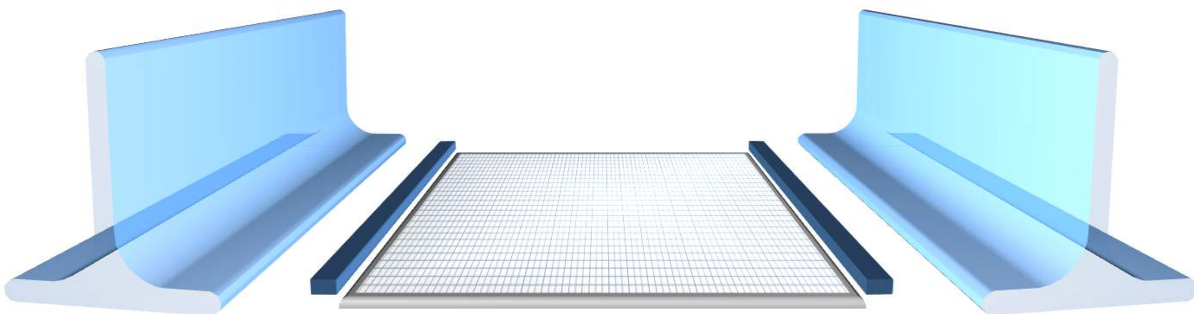
CHALMERS
UNIVERSITY OF TECHNOLOGY



A New Design of Human-Machine Interaction for Steering Articulated Truck Combinations

A Leap Towards Safe Driving

SYARIFAH SIREGAR

TU Delft

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden, 2015

Department of BioMechanical Engineering
DELFT UNIVERSITY OF TECHNOLOGY
Delft, The Netherlands, 2015

THESIS FOR THE DEGREE OF MASTER OF SCIENCE IN

MECHANICAL ENGINEERING
TRACK: BIOMECHANICAL DESIGN
SPECIALISATION: AUTOMOTIVE HUMAN FACTORS

A New Design of Human-Machine Interaction for Steering Articulated Truck Combinations

A Leap Towards Safe Driving

by

SYARIFAH SIREGAR

Student number
1309390

Supervision by:

Kristoffer Tagesson
Prof.dr. Bengt Jacobson
Dr. Riender Happee
Prof.dr. Edward Holweg

Department of BioMechanical Engineering
DELFT UNIVERSITY OF TECHNOLOGY
Delft, The Netherlands 2015

Department of Applied Mechanics
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2015

A New Design of Human-Machine Interaction for Steering Articulated Truck Combinations

SYARIFAH SIREGAR

Master's Thesis 2015:02
ISSN 1652-8549
Department of Applied Mechanics
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Image of the conceptual design of the new and intuitive steering interface for articulated truck combinations.

Chalmers Reproservice
Göteborg, Sweden 2015-04-29

I would like to dedicate this thesis

To

Those whose wish is to forgive, care, and love,

And those who risk their heart to make the world a better place,

Those whose wish is to learn, understand,and create,

And those who stretch their mind to inspire and be inspired,

Those who stay true to themselves,

Those who dare to take a stand,

And those who want to change the world.

Abstract

The main reason for accidents involving trucks or truck combinations is the lack of situation awareness. Drivers of particularly articulated truck combinations need a high level of awareness about the state of the vehicle combination and its surroundings. The current steering interface sets limits on the signals that the driver can perceive and the way the driver can act. I see an opportunity to break these limits on the interaction by introducing a new steering interface.

The new interface is intuitive and designed specially for articulated truck combinations. The interface consists of two physical walls on the left and right side of the driver, an active touch panel in front of the driver, and air vibration generators on the left and right side. The driver controls the lateral position of the truck by controlling the position of the walls. The idea is that the driver can easily associate the lateral position of the truck between the lane boundaries with the position of his or her own body between the walls. Further, the driver perceives a map of the surroundings by feeling and following surfaces on the active touch panel. Moving surfaces on the active touch panel represent the truck, trailers, road boundaries, and other traffic users. Important information about upcoming traffic is given through air vibrations that are sent by the air vibration generators towards the driver's hand.

The new interface is designed for highly automated driving, where automation allows the truck to follow a lane at a certain speed. The driver still actively participates in the control of the vehicle, and is always in direct control of the walls. There is thus only one mode and there is no need to switch between modes. If for any reason it is desired or needed that the vehicle does not follow a lane or course, then the driver can use the walls to control the heading of the truck.

The main strength of the new interface lies in the high level of intuitiveness. The definition that is adopted for the term 'intuitive' in the context of driving is 'easy to associate the vehicle with (part of) your own body'. The association is made through similarities in the order of control, sense mode, space, and time. Furthermore, the new interface exploits the possibilities with the haptic senses, which are the senses that allow us to physically feel our own body and our environment. Unlike other senses, the haptic senses are closely coupled with the motor function. After all, very often we use the same body part to manipulate as with which we sense haptic cues.

Surely, at this stage of the design, the effectiveness of the new interface cannot be proven. For now, we can only reason and argue. The effectiveness depends on different aspects, such as the driver's ability to operate the walls, the driver's ability to perceive and understand the haptic information, and the technologies for steer-by-wire and detecting lane markings. Physical prototypes of the walls and the touch panel have given more insight about the effectiveness, intuitiveness, and comfort. The prototypes have also helped to imagine what the new driving experience would be like. In particular, simple tests have been performed with the prototype of the walls in a real truck on a test track.

Key words: Human-Machine Interaction (HMI), intuitive steering, steering interface, steering device, haptic interface, articulated truck combinations, road safety, prototyping, steering concepts

Acknowledgements

I would like to thank my examination committee, from both Chalmers and TU Delft. Kristoffer Tagesson, Prof. Bengt Jacobson, Dr. Riender Happee, Prof.Dr. Edward Holweg, and Dr. Joost de Winter, thank you for your participation in the committee.

I would like to thank my supervisor Kristoffer for giving me the chance and the freedom to design and create according to my own ideas. Your patience for trying to understand and follow my thoughts and reasonings is exceptional. Your trust in me has been part of my own trust in my capabilities and instincts. Thank you for always having my back and thank you for always trying to keep the spirit up!

I would like to thank my colleagues and fellow thesis students at Volvo Trucks for enjoying lunch meals and discussions together, and for showing understanding for my somewhat radical and non-conventional ideas. Inge, thank you for being a kind manager and thank you for prolonging my stay at Volvo for a ridiculous number of times, no questions asked. Carl-Johan, thank you for being very helpful during the testing in Hällered. Sofi, thank you for cheerfully greeting me literally every single day no matter how grumpy I am.

I would also like to thank my colleagues and fellow students at Chalmers for welcoming me warmly to Sweden during the first few weeks. Bengt, thank you for your honest interest in my ideas and thank you for being so warm and kind. Sonja, thank you for helping me get started at Chalmers and thank you for being so kind and nice. Tessa, thank you for showing me around the first days in Gothenburg and on the campus of Chalmers.

I would like to thank my friends in Sweden for making me laugh and for easing the pain of being away from home. Karthik, Ajay, Nikki, Nikhil, Devo, Lobo, Que, Dani, Jan, and Niels, thank you for being so sweet and open and thank you for allowing me to come so close to you in a short period of time. Linnea, thank you for teaching me my first Swedish words and thank you for all your Swedish kindness and incredible hospitality.

I would like to thank my brother, my sister, and my dear friends in the Netherlands for letting me think and be the way I want. Club Ivy, Zoefjes, Ga, Trish, Yous, and Kaasje, thank you for all the enthusiasm you show for my project and thank you so much for simply always being there for me.

I would also like to thank my teachers in Engineering, Design, Music and Art for inspiring me. They have helped me to recognize, experience, and appreciate beauty in life. Gilbert and Marlijn, thank you for giving me understanding about how to create.

My endless gratitude goes to my dear parents, who have forgiven me so many times in so many ways, and who have taken care of me more than a child could ever wish for. They teach me and inspire me to on my turn forgive and take care of others.

Syarifah Siregar
Gothenburg, April 2015

Foreword

This report captures the relevant findings and reasonings within the research 'A New Design of Human-Machine Interaction for Steering Articulated Truck Combinations'. The research forms the graduation project of the Master Mechanical Engineering at the University of Technology Delft in the Netherlands. It was initiated, facilitated, and supervised by Volvo Group Trucks Technology in Sweden, and it has been awarded 45 ECTS-credits by Chalmers University of Technology in Sweden.

The purpose of this report is to enlighten the reader with new perspectives on human-machine interaction for safe driving.

I envision a world where road fatalities are simply not *accepted*. Fatalities cannot and should not be expressed in terms of time, cost, material, or energy. I believe that adopting this mentality is the very first step to making an honest contribution to the road safety.

I would like to make my own contribution to the road safety by drawing the design of human-machine interaction into a new direction. More specifically, I would like to introduce a new way for the driver to steer an articulated truck combination. The new way of steering allows the driver to intuitively control the truck combination, while constantly being aware of the situation.

The ambition for this project has been to design a driver interface that actually enables the new way of steering. I would like to emphasize that the new driver interface that I have designed, is merely a *glimpse* of what is actually possible within the design of human machine interaction for road vehicles.

With this research I wish to inspire and encourage those who are involved in the automotive industry to continuously challenge themselves to push the standards of road safety. Let us go beyond what is believed to be the standard, what is believed to be normal, what is believed to be possible. Let us continuously raise our own expectations and actually think and act according to it. Let us together make the roads as safe as we *wish* the roads to be.

I have faith in the scientists and engineers of today and tomorrow to join or continue to join my vision. One road fatality is one too many.

Syarifah Siregar
Gothenburg, April 2015

Contents

1. Introduction

Summary: Thorough analysis of the technical issues and cause of accidents involving trucks show that there is a strong need for situation awareness for the truck driver. The current steering interface, with or without additional systems, does not seem to be capable of giving a high level of awareness. The aim of this research is to find a new steering interface that gives the driver the awareness to safely and intuitively drive an articulated truck combination.

Long and Heavy Vehicles in Europe

Road transportation is the main mode of transportation in Europe. Due to developments in society and logistics, the high demand for road transportation is continuously growing [1]. At the same time, one of the main objectives of the European Union (EU) on European traffic is to reduce the negative impact on greenhouse gas emissions [2]. In order to meet both the high demand and the EU objective, road transportation must increase further in efficiency by decreasing the fuel consumptions per tonne transported.
The limit on size and weight of road vehicles in EU countries is 18.75 meters and 40 tonnes. However, as an attempt to increase the efficiency, the EU has raised the limits up to 25.25 meters and 60 tonnes in Sweden, Finland, Denmark, and the Netherlands. Truck combinations that are longer than 18.75 meters and/or heavier than 40 tonnes, are called Longer and Heavier Vehicles (LHVs). [2] Currently, truck combinations of no less than 32 meters and 80 tonnes are being studied and tested within the Duo2 project in Sweden [3].

The benefits of using long and heavy truck combinations are based on the fact that the number of vehicles is reduced, while the same amount of goods is transported. This reduction in number of vehicles directly leads to a reduction in fuel consumption, which in turn leads to a reduction in greenhouse gas emission, transport cost, and operation cost. However, as road transportation becomes more efficient, a modal shift might take place from rail and waterborne transportation to road transportation. As a consequence, the number of vehicles might increase, and the benefits would then be neutralized to some extent. [2]

Figure 1. An articulated truck combination that is used in the Duo2 project [4].

Safety Concerns of Longer and Heavier Vehicles (LHVs)

The main concern of a LHV compared to a regular truck is that it brings technical issues regarding safety. Firstly, the total area of blind spots increases due to the increased number of articulation points and the increased length of the vehicle [2]. Secondly, lateral instability is more likely to occur due to the increased number of articulation points [2][5]. Thirdly, crossing intersections, overtaking or being overtaken, all take more time due to the increased length of the vehicle [2]. Another important technical issue, which may be closely related to safety, is the decreased manoeuvrability and the increased swept path [2][5].

The negative effect of these technical issues is just one of many effects that LHVs have on the road safety. A positive effect is for example the effect of the number of vehicles. After all, if the number of accidents per vehicle is assumed to be constant, a reduction in the number of vehicles implies a reduction in the number of road accidents. Yet another example is the positive effect of the driving skills and driving style of the truck driver. Drivers of LHVs have generally had more training and are often more experienced than drivers of regular trucks. It is thus difficult to determine the overall effect that LHVs have on the road safety. [2]

Nonetheless, there is no doubt that any progress in solving the technical issues will contribute to the road safety. However, the aim of this project is not to simply solve these technical issues. Instead, the aim is to find solutions for the road safety even more effectively, by looking into the actual cause of road accidents that involve trucks. Road accidents are not simply a consequence of technical limitations or technical failure of the vehicle. In fact, the cause of road accidents is often a combination of factors related to not only the vehicle, but also the human and the environment.

Blind spots are by far the most common and important factor in accidents involving trucks. As mentioned before, it is one of the major technical issues for LHVs in particular. A common human factor is the misjudgement of path or speed, of either the truck itself or another road user. Another common human factor is the misallocation of attention, which is generally a result of the fact that the driver has to look at many different places. As for the environmental factors, the most common ones are a slippery road, an unsafe road layout, and lack of vision in bad light conditions. [6][7]

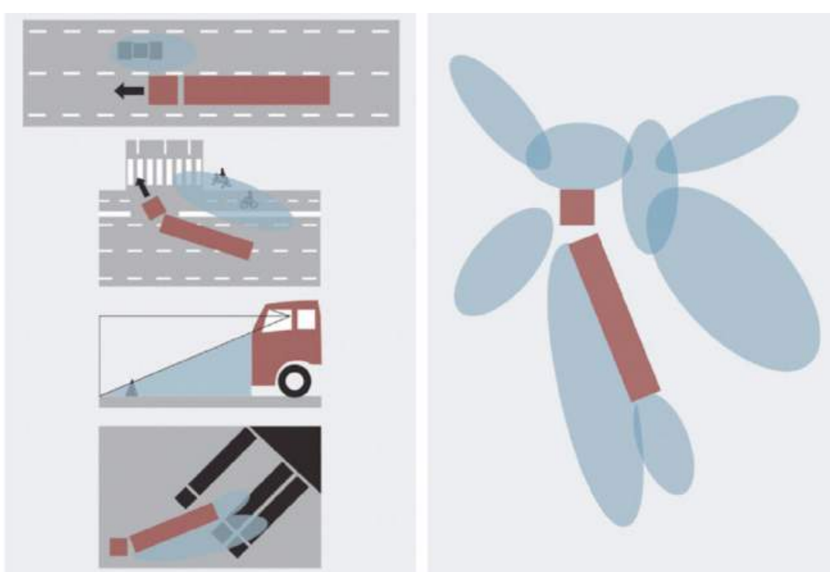


Figure 2. Blind spots and areas of limited visibility of a truck and trailer combination [6].

Need for a High Level of Awareness

Based on the factors in safety factors above, it can be concluded that there clearly is a lack of *situation awareness* prior to road accidents. More specifically, as for the truck driver, there is a strong need for a high level of awareness about the state of the vehicle and its surroundings. The need is even stronger for drivers of articulated truck combinations such as LHVs.

I see the *necessity* and the *urgency* of fulfilling this strong need of awareness. I have taken the challenge of finding a way to fulfil this need for drivers of articulated truck combinations.

Researchers have already made efforts in developing systems or technologies that help the truck driver obtain a high level of awareness, by somehow providing information about either the state of the vehicle, the state of its surroundings, or a combination of both.
For example, researchers have currently been working on creating an advanced image from a bird's-eye view, which is the top view [8][9]. Where currently available video systems only show an image of the rear or side view of a vehicle, this system can give an image of the entire nearby surroundings and the vehicle itself. Graphics of for example predicted trajectories can also be displayed together with the image, such as in Figure 3.
Another example of an interesting system that is currently under development is a 360° wraparound view system [10]. This system can give an image of the surroundings from any arbitrary point of view, such as in Figure 4. However, the technology is new and it has only been tested on cars.

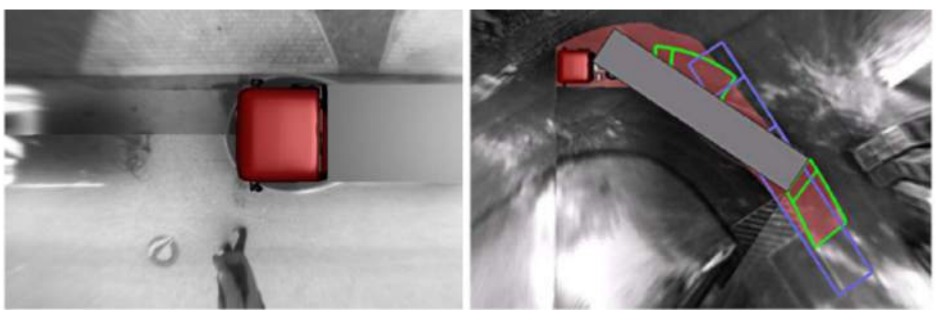


Figure 3. Images from a bird's-eye view [8][9]. The images are constructed by transforming and combining images that are taken from multiple sides of the vehicle.

