# Texting while driving: The impact of common cell phones and Head-Up Display based interaction on safety in simulated driving

SW10 master thesis


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**Abstract**
This master thesis deals with the question: *How does common cell phones and Head-Up Display based text entry methods affect road safety in a low-cost driving simulator?* This is related to the increasing tendency among drivers to use their cell phones to write text messages while driving. As touch-based smartphone usage increases, this could prove to be a greater risk to road safety, as lack of tactile feedback requires more of the driver's visual attention. We tested the impact on road safety of writing on cell phones and four Head-Up Display (HUD) based text entry methods. We developed a low-cost driving simulator for the purpose of being a test-bed for the experiments. Results showed that using a tactile cell phone increased the risk of collisions or being in a near-crash situation by a factor of almost 4, and touch-based smartphones increased it by a factor of almost 5. The use of a HUD decreased the amount of eye glances, and road safety improved significantly compared to common cell phones in low driving complexity scenarios. A text entry method using a tactile interface on the dashboard showed the most promising results related to road safety.

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# Preface

This paper documents work conducted by group d614a at the University of Aalborg. The project started in the fall 2010 semester where some of the empirical work was done. Some of the results from the first article is based on this work. The group was subsequently split up into two in accordance with the curriculum.
We would like to thank our supervisor Jan Stage for his help during the project.

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# Contents

# 1 Introduction

As issues arise with the development of car simulators, the subject of driver distraction towards specifically cell phone *communication* while driving, is a subject that has been given much attention. Unfortunately, mobile technologies today evolve at a fast pace, and it is only very recently that an official study has been conducted regarding the dangers of cell phone *texting* while driving, which was not clear on the specific types of cell phones used [3].

In recent years the cell phone has evolved rapidly from being a single-purpose communications device and has become a multi-purpose small portable computer. With the new generation of smartphones, users are now not only using cell phones to make phone calls, but also to interact socially, compose emails and listen to music. The downside to this trend, is that an increasing number of people, especially teenagers [4], are doing all this while also driving a car.

The possible threat to road safety is known in the research community, and much focus has been put on the challenges of driver distraction (e.g. [7]). A fundamental issue with this is the problem with epidemiological tests in real-world scenarios, as proper experimentation holds many challenges, primarily related to variability in the environment and more important, the dangers involved. Therefore, experiments are usually done using car simulators, which raises questions related to driving fidelity and the validity of the results that are produced [1].

This master thesis investigates how writing text messages while driving affects road safety, with the overall research question: *How does common cell phones and Head-Up Display based text entry methods affect road safety in a low-cost driving simulator?*

Touch-based smartphones have in recent times become common among the population. This has raised the question regarding the dangers of lack of tactile feedback and the impact of this on road safety. Because of this in order to answer our overall research question we must first answer the question: *How does texting using touch-based smartphones affect road safety compared to using a tactile cell phone?*

The dangers of texting while driving is a widely acknowledged problem. Many countries try to reduce the number of car accidents related to this with legislation. Unfortunately, studies have shown that this has little effect in practice [5]. Since legislation has not yet seemed to work, we want to investigate if a safer alternative to the current cell phones can be found, and therefore need to answer the question: *How can HUD-based methods for text messaging while driving affect the impact on road safety?*

Due to safety reasons related to in-vehicle experiments, a car simulator for testing of in-vehicle systems is required. In order to answer the main research question we need to answer the question: *How can a car simulator for testing of in-vehicle systems be developed with a satisfactory level of fidelity and at a low cost?*.

Enclosed with this summary are three articles that deals with answering the above mentioned questions.

# 2 Article Overview

This chapter covers the three articles, each of which answers one of the previous mentioned research sub-questions.

## 2.1 Article 1

In this article, we answer the research question: *How can a car simulator for testing of in-vehicle systems be developed with a satisfactory level of fidelity and at a low cost?*. The purpose is to develop a car simulator intended for testing of in-vehicle systems, and then iteratively improve its fidelity at a low cost.

The first part of the study is committed to developing a set of requirements to both the physical and virtual parts of the simulator, in order to balance the trade-off between fidelity and cost. We did this by reviewing existing literature on the subject and produced a minimal set of requirements that kept the cost low while producing a satisfactory level of fidelity, see figure 2.1.

The simulator consisted of a single car seat centered in front of a 32" screen. Two 21" monitors was placed on the sides to act as side-view windows. A standard driving kit was used to interact with the simulator. The kit included a steering wheel, pedal board with gas, brake and clutch pedals and a manual gear shift. The computer was midrange with two graphics cards to make it possible to use three screens.

The software for the simulator was created using the Unity 3D game engine and the virtual world was modeled using CityScape. The car physics was based on an open source tutorial which included the basic car physics.

The basic open source code was extended with support for the driving kit. An artificial intelligence module was developed to simulate traffic, and the city was outfitted with intersections and traffic lights. A logger module recorded reaction times, velocity, distance from the middle of the road and more.

The assessment test was with a group of test subjects going through a test scenario involving driving while interacting with an iPod touch. Test subjects were interviewed about their impression of the simulator's fidelity, and the session was recorded using video cameras and stored on DVD. Results identified a number of problems with the fidelity of the simulator.

Based on the interview from the assessment test a new set of requirements were produced, and the simulator was enhanced.

**Figure 2.1:** Original (left) and enhanced (right) car simulator.

The enhanced car simulator had both a passenger seat and a drivers seat. The screens used for front and side-view windows were replaced by a 37" screen and two 32" side-view screens. The side-view screens were placed at each side in a 90 degree angle to better represent a side-view windows. Tactile transducers called "bass shakers" were added to simulate engine vibration. A new computer was assembled with better hardware. A TripleHead2Go was acquired to better handle the task of splitting the main display to the three screens.

The simulator was tested again in a verification test, with a group of test subjects balanced across gender and cell phone experience, interacting with various forms of text entry methods distributed using latin squares. Two typical driving scenarios were used. Half of the subjects drove on a freeway with three lanes and traffic going at various speeds. The other half drove in a city scenario with traffic, intersections and traffic lights.

Results showed that the simulator successfully improved its fidelity at a low-cost.

## 2.2 Article 2

The purpose of this article is to answer the research question: *How does texting using touch-based smartphones affect road safety compared to using a tactile cell phone?*

We constructed an experiment using the simulator we had developed as a test-bed. We invited 28 test subjects which either owned a tactile cell phone or a touch-based smartphone, and asked them to perform a series of text writing tasks. In order to have a point of reference, the subjects also drove without texting, as a baseline condition. The subjects were asked to follow a car in front of them, which was programmed to brake at randomly selected intervals in order to monitor their reaction times.

In order to conduct the experiment based on the diversity of real-world environments, subjects either drove in a freeway or city scenario. The freeway was a straight road with a higher speed limit and ongoing traffic, and the city had curved roads, intersections, a hilly terrain and traffic.

The test subjects were instructed to type five messages, or as many as they could in the course of five minutes, using a T9 tactile cell phone and a touch-based smartphone. All text messages were randomly selected sentences of the same length and complexity.

**Figure 2.2:** A subject doing an eye glance while typing on a smartphone.

Data such as lane variability, velocity, eye glances and task load was collected for analysis. The experiment was recorded using video cameras and a link to the simulator screen in order to analyze the collected data, see figure 2.2.

Results showed that tactile cell phones was at least equally dangerous as touch-based smartphones. Furthermore, results showed that texting using tactile cell phones increased the risk of being in a crash or near-crash situation by a factor of almost 4. Using a touch-based smartphone had an equal effect on road safety and in some cases a higher effect increasing the risk of being in a crash or near-crash situation from a factor of almost 4 to a factor of almost 5.

## 2.3 Article 3

In this article, we provide 4 new forms of text entry methods combined with in-vehicle Head-Up Display (HUD). The purpose of this article is to answer the research question: *How can HUD-based methods for text messaging while driving affect the impact on road safety?*

The experiment was conducted in the same experiment as described in article 2, and besides from the T9 and touch-based phones, the subjects were asked to write messages with the four new text entry methods.


**Figure 2.3:** Left: 2x3-tree. Center: Directional Selection. Right: Tactile Multitap.

The methods consisted of a 2x3-tree selection, where buttons on the steering wheel interacted with boxes of letters on the HUD, see figure 2.3. Directional selection, where swipe-gestures on the steering wheel corresponded to boxes with letters positioned at top, bottom, left and right positions in the HUD. A tactile multitap method consisted of an external numeric keyboard which was keymapped to simulate the multitap text entry system of a common cell phone, and finally a touch-based multitap method was used which consisted of an Apple iPhone which displayed a virtual multitap keyboard on its screen. These four methods were implemented into the simulator.

Results showed that using a HUD decreased the amount of eye glances, and road safety improved significantly compared to common cell phones in low driving complexity scenarios. Results furthermore showed the tactile multitap method had the least negative impact on road safety.

# 3 Research Method

## 3.1 Research Method

Using terminology described in [6] and [8], this project is categorized as using Laboratory experiments by a researcher-created setting with experimenter control over the assignment of subjects to experiments. Experiments have been conducted with split-plot design and results have been analyzed using repeated measures ANOVA. Laboratory experiments are characterized as being conducted in a closed environment for experiments which require a high degree of researcher control over setting, variables and subjects. This holds both advantages and disadvantages which are described below:

Advantages:

- Variable control: Entails control of variables and methods to minimize outside interference from environmental interactions. It is therefore possible to reconstruct the same experiment for a further study with all the variables consistent.
- Replicability and reliability: When the environment is under control, it is possible to replicate scenarios, thus allowing for reliable results for all conditions. It is possible to reproduce the same scenarios in our simulator for each condition in the experiments. For example, the braking intervals of the lead vehicle is the same for every test subject.
- Precise measures: Under controlled experiments in a usability lab, it is easier to gather data from the experiment using video and audio recording equipment. As the entire environment of the simulator was digital, the precise measure of data such as lane positions and exact reaction times are possible to collect. Such data is harder to collect in a real-world scenario.

Disadvantages:

- Artificial setting: Using a controlled environment ignores real-world settings and can therefore be considered unrealistic. The test subjects in our simulator cannot endure physical injury if involved in an accident. As subjects are not concerned with being involved in an accident, this can affect their driving behavior.

- Unknown generalizability to real settings or real people: It is difficult to assess whether results gathered can be applied to a real-world setting.

Due to the nature of car simulators and driver distraction research, a lab experiment was an obvious choice of research method, as field-studies, which would provide the best possible results, was not possible to conduct primarily due to safety issues, but also related to general replicability. Since the master thesis is directly related to car simulators, which in its very nature can be considered a laboratory experiment, this research method was selected.

We also developed a tool in C# to ease the workload of gathering eye glance data. To record eye glances using the tool, the video should be looked at frame by frame, and designated keys should be pressed when a start of an eye glance occurred and when it ended. The frame numbers would then be written to a file for further analysis.

After the data was collected by the automated and manual logging we needed a way to process the data so it was ready for statistical analysis in R (software for statistical computing). The tool would parse all the log files and generate CSV (Comma Separated Values) files in a format that could be used in R.

It was made so that the conditions that was to be compared could be specified along with the road type and the type of phone the subjects owned, and only the relevant values would be included in the output. Because of this feature it was decided that NASA TLX data and the eye glances data should also be processed by the tool.

# 4 Limitations

The following overall limitations should be taken into considerations when reviewing the results of this paper:

- All results gathered in this thesis are based on simulated driving and not real-world scenarios.
- Subjects are tested in a safe environment, it is possible that subjects do not react naturally as there is no direct implications of their actions related to their own safety.
- Not all participants driving in the city scenario made much use of the gear shift, which can have had an effect on eye glance recording. Also some participants committed to having such a large following distance, that the lead car disappeared in the horizon which can have effected brake reaction time.
- The touch-based multitap and directional selection text entry methods used WiFi to communicate with the car simulator, which delayed response time from a letter was written until it was displayed in the HUD. This may have had an effect on the task completion times.
- In the T9 text entry method, there exists two different implementations which positions the "space"-key on different buttons, which initially caused confusion for subjects experienced in the other implementation than the one used on our test phone. This can have had an effect on the first text entry tasks.

Most critical to our results, is the limitations regarding replicability in real-world scenarios. A study has compared in-vehicle interaction behavior in a simulated environments with controlled environment in a real car, and concluded that the subject showed similar behavior [2]. Our results should therefore be looked at as a preliminary indicator of driver behavior, but would need real-world data to support our findings.

# 5 Conclusion and Future Work

In this master thesis we asked an overall research question: *How does common cell phones and Head-Up Display based text entry methods affect road safety in a low-cost driving simulator?* This question was answered by breaking it down into three subquestions which we answered in three articles.

The first part of the research question related to tactile cell phones and touch-based smartphones, and was: *How does texting using touch-based smartphones affect road safety compared to using a tactile cell phone?* We showed that writing text messages using both types of cell phones decreased road safety due to a significant change in driving behavior related to reaction time and lane keeping and a bigger risk of being in a crash or near-crash situation. This risk was increased by a factor of almost 4. When subjected to increased velocity and heavier traffic in the freeway scenario, writing text messages using a touch-based smartphone increased the risk from a factor of almost 4 to a factor of almost 5. When writing, the subjects spent significantly more time looking away, which was increased even more when using a touch-based smartphone.

The second part of the research question related to HUD-based text entry methods, and was: *How can HUD-based methods for text messaging while driving affect the impact on road safety?* We showed that introducing HUD-based text entry methods into a low driving complexity scenario reduced the risk of being involved in an accident compared to writing with common cell phones. All four methods showed no significant difference in the number of crash or near-crash situations when writing in a low complexity driving scenario, whereas the common cell phones had significantly more crashes or near-crashes when writing. We furthermore identified one method to have the lowest negative impact on road safety as it lead to the least crashes or near-crashes overall, and the subjects furthermore retained their lane keeping abilities when writing with this method.

The third part of the research question related to developing a test-bed in which to perform the experiments. The question was: *How can a car simulator for testing of in-vehicle systems, be developed with a satisfactory level of fidelity and at a low cost?* We described the development of a car simulator for testing of in-vehicle systems with a satisfactory fidelity at a low cost. We used mass-produced computer components and based our software on an open-source project. The simulator's fidelity was deemed satisfactory, as it was used successfully to conduct two tests of interaction with in-vehicle systems. The simulator was developed through two iterations and was enhanced to achieve a higher fidelity based on test subject feedback.

The experience gained from the experiments with the fidelity of the simulator and the text entry methods has made room for many new ideas. The current implementation of the simulator itself has room for many improvements such as graphical and technical development. The tests of the text entry methods could be improved in future experiments by focusing more on what types of interaction has an effect on specific factors of driver distraction, which in the long run could be used as a guideline for developing the optimal distraction-free forms of interaction. As mentioned in the limitations, a future improvement of our experiment would be to correct the problems related to latency on some of the HUD-based interaction methods. The issue with different T9 implementations could also be an issue to correct in a future study by screening our test subjects more thoroughly.

