateral position.

Description: The lateral positioning scenario took place on a long straight road. The driver was instructed to accelerate to 50 km/h. When the speed was reached the driver was asked to drive the vehicle with the left wheel pair on the road's center line. The driver was then instructed to drive with the right wheel pair on the road's right lane markers. Each of the positions was to be held for 10 s.

The scenario was repeated once so that more data could be collected. The lane width was 3.75 m and the lane markers was 10 cm wide.

Instructions to the driver: The driver was informed about the scenario and asked to inform the test leader when he/she had complied with each instruction, and hold their position until instructed otherwise. The following instructions were given to the driver during the drive:

1. Accelerate to 50 km/h.
2. Drive with the left wheel pair on the road's center markers!
3. Drive with the right wheel pair on the road's right lane markers!
4. Drive with the left wheel pair on the road's center markers!
5. Drive with the right wheel pair on the road's right lane markers!

4.2.2 Speed Estimation

Rationale: Measure the driver's longitudinal speed perception and control.

Description: The scenario was set to a rural road with no sharp turns. With the simulator's speedometer and tachometer set to zero, the driver was instructed to drive at a speed that the driver estimated to be 50 km/h, 70 km/h and 90 km/h. Each of the speeds should be held for about 15 seconds.

Instructions to the driver: The driver was informed about the scenario and was told to inform the test leader when the estimated speed was reached, and hold that speed until instructed otherwise. The instructions during the drive was:

1. Drive at the speed that you estimate to be 50 km/h!
2. Drive at the speed that you estimate to be 70 km/h!
3. Drive at the speed that you estimate to be 90 km/h!

4.2.3 Car Following

Rationale: Measure the driver's distance keeping, longitudinal speed perception and control when following a car.

Description: On a rural road with no sharp turns; the driver was instructed to follow a car at a close but safe distance. The driver follows the car for about 3 minutes. The lead car's speed was varied according to a sinusoidal function with a mean speed of 70 km/h, a period of 60 seconds, and an amplitude of 5 km/h.

Instructions to the driver: The scenario was explained and the driver was instructed to inform the test leader when the correct distance reached and hold that distance until instructed otherwise. The instruction at the start of the drive was: Follow the car at a close but safe distance!

4.2.4 Controlled Stop

Rationale: Measure the driver's perception of the longitudinal road position.

Description: The scenario was set to an urban environment with two road crossings, speed limit 50 km/h. At each crossing the driver was instructed to stop at a stop sign placed in front of the crossing. The scenario was driven two times.

Instructions to the driver: The driver was instructed to drive at 50 km/h and to stop at the stop sign!

4.2.5 Double Lane Change

Rationale: Standardized maneuvering performance measure.

Description: The scenario was set to a straight road with a cone track. The cones were positioned according to the ISO 3888-1 standard, a standardized maneuvering performance test. The cone track was driven three times, after a training session of two passes over the track. The cone track can be seen in figure 4.1.

Instructions to the driver: The driver was informed about the scenario and instructed to drive through the cone track with a constant speed of 50 km/h, knocking over as few cones as possible.

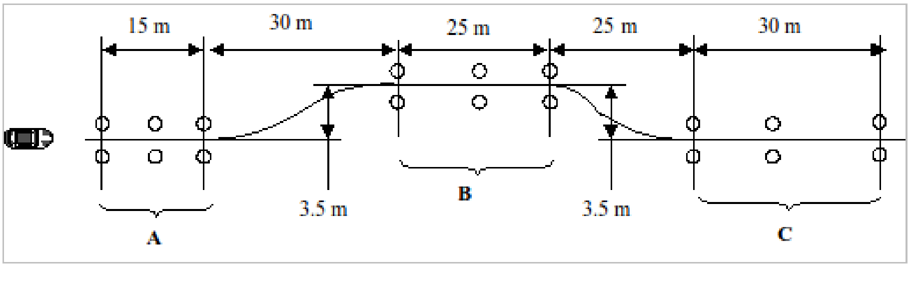


Figure 4.1: The double lane change maneuver. Lane widths A: $1.1 \cdot w + 0.25$, B: $1.2 \cdot w + 0.25$, C: $1.3 \cdot w + 0.25$. w is the car width [8].

	Unit	Simulator 3	VTI-F
Age	year	29 ± 5	31 ± 16
Licence holding time	year	10 ± 4	13 ± 16
Driving experience (last 12 months)	km	4400 ± 8700	5000 ± 4800
Driving experience (since licensed)	1000 km	288 ± 541	92 ± 173

Table 4.1: Demographic data. Age and licence holding time is rounded to nearest year. Driving experience is rounded to nearest 100 km for the driving experience the last 12 months, and rounded to nearest 1000 km for driving experience since licensed.

4.3 Participants

The participants of the experiment were recruited from the author's friends and colleagues, in total 10 drivers. The participants were divided into two groups of five persons each. The Simulator 3 group consisted of four male and one female driver. One person in the Simulator 3 group had vocational driver licence and experience. No one had past experience from simulator driving. The VTI-F simulator group consisted of three male and two female drivers. No one in the VTI-F simulator group had vocational driving experience. One person had previous experience with driving simulators.

The participants received no payment for their participation.

Table 4.1 shows the demographic data of the two groups.

4.4 Procedure

The participants were contacted by telephone and e-mail. They received brief information about the experiment and a time for the experiment was agreed on. On arrival to VTI, the participants were asked to read and sign an informed consent form.

Before the simulator drive all participants filled in three questionnaires:

1. Background information
2. Simulator sickness screening
3. Simulator sickness questionnaire (SSQ)

See appendix A.0.1, A.0.3 and A.0.4 for the respective questionnaires.

After the pre-drive questionnaires were filled in the simulator drive started. To let the participants familiarize with the simulator, the experiment started with a short training drive. The task was to drive the vehicle along a rural road with speed limit of 90 km/h for about 5 minutes.

The scenarios were then driven in the same order as described in 4.2 and according to the respective scenarios' description.

During the lateral position, speed estimation, and controlled stop scenarios the driver was instructed to indicate when he/she had complied with the instructions.

When the driver indicated a comply, a data marker was set by the test leader. The data marker was later used to extract relevant data for the statistical analysis. See section 4.6.2 for further description of the data extraction.

After each scenario a workload questionnaire with 3 questions was filled. The questionnaire can be seen in appendix A.0.2.

When the simulator drive was finished all participants were asked to fill in two more questionnaires:

1. Simulator sickness questionnaire (same as before the drive)
2. Simulator realism (see appendix A.0.5)

The experiment took about 45 minutes for each participant.

4.5 Measures

The measures used in the experiment is divided into objective and subjective measures. The subjective data was captured by questionnaires and the objective measures were driving behavior data recorded during the drive..

4.5.1 Objective Measures

The objective data were measured in the simulator environment during the experiment, such as vehicle position, speed or accelerations. Some objective data were also calculated from recorded data, such as TTC and THWY. Driving behavior data were recorded with a sampling rate of 50 Hz.

Table 4.2 shows the objective measures used in the analysis of the different scenarios. A short description of the different objective measures:

Lateral Position: The distance from the road's center to the center of the vehicle's front axle (r). However, the following derived measures were used in the analysis; mean distance between the left front wheel and center of the left lane marker (rl) and the mean distance between the right front wheel and the center of the right lane marker (rr). See figure 4.2 for an illustration of the lateral position measures.