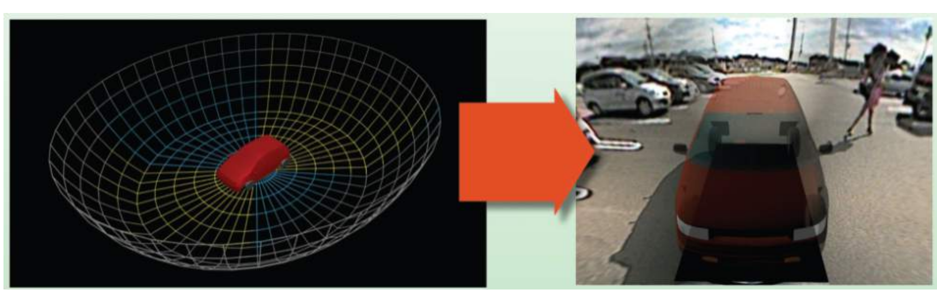


Figure 4. Image from a 360° wraparound view system [10]. The image is constructed by first projecting multiple images on a virtual 3D curved surface, and then converting the projection into an image as seen from the particular point of view.

Yet another example is a spatial sound system that gives information about the location and movement of other road users [11]. Researchers are currently working on finding the appropriate sound for each road user in specific situations. The experimental setup is shown in Figure 5. Spatial sound information is still a new area in the automotive research.

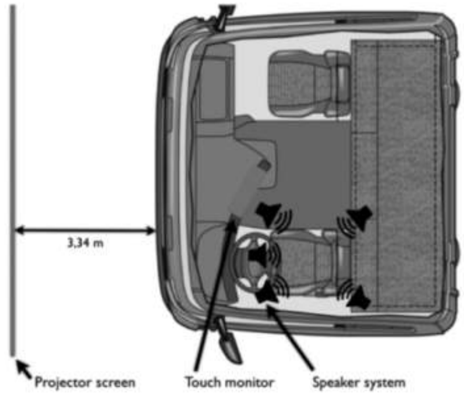


Figure 5. Setup of an experiment with a spatial sound system [11]. The system uses recognizable sounds that imitate the road user (e.g. pedestrian, playing child, cyclist, motorcyclist, car, or truck).

These examples of systems are promising and exciting, and indeed help the driver to become aware, either about the state of the vehicle or its surroundings. The systems are also definitely able to give all the required information in some way, but there are issues that limit the effectiveness.
For example, even though a visual display can give valuable spatial information, it still needs to be seen and understood by the driver in order to be effective. The driver needs to take his or her eyes off the road, even when the image is displayed on the windscreen, such as with a head-up display. There are also risks such as distraction and an overload of information.
As for the spatial sound system, the signals can be heard from every direction, without the driver needing to move his or her eyes, head, or body. However, it has still remained a challenge to make sure that the sound is clear and unambiguous. There are also risks such as annoyance and interference with other sounds or noise.

A full review and in-depth analysis of systems that provide the truck driver with visual and audial information about the vehicle or its surroundings, can be found in respectively Appendix A and B.

A New and Intuitive Interface for Steering Articulated Truck Combinations

Systems such as those treated above have limited effectiveness, and are therefore not able to give the high level of awareness about both the vehicle and its surroundings. Each one of these systems is simply added to or incorporated into the current interface. In fact, the systems are often *designed* to be added to the current interface.

Apparently, the combination of the current steering interface with any additional system has limited effectiveness. It is thus the combination that is not capable of giving the high level of awareness. The reason for this incapability is the physical and functional limits of the current interface. It seems to set limits on the signals that the driver can perceive and the way the driver can act.

So the only way to give the high level of awareness is to break these limits by finding a new way for the driver to interact with the vehicle. I believe that this interaction should be intuitive. Moreover, the interaction should be suitable for the specific application, which in this case is to steer an articulated truck combination. It is unwise and even naive to just assume that the best interaction for steering an articulated truck combination is to turn a steering wheel, which stems from boats, while checking several mirrors.

I would like to find a new steering interaction that allows the driver to intuitively steer an articulated truck combination, while constantly being aware of the situation.

The challenge is to answer the following questions:

- What way of interaction would be intuitive?
- What way of interaction would be suitable for steering an articulated truck combination?

The best way to facilitate the new interaction is through an entirely new interface that is specially designed for the new interaction. In fact, it is believed to be the only way, as the current interface is definitely not able to facilitate the new interaction.

With a new steering interface I see an opportunity to give the driver the awareness to safely drive an articulated truck combination. This research could bring us closer to preventing road accidents and making roads safer.

Chapter Overview

The two questions formulated above are treated in Chapter 2, *A New Steering Interaction*. The answer to particularly the first question is considered as one of the highlights of the research, as it contains a new definition of 'intuitive' in the context of driving.

Chapter 3, *The Search for a New Steering Interface*, explains the method that has been used for finding the concept for the new interface. It includes and motivates the design specifications and presents different concepts that are carefully analysed. One concept will be further developed into a conceptual design.

Chapter 4, *Conceptual Design of the New Steering Interface*, treats the conceptual design in more detail. It describes and motivates both the functional design and physical design of the new interface.

Chapter 5, *Evaluation of the Conceptual Design*, gives a critical assessment on the technical value of the new interface and compares it to the current interface. It further treats the design and fabrication of the first prototypes, and also explains the purpose of each prototype.

Chapter 6, *Conclusions*, indicates explicitly the significance and potential value of this research within the area of Human-Machine Interaction, the automotive industry, and road safety.

Finally, Chapter 7, *Recommendations for Further Research*, gives recommendations for continuation, extension, and expansion of this research.

2. A New Steering Interaction

Summary: The steering interaction defines exactly how the driver can act within the control of the vehicle and how the driver can perceive signals from the vehicle and the environment. The interaction is believed to be intuitive when the driver can easily associate the vehicle with (part of) his or her own body. The haptic senses offer great possibilities, due to the high potential of receiving information and the close coupling with the motor function.

Awareness for Every Level of Automation

Automation has already been applied in many aspects of driving road vehicles. Advanced Driving Assistance Systems (ADAS) such as Lane Change Warning (LCW) and Adaptive Cruise Control (ACC) are widely and successfully adopted. Automation can make driving easier, and therefore safer and more comfortable.
The level of automated driving has risen fast and probably will continue to rise in the future. Projects such as SARTRE and the Google Self-Driving Car have shown promising results of progress in highly automated driving. However, I do not think that driving could or should be fully automated. I think that as long as vehicles share the roads with vulnerable traffic users, such as pedestrians and cyclists, the driver should stay in-the-loop and actively participate in the control of the vehicle. After all, automated driving has limitations on situational, operational, and functional level. Indeed, any automated system is only as good as humans have designed it.
Since the driver should continuously participate in the control of the vehicle, then undoubtedly the driver *must* also be aware of the situation at all times. The driver needs to understand what the state of the vehicle is, what the state of the environment is, and how both states can or will develop. In other words, the driver needs to understand what is happening with the vehicle and what is happening with the traffic around it.

So regardless of the level of automation, the driver should continuously have a certain level of situation awareness to be able to act whenever desired or necessary. A high level of automation does certainly not remove or diminish the need for situation awareness of the driver.

Figure 6. Vehicle platoon from the SARTRE (Safe Road Trains for the Environment) project [12]. The task of following the leading truck is automated for the trucks and cars in the platoon.

The Steering Interaction and the Steering Interface

The steering interaction defines exactly how the driver interacts with the vehicle and how the driver becomes aware of the situation. More specifically, it defines how the driver can both act within the control and how the driver can perceive signals from the vehicle and the environment. The role of the interface is to facilitate this interaction, as depicted in Figure 7 below.

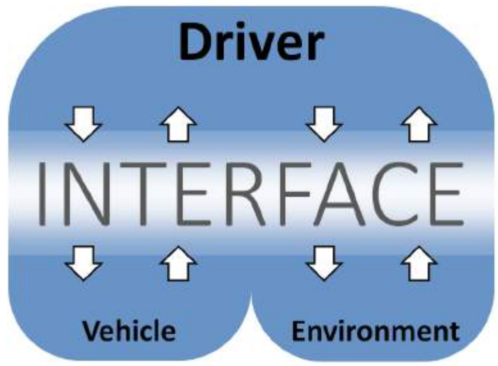


Figure 7. The role of the interface is to purely facilitate the interaction between both the driver and the vehicle, and the driver and the environment.

It is important that there is clear communication from the vehicle and its surroundings to the driver. The driver must have access to information about the state of the vehicle combination and its surroundings, whenever the driver wants or needs it. Then, the driver must understand what the information means and how crucial it is. In other words, the driver needs to be effectively informed about the situation.

It is also important that there is clear communication within the control. So when automation is involved, the driver must understand how to act within the control, and the automated system must understand what the intention of the driver is. In other words, the driver needs to be able to effectively act within the control of the vehicle.

Steering Intuitively

Now that we have a common understanding of what the steering interaction is, the next step is to answer the first question stated in the Introduction: *What way of interaction would be intuitive?*

Although the term ‘intuitive’ is often used in literature, there has not been given any clear definition or meaning in the context of driving. It is associated with terms such as ‘easy to localize’ [13], ‘easily recognizable meaning’ [13], ‘universal’ [14], or ‘natural’ [14] . To avoid any unclarities in the remaining part of this report and to contribute to the common understanding of this important term, I would like to propose and adopt my own definition of ‘intuitive’ in the context of driving:

‘easy to associate the vehicle with (part of) your own body’

I believe that a steering interaction is perceived by the driver as being intuitive, because the control of the vehicle can easily be associated with the control of his or her own body. For the driver, moving the vehicle feels like moving his or her own body, and signals affecting the vehicle are felt like signals affecting his or her own body. The association is claimed to be made through similarities in e.g. order of control, sense mode, space, and time. It is strengthened when information from all senses can be integrated and interpreted easily.

The High Potential of the Haptic Senses

The visual, audial, and haptic senses can all transfer valuable spatial information to the driver. The visual sense can receive much spatial information from one direction at once. The audial sense can receive spatial information from any direction without the driver having to move his or her eyes, head, or body. The haptic senses, which allow us to physically feel our own body and our environment, can in several ways even surpass both the visual and audial sense. For example, while the reference point for audial information can only be the head, the reference point for haptic information can be any part of the body. After all, haptic sensors are all over the whole human body.

Figure 8. The haptic senses are all over our body, and allow us to physically feel and be aware of our own body and our environment. Left [15], right [16].

Besides the high potential of receiving information, the haptic senses would also offer great possibilities for how the driver can act within the control of the vehicle. Unlike all other senses, the haptic senses are closely coupled with the motor function. After all, very often we use the same body part to manipulate as with which we sense haptic cues.

More information on visual and audial feedback for driving can be found in respectively Appendix A and B. More information on the haptic senses can be found in Appendix C.

Haptic technologies are developing fast and seem to enable the realization of almost any design of haptic application. Yet, designs for steering interfaces of road vehicles have not nearly exploited the almost unlimited possibilities of haptic technologies. Many studies have shown the benefits (e.g. lower cognitive workload, higher performance) and the reliability of haptic feedback that either replaces or supports visual or audial feedback [14]. The feedback is however limited to vibrations and forces acting on the steering wheel or the foot pedals.

A full review and in-depth analysis of systems that provide the driver with haptic information about the vehicle or its surroundings, can be found in Appendix D.

Visual and Haptic Information within the New Steering Interaction

Within the conceptual design of the new steering interface, I would like to push and exploit the possibilities of haptic technologies. The focus has therefore been put on the haptic senses and haptic information. If haptic information is given in the right form and on the right time, it can surpass the potential of visual and audial information.

No restrictions have been set on the haptic information, and the full potential of the haptic senses has been considered. The focus has been put on the haptic sensors in the arms and hands, as it makes sense that in a standing or sitting position the driver uses these body parts to manipulate or move anything.

The visual information has been limited to the real 3D view that the driver can see through the windows. The driver's position and movement with respect to the environment are exactly the same as those of the cab. So what the driver sees as the environment around him or her, is exactly the environment around the cab. The similarities in sense mode, space, and time, are in accordance with the adopted definition of 'intuitive'. It is for this reason that the new steering interface does not have any mirrors or displays. After all, in order for mirrors and displays to be effective, the driver needs to actually see and look at the image. Then, the driver needs to understand what the image exactly represents, what the perspective is, and what the actual depth in the image is.

Audial information is not given at all in the conceptual design. If, for any reason at all, the combination of visual and haptic information does not seem to be effectively perceived by the driver, then audial information might offer a solution. There is for example great potential in the spatial sound system that was briefly touched upon in the Introduction. There is also great potential in the usage of speech and auditory icons, which have been shown to be more effective and less annoying than arbitrary sounds such as beeps or tones [11][17].

Steering an Articulated Truck Combination

The second question from the Introduction is yet still to be answered: What way of interaction would be suitable for steering an articulated truck combination?

One way of answering this question is by first finding the characteristics of steering an articulated truck combination. The interaction can then be based upon these characteristics.

First of all, the dimensions of an articulated truck combination depend on the configuration. Figure 9 below shows four examples of truck combinations that are used in Europe. For the conceptual design, one articulated truck combination in particular has been considered: the B-double truck combination. The reason for this choice is the challenge in size and in having two articulation points.
The B-double truck combination, which is shown in Figure 9 as the second picture, has a width of 2.55 [m] and a total length of 25.25 [m] [18]. The container on the first trailer has a length of 7.8 [m] and (the container on) the second trailer has a length of 13.6 [m] [18][19]. The maximum weight is 60 tonnes [2].
Another characteristic of steering articulated trucks combinations, is that even though the driver controls the entire vehicle combination, the driver can only directly act within the control of the front vehicle, also known as the towing vehicle. In case of a B-double, the towing vehicle is a truck.

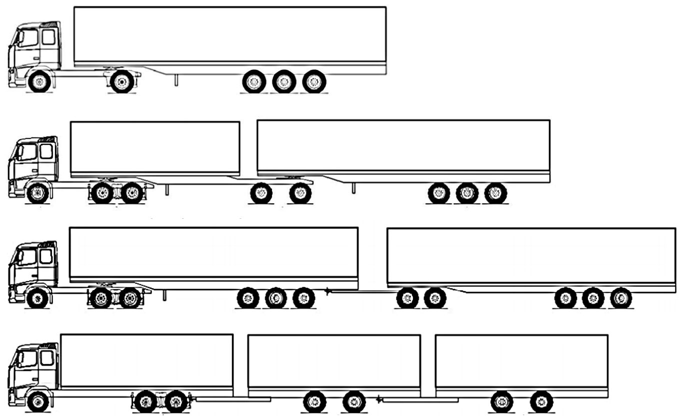


Figure 9. Examples of articulated truck combinations in Europe [5]. Particularly the second combination, also known as the B-double, has been considered for the conceptual design.

Thus, steering an articulated truck combination means steering a large and heavy road vehicle with multiple articulation points. The interaction between the driver and the truck combination should therefore involve the dynamics of not just the truck, but also the trailers. After all, the dynamics of each trailer is different. Each trailer has its own position, path, and forces acting on it. The interaction between the driver and the trailers is however also limited, as the driver cannot directly act within the control of the trailers. The driver can only directly act within the control of the truck.

3. The Search for a New Steering Interface

Summary: Six concepts of new steering interfaces have been designed using a morphologic chart. Sources of inspiration include haptic technologies, surgery, braille, sports, and music instruments. The concepts have been rated with great care on safety, comfort, intuitiveness, accessibility, and originality. A refined version of one concept will be further designed and evaluated.

In the process of finding a new steering interface, I have not restricted myself to currently available technologies and applications. After all, recent developments in haptic technologies are promising. It seems that practically any form of physical interaction can be realized in the near future, if not now. Moreover, users, especially young users, are highly responsive to new haptic interfaces and seem to have no difficulties with learning new haptic skills [20].

Certainly, haptic technologies and applications, especially those from the last decade, have been a source of inspiration for me. Another source of inspiration for me has been the many ways in which visually impaired people use the haptic senses to function and complete normal tasks, such as reading and finding their way in traffic. They rely heavily on the haptic senses, because they need to compensate for the lack of vision.

Figure 10. Sources of inspiration for finding a new steering interaction. Left: Intellect Motion's iMotion is a hand-held device that gives haptic feedback in virtual reality games [21]. Right: Special tiles serve to guide visually impaired pedestrians on railway stations [22].

Design Specifications

The first step in finding a new steering interface is to define the specifications of the design. In this step, the technical functions and technical requirements are defined so as to determine the scope of the design, and the limitations and assumptions are defined to draw the boundaries of the design.

Technical Functions

The technical functions are schematically shown in Figure 11 below, and can be considered as an answer to the question 'What does the new steering interface do?'

The first function of the interface is to purely **transfer the steering command** from the driver to the controller. The steering command that is received from the driver will be named 'Input 1' and is preferably a position or a force. The interface then sends that command, which will be named 'Output 1', to the controller. It is then up to the controller to actually execute the command from the driver. The controller is *not* part of the steering interface.
As indicated in the previous chapter, it is important that the driver understands how to act within the control.