# 6
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# A car simulator for testing in-vehicle systems: Achieving fidelity at a low cost

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## ABSTRACT
Car simulators today are a commonly used to test in-vehicle systems in a safe environment. This has raised questions regarding the trade-off between fidelity and the amount of funds required to achieve this. This study describes the process of developing a low-cost car simulator intended for use in testing of in-vehicle systems, and iteratively improving its fidelity at a low cost. The simulator was developed through two iterations involving requirements, development and testing. Our studies showed that the simulator successfully improved its fidelity at a low cost.

## INTRODUCTION
Car simulators are a safe and less expensive way to conduct in-vehicle tests and studies [2]. They are often introduced in order to mimic the behavior of some vehicle in a controlled environment, typically as a part of a training program, such as training of pilots or truck drivers. Simulators are also used for research and experiments such as development of new in-vehicle interaction systems.

Toyota has since 2007 held the record for the most advanced car simulator, measuring more than $550m^2$ and with a weight of almost 78 tons [7]. This simulator in the high end of the complexity spectrum offers a high degree of realism in form of a real car placed inside a 360-degree field of view, with complex hydraulics systems for motion and speed effects. Simple car simulators also exists, and are available at affordable prices primarily in relation to the gaming market, where a racing simulator is sold bundled with a steering wheel and pedals [12]. These simulators are in the low end of the complexity spectrum, and offer a simple driving experience where a racing game is played at home on a standard television or computer monitor.

In human-computer interaction research, experiments in simulators are popular. Both due to safety and liability issues related to unproven technology, and also because driving simulators offer advantages in terms of keeping the simulation scenario and variables constant between experiments [18]. Experiments in fields such as HCI often use simulators to test new interaction forms for in-vehicle systems or analysis of distraction while driving. A study concluded, that using a simulator for evaluating driving behavior is a viable solution [3].

Much attention has been given to the question of realism of a given simulator, often referred to as the simulator's *fidelity* [8]. A study has shown, that simulator complexity can be placed in a spectrum where fidelity and cost are proportional [18]. Another study argues, that if fidelity goes up, generally, so does cost [5].

A typical issue when attempting to increase fidelity, is that it affects the physical construction of a simulator, where the introduction of more complex machinery makes the price higher. Also, the cost of software is affected, as flexible source code, realistic car physics and actual in-vehicle system validation improves the level of fidelity in the simulator [10], [18], [4].

The focus of this article is to study the development of a car simulator with satisfactory fidelity while keeping the cost low. The article will give an overview of the current research on the subject, followed by an analysis of the requirements needed to construct a car simulator. An overview of the process of constructing the simulator will be presented followed by an assessment test of the simulator. Results from this test will then constitute the beginning of a new iteration with review of the requirements followed by a verification test based on the improvements made. Finally the results gathered from the two tests will be reviewed in a discussion.

## RELATED WORK
This section covers existing literature on development environment, physical setup and the simulated world.

### Development environment
Studies on car simulator development show a variety of possible solutions when weighing their baseline options. One study chose to construct a new car simulator from scratch. Using virtual-reality, the car simulator is based upon a database containing entries of virtual elements such as roads, houses and traffic. The simulator was constructed using affordable means and was considered low-end in graphics and perfor-



**Author keywords:** Car simulator, fidelity, low-cost, in-vehicle systems, human-machine interfaces, experimentation

**General terms:** Empirical study, Human Factors, Economics

**Categories and Subject Descriptors:** H.5.2 [INFORMATION INTERFACES AND PRESENTATION] User Interfaces - Benchmarking, Evaluation/methodology, Prototyping]

mance. The result was a low-cost yet effective simulator that lacked realistic elements in the virtual environment such as road dividers, slopes and realistic tire performance [10].

A study focused on portability and low cost [18]. The authors constructed a car simulator using an existing car game as basis for development on an open-source technology. The physical part of the simulator was constructed using mass produced computer hardware available in shops. The trade-off with this solution was that using the existing software limited their freedom in customizability, such as insertion of road elements. The result was a functioning car simulator for a price around $60,000 which had a level of fidelity comparable to that of more expensive simulators.

Another study used the simulated world of Second Life as a basis for car simulation. This resulted in significantly reduced development time and costs, but was conclusively not recommended as a testing environment as elements such as car physics and traffic was not customizable to their needs [4].

### Physical setup and simulated world

The literature reveals a division between hardware and software in a simulator, which we chose to describe as the physical setup and simulated world of a simulator. One study chose to focus on how artificial sound in the simulated world affects driving behavior [14]. The study examined the effect of realistic 3D sound which took into account issues such as the Doppler effect and wind noise. They concluded that more realistic sound heightened fidelity in a simulator, but discussed that the need for other elements such as realistic graphics and physical behavior was also dependent on the overall outcome of the results.

Other studies have focused on improving the artificial intelligence of traffic in the simulated world [1] and questioned using multiple projectors and a wide field of view as a mean of improving fidelity in a car simulator [11].

A study related to truck simulators defined four levels of complexity. Level 1 being the simplest, consisting of a standard PC connected to a large screen, levels 2 and 3 had more complex hardware setup and larger screens. Level four being the most advanced including a moveable platform and a life-size driver's cabin with 270 degree vision and the like. The article concluded that level 1 had a better fidelity than anticipated, and the level 4 was not significantly better than levels 2 and 3. [2].

### Comparison and validation

Some studies have focused on the issues of validation of simulator's performance with respect to fidelity and real-world scenarios. The issue of keeping variables constant in real-world scenarios is challenging [18],[17]. One study has shown that using recognizable elements in a car simulator such as genuine steering equipment and the degree to which a subject has an impression of fidelity contributes to how successful the performance of a car simulator is [16].

Another study focused on validating car simulators for in-vehicle testing, concluding that using a simulator does yield many similar results, but that test subjects tended to feel more safe in a simulator which led to longer eye glances and more frequent driving errors than in the real world [3]. This issue is common among simulator validation, where especially velocity is a factor that is higher in simulated environments opposed to the real-world counterparts, e.g. [17],[8].

## REQUIREMENTS

We produced a series of requirements in order to have a baseline of reference for what constituted a basic car simulator. The requirements were separated into four categories, physical setup of the simulator, development environment, simulated world and data collection. The requirements were made while maintaining that the cost of the simulator had to be produced from reasonable economic means, while still keeping a certain quality with respect to fidelity.

### Physical setup

This section relates to the external parts of the simulator not related to software, such as car seats, steering equipment and auditive feedback.

#### *Equipment*

The simulator must include a real car seat to reproduce the basic feel of sitting in a car. The seat should be adjustable to the various heights of test subjects.

#### *Input devices*

The simulator must include steering wheel, pedals and a transmission. The pedals should include a clutch to allow for manual transmission, and the gearbox should have six gears including the reverse gear.

#### *Video and graphics*

The simulator requires a large monitor for simulation of the front window, and two smaller screens for side view.

### Development Environment

In order for the simulator to be reproducible by an acceptable cost, the simulator software must be easy to comprehend by a third party. Also, have no or few limitations to its customizability, so that in-vehicle systems could easily interface with the software. All existing code available for use must include support for realistic car physics, be comprehensible, high-level and easy to modify. The software has to allow for third-party hardware compatibility for the steering equipment

### Simulated World

The 3D environment has to allow for full customizability. The environment should enable city driving and simulated traffic.

### Data Collection

The simulator must support video-based logging of the simulator and test subject interacting with an in-vehicle system. The simulator software must allow for log data, such as speed and lane keeping.

## CAR SIMULATOR

This section describes how we constructed the simulator.

### Physical Setup
The simulator was constructed using affordable means of materials. A genuine car seat was made available through a used car dealership. The car seat was adjustable as specified in our requirements. This seat was attached to wooden pallets making it adjustable for people of different heights. The steering equipment was located close to how they would be in a real car driving on the right hand side of the road. A Logitech G27 driving kit which included a steering wheel, pedal board and a manual gearbox. This kit satisfied our requirements.

A wide screen television proved to work better than a projector and was used as the front wind shield. We could not place the projector in a way such that the size of the picture was big enough and the drivers head was not in the way. As specified in the requirements, two other flat screen displays were placed on each side of the front to act as side-view windows, as wide field of vision improved fidelity [11]. The steering was attached to a table and the gear stick was positioned on a small adjustable tablet.

### Development Environment
This section describes an analysis of available options when developing a new car simulator.

In the literature study, three options for making a low-cost car simulator were mentioned. These were: starting from scratch, building upon an existing virtual world or using an open source project.

While starting from scratch would provide a lot of freedom it was decided that it would take too much time. Four options were explored: Second Life showed potential as a 3D environment but its API lacked customizability due to security and performance issues. Torcs is an open-source research platform for simulating car-related game physics, and had much freedom and modifiability through its GPL-licensed C++ libraries. Dolphinity Racer was also an open-source car simulator which emphasized realism through an advanced 3D graphics engine. Both Torcs and Dolphinity had a high learning curve which was deemed too time consuming. A free car tutorial from Unity Studios was therefore selected, as this solution provided car physics, a number of car models and a 3D environment. It was easy to add new functionality and Unity itself was an easy to learn game development too, which was in accordance with our requirements.

The software of the car simulator was developed in Unity using the existing car physics source code as a foundation for further development. This included existing code for car physics, car handling, transmission logic and graphical car models.

We implemented everything such that it would be possible to change or add functionality. The basic car game from Unity only supported keyboard steering, so we modified it to work with a steering wheel and pedals. We also added support for manual transmission.

The existing game did not implement traffic. We therefore developed an artificial intelligence-module for cars to simulate the presence of other drivers on the road. The route the artificial intelligence would take was controlled by a series of waypoints to enable autonomous cars to follow a predetermined route. We also implemented logic for traffic lights and intersections to enable city-specific behavior. This allowed for traffic to behave somewhat life-like by obeying their duty to give way, red lights and adjust their driving behavior to other cars on the road. In addition to traffic, we added pedestrians, that were programmed to walk between two given points.

### Simulated World
This section describes three potential solutions for the graphical development of a 3D-environment and the elements inside it.

Complex environments in a virtual world are often created using third-party applications and then imported into Unity for later work. We identified three options for achieving this: Create a 3D environment from scratch, CityEngine or Cityscape.

Creating a 3D environment from scratch required the right tools. 3D-modeling software for this solution was available which had compatibility with Unity, but also held challenges as every object in the environment (roads, trees, buildings, etc.) had to be produced from scratch. Using CityEngine would provide some of these objects automatically, but held limits to the variety of objects available for creating a life-like city environment, and cost about $495 for an academic license. CityScape provided some of the same functionality as CityEngine, but had greater usability in the 3D-modeling process and was available free of charge using an academic license. All three options fit our requirement and we chose CityScape because it was the cheapest solution to us.

### Data Collection
We added automatic logging functionality according to our requirements so that it would be easily expandable, but as a base it logged time, velocity, distance to the middle of the road, values from the steering wheel and pedals and the cars position in the virtual environment.

## ASSESSMENT TEST
This section describes the method conducted and the results produced from the assessment test, where the perceived fidelity of the simulator was tested.

### Method
The first test was conducted in order to assess fidelity issues perceived by test subjects while interacting with an in-vehicle music player.

#### *Setting*
The basis of the setup was the requirements generated in the beginning of the project. The simulator was constructed at the HCI-laboratories at Cassiopeia, The University of Aalborg, and the setup itself is presented at figure 2 on page 6.

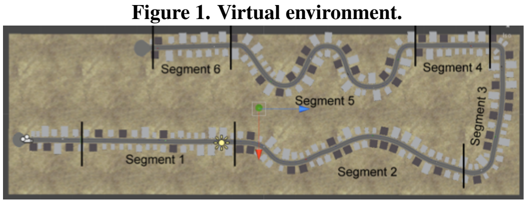
#### *Participants*
It was decided to locate 16 subjects, 8 male and 8 female, as groups of less tend to give less interesting results [9]. 8

of the males and 2 of the females were located at the Computer Science institute, and the final 6 were found at other branches of the University of Aalborg. The final composition all held valid driver's licenses and were from natural, humanistic or social sciences.

*Software*

The virtual environment displayed in figure 1, shown from directly above, constituted a straight main road partitioned in 6 segments. The purpose of these segments was to present an increasing level of difficulty for the test subject throughout the simulation. A controller-script was developed for the software which eased the work of the test leader, so switching between conditions and restarting the simulation could be done without much interruption of the simulation.

**Figure 1. Virtual environment.**




*Procedure*

The experiment was executed with the test subject being placed in the simulator. A few test-rounds was first conducted in an unrelated city environment in order to give the subject some time to get acquainted with the controls and behavior of the car. The subject then went through 4 simulations in random order with static and dynamic objects either shown or hidden from view, and instructed to keep a constant speed of 60 km/h. Afterwards the simulation was made again, only this time without a visible speedometer and instructed to drive at a pace they themselves felt secure about. The purpose of this was to examine if differences in subject's sense of speed could be determined. Meanwhile tasks were given at 30 second intervals which they were instructed to perform whenever they felt safe to do so.

*Data Collection*

The experiment concluded with a semi-structured interview of the subject. The interview constituted approximately 20 questions with relations to the subject's perception of the simulator's fidelity. The session was recorded using video cameras and stored on DVD.

*Data Analysis*

The video recordings were transcribed and interview answers were analyzed.

## Results

Questions were constructed to focus on three different subjects: The test subject's basis for participation in the experiment, how the simulation experience was perceived and finally suggestions for improvement.

*Basis for participation*

Subjects drove an average of once a month, and had no experience with car simulators other than basic computer games. The subjects ranged from 20 to 25 years old and were all active university students. 2 subjects had used an iPod Touch previously.

*General perception of the software*

There was an agreement between the subjects that the simulator worked well. Their general impression and more so their experience of audio and graphics was consulted, which received a mixed response.

S16: *"I thought it was very cool, really good!"*[1]

Others took a more critical standpoint:

S7: *"(...) There was not really the same feel between gearing and speed as there is in a real car."*.

Many of the subjects expressed problems with steering, which in some opinions seemed unnatural, especially during turns. For some of the subjects, backlash and resistance in the steering wheel did not feel as a real car.

*Audio and graphics*

Many stated a problem regarding the flow of graphics, which did not seem to be very smooth especially with the conditions where buildings were present. On multiple occasions it was stated that the graphics were twitching. One subject expressed that:

S5: *"The graphics was not very impressive. The world was completely flat, no hilltops and that sort of thing."*

Subjects had a problem with seeing when to turn, due to the static level of the ground:

S1: *"It was hard to see very far down the road, in order to see how radical the turns were going to be. It was hard to judge exactly how fast you were going and how acute the turns actually were."*
S2: *"It is hard to see ahead, compared to what you would in real life (...)"*.

There was mixed opinions about the coherence between the sound of the engine and the gear shift:

S2: *"The sound was fine, I could hear when I was changing gears."*
S1: *"You can't really hear when you are changing gears from what sound the engine makes. So when you e.g. put it in 4th, it does not matter if you press the clutch or not, you still hear the engine increasing in rotations. So it's hard to get a feeling from using the sound alone."*

Many described the sound as "monotonous" and some of the participants had contradictory impressions of what impact the sound had on the changing of gears:

S15: *"I think it works well, I did feel however that you could just drive in the wrong gear without any problems."*
S11: *"The engine sound was a little silly. I don't know if it was realistic or not, but I did think that it sounded a lot like you weren't driving in the right gear. But maybe that was just because I wasn't."*

[1] Answers translated from Danish.