SDLP: Standard deviation of the lateral position. A measure of the vehicle's swerving.

Speed: Mean speed of the subject's vehicle during a drive.

SDS: Standard deviation of speed. A measure of the variability of the vehicle's speed.

Distance Between Cars: The distance between the center point of the subject's vehicle front to the center point of the rear end of the lead vehicle.

Distance to Stop Line: The longitudinal distance from the center of the vehicle's front axle to the stop line.

NoCKO: Number of Cones Knocked Over.

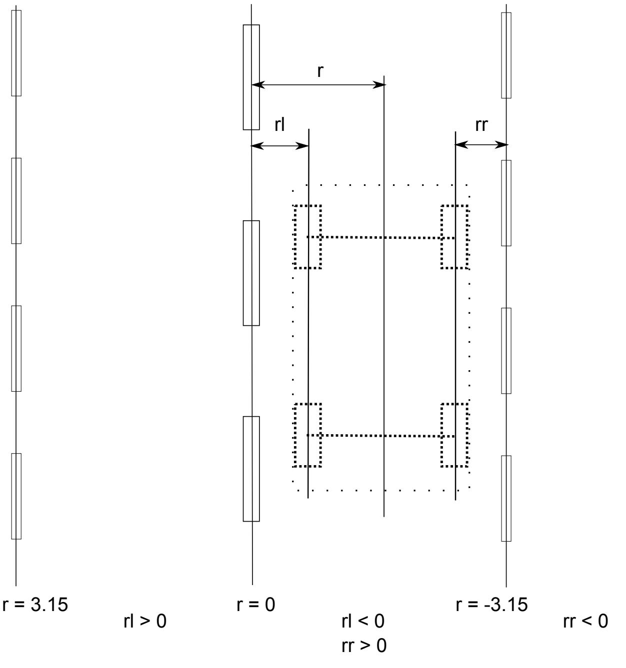


Figure 4.2: The Lateral position measure. The figure shows a schematic sketch of a road with a vehicle driving in the right lane (upwards = forward). r = the measured lateral position, rl = distance between left wheel pair and the road's center line, rr = distance between right wheel pair and the road's right lane markers. rl and rr is the measures used to present the results of the lateral position scenario in chapter 5.

Time To Collision

Time to collision (TTC) is the time to a collision with a lead vehicle. TTC is measured in seconds and is calculated as:

$$T_{tc}(t) = \frac{d(t)}{v_{lead}(t) - v_{fv}(t)} \tag{4.1}$$

where $d(t)$ is the distance between the lead vehicles rear end and the following vehicles front end, $v_{lead}(t)$ is the velocity of the lead vehicle and $v_{fv}(t)$ is the velocity of the following vehicle, all at the time t.

The TTC measure is analyzed through the mean of minimums of the absolute value of TTC (mmTTC).

Measure	Unit	Scenarios LP	SE	CF	CS	DLC
Lateral position	m	X				
SDLP	m	X				
Speed	km/h		X			
SDS	km/h		X			
Distance between cars	m			X		
Distance to stop line	m				X	
NoCKO	1					X
TTC	s			X		
THWY	s			X		

Table 4.2: Measures that were used in the different scenarios (LP=Lateral Positioning, SE=Speed Estimation, CF=Car Following, CS=Controlled Stop, DLC=Double Lane Change).

Time Headway

Time headway (THWY) is a measure that represents the time gap to a lead vehicle. THWY is measured in seconds and is calculated as:

$$T_{hwy}(t) = \frac{d(t)}{v_{fv}(t)} \tag{4.2}$$

$d(t)$ and $v_{fv}(t)$ same as for TTC.

THWY is used in two different ways:

Mean THWY: Reflects the safety margin to the lead vehicle and is a part of the subject's car following strategy[9].

Minimum THWY: If the minimum THWY is below 1 s there is a high risk of a collision [10].

4.5.2 Subjective Measures

The subjective measures of the experiment consisted of three questionnaires. The purpose of the questionnaires was to evaluate the experienced workload, simulator sickness and the realism of the simulators. All questionnaires except the workload and SSQ questionnaire was taken from [3].

Workload

The workload questionnaire was used as a tool to evaluate the perceived workload of a scenario. A workload questionnaire was filled after every scenario. The questionnaire can be seen in appendix A.0.2.

Simulator Sickness

Two simulator sickness questionnaires was used in the experiment. A simulator sickness screening questionnaire was used before the simulator drive to see if the participant are easily affected by simulator sickness, see appendix A.0.3. A simulator sickness symptom questionnaire (SSQ) was answered pre- and post-drive to detect simulator sickness[11], see appendix A.0.4.

Simulator Realism

This questionnaire was used to measure the perceived realism of the simulators. The simulator realism questionnaire can be found in appendix A.0.5.

4.6 Data Analysis

In this section the data handling and analysis is presented. Section 4.6.1 presents the statistical analysis of both subjective and objective measures. In section 4.6.2 the procedure of the data extraction is explained.

4.6.1 Statistical Analysis

The objective data, collected during the simulator drives, were assumed to have the properties to be tested with a one-way ANOVA [12]. The assumed properties are:

- The observed data is normally distributed.
- The groups have the same variance.
- Observations are mutually independent.

The statistical analysis of the objective data was conducted in Matlab version r2009b.

The subjective data, supplied by the workload and realism questionnaires, was ordinal data and thus analyzed with a non-parametric Mann-Whitney test. The scalar SSQ data was analyzed with a one-way ANOVA. SPSS version 16 was used for the analysis of the subjective data.

All analyzes were performed at 5% significance level. Trends were looked at 10% significance.

4.6.2 Data Extraction

During the scenarios the drivers were instructed to inform the test leader when he/she complied with an instruction. When the driver informed the test leader that he/she had e.g. the right speed or right position; the test leader set a data marker with a button in the GUI application to mark the start of a data interval. Just before a new instruction was given to the driver, the test leader set another

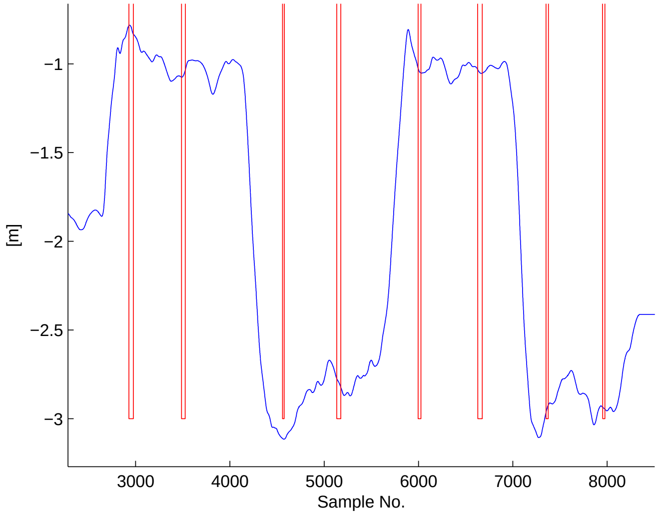


Figure 4.3: Lateral positioning raw data and data markers (vertical lines). Between the data markers (first and second, third and fourth, etc) the data analyzed is found. On the y-axis; the lateral position where the center of the road = 0 and center of right lane markers = -3.15.

data marker to mark the end of the data interval. The intervals between the data markers was used to extract data for the statistical analysis.