The second function of the interface is to purely **transfer information about the current state of both the vehicle combination and its surroundings** to the driver. The interface receives the information, but does not detect it. The information about the state of the vehicle combination consists of the articulation angles and the lateral forces acting on the trailers. This information that is received and then presented to the driver will be named respectively 'Input 2a' and 'Output 2a'. The information about the state of the surroundings of the vehicle combination consists of the position of other traffic users and the road boundaries. This information will be named respectively 'Input 2b' and 'Output 2b'. Both Output 2a and Output 2b are haptic signals and preferably a position or force.
As indicated in the previous chapter, it is important that the driver has access to the information whenever the driver wants or needs it. The driver must also understand what the information means and how crucial it is.

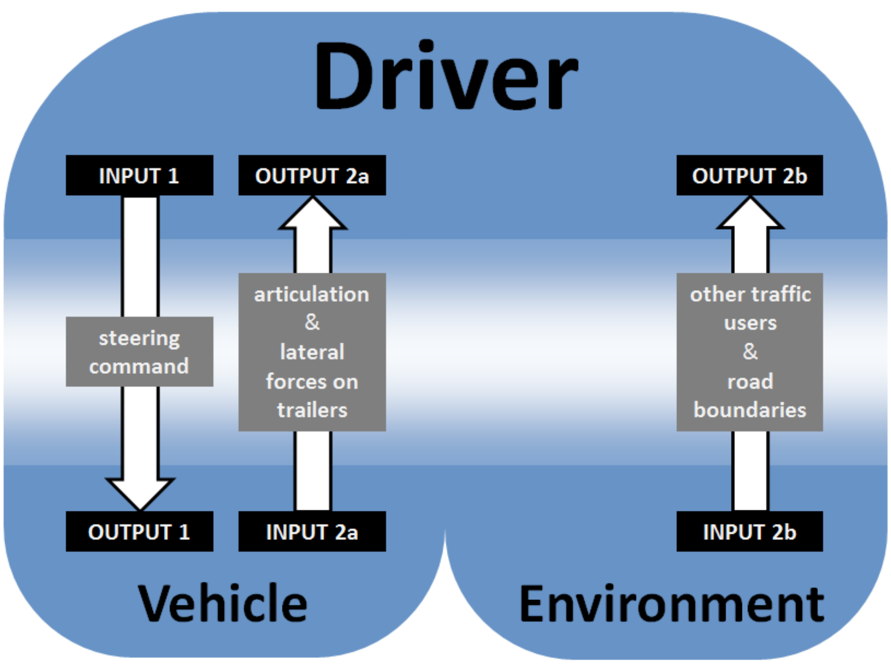


Figure 11. The functions of the steering interface is to transfer the steering command from the driver to the controller of the vehicle, and to transfer information from the vehicle combination and its surroundings to the driver.

Technical Requirements

The technical requirements below can be considered as an answer to the question 'What characteristics of the new steering interface are absolutely necessary?' I would like to make it clear that the requirements are not necessarily objective. So the actual question that is answered is 'What characteristics of the new steering interface are absolutely necessary, according to *my own beliefs*.'

Firstly, there are requirements for **performance**. The resolution for detecting Input 1, which is the steering command received from the driver, should be above a certain set value. The resolution of the amplitude, frequency, and time period of Output 2a and Output 2b, which represent information presented to the driver, should be above a certain set value. After all, a human also has a minimal resolution to perceive signals in terms of amplitude, frequency, and time period, which is defined by the so called Just Noticeable Difference (JND). Further, the precision and accuracy of the amplitude, frequency, and time period of Output 2a and Output 2b should be above a certain set value.
Also, any time delay or time lag should be below a certain set value.

Secondly, there is a requirement for **unambiguousness**. For a specific steering command there should be one meaning and one meaning only. The same holds for a specific signal that is presented as information to the driver.

Thirdly, there are requirements for **intuitiveness**. The control of the vehicle should be easy for the driver to associate with the control of his or her own body, or part of his or her body. The association is made through similarities in e.g. order of control, sense mode, space, and time. It is strengthened when information from all senses can be integrated and interpreted easily.
The information presented to the driver should be easy to identify, recognize, and understand. Moreover, the information should be continuously available to the driver, if not continuously given to the driver.

Fourthly, there are requirements for **comfort**. The driver should have a comfortable posture while giving steering commands or receiving information. The driver should also have freedom of posture to a certain extent. One option to ensure freedom is to adopt a flexible reference for a position or force, rather than a fixed reference, by using devices that are worn or somehow attached to the driver. However, the risk of flexible references is that unintended steering commands are easily made due to body movements during certain manoeuvres.
Furthermore, signals that are presented as information to the driver should have comfortable limits on amplitude, frequency, and time period. There also should not be an overload of information. The range and resolution of the steering command should be comfortable, so that the driver does not feel any fatigue, strain, or stress. Physical support or a small amount of play can help to increase the comfort in that sense. Finally, there should not be any unintended vibration or induced motion to any part of the driver's body.

Fifthly, there are requirements for **safety**. The driver should be safe from injury and pain during normal driving, which means that for example there are no sharp edges and no evident risk of getting electric shocks. There should also be possibilities for passive safety features, which means that for example there is room for an airbag and that certain parts are collapsible.

Sixthly, there is a requirement for **accessibility**. The driver should be able to access the driver's seat from either the left or right side of the cab. The driver should also be able to take position to start driving without any help from other people.

Finally, there are requirements for **reliability**. The complete interface should be durable. In addition, there should be a safe-fail system, so that when a part fails, the driver is informed about it and is still able to control the vehicle safely until the part is actually repaired or replaced. There might need to be redundancy of certain components.

Limitations

The limitations below can be considered as an answer to the question ‘What limitations can be set with full certainty on aspects that are involved in the design of the new steering interface?’

First of all, limitations have been set on the **driver**. The driver is in good condition, both physically and mentally. So the driver is not tired, stressed, or sleepy. Furthermore, the driver is motivated and feels responsible. The arms, hands, or fingers are not numb. Also, the driver is in a sitting position.

Secondly, limitations have been set on the **vehicle**. The vehicle has steer-by-wire technology, which means that the interface does not have to be mechanically linked to the steering mechanism of the front axle. Furthermore, there are no rear view mirrors, front view mirrors, or side view mirrors.
As, mentioned in the previous chapter, a B-double truck combination is considered. It has two articulation points, a width of 2.55 [m], and a total length of 25.25 [m]. The container on the first trailer has a length of 7.8 [m] and (the container on) the second trailer has a length of 13.6 [m]. The maximal weight is 60 tonnes. Furthermore, the maximal speed is 90 [km/h].

Thirdly, limitations have been set on the **environment**. The road is a European public road. The road is shared with other traffic users, namely articulated truck combinations, regular trucks, buses, cars, cyclists, and pedestrians. The vehicle is driven at both daytime and nighttime, in any weather condition.

Finally, limitations have been set on the **driving task**. The vehicle is only driven forward, backward driving is not considered. The driving speed can vary from 0 to 90 [km/h] on straight lanes, and from 0 to 30 [km/h] in curves.

Assumptions

The assumptions below can be considered as an answer to the questions ‘What assumptions are necessary to be made on aspects that are involved in the design of the new steering interface?’

With regard to the **vehicle**, the information about the current state (Input 2a), which consists of the articulation angles and the lateral forces acting on the trailers, is assumed to be fully reliable.
Furthermore, it is assumed that there is constantly a clear view through the windscreen and side windows. Also, it is assumed that, regardless of the design, a proper placement for the airbag, horn pad, and multifunctional buttons will be found.

An important assumption about the **environment** is that there are lane markings present.
Moreover, the information about the state of the surroundings of the vehicle combination (Input 2b), which consists of the position of other traffic users and the road layout, is assumed to be fully reliable.

The Search for Ideas and Inspiration

Now that the design specifications have been determined, the next step is to create concepts for different interfaces, that each facilitates a specific steering interaction. In order to find concepts, I have actively searched for ideas and inspiration in several ways.

One way of searching for ideas and inspiration has been to study steering devices for road vehicles that are different from the currently adopted steering wheel. Examples include devices that are operated with the hand, such as a joystick or a touch screen, but also devices that are operated with speech, arm gestures, or even the brain. The purpose of most steering devices has not necessarily been to give the driver awareness. Instead, the purpose has mainly been to either improve the steering performance or to simply explore new possibilities for the steering interaction. Nonetheless, the study of both the strengths and weaknesses of alternative devices have helped me to critically review and refine the design specifications, especially the technical requirements. More information on alternative steering devices can be found in Appendix E.

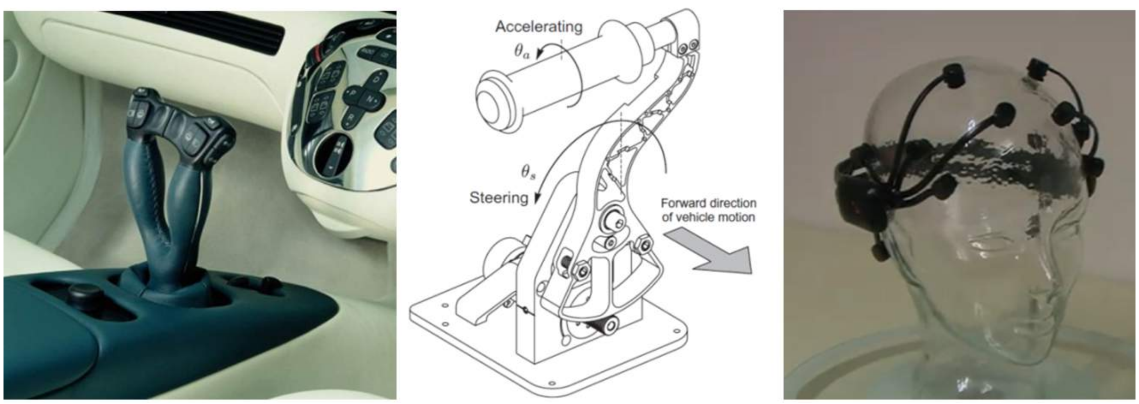


Figure 12. Examples of alternative steering devices. Left: Mercedes' joystick for the SCL600 concept car [23]. Centre: design of a device that shows strong similarities with GM's yoke for the Hy-wire [24]. Right: Emotive's Epoc neuroheadset that detects electrophysiological signals from the brain [25].

Another way of searching for ideas and inspiration has been to study haptic technologies and applications. Over the last decades, haptic applications have been developed to either reconstruct reality for tele-operation, to simulate reality in a simulator, or to enhance reality (e.g. shared control). The applications are used in a wide range of areas including automotive, aviation, space, submarine, military, nuclear plants, micro-assembly, surgery, gaming, communication, art, music, and rehabilitation. [26]

The major breakthroughs in haptic technology however have been made within the last few years. The purpose of these technologies is to let the user physically feel the control. Examples include touch screens and displays that give haptic feedback (e.g. TouchSense [27]), wearable devices that detect gestures and give haptic feedback (e.g. CyberGlove [28]), devices that induce gestures or motion (e.g. skin stretch device [29]), devices that detect gestures in mid-air (e.g. Nintendo Wii), and even devices that give haptic feedback in mid-air (e.g. air vortex generator [30]).

I have also asked the help of my professor and colleagues to brainstorm on concepts and to share their thoughts on future interfaces and on how they would like the new steering interface to be.

Figure 13. Examples of haptic applications and technologies. Left: a simulator for operating a medical device gives forces as haptic feedback [31]. Virtual Technologies Inc's CyberGlove detects gestures, and gives vibrations as haptic feedback about virtual objects [28]. Right: Disney's AIREAL device sends an air vortex as haptic feedback about virtual objects in mid-air [30].

Concepts for a New Steering Interface

I have made rough designs for 6 concepts using a morphologic chart, which is an overview of design characteristics of solutions for different sub functions. The morphologic chart is shown in Figure 14 below. It helped me to be both creative and critical in finding solutions for sub functions.

For the designs of the concepts, only certain sub functions are of interest. The first sub function is to let the driver give the steering command, which is related to receiving Input 1. The combination of the second and third sub functions is to let the driver detect the information about the vehicle combination, which is related to presenting Output 2a. The combination of the fourth and fifth sub functions is to let the driver detect the information about the surroundings, which is related to presenting Output 2b.

The design characteristics have been selected based on what seemed feasible and reasonable according to me. However, more than a third of the characteristics had not been used in the concepts. In fact, after carefully considering these characteristics, the following characteristics did not seem to be that reasonable or convenient: 'velocity', 'temperature', 'electric voltage', 'chest' and 'back'.

I would like to emphasize that the concepts were not designed after having created this morphologic chart. Instead, both the concepts and the morphologic chart were designed or created in a parallel and iterative way. The morphologic chart for each concept can be found in Appendix F. A schematic overview of key points for each concept can be found in Appendix G.

Sub Functions & Design Characteristics

steering command (INPUT1)	proprioceptive control			actuator (body part)		
	force	position	velocity	finger(s)	hand(s)	fore arm(s)
	direction					
	rotation	translation				

information about articulation (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction				reference				
	rotation	translation		top	bottom	inside/outside (left/right)		steering direction	cabin	1st trailer	2nd trailer	road boundaries

information about lateral forces (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about traffic users (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about road layout (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

Figure 14. A morphologic chart helps to be both creative and critical in finding solutions for sub functions.

Concept 1. Push-Steering

The first concept is mainly inspired by roller skating through a narrow corridor, where you tend to use your hands both to move forward and to steer.

An active touch panel or mechanical device in front of the driver gives information about the current state of the vehicle combination and its surroundings. Moving surfaces on the panel represent the truck, trailers, road boundaries, and other traffic users. The driver perceives a map of the surroundings by feeling and following the surfaces.
The driver sits between two physical walls and gives steering commands by moving either one of the walls to the left or right. The idea is that the driver can easily associate the lateral position of the truck between the road boundaries with the position of his or her own body between the walls. For example, if either one of the walls is pushed to the right, the position of the driver's body with respect to the walls moves to the left, and thus the truck will also move to the left.

The main strength of this concept lies in the high level of intuitiveness of giving steering commands. After all, the driver can easily associate his or her body with the truck, and the walls with the road boundaries. Another strength of this concept is that the driver can choose which hand to use for moving the walls and which hand to use for feeling the touch panel. There is also much freedom of posture.

The main concern is the risk that information is missed, especially information about other traffic users. Furthermore, the driver might get tired as the arms are not continuously supported.

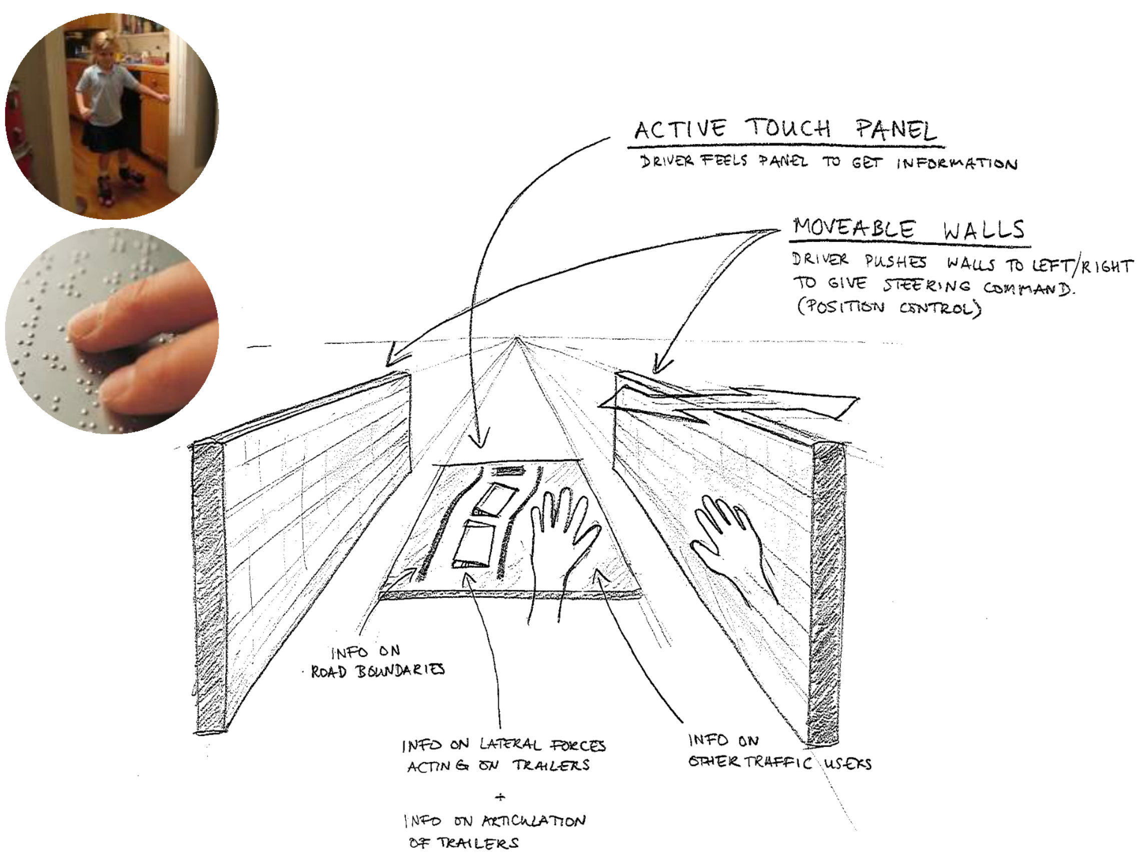


Figure 15. Sketch of Concept 1 (Push-Steering). Sources of inspiration include roller skating [32] and braille reading [33].