#### *Physical setup*

Regarding the physical setup of the simulator most subjects agreed that the car seat worked well. There were mixed emotions about the use of the other steering mechanisms, where some expressed a positive experience:

S15: *"I thought they worked well. The steering wheel is sort of small, but other than that, it's good."*
S6: *"The steering wheel is functioning fine, but I did feel an amount of backlash while using it."*

In concordance with the problems pointed out about the audio aspect of the simulator, another subject expressed that:

S1: *"The gear shift is hard to assess. The pedals worked fine once you figured out exactly how to press them. The steering wheel also worked well."*.

The stick and the pedals were only mentioned a few times, where one pointed out that the stick was too small compared to one in a real car, and that it had too much slack. Another subject referred to the pedals as *"very plastic-ish"* and that had they been attached more firmly, it would have made for a better experience. Conclusively one subject stated that

S12: *"You always have to get used to drive a new car."*.

Some of the subjects claimed that they had not used other displays than the center one. One subject stated that it was not up until the 5th run through that he remembered that there even were side windows in the simulator. Another subject expressed annoyance about the existence of the two side displays:

S4: *"I didn't really use them. I thought it was confusing when you were driving in the city, that you always had something in the corner of your eyes."*

Though some of the test subjects did address the fact, that the existence of side windows may have contributed to their overall impression subconsciously:

S2: *"No, it is only the center display that I am looking at. But maybe the side windows have affected me subconsciously."*,
S12: *"I was looking at the side windows to judge my position on the road, but I was mostly looking through the corner of my eyes."*.

One subject explicitly expressed happiness about the side windows:

S8: *"I thought you got a very good overview. Even though you don't look directly at them, they did facilitate to give you the general impression."*

#### *Validating fidelity*

Subjects were asked about their feeling of fidelity and presence while driving in the simulator.

S3: *It felt artificial, I don't think the car reacted in the way I expected.*

In continuation of the auditive issues expressed, one subject pointed out the correlation between sound and impression of speed as an issue of fidelity:

S1: *It felt weird to do an almost 90-degree turn with 60 km/h, which I in a regular car would have done at a much lover velocity. (...) Due to the issues with sound, I tried avoiding changing gears whenever possible, also when doing turns."*

One subject expressed both satisfactory and unsatisfactory fidelity issues:

S2: *"It felt different. Some of the parts of the simulator are the same as a real car: You have to pay attention, calibrate and keep focus. You have to keep an eye on the road, else you'll end up on the wrong side of the road. In that way things are the same. I had trouble determining the speed with which I was going. You don't really get the right feeling of when the velocity is about to reach dangerous proportions. Because it's a simulator, you don't feel that you're being moved physically."*

#### *Suggestions for improvement*

Issues such as the flat environment, the audio and the twitching graphics are some of the things that needs to be improved. Some of the subjects responded:

S7: *"I felt no change whatsoever when I depressed the clutch."*
S1: *"The physical setup is really good. When you released the clutch, the audio made it sound like it went into neutral. When you then put it in gear, the rotations went up before the release of the clutch. Furthermore, when you have the side windows, maybe insert some working side-view mirrors. I rarely look out the side windows, but I do often glance at the side-view mirrors."*

Another test subject expressed concordantly with the suggestion about the mirrors, that he was missing a rear-view mirror, since glancing at the rear-view mirror is a very essential part of driving.

S4: *"The placing of the driver is wrong. You're sitting in the middle. It would be better if you sat in the right side of the car, so things such as blind angles also exist."*

Conclusively two test subjects both claimed that they missed a feeling of movement and vibrations in the car seat:

S9: *"You could put in more vibrations, if you drive into another car or onto the curb of the side walk."*
S10: *"More movements in the seat. Other than that, it thought it was a good experience."*

## ENHANCED CAR SIMULATOR

Based on the issues identified during the assessment test, issues with both the previous hardware and software we identified new requirements for the simulator. Using the structure of the previous requirements, enhancements were made under each of the following requirement sections.

### Physical setup

New additions related to the previous hardware requirements of the simulator.

*Equipment*
Instead of one adjustable car seat placed in the middle of the setup, we extended the simulator to consist of two real-world adjustable car seats acquired from a used car dealership. The test subject's seat was furthermore relocated to the left side of the setup as opposed to being in the center.

We acquired two tactile transducers or "bass shakers". These are devices which emit low-frequency vibrations which can be felt as well as heard from whatever material they are physically attached to [15]. These devices were bolted on beneath the driver's seat and pedals in order to give the test subject a physical and audible feedback from engine vibrations and rotation, collisions and other sorts of feel from the road.

Since the bass shakers required connection to an amplifier, two speakers were also added to give a boost to the audio quality as opposed to just using the internal speakers of the front-side monitor which was done in the previous experiment.

*Input devices*
We adjusted the sensitivity of the steering wheel, pedals and the amount of backlash based on the comments of the users.

The previous setup had positioned the gear shift atypical. The table which the shift had been attached to was also constructed of metal in an odd shape which made it a challenge to actually keep the shift fixated, which caused it to become detached on some occasions during the experiment, if a subject would shift the gear too aggressively.

We therefore produced a wooden unit and bolted it on to the pallets underneath, which also kept the car seats fixed thus keeping it steady and in place, while being at a more realistic position of the driver.

*Video and graphics*
A new high-end PC was purchased which had a better graphics display adapter and CPU than the previous computer. In order to cope with the computer performance demands of displaying a high-resolution image on three large monitors, a Matrox TripleHead2Go-device was purchased, which enabled multi-monitor usage at a low performance-cost [13].

The three monitors used to simulate car windows were upgraded with respect to both size and performability. The front-view screen was upgraded from a 32" screen to a 37" which also was able to display a higher resolution.

As displayed on figure 2, the previous experiment had been conducted with the two 21" side-view screens placed in immediate continuation of the front view screen and tilted slightly. Some test subjects expressed that this solution rather produced the curved effect of a wide front-view screen than the effect of two side-view windows, which are commonly positioned perpendicular to the front-view.

The two 21" monitors were therefore replaced by two 32" and repositioned at a more adjacent angle, cf. figure 2 for a full display of the simulator.

**Development Environment**

**Figure 2. Physical setup before and after the verification test.**

More realistic traffic which was not only oncoming was also introduced, more realistic elements such as better car sounds, different look of the sky, more diverse soil and vegetation and a fog-effect in the far distances of the horizon was also introduced, as well as many more minor tweaks and minor upgrades. In general, the new flow of computer power to the project enabled the simulated world to reach a much higher level of visual complexity than was available previously.

We implemented a rear-view mirror and two side-view mirrors to the user's car in the simulator. Finally, the sound and behavior of the gear shift was improved.

**Simulated World**
We determined that the virtual world of the enhanced simulator would include a more diverse environment which had alterations in levels of the roads, as would be expected of a real-world scenario.

## VERIFICATION TEST
This section describes the method conducted and the results produced from the verification test, where the perception of how well the simulator performed was tested again. The test was part of another experiment investigating interaction of in-vehicle systems, but only the relevant parts are represented in this text.

**Method**
Opposed to interacting with an iPod Touch, which was suspected of not being demanding enough on the subject's attention, this test investigated cell phone texting while driving based on the structure of a previous study from 2009 [6]. This study investigated aspects of cell phone texting while driving. The test consisted of one baseline task plus six different text messaging tasks, which the subject had to perform while driving in the simulator.

*Setting*
The basis of the setup was the new requirements and improvements generated after the first test. The simulator was once again constructed at the HCI-laboratories at Cassiopeia, The University of Aalborg, and the setup itself is presented at figure 2.

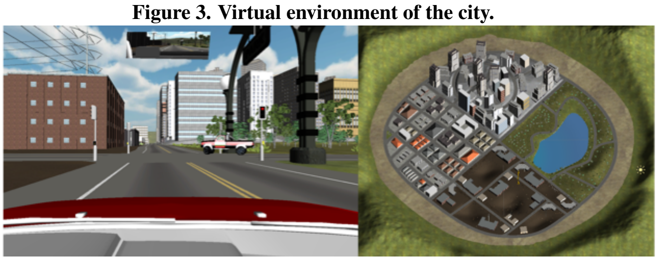
*Participants*
Based on the number of conditions the minimum latin square ordering we needed 28 test subjects. These were balanced across gender and cell phone experience. 20 the subjects were located at the Computer Science institute, whereas the

rest were located on other branches of the University of Aalborg as well as a few on other lines of education. The final composition of test subjects all held valid driver's licenses in the age of 20-32 years old, nine of which had been test subjects at the previous experiment.

### *Software*
The original virtual environment was replaced by two different visual scenarios and balanced between the subjects.

The first environment constituted a straight highway in an area with mountains and bridges, with traffic in three lanes driving at various speeds.

**Figure 3. Virtual environment of the city.**



The second environment displayed in figure 3, constituted a typical city with four different segments containing various architectures, ground levels and characteristics. The city was populated with traffic and traffic lights as well as a surrounding orbital road.

A controller-script similar to that of the assessment test was developed for the software, which eased the work of the test leader, so switching between conditions and restarting the simulation could be done without much interruption of the simulation.

### *Procedure*
The subject was given a chance to test-drive the car in the city environment to get acquainted with the controls and behavior of the car. The subject then went through the 7 tasks ordered by the latin square algorithm. In all conditions, the test subject had to write text messages while following a car which was programmed to brake at randomly selected intervals.

### *Data Collection*
Each test concluded with a semi-structured interview of the subject in question. The interview constituted approximately 20 questions with relations to the subject's perception of how well the simulator performed.

### *Data Analysis*
The recorded sessions were transcribed and interview questions and answers were inserted into a matrix for analysis. Answers were grouped together and identified as positive or negative feedback. The most prominent of which was represented in the next section.

## Results
After the experiment, the group of test subjects was interviewed in order to reveal if the enhanced simulator had improved their impression of fidelity.

Questions were constructed the same way as in the previous interview.

### *Basis for participation*
Subjects drove an average of once a month. Half of the attending people had been test subjects of the previous experiment. Their age ranged from 20 to 32 and were all active university students.

### *General perception of the software*
When asked about their general perception of the simulator, all test subjects who had attended the previous example agreed that the fidelity had been increased. One subject expressed feeling directly related to the new levels of the landscape:

S12: *"It was very good. Last time, I stated that I didn't feel like I was driving a car at all. This I indeed felt this time. For example, when I was driving up a hill side, it really felt like I was sitting at an increased angle. It was done really well."*

Others stated a more general satisfaction about the improvements:

S15: *"It is actually doing quite well. If anything, a lot has happened since last time, both with the graphics, the audio, or at least with how the car is reacting."*
S17: *"There has been a lot of improvements since the last time."*

Subjects which had not tried the simulator before expressed themselves more intense about the simulator in both ends of the spectrum. Some subjects had only good things to say:

S25: *"I actually thought it was extremely impressive, both the sound, graphics and the feel of it."*
S18: *"I think this is a really good simulator, and it is very realistic."*
S14: *"It felt like sitting in a real car. It was very much like in the real world."*

Other subjects expressed more constructive criticism:

S8: *"I thought it was well done, but there are some quirks that could have been taken care of."*
S5: *"I think it is very entertaining, but I still don't feel like I am really sitting in a car."*
S16: *"It was pretty good, but I couldn't always feel the driving sensation."*

Where finally some subjects where not satisfied with their experience:

S23: *"I found it to be ugly and unresponsive."*
S24: *"I thought it was OK, but nothing like a real car."*

### *Audio and graphics*

Opposed to the previous test, there were no comments about the smoothness of the graphics. The subjects from last experiment where generally satisfied:

S24: *"I thought the graphics felt very real."*
S1: *"I found the graphics to be very satisfactory."*

However, subjects new to the simulator had primarily only minor concerns:

S3: *"Regarding graphics, I did not feel like I was playing Need For Speed, but it was OK."*
S8: *"The graphics are not breathtaking, but on the other hand it gives a pretty realistic image of what is going on. You are not in any doubt about what you're looking at."*

Few subjects had general comments about the resolution:

S19: *"If there had been a higher resolution, it would have been perfect."*
S26: *"The resolution made everything very hard-grained when things reached a certain distance."*

The improvement of the previous issues regarding engine sound and gear shifting were noticed:

S3: *"The sound was very fitting and cohered with when I was changing gears."*
S6: *"The audio was consistent with what you could see and such, I could also hear when I was changing gears."*

One subject who had also been used in the previous experiment, expressed discontent, suggesting that the audio, despite being annoying, was actually working better than previously.

S12: *"The audio annoyed me, but it was because I did not have time to change gears, and the sound kept reminding me that I was constantly driving in the same gear."*

Others had more critical feelings towards the sound:

S13: *"The sound-part of the simulator was a good help as it is in a real car, but it was not the same as a real car."*
S19: *"(...) normally I can hear when a car is approaching me from behind, this was not the case here."*
S28: *"The sound was just boring. The way the engine sounded didn't convince me either."*

*Physical setup*

Subjects were asked about elements such as the steering equipment and the car seats. Most subjects expressed a satisfaction about the setup, and had shifted their focus from software-specific issues to hardware-specific.

S19: *"It does not matter whether you depress the clutch or not, so I stopped using it after a while."*
S21: *"You can feel that it is not a genuine transmission box, because there is no resistance."*
S24: *"It felt artificial because the pedals did not feel like my car."*

The introduction of the bass shaker received comments from the subjects:

S13: *"I felt the seat shake. (...) it made me feel like I was pushed forward in the seat when braking. It could also just have been a subconscious impression from the side monitors."*
S24: *"When you drove up onto the curb of the side walk, you could genuinely feel it."*

Despite efforts to improve the behavior of the side-view mirrors, with the exception of S13 above and a few others, most other subjects continued to state that they did not use them.

S16: *"I did not use them. It was not until very late in the experiment I remembered they were even there."*
S25: *"I really did not use them that much. A couple of times I glanced at them because I saw a car driving by, but nothing much."*

More subjects than last time agreed that there was a possibility that they had been affected by the monitors subconsciously:

S12: *"They may have given me an impression of where I was on the road."*

Only two subjects stated without any hesitation that they had made usage of them:

S24: *"(...) they worked pretty good, you saw a car in the side-view mirror of the door, and then knew when it would show up on the monitor, and then you could follow it when it drove past you and into the front-view screen."*
S12: *"I used this one [the left] when I was making turns and so on. I did not use that one [the right] that often."*

Despite the side-view monitors had been a request from previous test subjects, only S24 made any comments about using them. Multiple test subjects expressed surprise when the monitors were mentioned in the interview. Despite the city-scenario involved multiple turns on roads with traffic, this apparently did not make subjects take notice of the mirrors as one would in a regular car.

A number of test subjects also expressed that the reason they did not use the side monitors was due to a gap between the front-view monitor and the monitors on the side (cf. figure 2).