Figures 4.3 and 4.4 shows examples of raw data for one drive from the lateral positioning and the speed estimation scenarios. The data markers can be seen as double vertical lines in the figures.

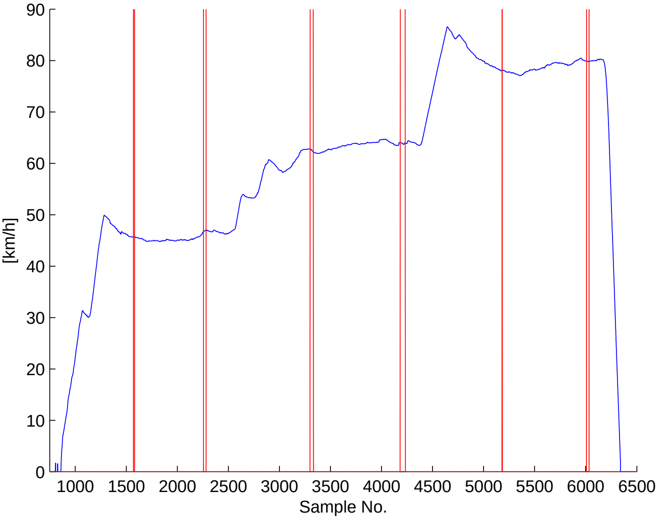


Figure 4.4: Speed estimation raw data and data markers. Between the data markers (first and second, third and fourth, etc) the analyzed data is found. Vehicle speed on the y-axis.

Chapter 5

Experiment - Results

The results from the simulator experiment and statistical analysis is presented in this chapter. The results from the scenarios is presented separately and in an concise manner, further discussion on the results can be found in chapter 6.

5.1 Objective Measures

The results of the analysis are presented in the form of box plots. The edges of the boxes marks the 25th and 75th percentile, the whiskers in the plots extends to the extreme values that is not considered outliers. Outliers are marked with a plus sign. The notches in the box plots marks a 95% confidence interval for the median of a group. See figure 5.1 for an example. In all the box plots' the notches extend past at least one of the percentiles, this is a result of a small sample size [13].

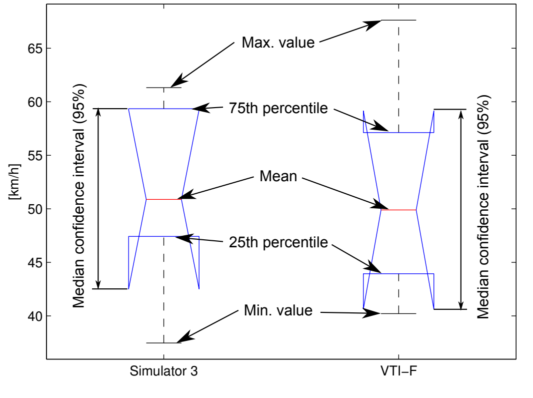


Figure 5.1: Box plot explanation.

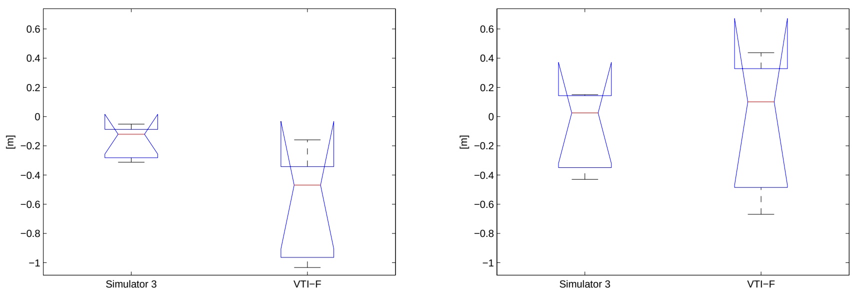
5.1.1 Lateral Positioning

The lateral position is presented using the *rl* and *rr* measures as defined in 5.1. A zero value in the plot means that the wheel's center line coincides with the lane marker's center line. If the measure is negative the wheel's center line is on the left side of the marking's center line. A positive value means that the wheel is on the right side of the lane marker, see figure 4.2. Left and right is defined relative the direction of travel.

The drivers of Simulator 3 succeeded significantly better to keep the car's left wheel pair on the road's center line than the VTI-F simulator drivers ($p < 0.05$). Simulator 3 group mean deviation was 12 cm to the left of the center line markings and the VTI-F simulator group mean is -47 cm. There was a also a significant difference for the SDLP between the groups when driving on the center line ($p < 0.05$). Mean SDLP is 6 cm for the Simulator 3 group and 10 cm for the VTI-F simulator group.

No significant differences between the groups, in either of the measures, could be found when driving on the right side lane markers.

The descriptive data for lateral positioning scenario data can be seen in figure 5.2 and 5.3.



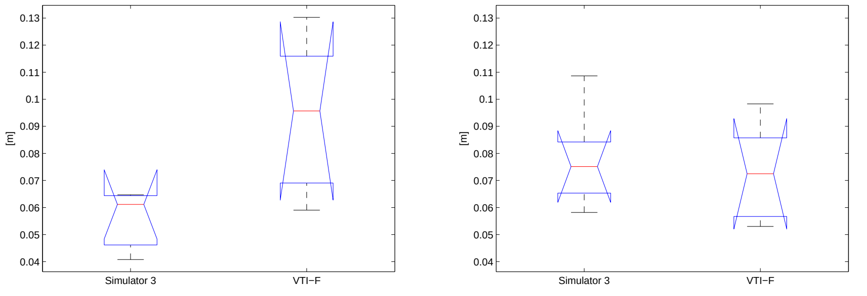
(a) (b)

Figure 5.2: Lateral positioning scenario, lateral position: *rl*, driving with left wheel pair positioned on the road's center line (a). *rr*, driving with right wheel pair on the right lane marking (b).

5.1.2 Speed Estimation

In the speed estimation scenario both groups succeeded well in estimating 50 km/h, the means of the groups was very accurate. The group means is 51 km/h for the Simulator 3 group and 50 km/h for the VTI-F group.

In estimating 70 km/h the means of the two groups is both just under 67 km/h. When estimating 90 km/h the two groups both misjudged the speed about 10 km/h to slow. See figure 5.4 for the ANOVA plots of the speed.



(a) (b)

Figure 5.3: Lateral positioning, SDLP: Driving with left wheel pair positioned on the road's center line (a). Driving with right wheel pair on the right lane marker (b).

The descriptive data plots of the SDS measure, figure 5.5, shows that the drivers held their estimated speed fairly well during the speed estimations. The group means is within about 1-2.5 km/h for all speed estimations.

No significant differences between the groups could be found in either speed or SDS. However, a trend could be found for the SDS measure when the drivers tried to estimate 90 km/h ($p < 0.10$), the VTI-F group had lower SDS group mean and less in-group variation than the Simulator 3 group.

5.1.3 Car Following

Figure 5.6 shows the descriptive data for minimum and mean THWY. The group mean for mean and minimum THWY was 2.6 s respectively 1.6 s for the Simulator 3 group, and 2.0 s respectively 1.4 s for the VTI-F group.