Concept 2. Double-Thumb-Steering

The second concept is mainly inspired by the articulation of the human body.

Both arms of the driver follow a mechanical platform. The forced articulation of the arms represents the articulation of the trailers. The driver can associate the hands with the first trailer, and the fore arms with the second trailer. Pressure or vibrations on the outer sides of the arms gives information about the distance to the road boundaries and about other traffic users nearby. Pressure applied on the bottom of the arms gives information about the lateral forces acting on the trailers.
The driver gives steering commands by moving both thumbs together to the left or right.

The advantage of this concept is that information cannot easily be missed. Furthermore, there is a large area available on the arms to present information to the driver.

However, there are many concerns. First of all, the continuously forced position and articulation is believed to be uncomfortable as it limits the freedom of posture of the arms. Secondly, the articulation angle of the wrist, that represents the second articulation of the vehicle, is limited. Thirdly, there is a risk of confusion when giving steering commands, because the position of the hands changes with the trailers. Finally, steering precisely with the thumbs might be difficult.

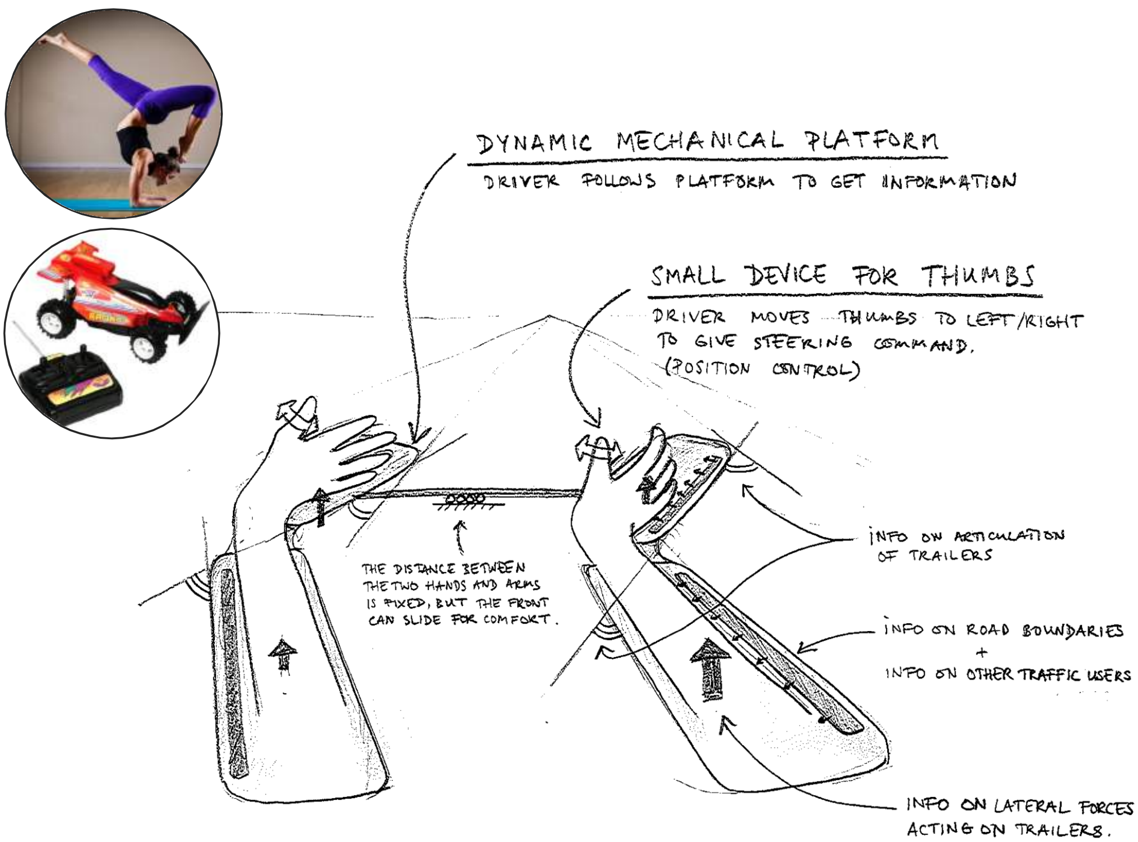


Figure 16. Sketch of Concept 2 (Double-Thumb-Steering). Sources of inspiration include yoga [34] and driving RC cars [35].

Concept 3. Double-Wrist-Steering

The third concept is mainly inspired by electric massage chairs.

Both fore arms of the driver rest on static mechanical platforms. Pressure or vibrations on the outer sides of the fore arms gives information about other traffic users nearby, including those behind the vehicle combination. Pressure or vibrations on the inner sides of the fore arms give information about the clearance between the road boundaries and both trailers. The driver is expected to derive the articulation angles from the passed trajectory and the clearance. Pressure or vibrations applied on the bottom of the fore arms give information about the lateral forces acting on the trailers.
The driver gives steering commands by rotating both hands together to the left or right. The articulation of the wrists represents the steering angle of the front axle. The driver can associate the hands with the front tyres.

The advantage of this concept is that the arms are continuously supported and do not need to move much. However, it can also be considered as a drawback, because the freedom of posture is limited. Furthermore, there is a large area available on the arms to present information to the driver.

The main issue is that it might be difficult for the driver to interpret the indirect information about the articulation angles. It might also be difficult to interpret the location of other traffic users.

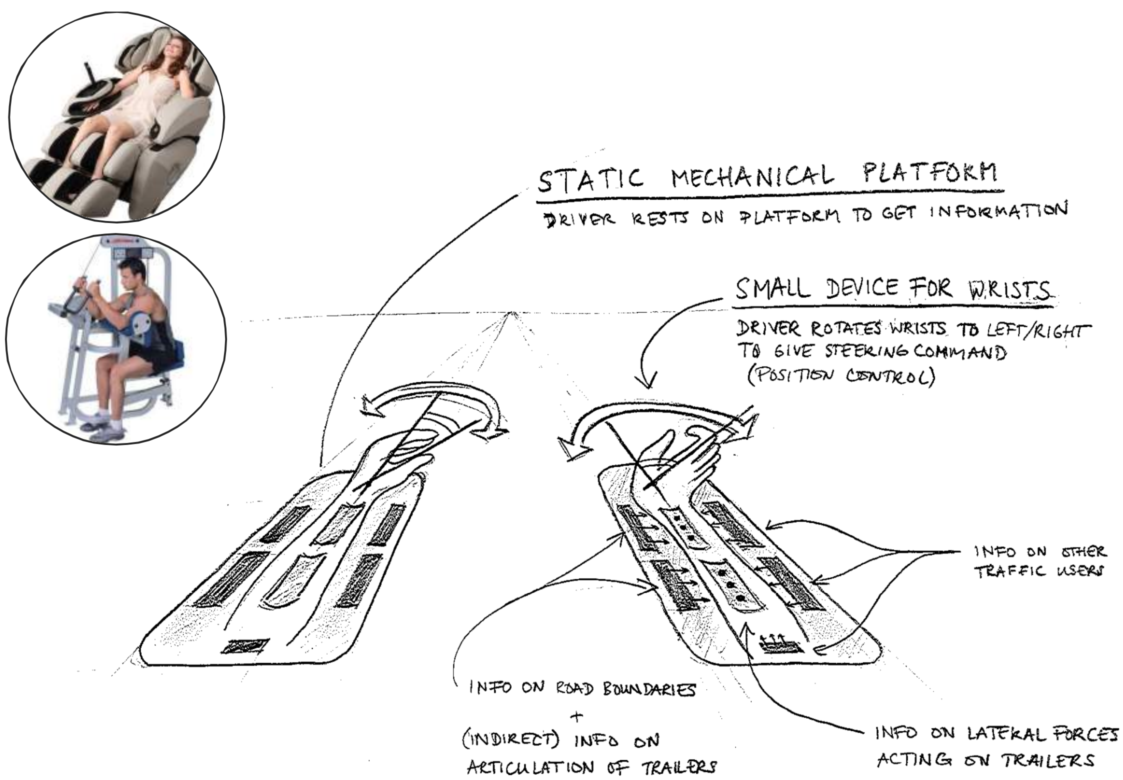


Figure 17. Sketch of Concept 3 (Double-Wrist-Steering). Sources of inspiration include electrical massage chairs [36] and fitness machines [37].

Concept 4. Single-Wrist-Steering

The fourth concept is mainly inspired by surgical devices, such as the Da Vinci Surgical System.

Three left fingers and three right fingers follow a small portable mechanical device. The idea is that the driver can relate each of the three fingers to the truck, the first trailer, or the second trailer. The position of two of the left fingers with respect to the third left finger represents the articulation angles of the trailers. Pressure or vibrations on the left fingertips give information about the lateral forces acting on the trailers. Pressure or vibrations on the proximal and second right finger parts give information about respectively the distance to the road boundaries and other traffic users nearby.
The driver gives steering commands by rotating the left wrist to the inside or outside.

The strength of this concept is that all motion of the fingers and hands is relative to another finger or to the arm. There is thus total freedom of posture. In addition, giving haptic information to the fingers makes sense, as the finger tips are the most sensitive area of the human body.

The main concern is that the driver undoubtedly needs to wear devices on the hands, which is not desired for comfort reasons. Furthermore, as the hands can be orientated freely in space, there is a risk that information about direction is interpreted incorrectly. Finally, the area of the second finger parts, on which information about other traffic users nearby is given, is small.

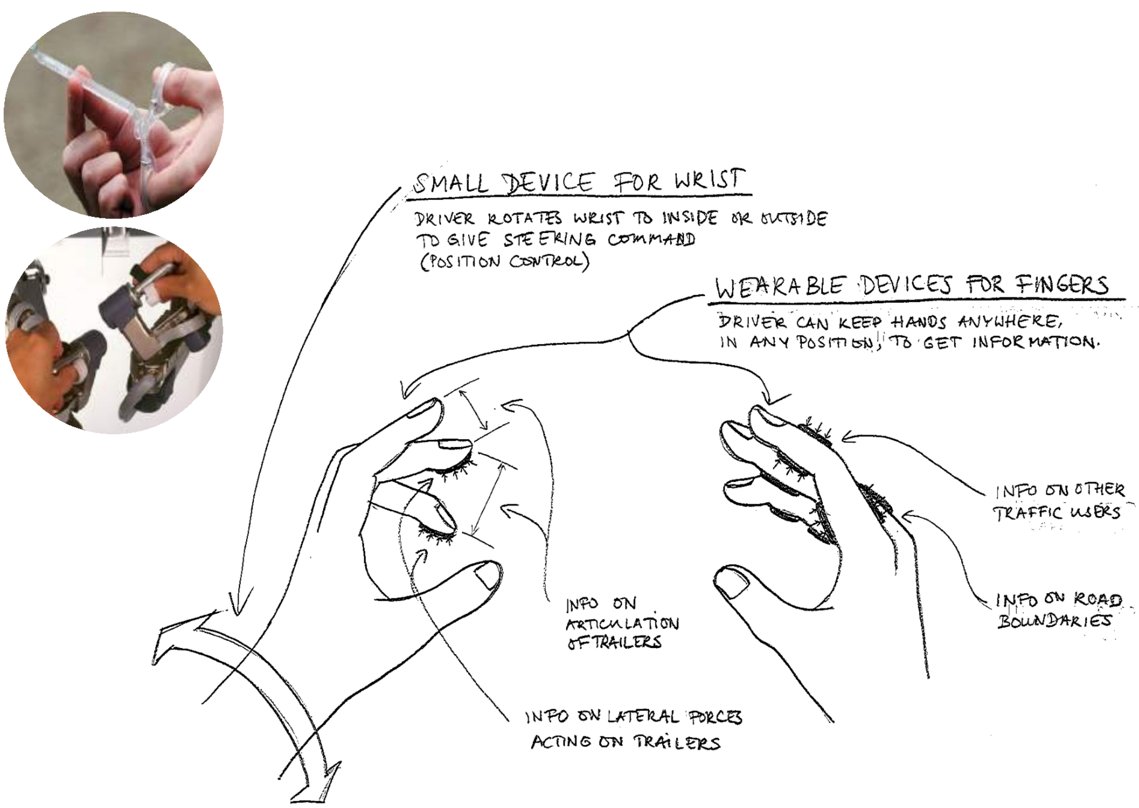


Figure 18. Sketch of Concept 4 (Single-Wrist-Steering). Sources of inspiration include the DaVinci Surgical System [38] and the DragonFlex [39].

Concept 5. Elbow-Steering

The fifth concept is mainly inspired by motor riding and playing piano.

Both hands of the driver lean on a desk in front of the driver, and can freely move independently from each other. The idea is that the driver can associate parts of the hand with parts of the vehicle combination. The left hand can be associated with the first trailer, and the right hand with the second trailer. Each wrist follows a mechanical device and the articulation of the wrist represents the articulation angle of the corresponding trailer. The fingers also follow a mechanical device. The distance from the index finger and ring finger to the middle finger represents the distance from the road boundaries to the trailer. Pressure or vibrations on the fingertips of the index finger and ring finger give information about other traffic users nearby. The position of the pinky relative to the thumb gives information about the lateral forces on the trailer.
The driver gives steering commands by leaning with the elbows to the left or right.

The advantage of this concept is that the way of giving steering commands is somewhat intuitive. The driver can associate his or her body to some extent to the truck. Also, giving haptic information to the fingers makes sense, as the finger tips are the most sensitive area of the human body.

The main issue is that the freedom of posture is limited to small movements of the hands and elbows. There is therefore a risk of strain in the shoulder. Furthermore, there is only little support possible for the arms. Finally, the area of the second finger parts, on which information about other traffic users nearby is given, is small.

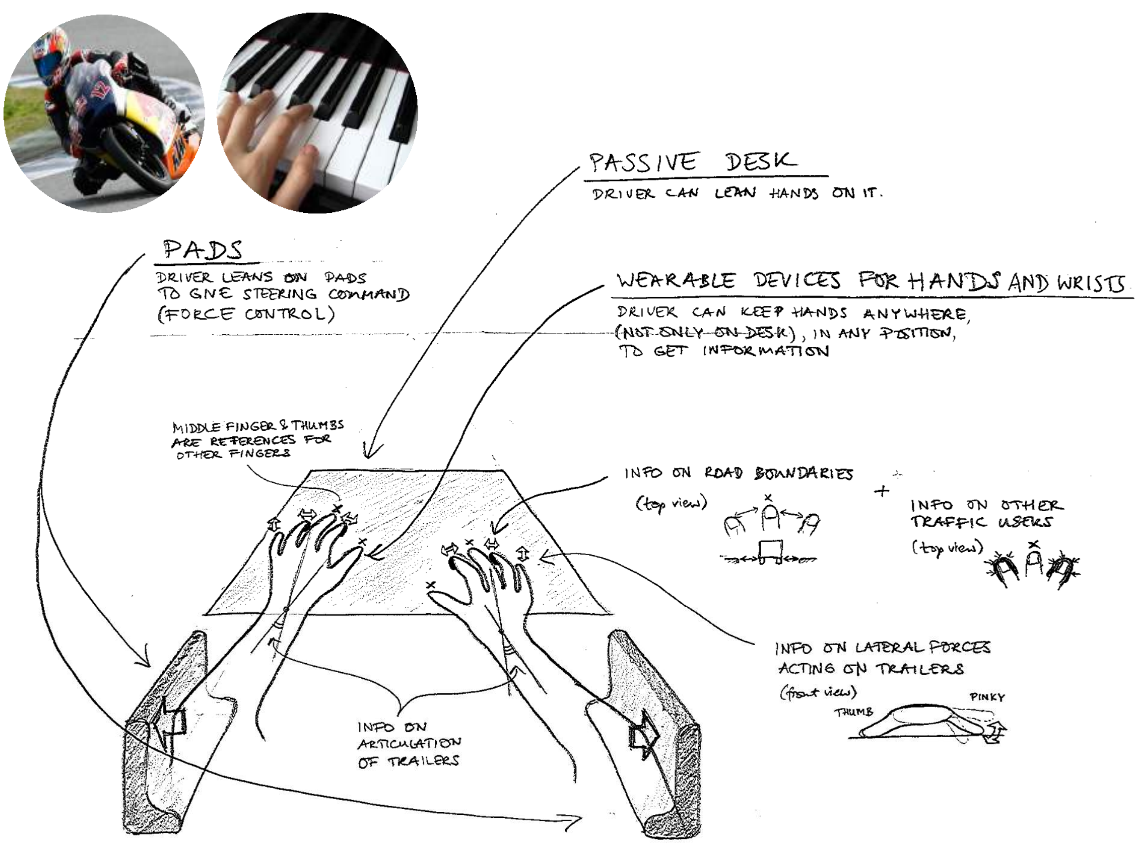


Figure 19. Sketch of Concept 5 (Elbow-Steering). Sources of inspiration include motor racing [40], and piano playing [41].

Concept 6. One-Arm-Control

The sixth concept is mainly inspired by haptic technologies that are used in products such as the CyberGlove [28].