*Validating fidelity*

Besides their general impression of the simulator, inquiries were also made on their feeling of fidelity, with focus on their feelings of presence and responsibility towards other cars in the environment. This was where there was the largest difference in what subjects felt while performing their prescribed tasks. Subjects ranged from being very stressed and even expressed anxiety and fear of collisions and atypical driving behavior:

S5: *"I hardly have any comments about the simulator, because I was too busy concentrating on not crashing or hitting the other car while completing the tasks."*
S14: *"This really did not depict how I normally drive. I did not do any orientation or taking notice of anything in the en-*

*vironment, I was way too busy keeping an eye on the car in front."*

Some of these subjects expressed great concerns and showed signs of serious discomfort when facing near-crash situations or atypical driving behavior such as lane drifting, driving off the road or not making a turn.

Others were somewhat indifferent to the consequences of atypical driving:

S13: *"I did not really feel any responsibility towards the other cars driving next to me. I was not as cautious as I would have been in the real world."*
S27: *"I think I would have paid more attention if there had been real depth in what I was looking at and if it had not been a monitor. I think I would have acted differently in a real car."*

One subject even involved themselves in multiple collisions on purpose, which suggested no sensation of responsibility or presence in the simulator what so ever.

Finally, a large amount of the subjects who drove in the city-scenario, instinctively reached for where the blinkers when about to do a turn, and continuing to do so even after they were told that no such device was available. Some subjects expressed this to be a missing feature that they would have liked, suggesting that they did feel some connection with the sensation of presence while driving.

### *Suggestions for improvement*

There was not recorded any criticism about the flat environment, twitching graphics or the audio of the gear shifting, which was all expressed in the previous experiment. There were still many comments on the way the gears were implemented, but comments were more related to the construction of the experiment rather than these not feeling realistic:

S1: *"I don't know if you should change how fast you can go without shifting gears. If I had to change gears more often, I would probably just focus all my attention on doing that, and end up never finishing a single text message while driving."*

Like many subjects expressed issues with gear shift at the last experiment, many people still had issues with the gears not working exactly as expected, and also variables such as acceleration and brake power was commented on:

S7: *"Compared to how slow the car accelerated, the brakes were way too effective."*
S10: *"When you make turns, brake and accelerate, the physical actions of doing so does not totally project onto how the car is reacting."*

One subject expressed a feeling of inaccuracy related to real-world physics:

S24: *"When you did turns, your missed that momentum of force that you normally feel while taking turns (...)"*

Asked about ideas for improvement, issues much less significant than last time were suggested, such as air condition, shifting weather conditions and a car radio.

**Table 1. Approximate cost per iteration (USD), as of 2011.** We define a man-month as 148 man hours, and a cost of $115 per hour.

| Iteration | Hardware | Development (man-months) | Total |
|---|---|---|---|
| First iteration | $1,600 | $25,530 ($1\frac{1}{2}$) | $27,130 |
| Second iteration | $4,300 | $34,040 (2) | $38,340 |
| Total | $5,900 | $59,570 ($3\frac{1}{2}$) | **$65,470** |

## DISCUSSION

The focus of this study was to develop a home-made car simulator and improve its fidelity while keeping the cost low. Both of these factors in the questions are, due to the nature of interview-based tests, by all means relative and needs comparison in order to be given an answer.

As indicated by the complexity-spectrum of previous studies (e.g. [18], [8]), studying the instinctive behavior of our test subjects suggest that we succeeded in developing a simulator that supported the basic principles of acting like a car. Of all the subjects presented with the simulator, not one person did not know what to do when asked to take a seat and do a short test-drive. This suggests that subjects accepted the fundamental devices presented to them such as the physical steering mechanisms, the front-view screen and even obeying traffic rules such as duty to give way and traffic lights.

Looking at the initial feel of the simulator, only about half of the subjects had positive feedback on the questions about fidelity, and most opinions were influenced by issues that caused irritation which affected their judgment. Since only about 20% of the subjects had prior experience with car simulators, it is difficult to judge their opinion without any basis of reference.

The enhanced simulator was perceived as having a higher fidelity than the original by the subjects that participated in the assessment test. The fact that subjects not familiar with this simulator had negative feedback which in some cases exceeded the negative feedback of the subjects in the original experiment suggests that general results about fidelity can be difficult to assess without some form of comparison.

The fact that many subjects generally shifted their criticism from issues apparent in low-fidelity simulators (such as small quirks in the software) to ones apparent in high-fidelity simulators (lack of hydraulics, motion feedback, lack of blinker-lever) suggests that our solution improved its fidelity. Subjects in the verification test expressed the sensation of force feedback in the steering wheel despite no such technology was implemented, which raises the question of how much subconscious impression are relevant to their sense of fidelity in a simulator.

Looking at cost and time consumption displayed in table 1, including hardware (car seats, computer, other accessories) and the aggregated development time distributed over the two iterations and writing about 2000 lines of new code, high-end estimates places the car simulator of a total cost of around $65,470, with a hardware cost of $5,900. It should be noted, that had this not been an academic project, the cost of the software for constructing the simulated world should also be taken into account.

In our literature search, we identified a car simulator that was denoted as "low-cost". It was stated to have a cost of \$60,000 [18], and that did not include development cost. In our study, development time was the primary contributing factor to the total cost. A comparison with our simulator is difficult, as the focus of their solution was different. As an example, their simulator included a \$40,000 eye glance recording device, while they spent only \$100 on software because they used an off-the-shelf product. Our simulator did not include eye glance recording software, but had more customizable software, which gave greater freedom in the types of experiments possible, and it also included software for logging driving data. Except for these differences, the two simulators have comparable functionality and cost. Therefore, we find it reasonable to denote ours as a low cost simulator.

A limitation to the simulator was the distraction caused from the in-vehicle equipment tested in the simulator, as was a part of the its purpose. The first test used the iPod Touch and the second used various other interaction elements. There is a possibility that the task load was too low in the assessment test, whereas the verification test had a much higher task load. This can have influenced subjects in a way that made them lose attention to the fidelity and focus primarily on task completion.

## CONCLUSION

In this paper we have described the development of a car simulator with a satisfactory fidelity at a low cost. We used mass-produced computer components and based our software on an open-source project. The simulator's fidelity was deemed satisfactory, as it was used successfully to conduct two tests of interaction with in-vehicle systems. The simulator was developed through two iterations and was enhanced to achieve a higher fidelity based on test subject feedback.

For a future study, most apparent issues throughout the experiments have been issues related to the sensation of gear shifts and the side-view windows. Research on how shifting gears related to engine sounds and car motion behavior could be an obvious next step in the improvement of the fidelity of our simulator.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# A Touch of Disaster: The effect on road safety of writing text messages using tactile and touch phones

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## ABSTRACT

Texting while driving has become an increasing threat to road safety. The introduction of touch-based smartphones has removed tactile feedback when texting. This could potentially increase the attention needed to operate such a device and thus decrease road safety. This study investigates the impact of texting during simulated driving on road safety, and seeks to measure the impact of touch-based smartphones compared to the common tactile cell phones. 28 subjects were asked to write sentences using both a common tactile cell phone and a modern touch-based smartphone in a simulator. Analysis of driving performance confirmed that texting while driving increased the risk of being involved in crashes or near-crash situations. Studies furthermore identified that use of touch-based smartphones further increased the risk of being in crashes or near-crash situations.

## INTRODUCTION

Up to one quarter of car crashes are estimated to be a result of driver's engaging in distracting activities [14][18]. Use of cell phones while driving has a range of negative effects on performance, including visual processing of the road environment, motor control and response, auditive and higher-order processing [20][22][25]. As an example, visual processing is affected by checking to see who's calling, motor control is affected when dialing a number, auditive distraction when attention is given to the conversation and not the sound of the traffic and higher-order (cognitive) processing when focusing on the conversation and not the act of driving [16].

As cell phones became more advanced, the introduction of text messaging has created another potential cause for distraction. The number of drivers using text messages has increased tremendously since it was introduced. Recent surveys has shown that as much as 51% of young drivers admit to have used text messaging during driving [11]. This is the age group of the population most prone to using text messages in general, and also the group with the least experience in driving.

In the late 90's the "text on nine keys" (T9) predictive text entry system was developed by Tegic Communications and shortly thereafter adapted as the primary form of text entry on products from all the major phone manufacturing companies [8]. Because of its reduction in required key taps, the T9 entry system allowed for text writing at about twice the speed as the previous multitap technology. This increase in text entry time has however not reflected on the dangers to road safety, as recent studies have found that text messaging while driving increases the risk of being in a crash or near-crash event by 23 times, compared to talking on the phone while driving, which doubles the risk.[5][12].

With the increase in touch-based smartphone usage, the use of 9-button tactile interfaces has been increasingly replaced by virtual full-size keyboards on touch screens, which renders tactile feedback impossible and leaves only visual feedback to the driver. This would suggest an increase in driver distraction as even more attention is needed to the text messaging task than before. Few studies on text messaging while driving exists, all of which has been conducted in simulated environments with and during a time before smartphones had gained much market share amongst the general population [17][14].

This study investigates how texting during simulated driving affects road safety, and especially what impact the rapidly increasing adaptation of touch-based smartphones in the general population has on the already significant dangers of texting while driving. The article will give an overview of the current research on the subject, followed by an introduction to the common text entry methods of cell phones today. The conducted experiment will then be described, followed by a presentation of the results which will finally be reviewed in a discussion.



**Author keywords:** Smartphones, tactile feedback, road safety, in-vehicle texting, driving simulator, accidents, safety, driver distraction, experimentation

**General terms:** Lab experiment, Human Factors, Road Safety

**Categories and Subject Descriptors:** H.5.2 [INFORMATION INTERFACES AND PRESENTATION] User Interfaces - Benchmarking, Evaluation/methodology, Prototyping]

## RELATED WORK

The use of cell phones and distraction while driving has been a subject of much research in recent years. In 2003, a study using a car simulator concluded that the overall driving of a person talking on a cell phone was more prone to being involved in a crash or near-crash event than that of a drunk driver [24].

Studies conducted in real-world scenarios are harder to conduct, but have shown similar results. One study based their research on accident analysis, where drivers who had been involved in car accidents were questioned about their cell phone use prior to the accident, and their statements were compared to data from their cell phone providers. The results showed that almost a quarter of these individuals had used their cell phone in the 10 minutes preceding the crash [23].

In recent studies, the dangers associated with cell phone usage has been quantified in more detail, where actions such as dialing a cell phone increases the risk of accidents by 6 times and talking and listening doubles the risk [5]. Many studies concluded, that despite most traffic departments around the world had banned the use of hand-held cell phones while driving, research concluded that the risks of using a hands-free cell phone was the same as using a hand-held (e.g. [21],[24]), since most of the distraction of talking on the phone was not related to motor control, but the cognitive workload.

Despite this conclusion, there was a difference in driver behavior between talking on a cell phone and talking to a passenger, and studies clearly showed a much smaller risk when engaging in conversations with the passenger [6].

Despite the dangers of hand-held and hands-free cell phone usage, only very few countries have banned both, where more countries have customized laws depending on age group of the drivers or the location of where the driving is conducted [1]. Much debate has been raised about the effectiveness of prohibition, as the task of actually enforcing these laws have proven to be very difficult [12].

Few studies have been conducted on the subject of text messaging while driving. Most notably, a study from Virginia Tech in 2009 which observed drivers for more than 6 million miles of driving concluded that texting while driving increased the risk of being involved in an accident by 23 times [5], and already have multiple notable accidents with multiple casualties been attributed to texting while driving [10].

Statistics show that teenagers are clearly the age group with the highest risk of being involved in accidents. Studies show that for every mile driven in the United States, teenagers are four times more likely to be involved in a car crash [2]. Studies on text-messaging habits in the last decade show an increase from 12 million to 135 billion text messages sent every month, where teenagers clearly being the most active age group, sending and receiving an average of 3,000 messages per month. [4][7]. Surveys conducted among teenagers conclude that half of all students admit to having texted while driving [14].

Studies on driving while interacting with touch-screen displays have not been conducted with relation to touch-based smartphones. Recent U.S. market share analysis expects touch-based smartphone adoption to surpass that of feature phones by the end of 2011 [9]. The main focus of this article is to investigate of the implications of using touch-based smartphones while driving.

## TEXT ENTRY METHODS

Prior to smartphones, the tendency was to place more than one letter on each physical button due to the limited space on a small mobile device. A widely used type of text entry method is the multitap and T9 predictive text entry system.

**Figure 1. Physical keypad on a Nokia 3210.**


Displayed on figure 1, the typical phone layout is a grid of 12 buttons where the alphabet is distributed on buttons 2-9. The method then allows multiple presses on each button depending on what letter is needed. To write the word `hey`, you would need to press twice on 4, twice on 3 and three times on 9. There is a timeout period of usually 0.5-2 seconds after each key press, which is used to delimit letter selections on the same button. So to write the word `hi`, you would need to press two times on 4, then wait the timeout period and then press three times on 4. The amount of words that can be written per minute with multitap is about 5-10 wpm depending on experience [15].

Using dictionaries to predict the desired text entry, based on the buttons being pressed, solutions such as T9 have been developed which is based on the same keyboard layout as multitap. T9 needs only one press on each button to predict what word is being written. If again the word `hey` was to be written, one would only need to press the buttons 4, 3 and 9, to have the software suggest the word `hey` and potentially other typical words that could be composed by tapping the same three buttons. Typically, the most frequent used word will then be predicted first. The amount of words that can be written per minute with T9 is about 7-25 wpm depending on experience [15].

With the introduction of smartphones, the use of a cell phone has exceeded that of simple telephony and short message sending. Smartphones are now also used for more advanced features such as document editing and mail composition, and research are continuously attempting to increase the efficiency of the limited space available for text entry methods.

Opposed to the common feature phones, most smartphones require larger screens in order to accommodate for the use of more advanced appliances such as email composition and text edition. This means that many smartphones such as Apple iPhone and many HTC Android-based phones remove the physical keyboard all together and instead use an on-screen, full-size keyboard which is stimulated through touch.

Figure 2. Writing text on an Apple iPhone.

Writing text on a typical on-screen keyboard such as the Apple iPhone, seen on figure 2, is done by touching the keyboard character on the screen. This solution also use dictionaries to predict the intended word, but does so by looking at the surrounding characters at each key press [19]. A study on the Apple iPhone touch-based smartphone concluded the text entry speed to be 15.9 wpm [3].

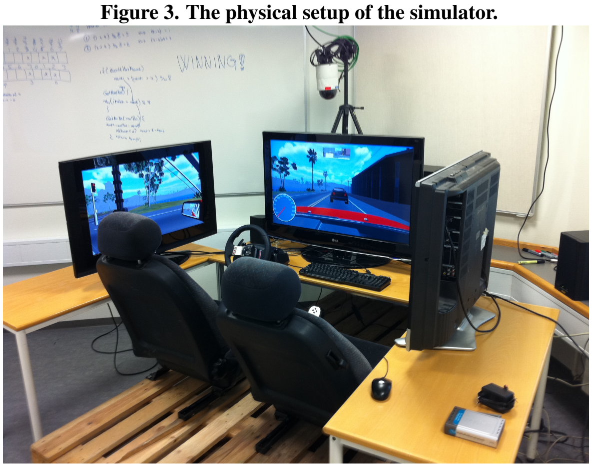
## METHOD

This section describes the method of the experiment, where the driver performance using a tactile cell phone and a touch-based smartphones was tested.