Figure 5.7 shows the mean of minimums of TTC (mmTTC). The group means of the mmTTC was approximately 100 s. The range was quite large for both groups, about 100 s for the Simulator 3 group and about 150 s for the VTI-F group.

No significant differences or trends could be found in either of minimum THWY, mean THWY or mmTTC.

5.1.4 Controlled Stop

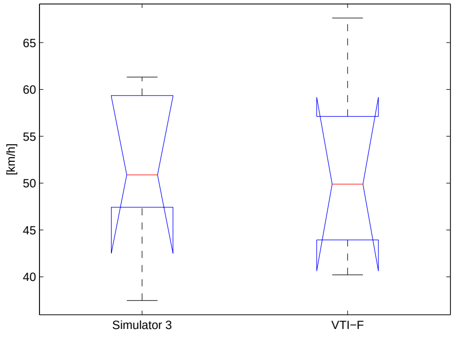
The results from the controlled stop scenario can be viewed in figure 5.8. The means of the groups is 4.8 m for the Simulator 3 group, and 5.2 m for the VTI-F group.

No significant difference or trend in the distance to the stop line could be found.

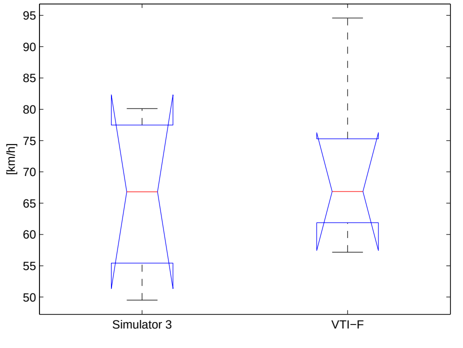
5.1.5 Double Lane Change

The results from the double lane change scenario can be seen in figure 5.9. The figure shows the group means of the averaged cone track passage. Average NoCKO was 7.8 for the Simulator 3 group and 7 for the VTI-F group.

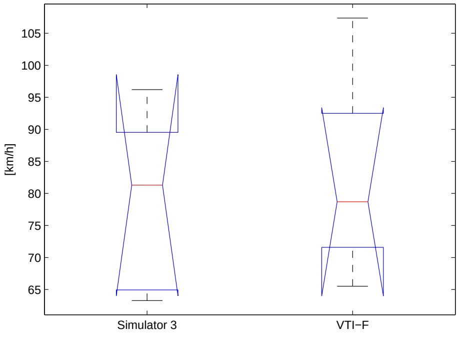
No significant or tentative difference between the groups could be established.



(a) Estimated 50 km/h

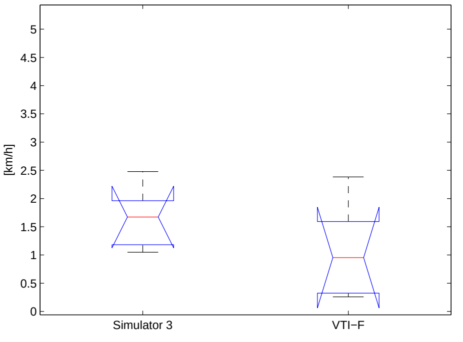


(b) Estimated 70 km/h

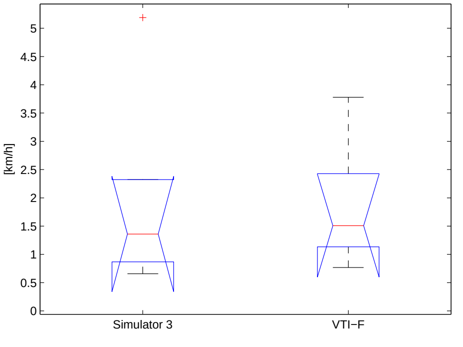


(c) Estimated 90 km/h

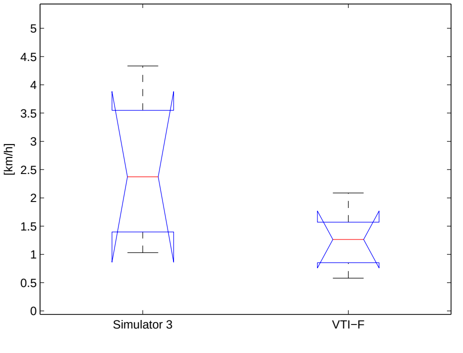
Figure 5.4: Speed estimation, speed.



(a) Estimated 50 km/h

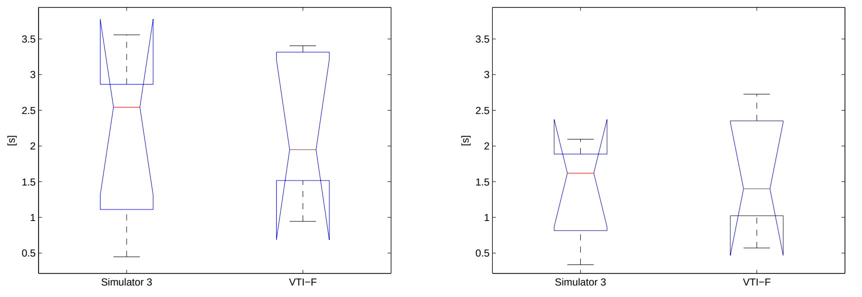


(b) Estimated 70 km/h



(c) Estimated 90 km/h

Figure 5.5: Speed estimation, SDS.



(a) (b)

Figure 5.6: Car following: Mean THWY (a), minimum THWY (b).

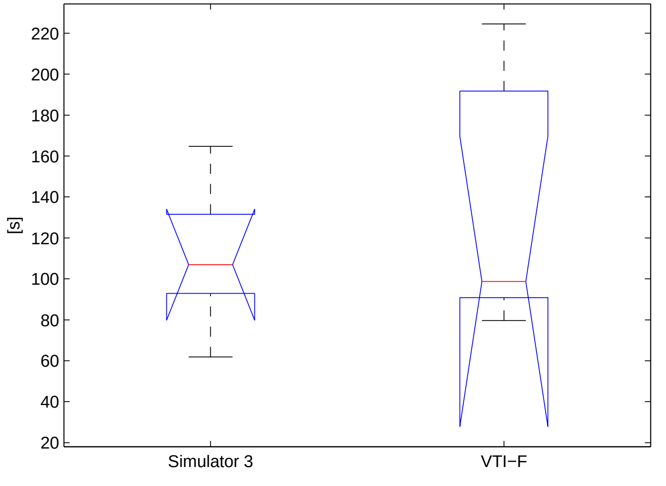


Figure 5.7: Car following: TTC, mean of minimums.

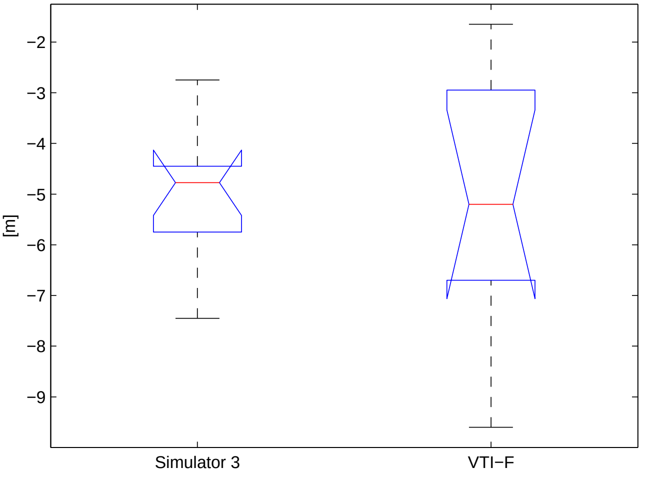


Figure 5.8: Controlled stop, distance to stop line.