The driver wears a mechanical device on one hand to both give steering commands and receive information. Surfaces that are attached to the hand palm and fore arm represent respectively the first and second trailer. Rotations of a surface give information about the articulation angle through skin stretch and information about the lateral forces acting on the trailer through pressure. Pressure or vibrations applied next to the surfaces give information about the distance to the road boundaries and about other traffic users nearby.
Steering commands are given by moving the two pairs of fingers on each side of the middle finger.

The main advantage of this concept is that the driver only uses one hand, so that the other hand is completely free from any device or task. Also, the reference for both the information and the steering command is the middle finger. There is thus total freedom of posture.

The main concern is that the driver undoubtedly needs to wear a device on the arm, which is not desired for comfort reasons. Furthermore, as the hand can be orientated freely in space, there is a risk that information about direction is interpreted incorrectly. Finally, there are risks of tickles on the hand palm and pain due to frequent skin stretch.

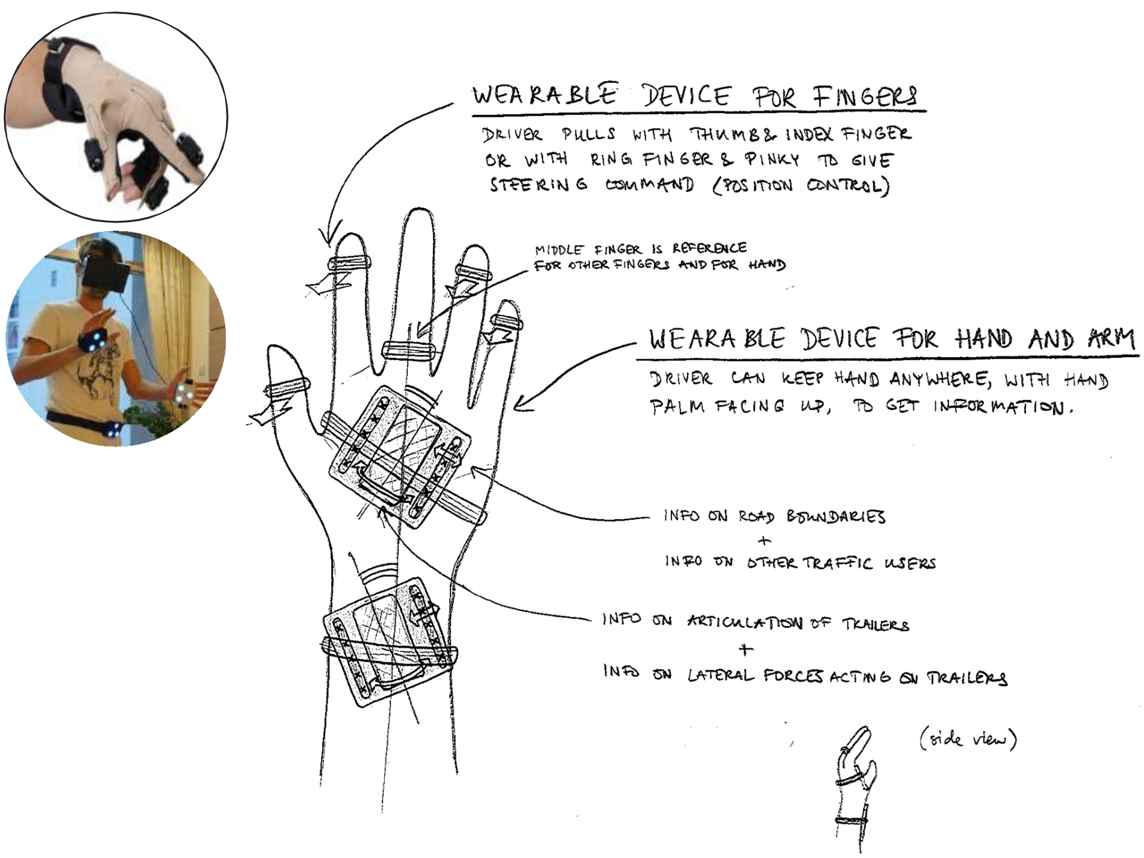


Figure 20. Sketch of Concept 6 (One-Arm-Control). Sources of inspiration include the Virtual Techologies Inc's CyberGlove [28] and Intellect Motion's iMotion [21].

Choosing the Concept for the New Steering Interface

All six concepts have their own strengths and weaknesses. A rating chart, in which every concept is given a score on different criteria, is a powerful tool to better understand the value of each concept. The purpose of the chart is not only to *assess* different concepts, but also to *distinguish* concepts from each other.

The criteria have carefully been chosen according to this purpose, and organized into the following groups: safety, comfort, intuitiveness, accessibility, and originality. The rating chart is shown in Figure **22** on the next page. A detailed explanation on the rating criteria can be found in Appendix H.
The concepts have been rated by first giving a score on the criteria ranging from 1 to 5, with 5 being the best. Then, every score has been weighed according to a weight factor. Even though the scores and the weight factors have been chosen with the utmost care and through an iterative process, I would like to stress the high level of subjectivity. The motivation for the scores on each criterion for each concept can be found in Appendix H.

As can be seen in Figure 21 below, concept 1 had the highest rating of all concepts. The strength of this concept lies mainly in the intuitiveness, both of giving steering commands and receiving information, and in the freedom of choosing which posture to take and which body part to use.

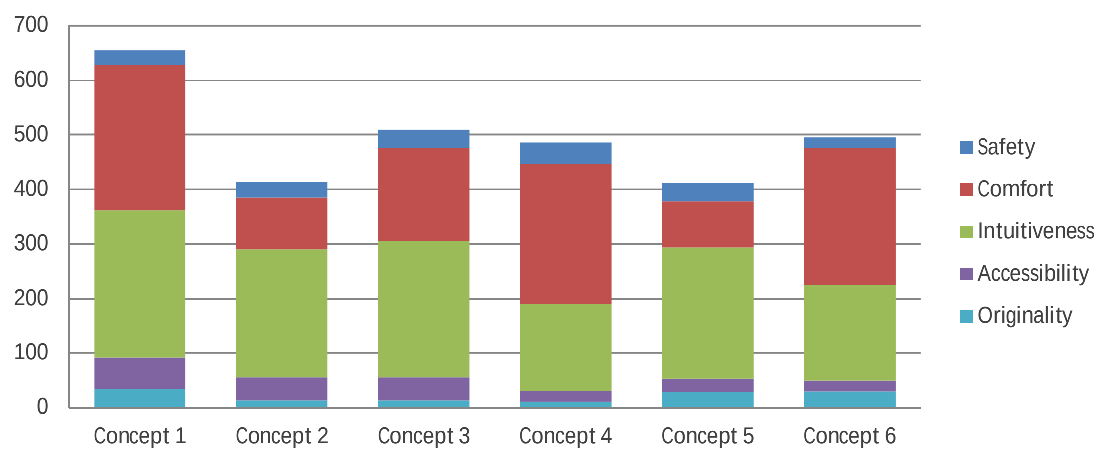


Figure 21. Rating scores for all six concepts. Diagrams of the scores per group of criteria can be found in Appendix I.

Even though concept 1 had the highest overall rating, it did not have the highest score on every criterion. This finding was the reason to further analyse the chart and key points extensively so as to find room for improvement. The concept has finally been improved in two aspects.
First of all, the body comfort and the freedom of posture both have been improved by adding a desk to support the fore arms and by adding a horizontal part to each vertical wall. This way the driver can lean and rest the arms while giving steering commands and receiving information.
Furthermore, the continuity of receiving information from the touch panel has been improved by adding an option to pan and zoom. This way the size and proportions of the surfaces on the panel can be made appropriate for the specific information that the driver wants or needs to receive. In addition, tactile information is given from the sides, whenever important information cannot be presented on the panel without loss of proportion.

This refined version of concept 1 is taken as the concept for the new steering interface. It will be further designed and evaluated in the next two chapters.

RATING CRITERIA	weight factor	CONCEPT 1 Push-Steering unweighed score	CONCEPT 1 Push-Steering weighed score	CONCEPT 2 Double-Thumb-Steering unweighed score	CONCEPT 2 Double-Thumb-Steering weighed score	CONCEPT 3 Double-Wrist-Steering unweighed score	CONCEPT 3 Double-Wrist-Steering weighed score	CONCEPT 4 Single-Wrist-Steering unweighed score	CONCEPT 4 Single-Wrist-Steering weighed score	CONCEPT 5 Elbow-Steering unweighed score	CONCEPT 5 Elbow-Steering weighed score	CONCEPT 6 One-Arm-Control unweighed score	CONCEPT 6 One-Arm-Control weighed score
Safety	*(8)*												
operational safety	*5*	5	25	5	25	5	25	5	25	5	25	1	5
passive safety possibilities	*3*	1	3	1	3	3	9	5	15	3	9	5	15
Comfort	*(65)*												
precision comfort for giving command	*15*	5	75	2	30	3	45	5	75	1	15	4	60
body comfort, when giving command	*10*	3	30	2	20	4	40	5	50	1	10	5	50
body comfort, when receiving feedback	*10*	3	30	1	10	5	50	4	40	1	10	2	20
freedom of posture, when giving command	*10*	4	40	1	10	1	10	5	50	2	20	5	50
freedom of posture, when receiving feedback	*10*	4	40	1	10	1	10	3	30	2	20	5	50
freedom of which body part to use when giving command	*5*	5	25	2	10	2	10	1	5	1	5	3	15
freedom of which body part to use when receiving feedback	*5*	5	25	1	5	1	5	1	5	1	5	1	5
Intuitiveness	*(65)*												
representation of steering command	*15*	5	75	1	15	5	75	2	30	4	60	2	30
representation of information about vehicle articulation	*10*	5	50	5	50	1	10	3	30	2	20	2	20
representation of information about lateral forces	*5*	3	15	5	25	4	20	1	5	3	15	2	10
representation of information about road boundaries	*10*	5	50	3	30	3	30	1	10	4	40	2	20
representation of information about traffic users	*10*	5	50	4	40	4	40	1	10	3	30	2	20
continuity of information	*15*	2	30	5	75	5	75	5	75	5	75	5	75
Accessibility	*(12)*												
accessibility from driver's side	*2*	4	8	1	2	1	2	5	10	2	4	5	10
absence of devices to be attached to body	*10*	5	50	4	40	4	40	1	10	2	20	1	10
Originality	*(8)*												
originality of giving command	*5*	5	25	2	10	2	10	1	5	4	20	3	15
originality of feedback	*3*	3	9	1	3	1	3	2	6	3	9	5	15

Figure 22. Rating chart for all six concepts.

4. Conceptual Design of the New Steering Interface

Summary: In the conceptual design, automation allows the vehicle combination to follow a lane at a certain speed. The driver controls the lateral position of the truck within the lane or the adjacent lane, by controlling the position of two physical walls in the cab. The driver can easily associate his or her body with the truck, and the walls with the lane boundaries. An active touch panel in front of the driver presents haptic information as a map of the truck combination and its surroundings.

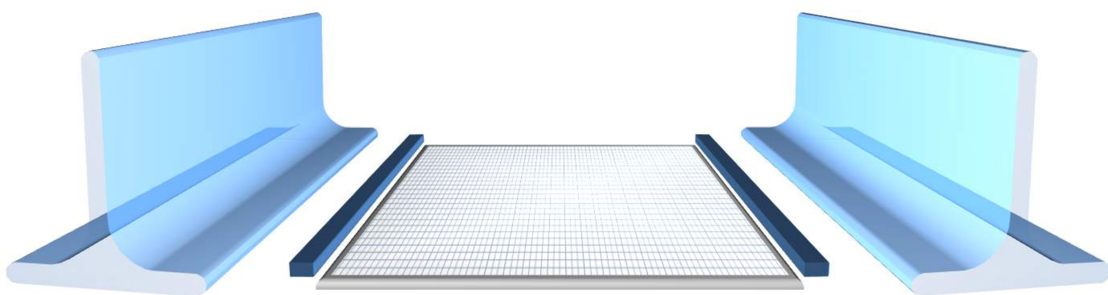


Figure 23. Image of the new steering interface: the walls, the touch panel, and two rows of air vibration generators.

Figure 23 shows an image of the new steering interface. Before going into the actual design of the new steering interface, I would like to make clear that the purpose of this chapter is not to present a full and complete technical design. Instead, the purpose is to explore the technical possibilities within the concept, and to present merely a *conceptual* design. Quantities and dimensions are therefore only given to make the conceptual design concrete or to give an indication for any further designing.

Lane Steering

In the conceptual design, automation allows the vehicle combination to follow a lane at a certain speed. The vehicle combination is for example equipped with cameras that detect the lane boundaries, or with GPS that accurately provides the location of the vehicle combination. The speed is either controlled by the driver or the automation.

Lane steering allows the driver to control the lateral position of the truck with respect to the boundaries of the lane in which the vehicle combination currently is, see Figure 24. The driver does so by controlling the position of two physical walls in the cab. The idea is that the driver can easily associate the lateral position of the truck between the lane boundaries with the position of his or her own body between the walls. In other words, the driver's body represents the truck, and the walls represent the lane boundaries. It is for this particular reason that the driver sits in the middle of the cab, that is to say not on the left or right side.

Besides lane steering there are possibilities within the concept for *free steering*. Free steering allows the driver to control the heading of the truck, without the vehicle combination following any particular lane or course, see Figure 24. The interaction for free steering is somewhat more complicated and less elegant than for lane steering. Free steering will be treated in more detail in the next chapter.

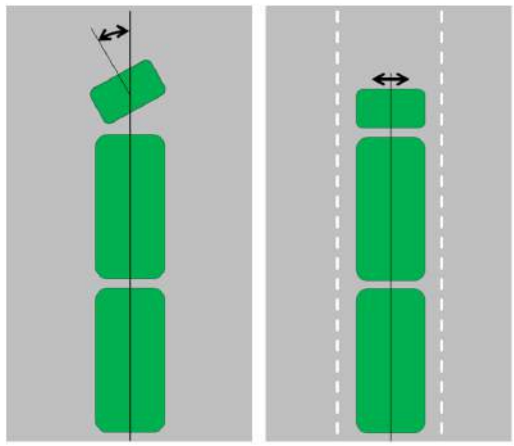


Figure 24. Left: lane steering, where the driver controls the lateral position of the truck. Right: free steering, where the driver controls the heading of the truck.

Functional Design of the Steering Command

The functional design of the steering command describes *how* the driver operates the walls to control the lateral position of the truck.

<u>Steering Scenarios</u>

The following steering scenarios demonstrate the basic principles of giving steering commands.

- The driver drives the truck in the middle of the lane by simply not pushing the walls to either side, thereby allowing the walls to keep centre position. This steering action requires zero effort. The hands can rest on the horizontal part of the walls. The corresponding top view of both the road and the cab are shown in the left picture of Figure 25 below.

- The driver avoids an obstacle on the right by pushing either one of the walls to the right. The position of the driver's body with respect to the walls moves to the left, so the truck will also move to the left. Once the entire vehicle combination has passed the obstacle, the driver can steer back to the centre of the lane by either pushing one of the walls to the left or by simply letting the walls take centre position. The corresponding top view of both the road and the cab are shown in the right picture of Figure 25 below.

- The driver makes a lane change to the left by pushing either one of the walls to the far right until it reaches a certain threshold. The left wall is then automatically moved to take a position that now represents the left boundary of the new lane. The position of the right wall is automatically fixed. So as the truck moves to the new lane on the left, the left wall moves closer to the driver's body, but the right wall remains at a fixed position that is on the far right. Once the truck has taken centre position in the new lane, the right wall is automatically moved to take position that now represents the right boundary of the new lane. The corresponding top view of the road and the cab are shown in Figure 26 below, for each step.

- The driver overtakes another vehicle by making two lane changes according to the above.

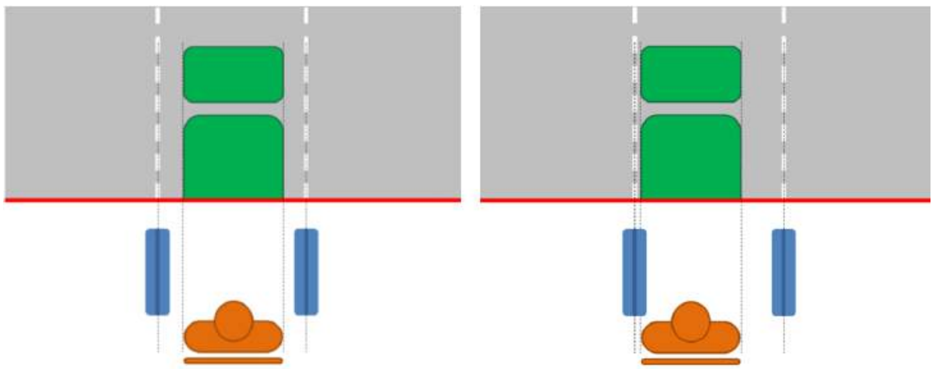


Figure 25. Schematic top view of the road and the cab. Left: the driver drives in the middle of the lane. Right: the driver avoids an obstacle on the right.