### Setting

For the study a simulator was constructed, which is described in detail elsewhere. The simulator was constructed at the HCI-laboratories at Cassiopeia, The University of Aalborg.

Figure 3. The physical setup of the simulator.



### Participants

The group of test subjects consisted of 28 people, where 18 were male and 10 were female. Among the participants 10 normally used a T9 cell phone and 18 normally used a touch-based smartphone. About half of the subjects were located at the Computer Science institute, whereas the rest were located on other branches of the University of Aalborg as well as a few on other lines of education. The participants all held valid driver's licenses and were in the age of 20-32 years old.

### Procedure

The subject was given a chance to test-drive the car in a city environment to get acquainted with the controls and behavior of the car.

The subject then went through 7 tasks in different orders given by a latin square to balance the effect of learning. Two of these were texting on a touch-based smartphone and on a tactic T9, the other methods are subject of another experiment described in detail elsewhere. While texting, the test subject had to follow a car driving in front of them which was programmed to brake at randomly selected intervals.

Two typical driving scenarios were used. Half of the subjects drove on a freeway with three lanes and traffic going at various speeds. The other half drove in a city scenario with traffic, intersections and traffic lights. The participants were balanced over the two scenarios with gender and cell phone experience in mind.

The car in front of the subject would continue to break until the test subject pressed the brake pedal or collided with the decelerating vehicle in front of them. This solution would produce a way to measure test subject reaction time in simulated driving [8]. The baseline condition constituted a 5-minute drive without interacting with texting equipment, where the other 6 conditions were various variants of such. The test subjects were instructed to enter a maximum of five different text messages or as many as they were able to type in the course of 5 minutes.

All text messages were randomly selected sentences of the same length and complexity [19] which was then distributed amongst the subjects also using latin squares. Each subject filled out NASA Task Load Index (TLX)-scales after each completed condition which is a NASA developed method for measuring task load [13].

### Data Collection

Two cameras were utilized: one focused on the test subject's eyes for eye glance recording and the other was focused directly down on the subject's interaction with the phone. These two images together with a direct line to the front-view screen (the side-view screens were not recorded) produced the material which was recorded on DVD and later analyzed, see figure 4.

The simulator was programmed to create log files for each condition. These log files included values such as distance to the center of the lane, distance to the followed car, velocity, user reaction time, crashes and task completion times.

### Data Analysis

Eye glances were recorded manually by analyzing the videos of 27 subjects as the camera was not positioned correctly in one video. The NASA TLX answers and weights were grouped as prescribed by the manual [13]. The data from

**Figure 4. A subject doing an eye glance while typing on a smartphone.**

the driving scenarios was cleaned manually and organized using software developed specifically for this task and then imported for statistical analysis in the R statistical software environment.

Videos were analyzed and crashes were detected as well as near-crash situations. Crashes were considered every time the subject failed to stop the vehicle in time and had a physical contact with the lead vehicle. Near-crash situations was considered any situation where the subject only narrowly avoided a collision with either the lead car or other elements in the environment.

We performed repeated measures ANOVA with condition as the repeated factor and road type as a between-subject factor.

## RESULTS

The results section contains the results from the experiment. They are grouped into driving performance, task performance and eye glances.

### Driving performance

The results for driving performance are shown in Table 1.

*Reaction time*

As shown in Table 1 the reaction time is approximately doubled, an increase of a little more than one second, when writing text messages, and this difference was significant both on the freeway ($F = 21.4, p < 0.001$) and in the city ($F = 17.6, p < 0.001$). There was no significant difference on reaction time between Touch and T9 conditions. The analysis showed no significant difference on reaction time when driving in the city and the freeway.

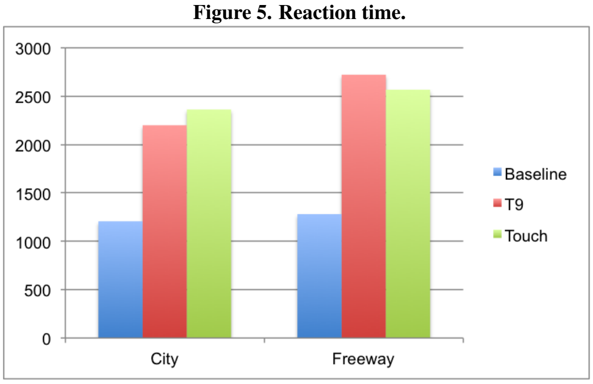
Assuming the subject is driving at 50 km/h, as the speed limit was in the city scenario, one second of increased reaction time would translate to an extra 13 meters of breaking distance.

*Crash or near-crash*

**Table 1. Means and standard deviations of driving performance**

| | Condition | | |
|---|---|---|---|
| Variable | Baseline | T9 | Touch |
| **Freeway** | | | |
| Reaction time (ms) | 1281 (397) | 2723 (1181) | 2568 (908) |
| Crash or near-crash | 0.64 (1.00) | 1.14 (0.86) | 2.43 (2.24) |
| Following distance (m) | 32.50 (8.39) | 43.73 (14.14) | 42.85 (12.18) |
| Following distance variability | 12.55 (4.08) | 23.59 (9.41) | 23.42 (8.60) |
| Lane crossings per kilometer | 0.00 (0.00) | 0.22 (0.56) | 0.81 (1.03) |
| Time in wrong lane per kilometer (s) | 0.00 (0.00) | 4.027 (10.45) | 10.73 (20.21) |
| Lane variability | 0.27 (0.07) | 0.45 (0.17) | 0.57 (0.30) |
| **City** | | | |
| Reaction time (ms) | 1206 (454) | 2200 (1104) | 2363 (720) |
| Crash or near-crash | 0.36 (0.50) | 1.36 (1.39) | 1.71 (1.38) |
| Following distance (m) | 23.52 (6.52) | 29.30 (6.62) | 29.21 (69.44) |
| Following distance variability | 10.66 (3.42) | 14.09 (3.85) | 14.43 (4.14) |
| Lane crossings per kilometer | 8.98 (1.46) | 9.58 (2.92) | 10.08 (2.27) |
| Time in wrong lane per kilometer (s) | 48.60 (20.14) | 82.23 (46.70) | 97.40 (37.05) |
| Lane variability | 1.79 (0.12) | 1.61 (0.36) | 1.71 (0.25) |

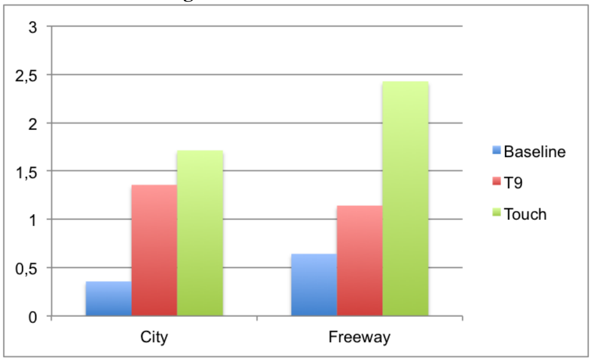
**Figure 5. Reaction time.**




The number of crashes and near-crashes increased significantly between the baseline condition and the writing conditions both in the city ($F = 6.40, p < 0.01$) and on the freeway ($F = 5.13, p < 0.05$). There were significantly more crashes or near-crashes when writing with Touch than with T9 on the freeway ($F = 5.92, p < 0.05$), but not in the city. This might be explained by the increased velocity and heavier traffic on the freeway.

This shows that writing text messages while driving increases the risk of being in a dangerous situation by almost 4 times in the city, and almost 5 times on the freeway. It also shows that overall writing with Touch is more dangerous than writing with T9.

**Figure 6. Crash or near-crash.**




*Following distance*

The average following distance shown in Table 1 reveals that the participants increased their distance to the car in front of them when they were writing text messages. The analysis showed significant difference between the baseline condition and the writing conditions both on the freeway ($F = 11.64, p < 0.001$) and in the city ($F = 11.59, p < 0.001$).

The variability of the following distance significantly increased when the participants were writing text messages compared to the baseline condition both on the freeway ($F = 20.13, p < 0.001$) and in the city ($F = 11.04, p < 0.001$).

There were no significant differences in following distance or following distance variability between Touch and T9 conditions.

These results show a clear change in driving behavior when writing text messages.

*Lane Maintenance*

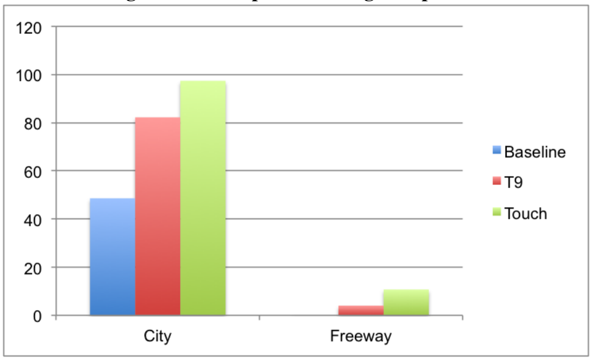
The average lane crossings per kilometer increased in the writing conditions, but the increase was only significant on the freeway ($F = 6.28, p < 0.01$). The Touch condition had more lane crossings per kilometer than the T9 condition, and this difference was significant on the freeway ($F = 5.66, p < 0.05$).

The difference in the time spent in the wrong lane between the baseline condition and the writing conditions is significant in the city ($F = 16.25, p < 0.001$), but not on the freeway. This means that although the number of lane crossings in the city is not significantly higher when writing, the time to correct the car is longer.

The time spent in the wrong lane is also greater in the Touch condition than in the T9 condition, but this difference is not significant.

The variability in lane increased when writing on the freeway, and this increase was significant ($F = 8.66, p < 0.01$).

**Figure 7. Time spent in wrong lane per km.**




No such increase was found in the city, and there was no significant difference in lane variability between Touch and T9 conditions.

This difference between city and freeway are most likely related to the straight and wider road of the freeway, compared to the many curved roads and intersections in the city. This causes more a greater impact in the results on the freeway when a lane crossing does occur.

The lane variability shows a severe change in driving behavior, and swerving into another lane increases the risk of the driver being involved in a crash or near-crash situation. This risk increases the more time the driver spends in the wrong lane.

## Task performance

**Table 2. Means and standard deviations of task performance**

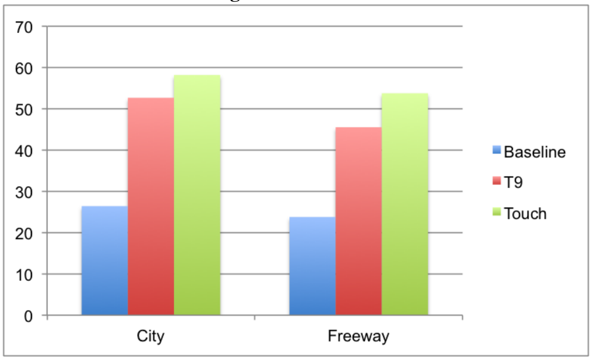
| | Condition | | |
|---|---|---|---|
| Variable | Baseline | T9 | Touch |
| **Freeway** | | | |
| Task load | 23.79 (15.29) | 45.54 (26.42) | 53.77 (26.89) |
| Task completions | N/A | 4.64 (0.74) | 4.00 (1.66) |
| Task completion time (s) | N/A | 30.23 (8.85) | 44.61 (29.34) |
| Characters per minute | N/A | 53.55 (16.85) | 47.14 (22.43) |
| **City** | | | |
| Task load | 26.42 (12.55) | 52.67 (21.04) | 58.19 (20.89) |
| Task completions | N/A | 3.86 (1.56) | 3.79 (1.58) |
| Task completion time (s) | N/A | 38.17 (31.85) | 44.87 (25.93) |
| Characters per minute | N/A | 61.91 (24.92) | 49.84 (26.59) |

The results for task performance are shown in Table 2.

*Task load*

The subjects average perceived task load doubled when they were asked to write text messages. This was significant both on the freeway ($F = 11.36, p < 0.001$) and in the city ($F = 17.73, p < 0.001$). The task load was also slightly higher when writing with Touch than it was when writing with T9, but this difference was found not to be significant. The average perceived task load was slightly higher when driving in the city than it was when driving on the freeway, but this difference was not significant.

**Figure 8. Task load.**

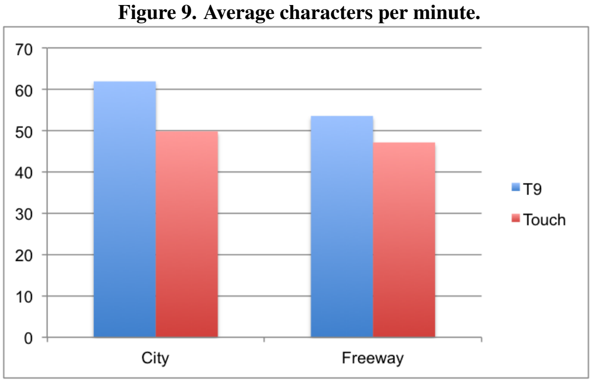



*Task completion*

The number of average successfully completed task per subject was higher for T9 than it was for Touch, but this difference was not found to be significant.

*Writing speed*

**Figure 9. Average characters per minute.**




The average characters per minute was higher with T9 than it was with Touch, but no significant difference was found.

### Eye glances

**Figure 10. Average time spent looking away.**

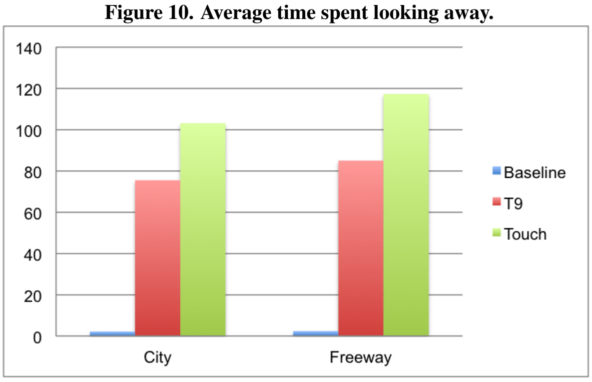



**Table 3. Means and standard deviations of eye glances**

| | Condition | | |
|---|---|---|---|
| Variable | Baseline | T9 | Touch |
| **Freeway** | | | |
| Time spent looking away (s) | 2.40 (2.23) | 85.02 (33.57) | 117.35 (44.59) |
| Category 1 (< 0.5 seconds) | 0.14 (0.36) | 0.50 (0.85) | 1.07 (1.32) |
| Category 2 (0.5-2.0 seconds) | 2.79 (2.69) | 43.57 (11.69) | 39.00 (23.90) |
| Category 3 (> 2.0 seconds) | 0.00 (0.00) | 12.07 (9.30) | 24.07 (9.93) |
| **City** | | | |
| Time spent looking away (s) | 2.18 (1.56) | 75.52 (27.55) | 103.14 (32.75) |
| Category 1 (< 0.5 seconds) | 0.54 (0.66) | 1.39 (2.06) | 2.15 (1.95) |
| Category 2 (0.5-2.0 seconds) | 2.54 (2.54) | 45.31 (13.96) | 42.31 (25.36) |
| Category 3 (> 2.0 seconds) | 0.00 (0.00) | 9.00 (8.85) | 18.69 (8.92) |

The effect of writing on time spent looking away was significant both on the freeway ($F = 48.81, p < 0.001$) and in the city ($F = 59.69, p < 0.001$).There was a significant increase in time spent looking away when writing with Touch compared to T9 both in the city ($F = 5.66, p < 0.05$) and on the freeway ($F = 4.87, p < 0.05$). This was caused by a significant increase in category 3 eye glances both in the city ($F = 9.92, p < 0.01$) and on the freeway ($F = 10.00, p < 0.01$). There was no significant difference in category 1 and category 2 eye glances between Touch and T9. Results showed no significant difference time spent looking away when driving in the city and the freeway.