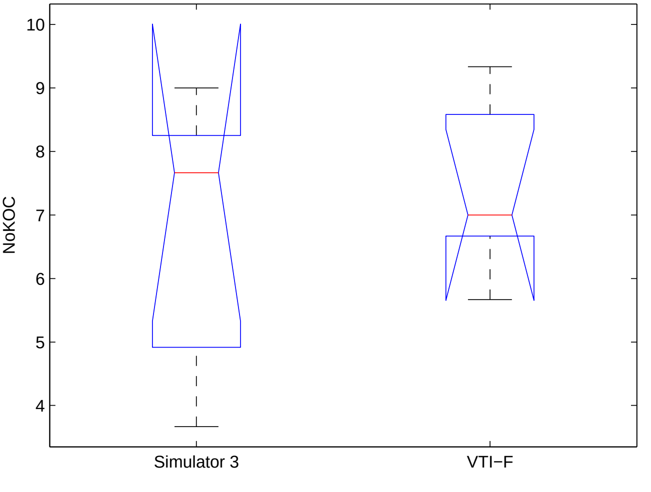


Figure 5.9: Double lane change, number of knocked over cones.

5.2 Subjective Measures

5.2.1 Simulator Sickness

No significant differences could be found between the pre-drive and post-drive simulator sickness measures for the VTI-F drives.

Almost all measures in the Simulator 3 group at least doubled from pre- to post-drive, but the standard deviations was large. The only significant difference found was that the disorientation SSQ score was higher post-drive for the Simulator 3 drivers. Furthermore, there was a tentative difference in the total SSQ score. It can be noted that the mean total SSQ score was almost 40 post-drive, which means that the Simulator 3 drivers were really affected. There was one subject in the VTI-F group who had a SSQ total > 20 pre-drive and two in the Simulator 3 group.

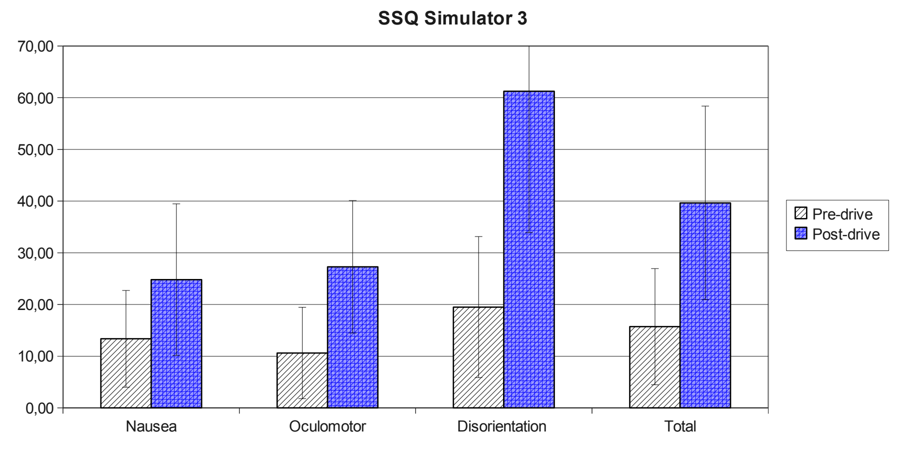
See figure 5.10 for a diagram of the SSQ measures.

5.2.2 Workload

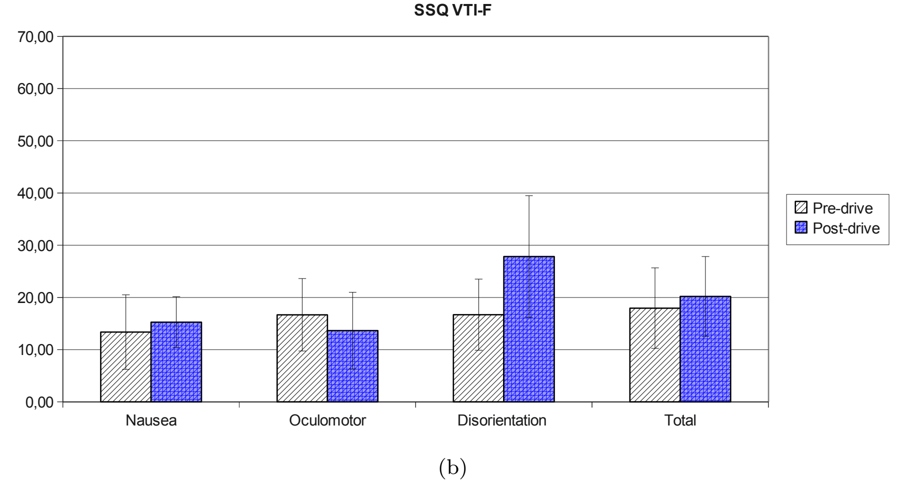
In the workload questionnaire one significant difference could be found and that was for the effort measure in the controlled stop scenario. All other measures were quite similar.

5.2.3 Simulator Realism

In the realism questionnaire a significant difference was found in the answers of the braking realism questions. Three tentative differences could be found in the answers of the steering, feedback steering and vibration realism questions. As can be seen in figure 5.12; the Simulator 3 group scored steering, feedback steering and vibrations realism higher, and braking realism lower than the VTI-F group.



(a)



(b)

Figure 5.10: Simulator SSQ results. VTI-F simulator (a), Simulator 3 (b).