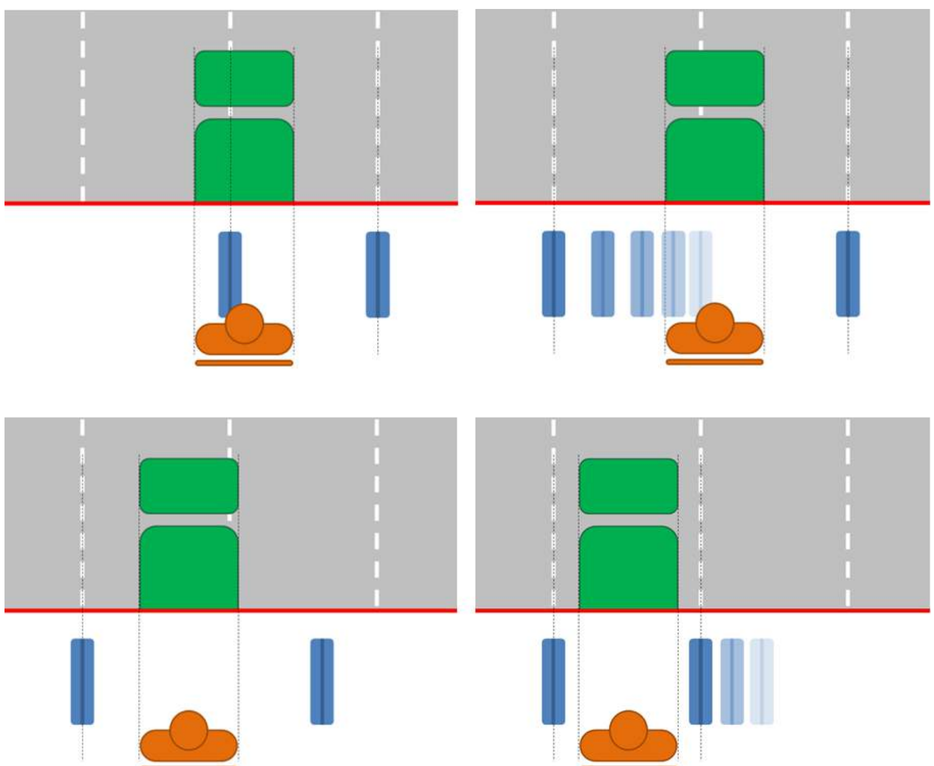


Figure 26. Schematic top view of the road and the cab. The driver makes a lane change to the left. Top left: the driver pushes the walls to the far right. Top right: the left wall is automatically moved to a new position and the right wall is automatically fixed. Bottom left: the truck moves to the new lane. Bottom right: once the truck has taken centre position in the new lane, the right wall is automatically moved to the new position.

Control Schemes

The functional design of the steering command will be explained in more detail using the control schemes that follow.

First of all, let us consider the overall control scheme of the lateral position of the truck, u, using Figure 27 below. In order for it to follow a desired value, $u_{desired}$, the driver gives a steering command by setting the position of the walls, d. In order to do so, strictly spoken, the driver uses both feedback and feedforward control. The value of d is multiplied by a gain G to obtain the reference value for the automated controller, u_{ref}. It is up to the automated controller to ensure that the truck will be positioned properly and according to the steering command. The entire latter part of the overall control is considered to be the steering control system, as indicated in the figure.

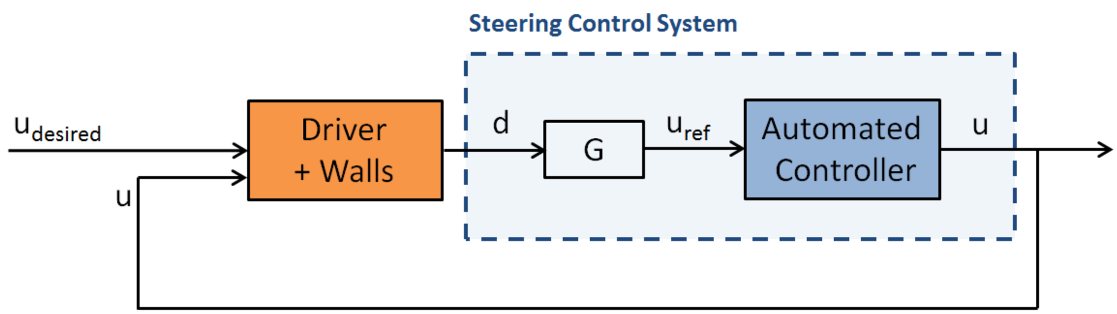


Figure 27. The overall control scheme of the lateral position of the truck, u.

Let us now consider the block 'Driver + Walls' in more detail, using Figure 28 below. The driver can perceive the lateral position of the truck, u, by simply looking through the windows at the lane boundaries, by looking at the position of the walls, or even by feeling the position of the walls. Whenever the lateral position that is perceived, is different from what is desired, $u_{desired}$, the driver can try to correct the lateral position with $u_{command}$, by moving the walls accordingly with $d_{command}$. The mental model that is used by the driver, is simply the inverse of the gain G. Then, the driver uses a mental model of the mechanics of the walls to determine what force to apply on the walls, F_{driver}. The result is the actual position of the walls d, which is the steering command Input 1 that the interface receives from the driver.

The simplicity and clarity of both mental models, and the general absence of perturbations and disturbances, allow for proper and effective feedforward control. To be clear, as mentioned before, in order to steer and make steering commands, the driver uses both feedforward and feedback control.

The simplicity of the relationship between u and d, which is just a gain, particularly contributes to the intuitiveness of the interface. As mentioned before, the driver can easily associate the lateral position of the truck between the lane boundaries with the position of his or her own body between the walls. The scheme from Figure 28 is therefore claimed to be perceived by the driver as the one from Figure 29, in which the variations on u are replaced by similar variations on d. As a consequence, the feedback on u in Figure 28 can even be eliminated.

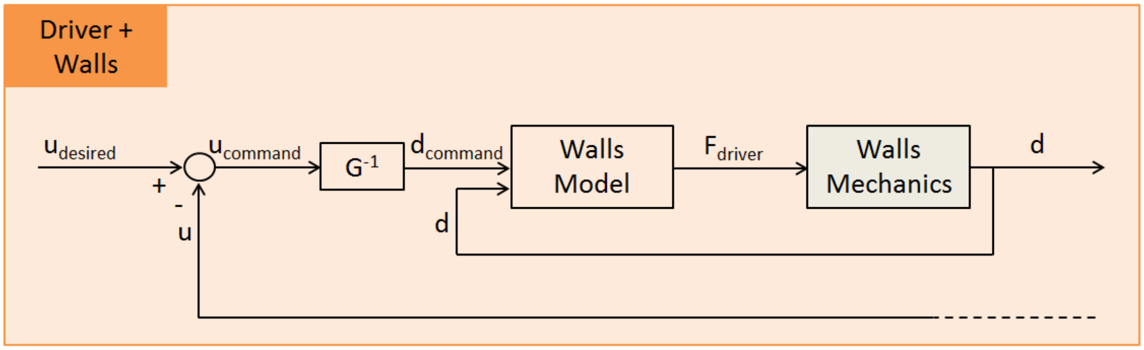


Figure 28. Content of block 'Driver + Walls'. The driver is somewhat simplified, as it is assumed that the perceived value of *u* is accurate and even equal to the actual value of *u*. Also, the mechanics of the walls depends on the position of the walls *d*, hence the feedback to the driver. The feedback in this loop does thus *not* serve as a reference value.

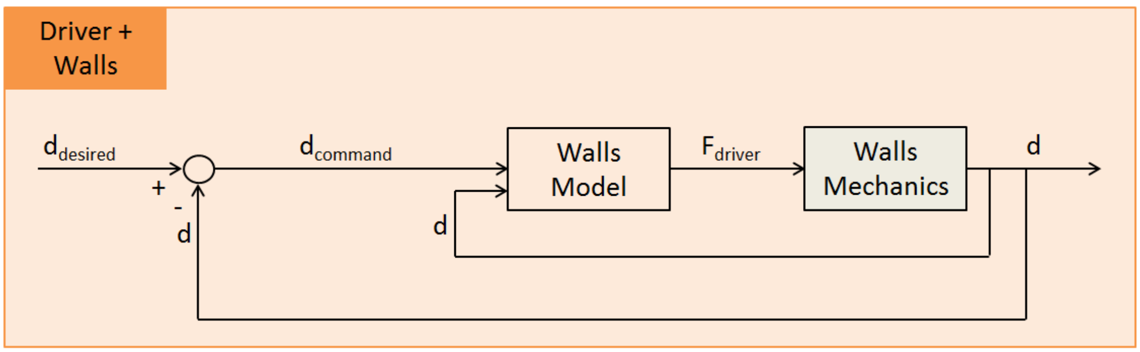


Figure 29. Content of block 'Driver + Walls', as claimed to be perceived by the driver.

Mechanics of the Walls

The mechanics of the walls can be actively controlled using motors, which means that it can be shaped into literally anything we want. For the conceptual design, the mechanics is kept relatively simple. The corresponding control scheme, which is shown in Figure 30 below, is basically similar to that of a mass-spring-damper system with damping $c(\dot{d})$ and stiffness $k(d)$. So when the walls are in equilibrium, there is a one-on-one relationship between the applied force and the position of the walls.

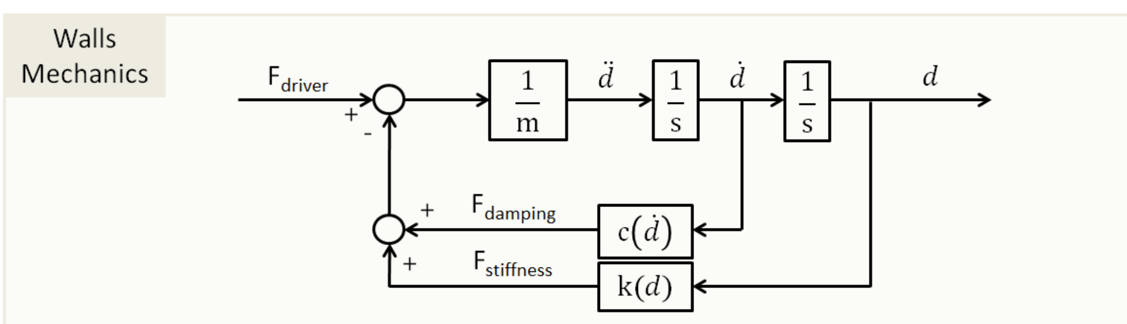


Figure 30. The mechanics of the walls is basically similar to that of a mass-spring-damper system.

There are basically three forces that act on the walls, as depicted in Figure 31 below. There is a force applied by the driver, F_{driver}, and there are resulting resistive forces delivered by a motor, $F_{damping}$ and $F_{stiffness}$. The damping force, $F_{damping}$, depends on $\dot{d}$ and is controlled in such a way that the system is critically damped or over-damped. The stiffness force, $F_{stiffness}$, depends on d and is controlled according to a predefined stiffness profile that in fact represents $k(d)$.

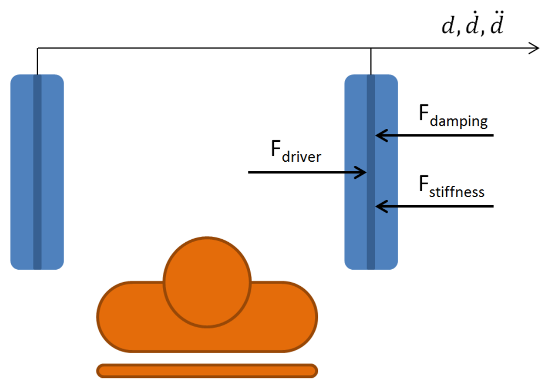


Figure 31. Forces that act on the walls. The forces $F_{damping}$ and $F_{stiffness}$ are delivered by a motor.

Figure 32 shows three stiffness profiles that I believe to be the most reasonable. Each one of these profiles can be represented by a function that is strictly increasing. The stiffness at every point is positive. In other words, the more the driver wants to push the walls from the centre position, the more force needs to be applied.

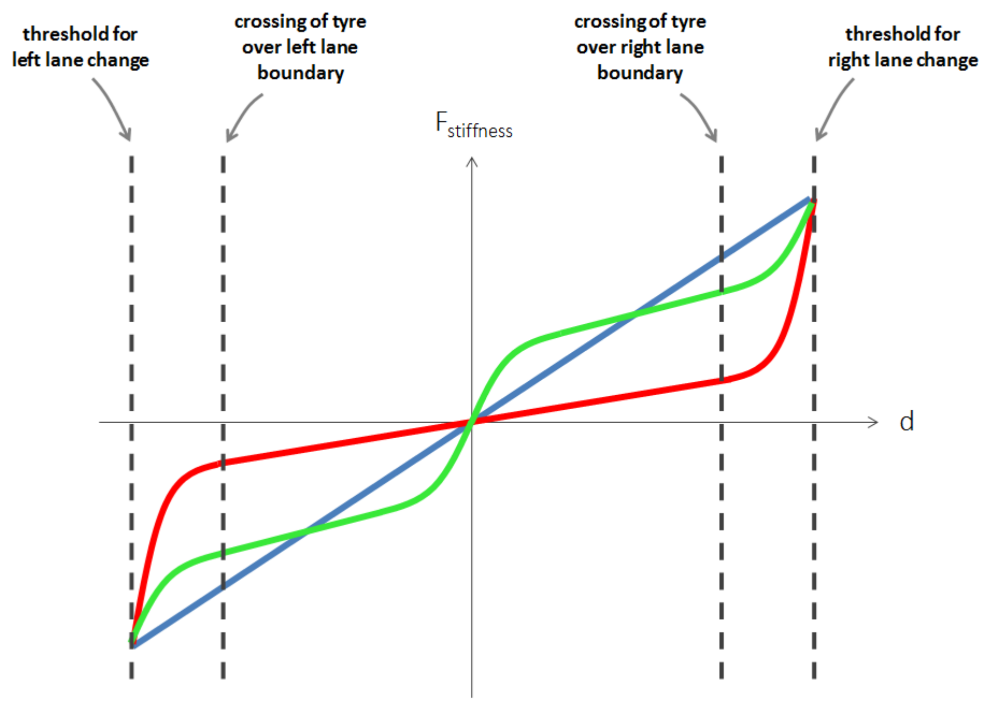


Figure 32. Three stiffness profiles of the walls, for which holds that the driver needs to increase the applied force in order to move the walls further from the centre position. The green profile is adopted for the conceptual design.

The blue profile is the simplest one of the three profiles from Figure 32 above, and can be compared with that of a linear spring. The red profile is only linear when the tyres of the truck are between the lane boundaries. Once the tyres cross the boundaries and up until the threshold that marks the start of a lane change, the stiffness increases as the walls move further away from the centre position. The green profile is even nonlinear near the origin. In this area, the stiffness is high at the centre position, but it decreases as the walls move away from the centre position.

Figure 33 below shows variants of the three profiles from Figure 32. These profiles can be represented by a function that is monotonically increasing. The stiffness at every point is either positive or zero. In other words, if the driver wants to push the walls further away from the centre position, either the same amount of force or an increased amount of force needs to be applied.

The green profile from Figure 32 above is adopted for the conceptual design. It is believed to add the most value of all profiles, as it is meaningful, yet logical and easy to understand. The first mental model for the driver is thus simply this profile.

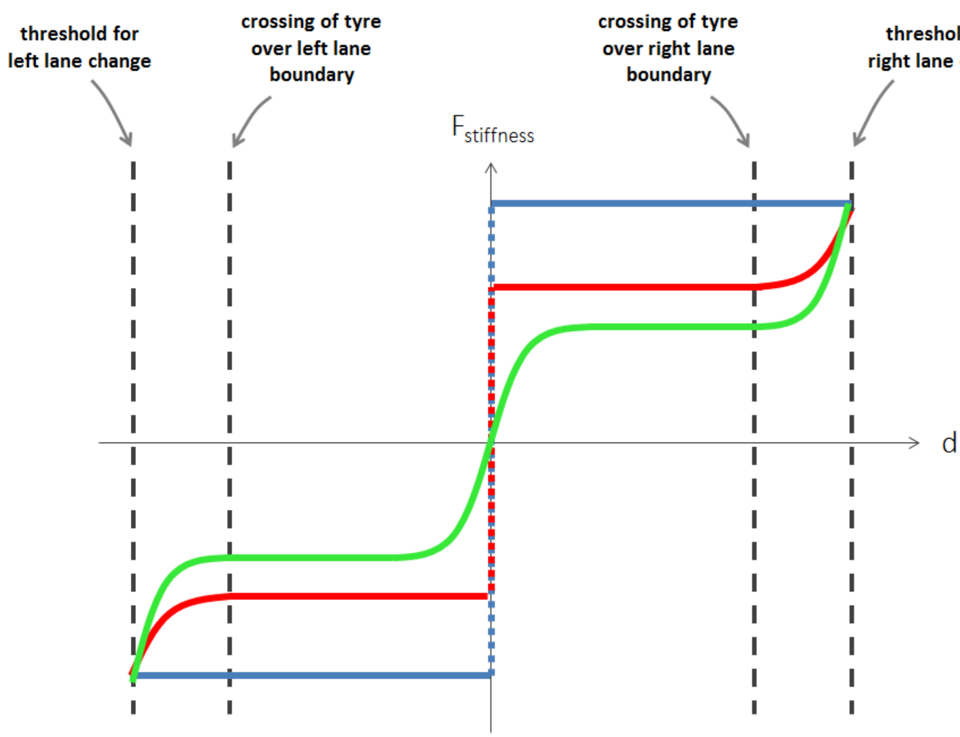


Figure 33. Three alternative stiffness profiles of the walls, for which holds that the driver needs to either maintain or increase the applied force in order to move the walls further from the centre position.