This shows that writing messages causes the driver to look away more often and with longer intervals, and that this tendency is increased on touch-based smartphones.

### Expert comparison

We also examined the expert groups by performing between-subject ANOVA tests between T9 users in the T9 condition and Touch users in the Touch condition. The analysis showed no major differences compared to the overall results. This could suggest increased experience with a cell phone does not change the impact on road safety when writing while driving.

## DISCUSSION

Overall, the results confirmed that texting during simulated driving had significant impact on road safety. Subjects showed to clearly increase their following distance when texting, suggesting that subjects subconsciously attempt to reduce the likelihood of being involved in a crash [8], or that the overall task load refrained them from keeping a closer distance than they otherwise had in the baseline condition. This increase in task load was also confirmed by subjects in the TLX survey.

The subject's reaction time doubled when typing while driving, and they were almost 4 times as likely to be involved in a crash or near-crash situation. As subjects increased the following distance in general, this could have had an unintentional effect on reaction time, as some subjects increased their following distance so much, that the lead vehicle sometimes disappeared in the horizon, and the subject would therefore not brake until the breaking lead vehicle reappeared.

Virginia Research [5] found that texting while driving increased the odds of crashes or near crashes increased by 23 times. We only found an increase of four but this is possibly attributed to the difference in the type of study as their data was based on real-world incidents. Furthermore, our simulator did not have elements such as pedestrians or cyclists, which, if present, could have increased the likelihood of crash and near-crash situations.

Regarding whether touch-based smartphones poses greater threat to road safety, data varied between smartphones being just as distracting as common tactile cell phones in some cases and more distracting on others. Data was in some cases dependent on the scenario.

Subjects lane variability, crash/near-crash ratio and time spent in the wrong lane as well as time spent looking away was increased when using a smartphone. This could suggest that the lack of tactile feedback on the phones caused the subject to look away for longer periods of time, which is why only category 3 eye glances (above 2 seconds) was significantly greater when using a smartphone.

That being said, we documented no significant difference in reaction times between tactile and smartphone users, or in following distance variability and lane maintenance variability. It is possible that these things are influenced more by general factors such as holding a phone and glancing at the display and less by the task of interacting with the device.

A limitation of the results of this study is that they have been conducted in a simulator, and would therefore require some form of epidemiological data to support them. Furthermore, there are several findings in this study which lacks sufficient research on effects on driver distraction specifically on cell phone usage while driving.

## CONCLUSION

In this paper we showed that writing text messages using both types of cell phones significantly decreased road safety. This was caused by a significant change in driving behavior related to reaction time and lane keeping. We showed that writing while driving increased the risk of being involved in a crash or near-crash situation by a factor of almost 4. When subjected to increased velocity and heavier traffic in the freeway scenario, writing text messages using a touch-based smartphone increased the risk from a factor of almost 4 to a factor of almost 5. When writing, the subjects spent significantly more time looking away, which was increased even more when using a touch-based smartphone.

For a future study, it could be interesting to identify which factors of cell phone interaction while driving affects the factors of distraction. It could also be interesting to further identify where the exact factors of touch-based smartphones differ from those of common tactile cell phones.

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# Keep Your Head Up: The impact of HUD-based text entry methods on road safety

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### ABSTRACT

Using cell phones to write text messages while driving has proven to significantly increase the risk of accidents. Despite legislation against this tendency in many places of the world, studies have shown that this has had little effect in practice. As an alternative approach, this study provides four new text interaction forms supported by a Head-Up Display (HUD), as an attempt to decrease the impact on road safety. The study tests two tactile and two touch-based interaction forms and investigates how these perform compared to the common cell phones. Results showed that using a HUD decreased the amount of eye glances, and road safety improved significantly compared to common cell phones in low driving complexity scenarios. Results furthermore showed that a tactile external numeric keypad which used the multitap technology had the least impact on road safety.

### INTRODUCTION

Up to one quarter of car crashes are estimated to be a result of driver's engaging in distracting activities [15][19]. Use of cell phones while driving has a range of negative effects on performance, including visual processing of the road environment, motor control and response, auditive and higher-order processing [21][23][27]. As an example, visual processing is affected by checking to see who's calling, motor control is affected when dialing a number, auditive distraction when attention is given to the conversation and not the sound of the traffic and higher-order (cognitive) processing when focusing on the conversation and not the act of driving [17].

The introduction of text messaging has created another potential cause for distraction. The number of drivers using text messages has increased tremendously since it was introduced. Recent surveys has shown that as much as 51% of young drivers admit to have used text messaging during driving [10]. This is the age group of the population most prone to using text messages in general, and also the group with the least experience in driving.



**Author keywords:** Text entry methods, in-vehicle interaction, directional selection, 2x3-tree, tactile- and touch-based entry, driving simulator, safety

**General terms:** Lab experiment, Human Factors, Road Safety

**Categories and Subject Descriptors:** H.5.2 [INFORMATION INTERFACES AND PRESENTATION] User Interfaces - Benchmarking, Evaluation/methodology, Prototyping]

In the late 90's the "text on nine keys" (T9) predictive text entry system was developed and shortly thereafter adapted as the primary form of text entry on products from all the major phone manufacturing companies [9]. The T9 entry system allowed for text writing at about twice the speed as the previous multitap technology, using the same amount of tactile buttons. This increase in text entry time was not reflected on the dangers to road safety, as studies found that text messaging while driving increases the risk of being in a crash or near-crash event by 23 times, compared to talking on the phone while driving, which doubles the risk [4][11].

With the increase in smartphone usage, the use of 9-button tactile interfaces has been increasingly replaced by virtual full-size keyboards on touch screens, which renders tactile feedback impossible and leaves only visual feedback to the driver. The authors of this text conducted an experiment which is described elsewhere, which investigated the distraction of text messaging on a smartphone while driving, compared to a T9, and concluded that in some cases writing with a smartphone had a negative impact on road safety compared to writing with a T9, and in other cases it had at least an equal impact.

In order to generally decrease driver distraction, much focus has been given to the idea of implementing Head-Up Displays (HUD), known from the aviation industry, for automotive appliances as well. Reports and studies on the effects on implementing HUDs in cars not related to phone-use have been conducted. One study used a HUD for visual longitude and latitude assistance [26]. Results showed that the use of the HUD had a positive effect on driving performance and did not increase the mental load. Another study placed the speedometer on a HUD. Their results showed that people monitored the velocity more frequently and rapidly but that this did not affect speeding behavior. They conclude that the most significant benefit for having the speedometer on a HUD is that they allow for quicker and more accurate reactions to roadway [13].

The focus of this article is to combine a Head-Up Display with new ways of writing text messages while driving in a simulated environment, in order to determine if such improvements can lessen the negative effect on road safety. The article will give an overview of the current research on the subject, followed by an introduction to four HUD-based text entry methods. The conducted experiment will then be described, followed by a presentation of the results which will finally be reviewed in a discussion.

## RELATED WORK

General use of in-vehicle systems and their effects on driver performance is a common question in the research literature. One recent study provided a breakdown of odds ratios of crashing or being in a near-crash situation. Results showed among other things, that interaction with any in-vehicle device increased the risk by 6 times and simply reaching for an object increased the risk by 3 times [4]. Another study further investigated the differences in attention and distraction regarding what kind of scenario the subject was driving in, which showed that subjects adjusted their movement behavior to the driving situation regardless of what their secondary task was [24].

Due to the imminent dangers of driver inattention, studies has been conducted in order to enable secondary task interaction without disrupting the driver's visual attention to the road. One study investigated three different ways to interact with a car radio, using a gesture-based, touch and tactile method. Results showed that gesture interaction had a significant effect on the number of eye glances, and that touch interaction lead to faster and more efficient task completion. Tactile was considered inferior [3]. Another study used buttons on a steering wheel to be used as controls for navigating a list of on-screen street names, with seven different methods for selection. Results showed various variances in driving performance and task completion among the different methods, but one gestural selection method had a less negative effect on driving performance and a positive effect on task completion [12].

The previous study on crash odds also showed, that texting while driving increased the risk of crashing or near-crashing by 23 times. Studies have shown that driver texting especially among young drivers are increasing despite substantial legislation in most parts of the world [11]. Because of this, much effort have been done to attempt to enable phone texting while driving without affecting road safety. All studies on this matter have attempted to use voice communication in various ways to substitute the need for texting. Studies have used methods for voice input for text composition [8], voice-commands for selecting pre-defined messages [18] and recording of voice responses to be used as replies [11]. Most of the studies found the methods to be effective, but all discussed that the text-recognition face challenges in a loud environment that exist when driving in a genuine car. For most of the mentioned studies, the research setting have been mid- to high-fidelity car simulators, and not a real driving environment.

The HUD technology was originally used in military aviation, but has since the beginning of the century been used in the automobile industry. Cars using HUD-technology have been commercially available in the last ten years from manufacturers such as General Motors and BMW [1].

Research on the effects of HUDs in the automobile industry have been conducted, both for the private consumer and in trucks for the transportation business. A study conducted in Taiwan, compared the driving performance of commercial truck drivers when using a head-up display in the windshield and a head-down display on the instrument bar. Results indicated that for some tasks, performance showed no significant differences, but when reacting to an unexpected urgent event, reaction time was much faster in the HUD-scenario [22].

Use of HUD has also been tested as means of improving driver performance. A study from 2004 investigated if use of a in-vehicle signs to advice drivers on optimal speed and brake distances when approaching intersections and traffic lights. Results showed that the HUD influenced the subjects to drive more carefully when approaching intersections [5].

HUDs to improve driver performance when driving in low-visibility scenarios have also been researched. One study used a warning and notification system when approaching sharp turns or traffic jams in dangerous weather. Results showed an increase in driving performance with respect to data such as lateral positioning, distance to lead vehicles and avoided collisions [6].

Similar HUD systems have been implemented which displayed a minimal brake distance indicator and projected turning curve in the windshield. Results showed that the visual aid improved driving performance and did not increase mental workload [26]. The most recent studies in HUD-technology investigate the possibility of augmented reality, where HUD-elements merges with the outside world to e.g. emphasize street signs [25],[7]. Results from this research has received overall positive feedback from test subjects.

With the evolution of automobile HUD systems, research has also been conducted on the visual representation of the HUD elements. One study investigated, if variating the position of an on-screen speedometer would have an impact on driver performance. Results showed that opposed to being in the immediate visual vicinity, peripheral regions in the retinal projection received less amount of mental processing, which would cause the driver to respond slower [2].

## TEXT ENTRY METHODS

For this study we tested four different HUD-based text entry methods against two benchmarks.

### 2x3-tree selection: "2x3-tree"

**Figure 1. 2x3-tree selection HUD.**

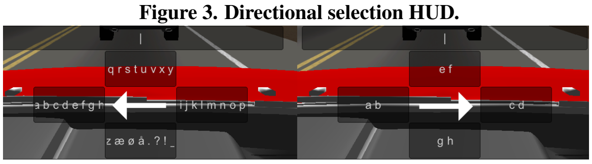

The steering wheel used in this experiment, was equipped with 6 buttons arranged 2 by 3. Three buttons were positioned vertically in reach of the left hand thumb, and likewise on the right-hand side, see figure 2 and figure 7.

Figure 2. 2x3-tree selection interaction

The HUD displayed 6 boxes of letters arranged in the same fashion, each button corresponding with each box containing six letters. When pressing the button corresponding to the box `abcdef`, the HUD will display the one letter in each of the boxes, as descending a level in a tree-structure, see figure 2.

### Directional selection: "Directional"

Figure 3. Directional selection HUD.




Directional selection followed the same selection paradigm as 2x3-tree selection. Instead of buttons, an Apple iPhone 4 was attached to the right-hand side of the steering wheel using velcro tape, and navigation through the levels was conducted using directional swiping of the finger, see figure 4 and 3. The swipe directions corresponded to boxes of letters in the HUD positioned at the top, bottom, left and right side. The text was sent to the car simulator over WiFi.

Figure 4. Directional selection.

### Tactile Multitap: "Numpad"

Using a physical numeric keyboard, text entry was conducted using the same method as a multitap cell phone, displaying

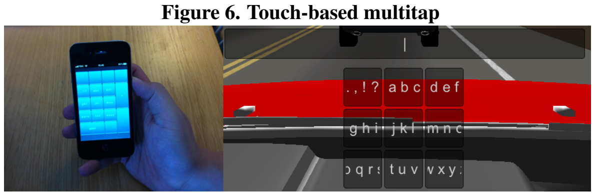
Figure 5. Tactile multitap.


the inserted text on the HUD of the car, see figure 5. The numeric keyboard was placed on the right side of the steering wheel.

### Touch-based Multitap: "NumpadTouch"

Using an Apple iPhone 4, a virtual 3 by 4 keyboard, imitating the common cell phone layout, was generated on a touch-screen instead of the normal full-size QWERTY. Entering text was then displayed on the HUD of the car over WiFi. The touch-based multitap device was held by the user, see figure 6.

Figure 6. Touch-based multitap




### Benchmarks: T9 and Fulltext

On most cell phones today, the physical layout of buttons consist of 12 buttons arranged 3 by 4. Each button is typically assigned three letters, and typing any letter requires to tap the buttons the amount of times a letter is represented on a button, hence the description multitap. As an improvement, the use of dictionaries was added, which allowed for a button only to be pressed once, and then having the phone software make a qualified guess as to the word intended to be written. This solution doubled the typing speed [16] and was called T9, or "text on 9 keys".

With the emergence of smartphones, screen sizes are typically expanded as much as possible in order to fulfill the needs for more complex graphical applications such as photos, mail and calendars. This has caused most phone manufacturers to remove the physical keyboard and replace it with a virtual full-text QWERTY keyboard which reacted to touch.

## METHOD

This section describes the method of the experiment, where the driver performance was tested.

### Setting

For the study a simulator was constructed, which is described in detail elsewhere. The simulator was constructed at the HCI-laboratories at Cassiopeia, The University of Aalborg.

### Participants

The group of test subjects consisted of 28 people, where 18 were male and 10 were female. Among the participants 10

Figure 7. The physical setup of the simulator, displaying a subject interacting with Numpad.


normally used a T9 cell phone and 18 normally used a touch-based smartphone. About half of the subjects were located at the Computer Science institute, where the rest were located on other branches of the University of Aalborg as well as a few on other lines of education. The participants all held valid driver's licenses and were in the age of 20-32 years old.

## Procedure

The subjects were given a chance to test-drive the car in a city environment to get acquainted with the controls and behavior of the car. The subject then went through 7 tasks in different orders given by a latin square to balance the effect of learning. While texting, the test subject had to follow a car driving in front of them which was programmed to brake at randomly selected intervals.