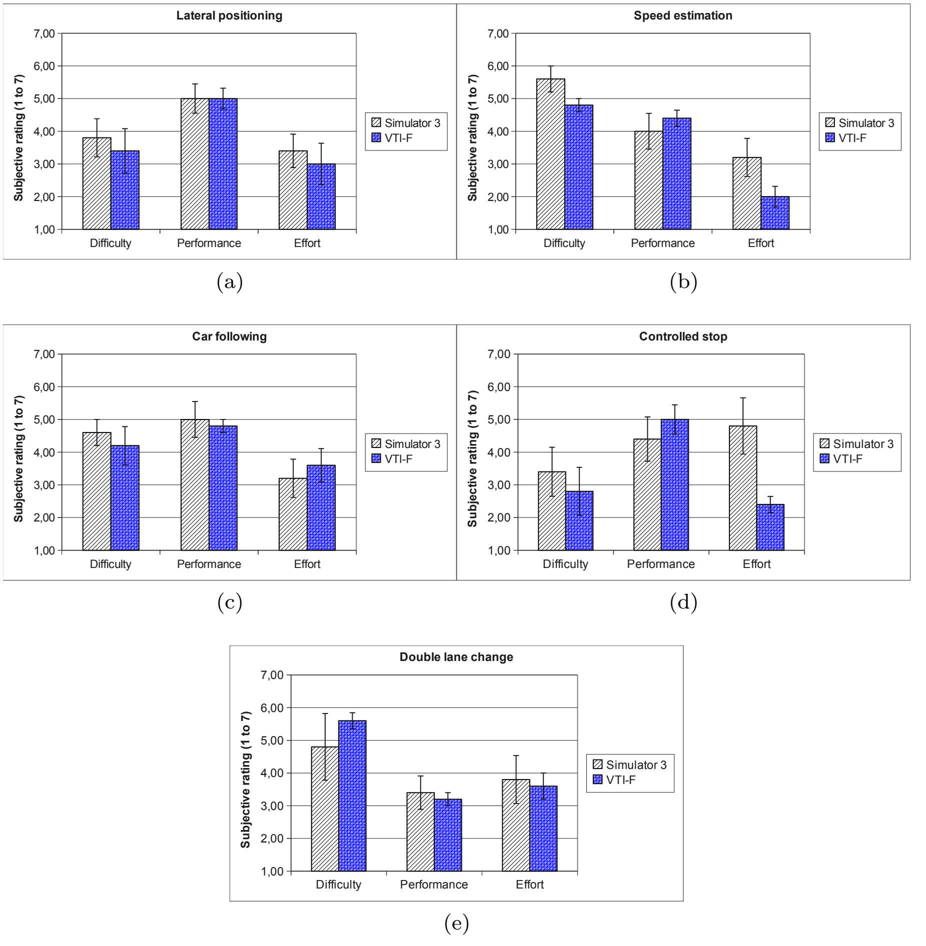


Figure 5.11: Workload questionnaire results.

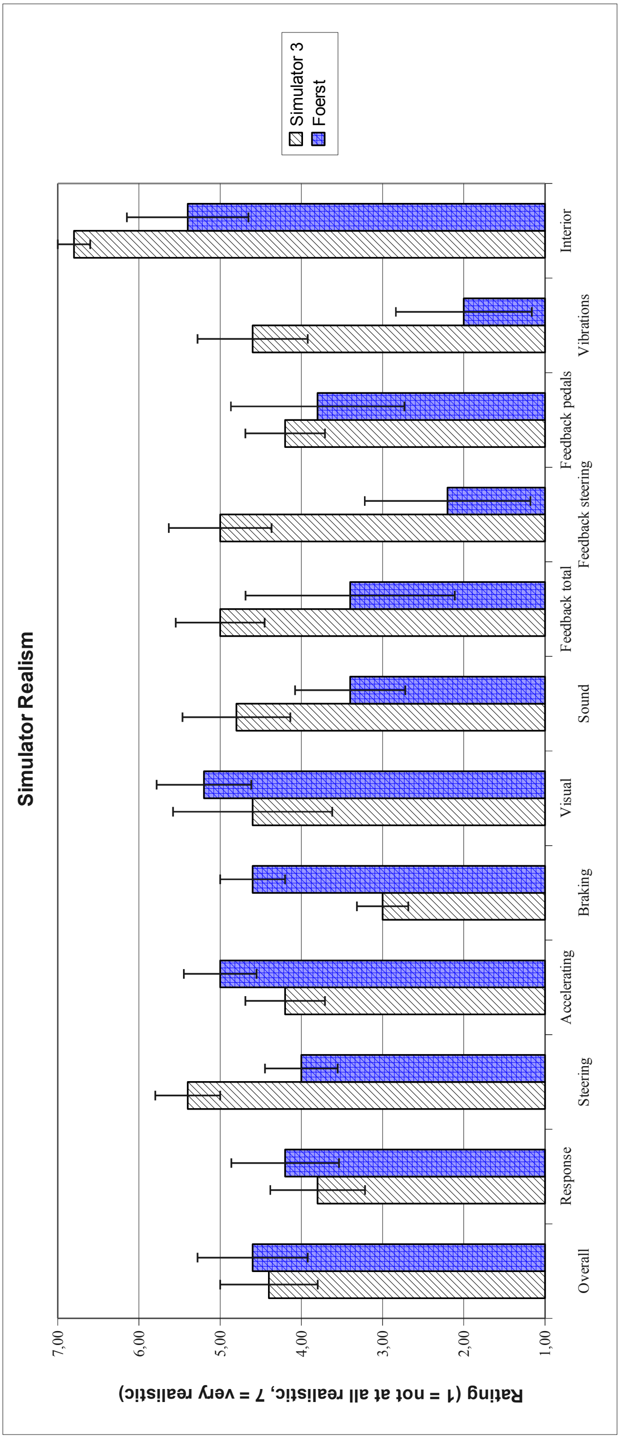


Figure 5.12: Simulator realism questionnaire.

Chapter 6

Discussion

This chapter provides a discussion about the results presented in chapter 3 and chapter 5. The VTI-F simulator, that is the result from the integration of the Foerst Trainer simulator hardware and the VTI simulation software, is discussed in section 6.1. The experiment is discussed in section 6.2. Suggestions for further development and future work is presented in section 6.3.

6.1 System Integration and Software Development

The VTI-F simulator's overall performance during the experiments was good, and this was confirmed by the experiment results. The software performance is evaluated implicitly by the subjective measures collected during the experiments, especially the simulator realism questionnaire. The realism questionnaire provides information about the drivers' perception of the VTI-F simulator performance (see 6.2).

6.1.1 Simulator Development

The resulting simulator system performed satisfactorily but there are refinements that can be made:

- The steering wheel feeling of the VTI-F simulator was rough when the TARP was relaying data between the simulator and the VTI simulation kernel. This lack of smoothness was irregular in that it appeared with different intensities every time the simulator was started, however, the intensity was constant until the simulator and the TARP was restarted. The suspected cause of this problem was the timer used in the TARP for sending output to the simulator kernel. This suspicion is based on the fact that a `WM_TIMER` window message is non-deterministic and is not really suitable for a system with real-time demands [7]. The timer resolution may also be to low. Setting the timer in the TARP to 15 ms seemed to minimize the unsmoothness of the steering wheel. This problem should be further investigated.

- When the VTI simulation software was executed with the VTI-F simulator hardware there was no vehicle cabin (virtual or real) to act as a visual reference of the vehicles outer dimensions. In Simulator 3 there is an real vehicle cabin, and in the Foerst Trainer simulator, when running the Foerst simulation software, there is a software rendered, virtual cabin shown on the monitors (see figure 2.2). Despite the absence of a visual cabin reference; the VTI-F simulator group did not perform significantly different from the Simulator 3 drivers in almost all of the scenarios where this might be considered a problem. The exception was in the lateral positioning scenario, when positioning the car's left wheel pair on the road's center line. See 6.2 for further discussion on the experiment results.

- Another imperfection related to the lack of a vehicle cabin was that there was no rear view mirrors. As described in chapter 2 the Simulator 3 have small monitors installed in the rear view mirrors of the vehicle cabin. The Foerst Trainer simulator solves this by rendering rear view mirrors on the monitors. The impact on the results from the lack of rear view mirrors is unclear: No rear view mirrors was explicitly needed in any scenarios, but the realism of the VTI-F simulator is negatively affected.

6.1.2 Experiment Preparations

The software implementation for the experiments was satisfactory. The Demo2008 scenario module provided an excellent environment for the scenarios, with exception for the controlled stop scenario which had to be run twice to get sufficient amount of data.