Alternative for the Mechanics of the Walls

An alternative for the mechanics of the walls is based on the actual dynamics of the truck. The force needed to move the walls is made proportional to the actual lateral force needed to move the truck accordingly. Figure 34 to Figure 36 below show the corresponding control schemes. The lateral force acting on the truck is represented by $F_{lateral}$. For each increment of u, $F_{lateral}$ is measured and compared

to the force that is applied on the walls by the driver, F_{driver}. Hence, the feed of $F_{lateral}$ in all three schemes serves purely as information and not as a force to be applied on the walls.
This kind of mechanics might seem intuitive at first sight, as the force that the driver applies on the walls represents the lateral force that is applied on the truck. The driver could therefore associate the forces acting between his or her own body and the walls, with the lateral forces acting between the truck and the road. However, there is a risk that the driver incorrectly perceives the applied force, because the dynamics of the body and the walls can be heavily influenced by movements of the cab.
Moreover, the mental model for the driver becomes rather complex, because it incorporates the actual vehicle dynamics. The position control of the walls becomes a second-order control[1] task and the driver needs to act as a double integrator. It is therefore questionable whether the driver can easily understand what force to apply in order to get the desired position of the walls.
In addition, the automated controller does not directly apply a lateral force on the truck. Rather, it controls the steering angle and measures the lateral force on the truck that results from it. There is thus a by definition a time lag that could mislead the driver and cause confusion or low accuracy of the control.

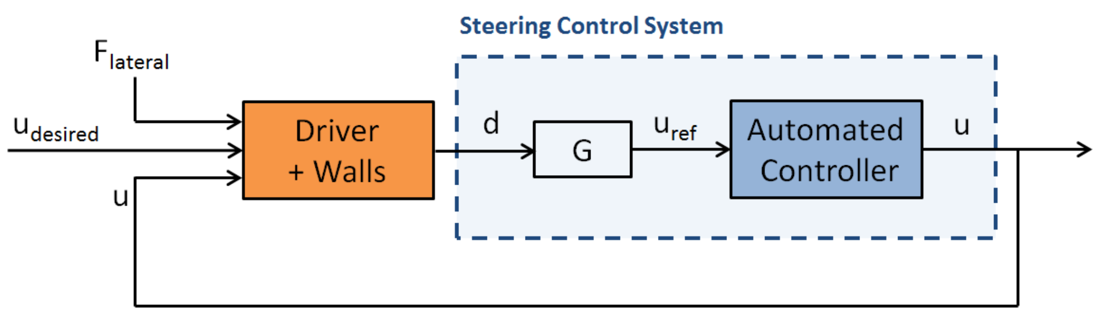


Figure 34. An alternative overall control scheme of the lateral position of the truck, *u*. The mechanics of the walls is based on the actual dynamics of the truck. $F_{lateral}$ represents the lateral force acting on the truck. The feed of $F_{lateral}$ serves as information, and hence not as a force to be applied on the walls.

Figure 35. Content of block 'Driver + Walls' for the alternative mechanics of the walls. First, the force applied by the driver on the walls, F_{driver}, is measured. Then, the position of the walls, d, is incremented. The lateral position of the truck, u, is incremented accordingly. For each increment of u, the lateral force acting on the truck, $F_{lateral}$, is measured, scaled, and compared to F_{driver}. The feed of $F_{lateral}$ serves as information and should not be mistaken for a force to be applied on the walls.

[1] Order of control denotes the number of integrations between the human's control movement and the output of the system being controlled. It is the highest derivative in the differential equation. [26]

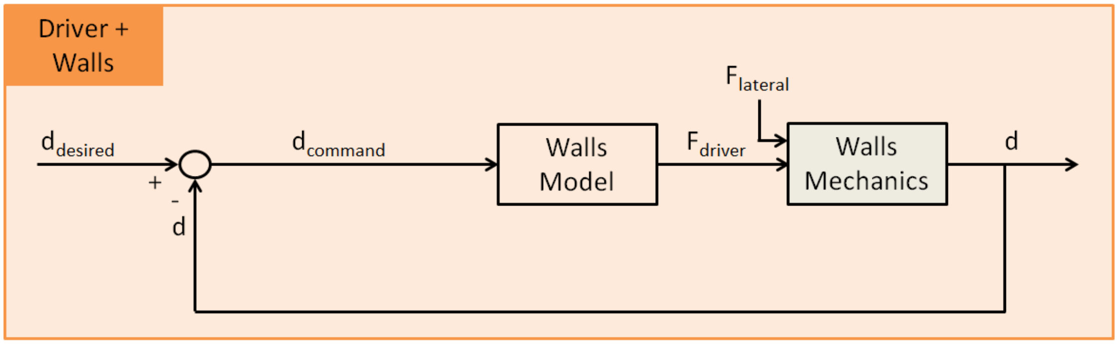


Figure 36. Content of block 'Driver + Walls' for the alternative mechanics of the walls, as claimed to be perceived by the driver. As mentioned earlier, the feed of $F_{lateral}$ serves as information and should not be mistaken for a force to be applied on the walls.

Automated Controller

Although the automated controller plays an important role in the steering interaction, it is *not* part of the steering interface. The block 'Automated Controller', which is shown in Figure 37 below, will therefore be explained only briefly.
The automated controller receives the value u_{ref}, which is simply the actual position of the walls d multiplied by the gain G. The controller uses this value as a reference for the actual lateral position of the truck u. It compares the two values to each other and determines the necessary correction, u_{corr}. The controller then uses a P, PI, or PID controller[2] that is based on a model of the steering mechanism, to determine what steering angle to apply. The result is the actual lateral position of the truck u.

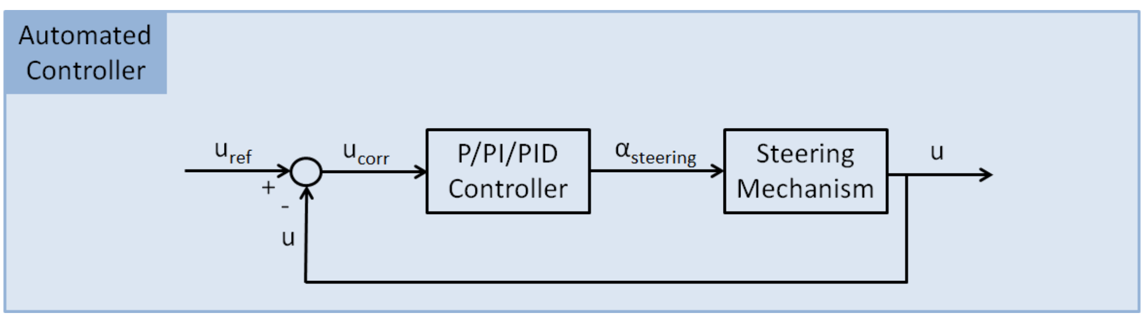


Figure 37. Content of block 'Automated Controller'

[2] A proportional-integral-derivative (PID) controller is a control loop feedback mechanism that tries to minimize the error by adjusting the process through use of manipulated variables.

Physical Design of the Walls

The dimensions of the walls for the conceptual design are shown in Figure 38 below and are mainly based on my own preferences. I would like to emphasize again that the dimensions merely serve as a concretization of the conceptual design or as an indication for any further designing.
The height of the walls is kept low, so that the driver can easily hold the walls or move a hand over to either side of them. In fact, the walls can be both pushed and pulled. A low height of the walls is also preferred for safety reasons, because it lowers the risk of the driver hitting them in case of heavy braking or in case of a collision. The cross-sectional profile is chosen is such a way that the arms can lean or rest on both sides of the walls. Other cross-sectional profiles that would be appropriate are shown in Figure 39 below.

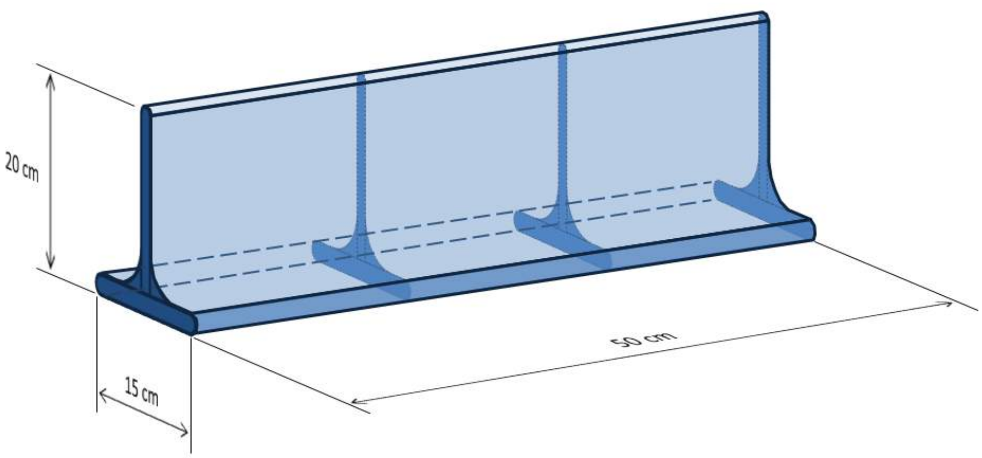


Figure 38. Dimensions of the walls, based on personal preferences.

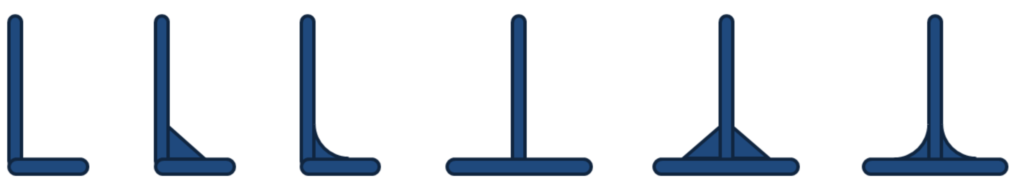


Figure 39. Cross-sectional profiles of the walls. The one on the far right is adopted for the conceptual design.

The material of the walls for the conceptual design is chosen to be transparent plastic. Plastic has a comfortable temperature at room temperature and does not need to be heated or cooled. Any kind of surface roughness for a comfortable grip can also be realized. Transparent walls do not block the view, but can still be seen by the driver. A downside of transparent plastic is that dirt and finger prints are easily visible.

If needed, visual information could be given that is simple and aesthetic. For example, during lanechanges the walls could light up with a specific colour. Also, if needed, tactile input from the driver could be sensed using technologies such as capacitive sensing. Disney has for example developed a system called Touché, which is based on this technology [42].
Similar characteristics of the walls could also be accomplished with other materials, such as metal, wood, rubber, textile, and leather. Still, plastic is believed to be the best suitable material.

Each wall is equipped with a motor, a force sensor and a position sensor. The force sensor measures the applied force, F_{driver}, and the position sensor measures the position of the walls, d. The motor moves the wall according to the green stiffness profile from Figure 32. During lane changes, depending on the side of the lane change, the motor either fixes the wall or moves it so that it represents the outer boundary of the new lane.

Figure 40. Transparent plastic. Left: sheets of different thickness [43]. Centre: bent sheet serving as photo frame [44]. Right: boxes lit up with led lights [45].

Functional Design of the Haptic Information

The functional design of the haptic information describes how the driver both *senses* and *perceives* the information that is presented by the active touch panel and the air vibration generators.

<u>Traffic Situations</u>

The following traffic situations demonstrate how the driver uses the touch panel to sense the haptic information. Information is given in such a way that the driver perceives a map of the surroundings in which the truck takes centre position.

- The truck combination is following a straight lane. Other trucks and cars are driving on the same or adjacent lane. One hand is on the panel and rests on the surfaces that represent the truck and trailers. The driver can constantly feel surfaces that represent the road boundaries and moving surfaces that represent passing trucks or cars on the adjacent lanes. The corresponding top view of the touch panel is shown in the top left picture of Figure 41 below.

- The truck combination is following a modestly curved lane. Other trucks and cars are driving on the same or adjacent lane. The driver feels the surfaces that represent the trailers moving both in plane and out of plane. The in-plane movements inform about the articulation angles and the position of the trailers with respect to the truck. The out-of-plane movements represent the roll of each trailer and inform about the lateral force acting on it. The driver also keeps track of the road boundaries and trucks or cars that are in particular getting close to the truck combination. The corresponding top view of the touch panel is shown in the top right picture of Figure 41.

- The truck combination is following a sharply curved lane on an intersection. All kinds of other traffic users are crossing or approaching the intersection, including vulnerable cyclists and pedestrians. The driver uses two hands to closely keep track of the traffic users. The corresponding top view of the touch panel is shown in the bottom left picture of Figure 41.

- The truck combination is following a straight lane that is soon to be joined by another lane. The trucks and cars driving on it are still at a relatively far distance from the truck combination, so they are not yet presented on the touch panel as moving surfaces. In order to inform the driver about the upcoming traffic, an air vibration is sent from aside towards the driver's hand that is on the surface that represents the truck. That same hand is used to pan towards the upcoming traffic, while the other and is used to keep track of the upcoming traffic. As the two lanes are close to joining, the driver pans back and continues with one hand on the panel. The corresponding top view of the touch panel is shown in the bottom right picture of Figure 41.

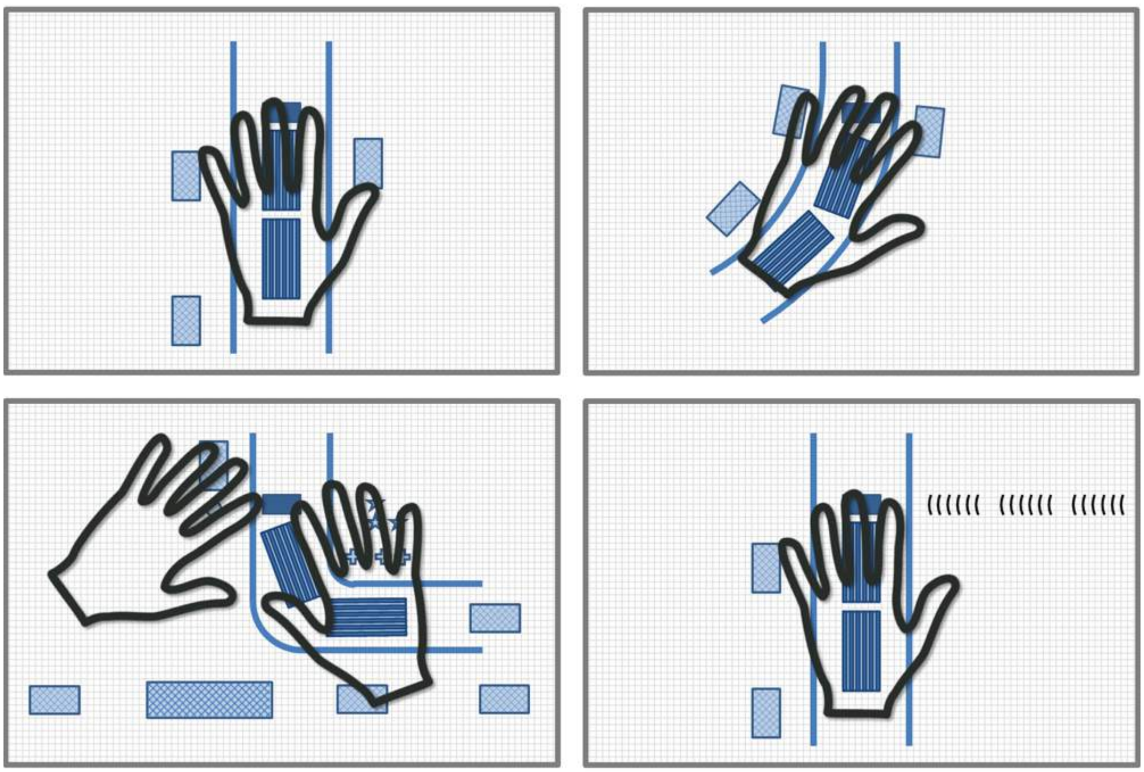


Figure 41. Schematic top view of the active touch panel. Top left and top right: the driver uses one hand to feel how the truck combination follows a lane with other trucks and cars on adjacent lanes. Bottom left: the driver uses two hands to closely keep track of other traffic users on an intersection. Bottom right: the driver feels an air vibration from aside that informs about upcoming traffic.

<u>Sense and Perception of State of Truck Combination</u>

The surface on the touch panel that represents the truck is flat. It is the reference for all other surfaces on the panel and most of the time it is not moved by the driver. The surfaces that represent the trailers are ribbed in such a way that movements, particularly in-plane movements, can be sensed and recognized easily. Figure 42 shows the surfaces that represent the truck and the trailers. The dimensions of the surfaces are non-proportional and will be treated later on in the chapter.

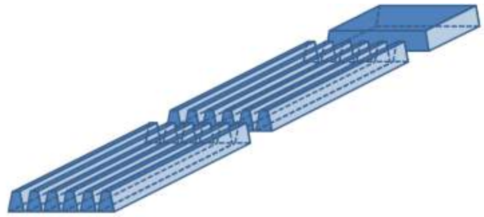


Figure 42. Surfaces on the touch panel that represent the truck (flat) and the trailers (ribbed).