Two typical driving scenarios were used. Half of the subjects drove on a freeway with three lanes and traffic going at various speeds. The other half drove in a city scenario with traffic, intersections and traffic lights. The participants were balanced over the two scenarios with gender and cell phone experience in mind.

The car in front of the subject would continue to break until the test subject pressed the brake pedal or collided with the decelerating vehicle in front of them. This solution would produce a way to measure test subject reaction time in simulated driving [9]. The baseline condition constituted a 5-minute drive without interacting with texting equipment, where the other 6 conditions were various variants of such. The test subjects were instructed to enter a maximum of five different text messages or as many as they were able to type in the course of 5 minutes.

All text messages were randomly selected sentences of the same length and complexity [20] which was then distributed amongst the subjects also using latin squares. Each subject filled out NASA Task Load Index (TLX)-scales after each completed condition which is a NASA developed method for measuring task load [14].

## Data Collection

Two cameras were utilized: one focused on the test subject's eyes for eye glance recording and the other was focused directly down on the subject's interaction with the various text entry methods. These two images together with a direct line to the front-view screen (the side-view screens were not recorded) produced the material which was recorded on DVD and later analyzed, see figure 8.

Figure 8. A subject interacting with directional selection on the freeway.

The simulator was programmed to create log files for each condition. These log files included values such as distance to the center of the lane, distance to the followed car, velocity, user reaction time, crashes and task completion times.

After each test, the subjects were questioned about their impression of the text entry methods.

## Data Analysis

Eye glances was recorded manually by analyzing the videos. The video footage of the interviews were transcribed and the responses were evaluated. The NASA TLX answers and weights were grouped as prescribed by the manual [14]. The data from the driving scenarios was cleaned manually and organized using software developed specifically for this task and then imported for statistical analysis in the R statistical software environment.

Videos were analyzed and collisions was detected as well as near-crash situations. Collisions was considered every time the subject failed to stop the vehicle in time and had a physical contact with the lead vehicle. Near-collision situations was deemed any situation where the subject was unintentionally seconds from colliding with either the lead car or other elements in the environment.

We performed repeated measures ANOVA with condition as the repeated factor and road type as a between-subject factor.

**Table 1. Means and standard deviations of driving performance**

| | Condition | | | | | | |
|---|---|---|---|---|---|---|---|
| Variable | Baseline | T9 | Touch | Directional | 2x3-tree | Numpad | NumpadTouch |
| **Freeway** | | | | | | | |
| Reaction time (ms) | 1281 (397) | 2723 (1181) | 2568 (908) | 2449 (901) | 2867 (1259) | 2609 (810) | 2712 (820) |
| Crash or near-crash | 0.64 (1.01) | 1.14 (0.86) | 2.43 (2.24) | 1.50 (1.29) | 1.93 (2.09) | 0.57 (1.09) | 1.00 (0.68) |
| Following distance (m) | 32.50 (8.39) | 43.73 (14.14) | 42.85 (12.18) | 39.46 (9.44) | 39.74 (10.51) | 43.25 (12.02) | 43.80 (9.47) |
| Following distance variability | 12.55 (4.08) | 23.59 (9.41) | 23.42 (8.60) | 17.69 (4.57) | 19.59 (6.25) | 20.64 (5.74) | 21.43 (5.71) |
| Lane crossings per kilometer | 0.00 (0.00) | 0.22 (0.56) | 0.81 (1.03) | 0.32 (0.47) | 0.61 (0.92) | 0.31 (0.61) | 0.06 (0.23) |
| Time in wrong lane per kilometer (s) | 0.00 (0.00) | 4.027 (10.45) | 10.73 (20.21) | 4.31 (8.07) | 5.88 (10.78) | 4.63 (11.43) | 0.34 (1.22) |
| Lane variability | 0.27 (0.07) | 0.45 (0.17) | 0.57 (0.30) | 0.41 (0.18) | 0.46 (0.17) | 0.49 (0.45) | 0.43 (0.11) |
| **City** | | | | | | | |
| Reaction time (ms) | 1206 (454) | 2200 (1104) | 2363 (720) | 2250 (769) | 2200 (1064) | 2178 (841) | 2205 (800) |
| Crash or near-crash | 0.36 (0.50) | 1.36 (1.39) | 1.71 (1.38) | 1.29 (0.91) | 2.36 (2.24) | 1.14 (1.70) | 2.14 (2.07) |
| Following distance (m) | 23.52 (6.52) | 29.30 (6.62) | 29.21 (69.44) | 27.199 (4.76) | 27.36 (5.87) | 28.95 (7.52) | 28.83 (8.28) |
| Following distance variability | 10.66 (3.42) | 14.09 (3.85) | 14.43 (4.14) | 13.44 (4.30) | 13.18 (4.19) | 11.93 (3.12) | 13.33 (4.22) |
| Lane crossings per kilometer | 8.98 (1.46) | 9.58 (2.92) | 10.08 (2.27) | 9.97 (2.42) | 8.97 (0.93) | 8.46 (1.30) | 10.08 (1.63) |
| Time in wrong lane per kilometer (s) | 48.60 (20.14) | 82.23 (46.70) | 97.40 (37.05) | 80.55 (31.02) | 78.09 (28.26) | 70.08 (41.78) | 74.51 (26.17) |
| Lane variability | 1.79 (0.12) | 1.61 (0.36) | 1.71 (0.25) | 1.99 (0.39) | 2.01 (0.37) | 1.70 (0.43) | 1.85 (0.32) |

**Table 2. Means and standard deviations of task performance**

| | Condition | | | | | | |
|---|---|---|---|---|---|---|---|
| Variable | Baseline | T9 | Touch | Directional | 2x3-tree | Numpad | NumpadTouch |
| **Freeway** | | | | | | | |
| Task load | 23.79 (15.29) | 45.54 (26.42) | 53.77 (26.89) | 61.90 (20.45) | 61.77 (23.99) | 38.15 (18.33) | 60.33 (21.84) |
| Task completions | N/A | 4.64 (0.74) | 4.00 (1.66) | 1.21 (0.58) | 2.21 (0.89) | 4.14 (0.95) | 2.71 (1.33) |
| Task completion time (s) | N/A | 30.23 (8.85) | 44.61 (29.34) | 158.39 (42.54) | 112.47 (29.71) | 48.98 (16.43) | 86.48 (22.74) |
| Characters per minute | N/A | 53.55 (16.85) | 47.14 (22.43) | 10.00 (1.69) | 15.06 (3.16) | 38.02 (10.81) | 21.15 (4.91) |
| **City** | | | | | | | |
| Task load | 26.42 (12.55) | 52.67 (21.04) | 58.19 (20.89) | 63.98 (20.21) | 69.90 (11.95) | 41.17 (18.66) | 66.50 (15.06) |
| Task completions | N/A | 3.86 (1.56) | 3.79 (1.58) | 1.071 (0.83) | 1.29 (0.83) | 4.29 (0.73) | 2.79 (1.05) |
| Task completion time (s) | N/A | 38.17 (31.85) | 44.87 (25.93) | 173.90 (41.57) | 156.07 (53.73) | 40.85 (9.90) | 94.76 (26.39) |
| Characters per minute | N/A | 61.91 (24.92) | 49.84 (26.59) | 8.63 (1.59) | 11.22 (3.48) | 38.43 (9.03) | 18.13 (2.94) |

**Table 3. Means and standard deviations of eye glances**

| | Condition | | | | | | |
|---|---|---|---|---|---|---|---|
| Variable | Baseline | T9 | Touch | Directional | 2x3-tree | Numpad | NumpadTouch |
| **Freeway** | | | | | | | |
| Time spent looking away (s) | 2.40 (2.23) | 85.02 (33.57) | 117.35 (44.59) | 11.50 (12.87) | 14.53 (13.39) | 36.47 (31.09) | 114.34 (29.80) |
| Category 1 ($<$ 0.5 seconds) | 0.14 (0.36) | 0.50 (0.85) | 1.07 (1.32) | 5.43 (8.06) | 7.21 (8.51) | 10.43 (18.27) | 8.07 (8.24) |
| Category 2 (0.5-2.0 seconds) | 2.79 (2.69) | 43.57 (11.69) | 39.00 (23.90) | 14.50 (17.43) | 17.50 (17.81) | 43.43 (38.11) | 128.21 (30.39) |
| Category 3 ($>$ 2.0 seconds) | 0.00 (0.00) | 12.07 (9.30) | 24.07 (9.93) | 0.00 (0.00) | 0.00 (0.000) | 0.07 (0.27) | 1.43 (1.56) |
| **City** | | | | | | | |
| Time spent looking away (s) | 2.18 (1.56) | 75.52 (27.55) | 103.14 (32.75) | 10.02 (15.60) | 18.50 (10.07) | 23.10 (17.16) | 79.47 (16.10) |
| Category 1 ($<$ 0.5 seconds) | 0.54 (0.66) | 1.39 (2.06) | 2.15 (1.95) | 6.92 (6.72) | 15.23 (11.37) | 9.54 (9.14) | 13.85 (10.07) |
| Category 2 (0.5-2.0 seconds) | 2.54 (2.54) | 45.31 (13.96) | 42.31 (25.36) | 11.85 (22.98) | 20.23 (11.40) | 29.69 (23.17) | 97.85 (20.65) |
| Category 3 ($>$ 2.0 seconds) | 0.00 (0.00) | 9.00 (8.85) | 18.69 (8.92) | 0.00 (0.00) | 0.00 (0.00) | 0.00 (0.00) | 0.46 (0.66) |

## RESULTS

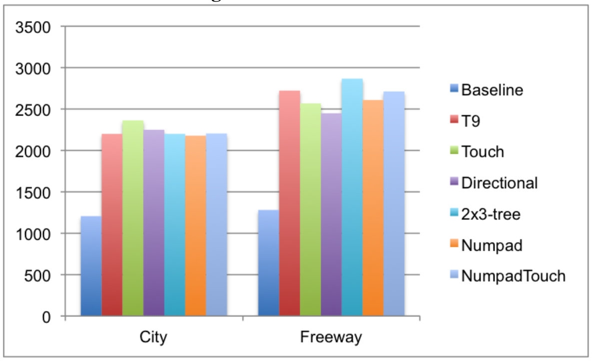
The results section contains the results from the experiment. They are grouped into driving performance, task performance and eye glances, and results from the interview.

### Driving performance

The results for driving performance are shown in Table 1.

*Reaction time*

**Figure 9. Reaction time.**

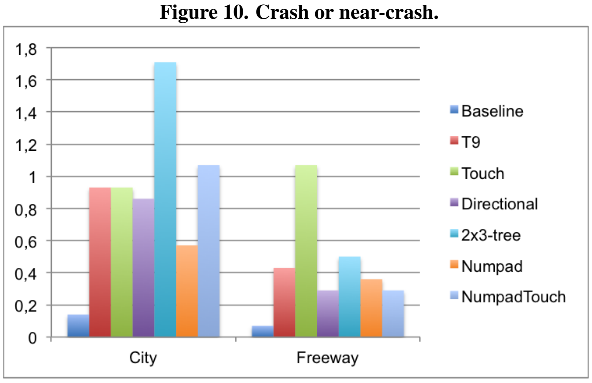



The effect of writing was significant both on the freeway ($F = 15.12, p < 0.001$) and in the city ($F = 6.79, p < 0.001$). As shown in Table 1 the reaction time is approximately doubled, an increase of a little more than one second, when writing text messages. There was no significant differences on reaction time between different input methods. The analysis showed no significant difference on reaction time when driving in the city and the freeway.

Assuming the subject is driving at 50 km/h, as the speed limit was in the city scenario, one second of increased reaction time would translate to an extra 13 meters of breaking distance.

*Crash or near-crash*

**Figure 10. Crash or near-crash.**



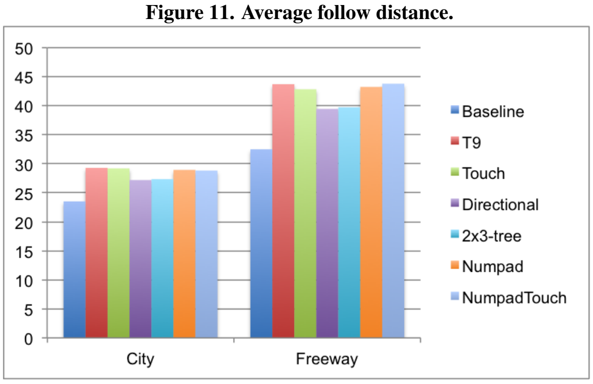

In the city the average amount of crashes or near-crashes increased when writing, and analysis showed that the increase was significant for the commonly used cell phones, Directional, 2x3-tree and NumpadTouch, but not for Numpad ($F = 6.40, p < 0.01$, $F = 9.58, p < 0.01$, $F = 10.51, p < 0.01$, $F = 10.30, p < 0.01$). On the freeway analysis showed no significant increase in crashes or near-crashes with any of the four HUD-based input methods but it was significant for the two benchmark conditions ($F = 5.13, p < 0.05$).

The analysis showed no significant difference in number of crash or near-crash when driving in the city and the freeway.

This showed that when writing with Numpad there was less crash or near-crash situations than with the commonly used cell phones and the three other methods. The four HUD-based methods all had no significant increase in crashes or near-crashes compared to baseline on the freeway, while the commonly used cell phones did. Writing while driving is more challenging in the city than on the freeway because the driving task in the city also includes turning, and following the curve of the road oppose to the freeway which is driving in a straight line. The HUD might help more on the freeway because the driving task requires less attention. Assuming the driver spends the same amount of attention on the writing in both scenarios, the increase in focus on the road gained from using a HUD is not enough to compensate for the more challenging environment of the city.

*Following distance*

**Figure 11. Average follow distance.**




The average following distance was significantly greater when texting while driving for all input methods, both on freeway ($F = 5.36, p < 0.001$) and in the city ($F = 4.49, p < 0.001$). Following distance variability was also found to be greater while driving for all input methods both on the freeway ($F = 9.67, p < 0.001$) and in the city ($F = 3.25, p < 0.01$), but not significantly greater for Numpad in the city.

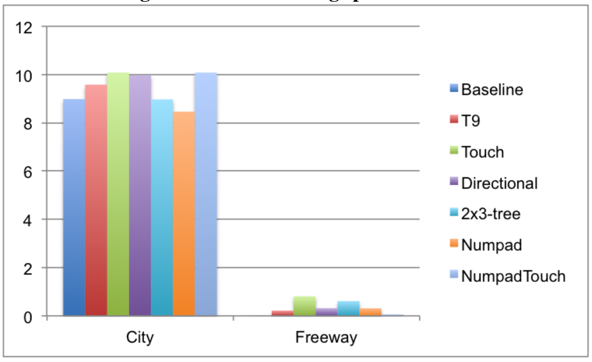
Assuming the city scenario has a greater impact on driver attention, this showed that the Numpad had a lesser impact on road safety than the other text entry methods in the city.

*Lane Maintenance*

The time spent in the wrong lane increased significantly in the city when writing with the commonly used cell phones, 2x3-tree, Directional and NumpadTouch, but not with Numpad ($F = 13.71, p < 0.01$, $F = 14.70, p < 0.001$, $F = 10.80, p < 0.01$).