6.2 Experiment

The experiment's results showed few differences between the two simulators. This shows that the integration was successful and the VTI-F simulator's performance was satisfactory. However, the results from the experiment suffer from two weaknesses:

1. The number of participants were low. This contributes to a lack of power of the statistical analysis.

2. The scenarios and/or measures might have been too trivial. This could obscure possible differences between the simulators which could be revealed during more advanced scenarios. In other words: The lack of differences between the simulators does not necessarily mean that there does not exist any.

3. The data markers was set manually during the experiment with the effect that all data intervals had different length. All data was averaged before the statistical analysis so no data had more weight because of the sample length, however, the means will carry a unknown error.

In the following sections the results of the scenarios and subjective measures are discussed.

6.2.1 Scenarios

Lateral Positioning

In this scenario the only significant differences found was that when the drivers was asked to position the car's left wheel pair on the road's center line. The difference was both in lateral position and SDLP. Mean lateral position for the Simulator 3 group was significantly closer the road center line than what was found for the VTI-F group. Furthermore the Simulator 3 group's swerving was significantly smaller. This might be a result of, in no particular order:

1. Simulator 3 had an more realistic car cabin than the VTI-F simulator.
2. The Simulator 3 drivers got motion feedback from the Simulator 3's motion system, while the VTI-F simulator drivers did not get motion feedback.
3. The Simulator 3 drivers utilized the rear view mirrors to position the car. The VTI-F drivers had no rear view mirrors.

Items 1 and 2 are both related to simulator realism. A more realistic simulator should enable the drivers to utilize past real driving experience in a more natural way than a less realistic simulator. The car body in Simulator 3 could also have been a visual reference when positioning the car. Furthermore, the steering was perceived as more realistic by the Simulator 3 drivers.

Item 3 allows the Simulator 3 drivers to use the rear view mirrors when aligning the car with the road markers. If it ever happened is however uncertain, no explicit questions about the rear view mirrors was asked, and only one driver (VTI-F driver) comment were received[1]. If the rear view mirrors were used it could explain the significantly smaller SDLP and the better lateral position, but it would also been seen on the right lane markers drive, which it was not.

None of the explanations, items 1-3 can alone explain how the center line drive results are significantly different for the two groups. Thus, this should be further investigated with more participants and possibly additional measures.

Speed Estimation

The two groups both had very similar results in the speed estimation scenario and no significant differences could be found at the 0.05 level. A trend ($p < 0.10$) could be found in the SDS measure at the estimation of 90 km/h.

The accurate values at the 50 km/h and 70 km/h speed estimates could be explained with the manual gear box. An approach that could have been used for estimating 50 km/h is: Drive at third gear with medium RPM, alternatively:

[1]The comment was received on the 12th question of the realism questionnaire: "Was the internal environment (car body) realistic?" Comment: "No A-pillars, no rear view mirrors, etc [translated from Swedish]".

Drive at fourth gear with low RPM. Same algorithms could be used for estimating 70 km/h but with one gear higher.

When driving at 90 km/h the drivers estimates was about 10 km/h to low. This might be explained with that there are no easy way to tell when one drives at 90 km/h since it's a speed that is suited for fifth gear at medium-high engine RPM.

There is no obvious explanations of the trend found in the SDS measure. As can be seen in figure 5.5 there is no clear pattern in how the SDS extreme value range changes for the different speed estimates for the two groups. The mean is quite steady over the different speed estimates for the VTI-F group, and more variating for the Simulator 3 group.

The trend could be an effect of low number of participants. A driver that varies the speed a lot have a large impact on the analysis. A moment of unconcentration of one of the Simulator 3 drivers, coincidental with the VTI-F simulator group's good performance, might very well be the explanation of the trend. The outlier in 5.5b gives further support to this explanation. However, further investigation with more participants is needed before a conclusion can be drawn.

Car Following

The car following scenario did not show any significant differences between the two groups in any of the used measures.

Minimum and mean THWY does not differ much, about 1 s difference for the Simulator 3 group and even less for the VTI-F group. The car following strategy (mean THWY) was a distance of approximately 2.0 s for the VTI-F group and 2.5 s for the Simulator 3 group. When the distance decreased to around 1.5 s it was considered unsafe (minimum THWY) by both groups. In [10] a cautious driver is defined as a driver "who usually follows at 2 s time headway" and a risky driver "has a normal following headway of less than 1 s". Using these definitions both groups perceived the "close but safe" distance well.

The interpretation of the results of this scenario is difficult because of the lead car's variating speed. The interpretation would have been easier if the lead car had held an constant speed [9]. The thought behind this scenario was to have a way of measuring the visual impression in the simulation in relation to an moving object. A better scenario setup might have been a constant lead vehicle speed and the instrumentation turned off, and keeping the distance with visual reference only, as in the speed estimation scenario.

Controlled Stop

No significant differences, or trends, between the two groups were found in the controlled stop scenario. It was surprising that the drivers of both groups stopped at the relatively long distance of 5 m from the stop line. This might be a result of driver uncertainty because of the instruction: "Stop at the stop sign!" It is possible that the measured value does not represents the drivers' impression of the car's outer dimensions. The measured value might be the drivers' notion of a correct stopping distance, the drivers' interpretation of what were asked of them, or something else. If the instructions were clarified to: “Stop with the cars front at the stop line!”, the correct measure would be obtained.

Dual Lane Change

No significant or tentative difference was found in this scenario. One would think that the Simulator 3 group would do better in this scenario than the VTI-F group, considering that the motion system should provide a better control and better feeling of the vehicle dynamics. The motion of the Simulator 3 might also have been a disadvantage in this scenario, considering that it is rather forceful and might disturb the drivers if they are unfamiliar with such maneuvers. The VTI-F simulator drivers did not have a motion system so the vehicle dynamics feeling is surely lower, but on the other hand, no forceful motions were applied. The advantages and disadvantages of the two simulators may equalize the results of the NoCKO measure.

The NoCKO measure used was probably too simple to accurately evaluate this scenario. For example, reduced speed through the cone track would have a great impact on the result. The results would gain strength from using more measures, such as velocities and/or accelerations at different parts of the cone track, e.g. at the turns, and at the entrance and the exit of the cone track.

In the Simulator 3 group the two drivers that was most affected by simulator sickness, total SSQ score was 97 and 71 (the third most affected driver had a total SSQ score of 15), was the two that knocked over most cones in that group. In the VTI-F group the NoKOC was rather evenly distributed between the drivers, even though the SSQ scores ranged from approximately 4 to 49. The Simulator 3 drivers driving during this scenario might have been affected by the simulator sickness.

6.2.2 Subjective Measures

Neither pre- or post-drive SSQ scores had significant or tentative differences between the groups (and the pre-drive scores should not have any differences). Post-drive, all of the Simulator 3 group mean scores are almost double of that of the VTI-F group. The standard deviation of the scores was however quite large so no significant change or trends could be found.

In the workload questionnaires; one significant difference between the two simulators could be found. It was in the effort question of the controlled stop. The Simulator 3 group experienced that a significantly higher effort was required to complete the controlled stop scenario than the VTI-F group. This result is reflected in the realism questionnaire where the Simulator 3 group gave the braking realism question a significantly lower score than the VTI-F group. The braking realism was commented by all Simulator 3 drivers and the comments were either that there was to little force feedback from the deceleration, or that the car stopped to fast. In other words: The cue from the motion system was experienced as to small in relation to how fast they were stopping.