The number of lane crossings increase significantly when writing with 2x3-tree ($F = 5.82, p < 0.05$) and Directional ($F = 5.94, p < 0.05$) on the freeway, while the time spent

**Figure 12. Lane crossings per kilometer.**



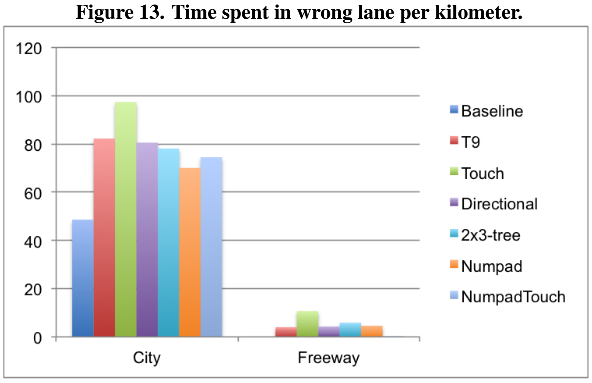

in wrong lane on the freeway did not increase significantly for any writing methods.

The lane variability increased when writing while driving for all input methods on the freeway ($F = 2.54, p < 0.05$), but only for 2x3-tree in the city ($F = 4.79, p < 0.05$).

This difference between city and freeway are most likely related to the straight and wider road of the freeway, compared to the many curved roads and intersections in the city. This causes more a greater impact in the results on the freeway when a lane crossing does occur.

The subjects retained their lane keeping abilities when writing on the Numpad. Since the number of lane crossings was increased only for the two new methods attached to the steering wheel, this could mean that interaction disrupted the lane keeping ability of the driver.

**Figure 13. Time spent in wrong lane per kilometer.**




## Task performance

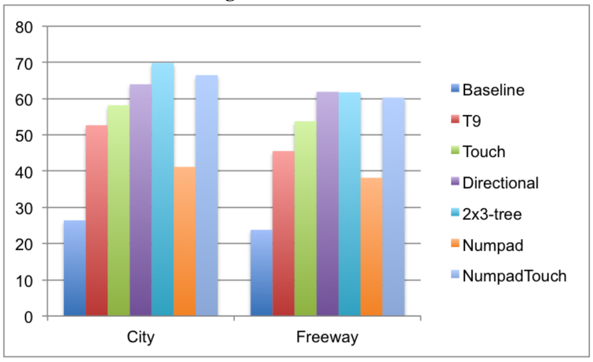
The results for task performance are shown in Table 2.

### *Task load*

The perceived task load was significantly higher when writing, both on the freeway ($F = 11.92, p < 0.001$) and in the city ($F = 11.96, p < 0.001$).

There was a significantly higher task load when comparing T9 with 2x3-tree in the city ($F = 8.25, p < 0.05$), and 2x3-tree ($F = 6.09, p < 0.05$), Directional ($F = 7.80, p < 0.05$) and NumpadTouch ($F = 7.69, p < 0.05$) on the freeway.

**Figure 14. Task load.**



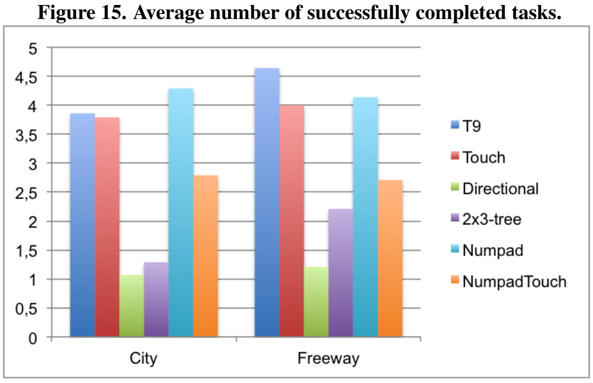

There was no significant difference in task load between Touch and 2x3-tree, Directional, Numpad and NumpadTouch.

### *Task completion*

The average number of successfully completed tasks was significantly lower on 2x3-tree, Directional and NumpadTouch than on T9 in the city ($F = 51.36, p < 0.001$, $F = 45.53, p < 0.001$, $F = 5.37, p < 0.05$), and significantly lower on 2x3-tree, Directional, Numpad and NumpadTouch than on T9 on the freeway ($F = 144.5, p < 0.001$, $F = 288, p < 0.001$, $F = 6.07, p < 0.05$, $F = 32.35, p < 0.001$).

The task completion time was significantly higher on 2x3-tree, Directional and NumpadTouch than on T9 in the city ($F = 51.06, p < 0.001$, $F = 82.87, p < 0.001$, $F = 22.48, p < 0.001$), and significantly higher on all the four new methods than on T9 on the freeway ($F = 51.46, p < 0.001$).

**Figure 15. Average number of successfully completed tasks.**



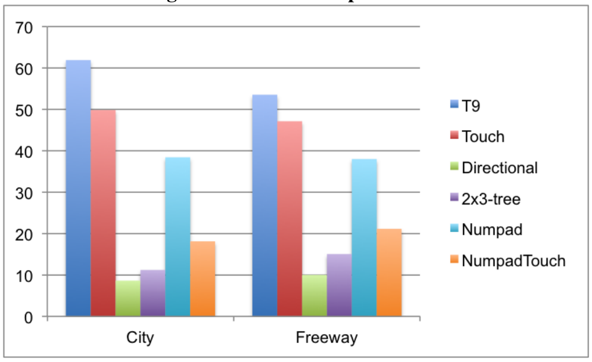

Comparing with Touch the average number of successfully completed tasks was significantly lower on 2x3-tree and Directional in the city ($F = 22.09, p < 0.001$, $F = 28.62, p < 0.001$), and significantly lower on 2x3-tree, Directional and NumpadTouch on the freeway ($F = 25.96, p < 0.001$, $F = 46.53, p < 0.001$, $F = 5.92, p < 0.05$). The task completion time was significantly higher on 2x3-tree, Directional and NumpadTouch than on Touch both in the city

$(F = 64.47, p < 0.001,\ F = 73.81, p < 0.001,\ F = 14.31, p < 0.01)$ and on the freeway $(F = 43.45, p < 0.001,\ F = 72.32, p < 0.001,\ F = 17.51, p < 0.01)$.

The average number of successfully completed tasks was significantly higher and the task completion time was significantly lower on 2x3-tree than on Directional on the freeway $(F = 30.33, p < 0.001,\ F = 15.46, p < 0.01)$ but not in the city. The difference in the average successfully completed tasks and task completion time was significant between Numpad and NumpadTouch both in the city $(F = 23.3, p < 0.001,\ F = 46.76, p < 0.001)$ and on the freeway $(F = 17, 33, p < 0.01,\ F = 33.75, p < 0.001)$, with Numpad performing better than NumpadTouch.

*Writing speed*

**Figure 16. Characters per minute.**




The average characters per minute were significantly lower on the HUD-based methods than on T9 both in the city $(F = 36.21, p < 0.001)$ and on the freeway $(F = 48.91, p < 0.001)$. This is also the case when comparing Touch with 2x3-tree, Directional and NumpadTouch both in the city $(F = 29.72, p < 0.001, F = 18.17, p < 0.01, F = 16.70, p < 0.01)$ and on the freeway $(F = 30.44, p < 0.001, F = 43.09, p < 0.001, F = 29.79, p < 0.001)$, but not with Numpad.

This showed that the cell phones in all conditions was able to complete text messages faster than the four HUD-based methods. The only exception was the Numpad, which was not significantly slower than Touch.

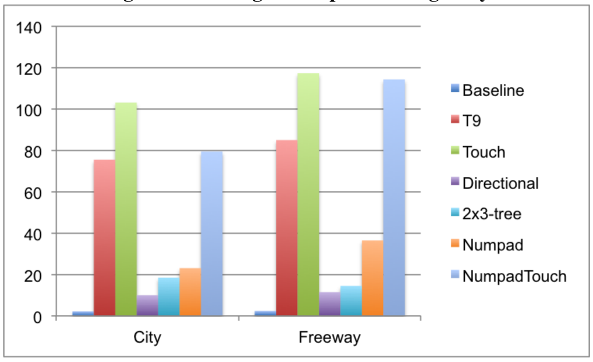
### Eye glances

The results for the eye glances are shown in Table 3.

The average time spent looking away from the road was significantly higher when writing both in the city $(F = 62.14, p < 0.001)$ and on the freeway $(F = 50.47, p < 0.001)$.

There was a significant decrease in time spent looking away when writing with Directional, 2x3-tree and Numpad compared to writing with T9 in the city $(F = 112.30, p < 0.001,\ F = 55.60, p < 0.001,\ F = 31.87, p < 0.001)$ and on the freeway $(F = 90.11, p < 0.001,\ F = 57.57, p < 0.001,\ F = 17.90, p < 0.001)$ and a significant increase when writing with NumpadTouch $(F = 10.11, p < 0.01)$ on the freeway, but no significant difference was found in the city.

**Figure 17. Average time spent looking away.**




Similarly there was a significant decrease in time spent looking away when writing with Directional, 2x3-tree and Numpad compared to writing with Touch both in the city $(F = 73.23, p < 0.001,\ F = 89.99, p < 0.001,\ F = 92.57, p < 0.001)$ and on the freeway $(F = 71.37, p < 0.001,\ F = 57.01, p < 0.001,\ F = 21.10, p < 0.001)$. Analysis showed no significant difference in time spent looking away between NumpadTouch and Touch.

This showed that writing with Directional and 2x3-tree allowed the subjects to keep their eyes on the road more. These two and Numpad performed significantly better in this regard than the common cell phones.

### Interview

Asked about which entry method they were most comfortable with, the two primary groups of preference were the tactile cell phone and Numpad. 12 of the subjects preferred the tactile cell phone over any other method. If these subjects had to choose one of the four new methods, 10 of the subjects preferred Numpad, one preferred the directional selection and one chose the 2x3 tree.

Looking at the four new entry methods, 21 subjects (75%) preferred Numpad. Out of the remaining 7, 4 (14%) preferred the 2x3 tree, 2 (7%) the directional selection and finally 1 (4%) preferred NumpadTouch.

S14 (2x3-tree selection): *If T9 was added, and you had a little time to learn, this would definitely be useful.*

S2 (Directional selection): *This was better than many of the others, but you also had to get used to it. It was confusing when doing a turn and the wheel was upside down.*

S6 (Numpad): *It is a combination of something you know from old phones and the fact that you don't have to look away that makes me feel safe when using it.* This statement was shared among multiple subjects.

S12 (NumpadTouch): *This was not my favorite, but it was OK. It was annoying that there was a delay.*

## DISCUSSION

Overall, the results showed that all text entry methods were more distracting than the baseline condition of simply driving, with a doubling of the overall reaction time for all other input methods. This suggests that it is not possible to achieve the same driving performance with our HUD-based interactions forms. Studies have shown that test subjects in simulators are aware of the increased risk of collisions when texting, and therefore increase their following distance to avoid this [9]. Despite the increased following distance, the collision and near-collision incidents still increased in almost all of the conditions, suggesting that the subject's subconscious was inadequate.

The only text entry method to not cause more collisions or near-crash incidents was the Numpad, which did not cause significantly more incidents than that of the baseline condition where no texting was done. This is consistent throughout most of the variables for driving performance, where the Numpad clearly stands out from all the other input methods. Likewise, the time spent in the wrong lane in the city was also not greater for the Numpad, though it was so for all other conditions. The freeway scenario did not reflect this. All input methods including the Numpad had greater times in the wrong lane. This could be explained by the road of the freeway being straight where less lane variability is present than in the city, which holds many turns and curves.

Regarding the efficiency of the HUD-based interaction forms compared to the common ones, we looked at task completion and writing speed. Results both investigated the amount of characters they were able to write per minute, and the amount of tasks they were able to finish in the 5 minutes time each condition took.

The study showed that the subjects were slower when writing text messages on Directional, NumpadTouch and the 2x3-tree, than they were on the common cell phones. The Numpad was the only method which showed results like the touch-based or T9 methods completion times. During the interviews, many subjects agreed that if they had been able to practice, they might have written faster.

It was interesting to note, that despite none of the subjects had ever used an external numeric keyboard for texting, most of them instinctively knew where the letters were. During the interviews, many subjects claimed that this was because they all knew how to use a multitap, and that the tactile feedback assured them of the button's locations.

Comparing the tactile text entry methods (2x3-tree, Numpad) with the touch-based ones (Directional, NumpadTouch) the touch-based are outperformed in almost all cases, see figure 15. Numpad and the 2x3-tree had a higher CPM than the Directional and NumpadTouch, see figure 16. In task load index, subjects reported Numpad to have a lower load than NumpadTouch. NumpadTouch caused more lane crossings than Numpad. Only in the case of the collisions, which again was only noticed in the city-scenario, did the 2x3-tree have more involvements in collisions or near-crash situations than its Directional counterpart, though Numpad still had fewer than NumpadTouch.

A limitation of the results of this study is that they have been conducted in a simulator, and would therefore require some form of epidemiological data to support the results from this study. Also, subjects in many cases increased their following distance so much, that the leading car could disappear in the horizon, therefore also slowing reaction time, since the subjects would not see the lead car breaking right away. Other clear limitations are the fact also stated by the subjects, that the learning effect was present on the common cell phone, but the subjects had had no previous experience with the HUD-based ones. Finally, no eye-tracking hardware was available during the experiment, and eye glances were manually logged only when subjects looked away from the monitor. This is a clear limit to the HUD-based scenarios, where it was not possible to note when the subject actually looked at the driving scenario or the HUD. The NumpadTouch and Directional text entry methods used WiFi to communicate with the car simulator, which delayed response time from a letter was written until it was displayed in the HUD. This may have had an effect on the task completion times.

## CONCLUSION

In this paper we showed that introducing HUD-based text entry methods into a low driving complexity scenario reduced the risk of being involved in an accident compared to writing with common cell phones. All four methods showed no significant difference in the number of crash or near-crash situations, whereas the common cell phones had significantly more crashes or near-crashes when writing. We furthermore identified the Numpad to have the lowest negative impact on road safety as it lead to the least crashes or near-crashes overall, and the subjects furthermore retained their lane keeping abilities when writing on the Numpad.

The two fastest methods were still the common cell phones, but not the safest. Subjects were able to write almost as fast on the Numpad as they were on the Touch text entry method. Since the Numpad had a lower negative impact on road safety than the common cell phones without sacrificing much of the writing speed, this method showed the most promise for a further study.

An enhancement for a future study, would be to allow subjects to practice the new text entry methods before testing them in the scenario. The fact that subjects had no experience in any of the interaction forms, but still showed to have a subconscious idea of how to use Numpad, clearly indicates an interesting point: that previous experience can possibly be implemented in new interaction forms, and could avoid the need for a learning curve. It could furthermore enhance the study if the Numpad instead used a T9 dictionary. Finally, the directional selection had the lowest amount of eye glances in any of the interaction forms, but still did not perform that well overall. Since the interface was positioned in the right-hand side of the steering wheel, subjects had to use that hand to change gears, which also affected eye glances and general driving behavior. Moving this to the left-hand side, could also be a subject for a future study.

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