Apart from the significant difference in braking realism, trends was found in the realism of steering, feedback steering and vibrations. The trend in the steering and feedback steering realism can be explained by the problem with the unsmoothness in the steering wheel mentioned in 6.1.1. The trend in vibrations score can be explained by the non-existent vibrations in the VTI-F simulator.

Considering all the realism scores it can be concluded that the two simulators' realism probably were judged by different scales. The VTI-F group was more liberal in their realism scoring and the Simulator 3 group was more strict.

The results from the realism questionnaire shows that the VTI-F simulator implementation was satisfactory. No comments were given on latency or other deficiencies than the steering wheel.

6.3 Future Work

In this section suggestions of improvements of the VTI-F simulator is presented. Suggestions for software and hardware improvements are:

- Investigate the steering wheel problem mentioned in section 6.1.
- Investigate the possibility of integrating rear view mirrors.
- Implement the motion system.
- Improve the sound quality of the simulator. Obtain hardware, or write software, so that it is possible to use the same sounds, e.g. road and wind noise, as the Simulator 3.
- Obtain hardware so that it's possible to easily switch the hardware configuration between the original Foerst Trainer simulator and the VTI-F simulator.
- If possible, reduce the noise of the computers in the room where the VTI-F/Foerst Trainer simulator is located.

To improve on the experiment the following improvements are suggested:

- Larger scale on the experiment with more participants.
- Simplify the car following scenario by using a steady state following situation as suggested in [9].
- Clarify the instructions on the controlled stop scenario.
- Make a more in depth analysis of the dual lane change scenario.

Chapter 7

Conclusions

The integration of the Foerst Trainer simulator and the VTI simulation environment was successfully realized resulting in the VTI-F simulator. However, there is a need of further improvements if the VTI-F simulator is to be used in research. In the current state it is possible to use the simulator for software development and scenario testing. This may release time on VTI's more advanced simulators so that it is possible to increase the simulators' degree of research utilization.

The performance evaluation was conducted through an experiment consisting of five scenarios. The scenarios were intended to measure the driving performance and the drivers perceived realism of the VTI-F simulator. The evaluation was conducted successfully as a between-group experiment with ten participants divided in two equally sized groups. One group drove the VTI-F simulator and one group drove Simulator 3.

Not many significant differences were found, and the differences that were found may not be very reliable. Further evaluation is needed for conclusive results. Even so, the obtained results shows that the VTI-F simulator performs rather good, at least at simple driving tasks, when compared to VTI's Simulator 3.

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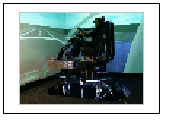
Appendix A

Questionnaires

A.0.1 Background Information Questionnaire

1. Fill in your age: _____
2. Gender: Male ☐ Female ☐
3. Do you have a driving licence? Yes ☐ (No ☐)
   If yes, what type and when? (fill in the year when granted)
   ___A,___B,___C,___D,___BE,___CE,___DE
4. Are you a professional driver? Yes ☐ No ☐ (go to 7)
   If yes, what is your profession:
5. Did you receive any vocational driver training? Yes ☐ No ☐
   If yes, did it include driving simulator training? Yes ☐ No ☐
6. Driving experience:
   a. How much did you drive in the past 12 months? ___________ km
   b. How much total driving experience do you have? ___________ km (since licensed)
7. Do you have experience from driving in a simulator? Yes ☐ No ☐
   If so, what type of simulator? (indicate all relevant types)
   ☐ **Low-level system (a)** (Pc monitor. Car seat. Videogame-like steering wheel and pedals. No motion system)
   ☐ **Static/semi-dynamic system (b)** (Multiscreen. Car seat. Simple mockup with a dashboard. Steering wheel and pedals with simple force feedback. No or limited motion)
   ☐ **Fixed driving simulator (c)** (Multi- och semi-circular screen. Real vehicle. Real steering and pedals with force feedback. No or limited motion)
   ☐ **Dynamic or advanced simulator (d)** (Semi-circular or circular screen.

Real vehicle. Real steering and pedals with force feedback. Advanced motion platform)
☐ **Virtual reality simulator (e)** (HMD or CAVE©simulator)

a	b	c	d	e
				

A.0.2 Workload Questionnaire

Hur lätt eller svår var köruppgiften som du nyss gjorde?

Mycket lätt						Mycket svår
1	2	3	4	5	6	7

Hur bra tycker du att det gick?

Mycket dåligt						Mycket bra
1	2	3	4	5	6	7

Hur ansträngande var köruppgiften?

Inte ansträngande alls						Mycket ansträngande
1	2	3	4	5	6	7

A.0.3 Simulator Sickness Screening Questionnaire

	Strongly disagree				Strongly agree			
	1	2	3	4	5	6	7	NA
I like to sit in the front rows when I go to the movies.								
I have no problems reading a book or a map in a car while somebody else is driving								
I like playing computer games.								
I play computer games with interactive simulations often								
I feel dizzy or uncomfortable during playing interactive computer games.								
I feel dizzy or uncomfortable when I watch somebody else playing interactive computer games.								
I like watching wide screen TV								
I suffer from sea-sickness/ motion sickness? E.g. Airplane, boat, car (back-seat).								
I am very interested in technology and new technological developments.								
I get sick in roller coasters or in other entertainment machines.								
I am able to stand in a 180 degree or 360 degree angle of view surround cinema dome.								
In my past, I experienced Simulator Sickness during a simulator drive/fly.								

A.0.4 Simulator Sickness Symptom Questionnaire

#	Symptom	Severity			
		None	Slight	Moderate	Severe
1	General discomfort				
2	Fatigue				
3	Headache				
4	Eye strain				
5	Difficulty focusing				
6	Salivation increased				
7	Sweating				
8	Nausea				
9	Difficulty concentrating				
10	”Fullness of the head”				
11	Blurred vision				
12	Dizziness with eyes open				
13	Dizziness with eyes closed				
14	*Vertigo				
15	**Stomach awareness				
16	Burping				

* Vertigo is experienced as loss of orientation with respect to vertical upright.
** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

A.0.5 Realism Questionnaire

The questionnaire have several questions where the answer to the questions is given in a scale from 1-7. For a more compact presentation, the scale and questions has been separated. In the questionnaire the scale can be seen after each question.

Questions

1. How realistic was the drive in the simulator?
2. Where the vehicle responses to your control actions realistic?
3. Was the steering realistic?
4. Was the acceleration realistic?
5. Was the braking realistic?
6. Was the visual impression in the simulator realistic?
7. Was the sound impression in the simulator realistic?
8. Was the force feedback (whole car) sufficiently realistic?

9. Was the force feedback in the steering wheel realistic?
10. Was the force feedback in the pedals realistic?
11. Where the vibrations in the car realistic?
12. Was the internal environment (car body) realistic?
13. Was there anything in particular that you missed in the simulator?
    If yes, please specify:
14. Do you have any suggestions on how the simulation can be made mor realistic?

Scale

Not at all realistic			Rather realistic			Very realistic
1	2	3	4	5	6	7