The in-plane movements of the ribbed surfaces are combinations of both translation and rotation. The position of the surfaces informs the driver about the position of the trailers. In fact, the angles between the surfaces, which are shown below in the left picture of Figure 43, are exactly the same as the articulation angles that are measured directly from the actual truck combination.
The out-of-plane movements of each ribbed surface are limited to rotation along its longitudinal axis, as shown below in the right picture of Figure 43. The rotation should not be mistaken for a scaled-up representation of the actual roll of the trailers. In fact, the rotation is not intended to inform about the roll of the trailers. Instead, it is intended to inform about the lateral force acting on the trailers, which is directly measured from the actual truck combination. Even though lateral force and roll are closely related, they are not necessarily one-on-one related, especially when there are anti-roll systems involved.

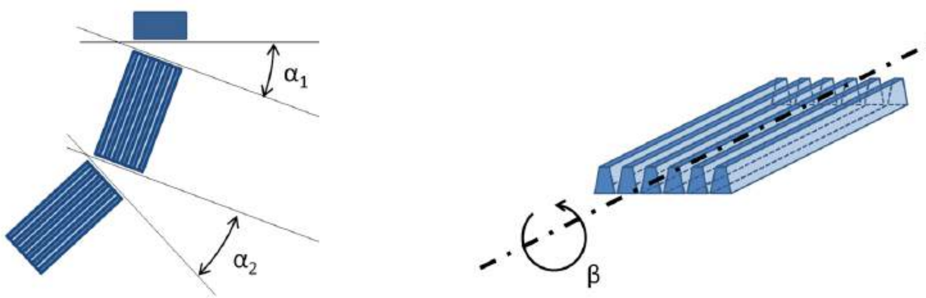


Figure 43. Surfaces that represent the trailers. Left: the angles α_1 and α_1 on the touch panel are exactly the same as the articulation angles of the actual vehicle combination. Right: the angle β informs about the lateral force acting on a trailer.

Sense and Perception of State of Surroundings

Road boundaries are represented on the touch panel by rims. The two rims next to the surfaces that represent the truck combination, inform the driver particularly about the clearance between the actual truck combination and the road boundaries. Figure 44 below shows these two rims. The clearance is scaled onto the panel in such a way that the driver can easily feel the rims.

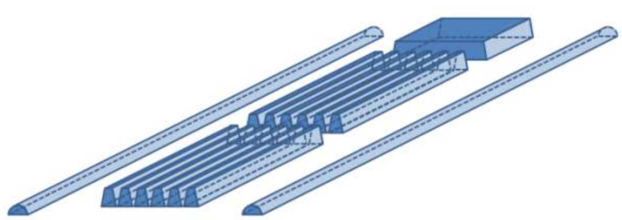


Figure 44. Two rims that inform about the clearance of the road boundaries.

Traffic users in the nearby surroundings of the truck combination are represented by surfaces that have a specific shape according to the type of traffic user, as shown in Figure 45 below. Cars and trucks are represented by rectangular shaped surfaces. Both the size and the roughness of the surface allow the driver to distinguish them from one another. Motor cyclists, cyclists, and pedestrians are represented by small and smooth surfaces. They can be distinguished from one another by the different shapes.

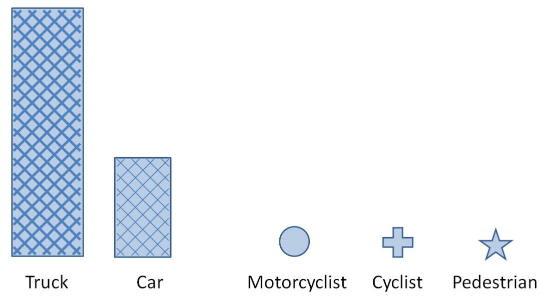


Figure 45. Surfaces that represent different traffic users in the nearby surroundings.

The position and size of each traffic user are scaled onto the panel to fit a certain grid. The grid is not constant throughout the entire panel. Between the rims it is based on the scaling of both the length and the width of the truck combination, whereas outside the road boundaries it is based entirely on the scaling of the length of the truck combination. The grid is yet again different near the rims, where it is somewhat stretched in the direction perpendicular to the rims. The differences in grid require smooth transitions. Figure 46 below shows so called isodistances that are used for the transition of the grid outside the rims. All points on an isodistance are at equal distance from the nearby lane boundary.

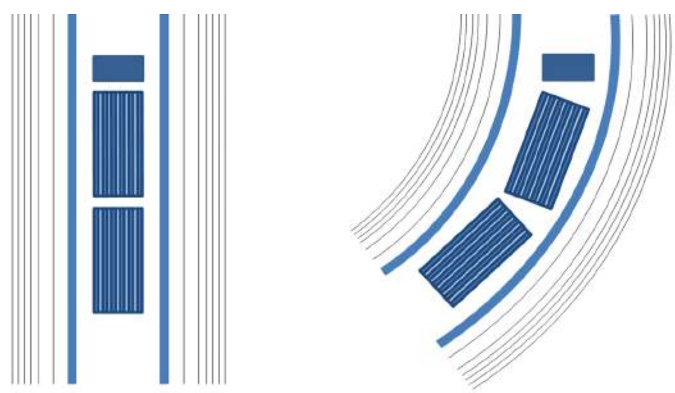


Figure 46. Isodistances for smooth transitions of the grid outside the rims. All points of an isodistance are at equal distance from the nearby lane boundary.

If there is upcoming traffic that the driver should be informed about, but it is too far away to be presented on the touch panel, then an air vibration is sent from aside towards the driver’s hand, as shown in below. The vibration is sent from a direction that corresponds to a virtually mapped position of the traffic user, as shown in Figure 48 below. So for example, if a car is mapped outside the touch panel on the lower left corner, then a vibration is sent from the lower left corner and it is directed towards the driver’s hand.

An air vibration can carry only a limited amount of information through amplitude, frequency, and time duration. For the conceptual design, the vibration varies only in amplitude and frequency. The amplitude informs the driver about the distance to the truck combination, whereas the frequency informs about the velocity component towards the truck combination. Figure 48 below shows examples of air vibrations that inform about different upcoming traffic users.

Figure 47. An air vibration that is sent from aside, just above the touch panel. Air vibrations inform about upcoming traffic.

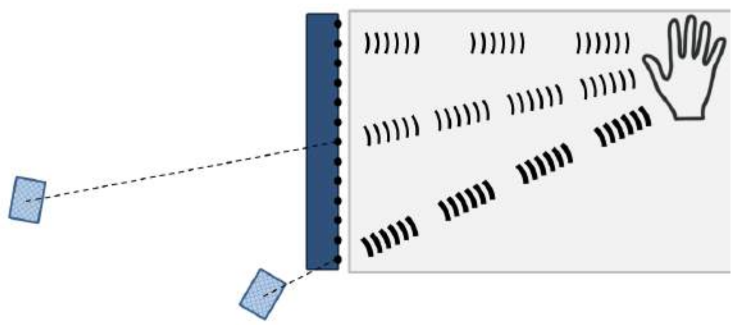


Figure 48. Air vibrations that are sent from virtually mapped positions of traffic users. The amplitude of a vibration is high for traffic users nearby. The frequency of a vibration is high for traffic users approaching at high speed.

The driver can pan towards the upcoming traffic by softly pushing the surface that represents the truck, away from the centre of the panel. The other hand can then be used to keep track of the upcoming traffic, as shown in Figure 49 below. The driver can pan back by simply releasing the pressure on the surface that represents the truck, which will then automatically move back to the original centre position.

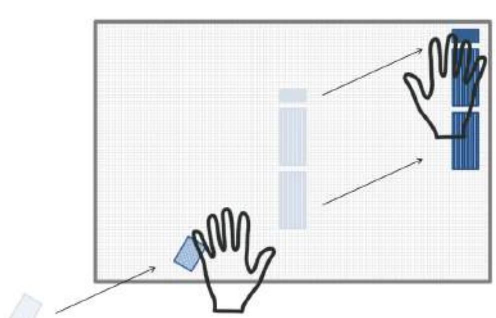


Figure 49. Panning towards upcoming traffic. The driver uses one hand to pan, and another hand to keep track of the traffic.

Physical Design of the Active Touch Panel

The shape of the panel for the conceptual design is square, and the dimensions are given in Figure 50 below. An interesting alternative is a circularly shaped panel, which makes perfect sense for mapping the surroundings of a vehicle. However, unlike a square panel, it does not optimally use the available space between the walls. The dimensions of the panel are chosen in such a way that the walls cannot cross over the panel as long as the truck is driving in a lane, while allowing comfortable positions for the arms and hands. As a final note, there are also alternative cross-sectional shapes for the panel, as shown in Figure 51 below.

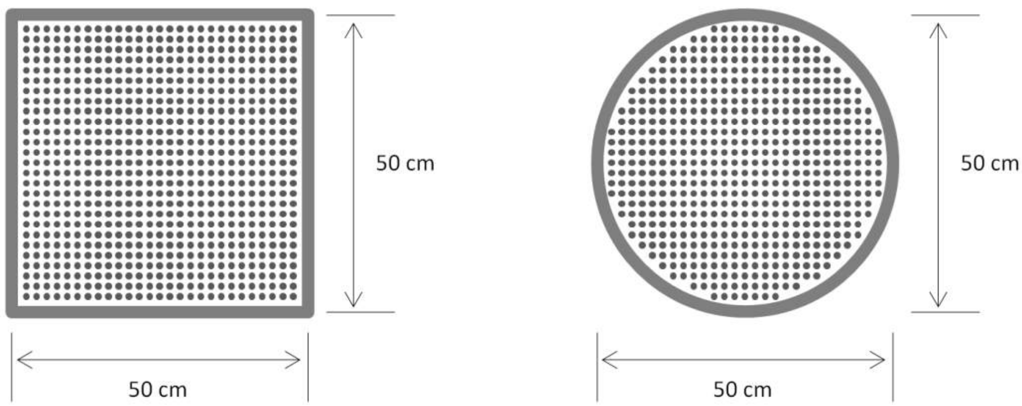


Figure 50. Dimensions of the touch panel. The square shaped panel is adopted for the conceptual design.

Figure 51. Cross-sectional shapes for the touch panel. The flat shape is adopted for the conceptual design.

The touch panel consists of an array of small vertical pins, that each have three degrees of freedom, as shown below in Figure 52. The vertical movement of the pins allows surfaces on the panel to be created almost instantly. A surface can appear and disappear, and even change size or shape, by simply letting a specific combination of pins move up or down. Obviously, the precision of position and the level of detail of surfaces both depend on the resolution of the panel.

Even though the driver can constantly feel and touch these created surfaces, it might be difficult to understand how the shape and position on the panel change with time. In fact, it might be difficult to even perceive moving surfaces, as there are no actual surfaces or objects moving horizontally. In order to give the driver the sensation of moving surfaces, additional shear stress is applied on the skin, using rotational movements of the pins.

Besides imitating moving surfaces, the pins also need to be able to sense forces that are applied by the driver during panning. Furthermore, if it is desired to provide the driver with visual information through the panel, the pins can light up. It might be useful to for example light up each created surface with a specific colour.

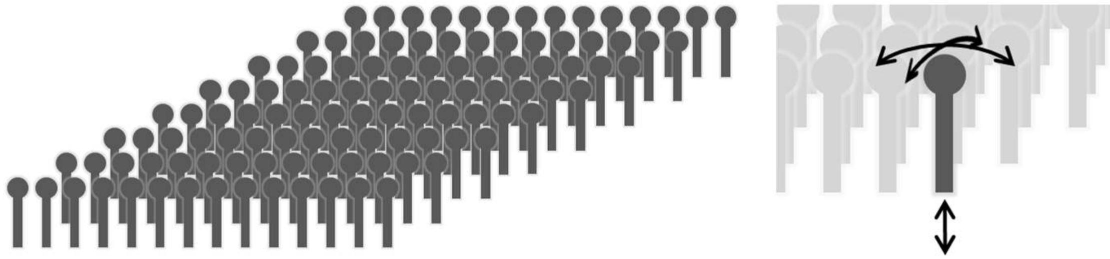


Figure 52. Construction of the touch panel. Left: part of the array of small pins. Right: the degrees of freedom for each pin.

Figure 53. Principles of motion that are similar to that of the touch panel. Left: fictive table display from the film 'X-Men' (2000), that can also almost instantly create surfaces [46]. Right: crowd surfing, where many hands pass on the surfer by moving up and down, and sideways [47]. The hands have similar degrees of freedom as the pins from the touch panel.

Physical Design of the Air Vibration Generators

Multiple small devices along the right and left side of the touch panel can send air vortices. An air vortex retains its shape and velocity, until it hits something and collapses, thereby releasing a pressure. When a sequence of air vortices hits the driver's hand, it can be perceived as an air vibration with a certain amplitude and frequency. The air vortices can be generated using a system such as AIREAL, which is developed by Disney. The original purpose of the AIREAL system is to provide haptic sensations in free air, so as to enhance the interaction with virtual objects [30].

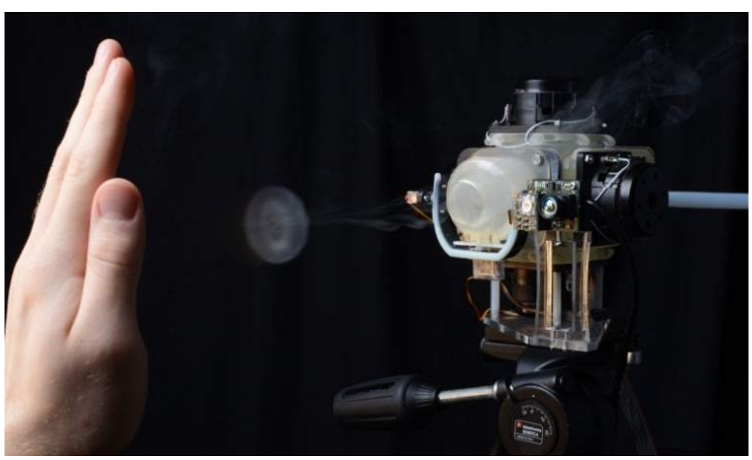


Figure 54. Disney's AIREAL, that generates air vortices [30]. A sequence of air vortices can be perceived as an air vibration.

5. Evaluation of the Conceptual Design

Summary: The main strength of the new interface lies in the high level of intuitiveness. Physical prototypes with simplified functionality have given insight about the comfort, the intuitiveness, and the effectiveness, and have helped to imagine what the new driving experience would be like. The prototype of the touch panel consists of a modified flipdots board. The prototype of the walls consists mainly of a plastic U-shape and has also been tested in a real truck on a test track.

Any design for human-machine interaction needs to go through an iteration of design cycles. The evaluation is not only the final part of a design cycle to be finished, but it is also the base for a new design cycle to be started. Proper and clean evaluation of a design is thus important, but probably just as difficult. A good first step is to analyse the technical value of the design on paper, so as to gain insight into the strengths and weaknesses of the design.
However, it remains a challenge to determine the impact it might have on the long term and how it will evolve. People need time and experience to become familiar with new interfaces and new haptic technologies, especially when it comes to an activity such as driving, which is so deeply integrated in our culture. Physical prototypes can offer a first experience with the interface and help to share opinions, thoughts, and even emotions.

Technical Assessment of the Conceptual Design

The rating chart from the chapter 'The Search for a New Steering Interface' has given a first indication of the technical value of the conceptual design. It is a good starting point for analysing the design in terms of *safety*, *comfort*, and *intuitiveness*.

- Regarding *safety* during normal driving, there has been found no major risks for the driver to get hurt or injured. There are no sharp edges, no hard objects near the head, no parts sticking out to the torso or head, and no evident risk of getting electric shocks. However, the driver should bear in mind that the walls are moved automatically during lane changes. Regarding safety during a crash, or even during severe braking, the driver needs to be protected from both the panel and the walls. Passive safety features, such as collapsible parts, have not been considered within this project, and are still to be designed.

- Regarding the *comfort*, there has been found no reason for any awkward posture, strain, or fatigue. The driver can continuously take a comfortable posture, and the panel and walls offer sufficient support. There is much freedom in articulating and positioning the fingers and the wrist, and there is even room to move the torso without necessarily interfering with the steering. Not a single body part is forced into any position. The range of the walls, together with the mechanics of the walls, can be chosen in such a way that the precision of control is also comfortable. Furthermore, the presented information has been designed in such a way that the risk of an overload of information is kept low. Moreover, there are no devices or whatsoever to be worn or attached to the driver's body, which means that in that sense there is no preparation necessary before driving.

- Regarding the *intuitiveness*, the interface has been designed from the very start to allow the driver to easily associate the vehicle with his or her own body. The intuitiveness of the entire design is therefore based on the definition for steering intuitively from the chapter 'A New Steering Interaction'. The intuitiveness of the walls is believed to be achieved by proper positioning of the walls, proper dimensions of the walls, and the simple and elegant relationship between u and d. The driver can therefore easily associate the truck with his or her own body. The intuitiveness of the touch panel is believed to be achieved by both the fixed reference point of the truck and proper dimensions of the surfaces that represent the truck combination. The driver can therefore associate the truck and trailers with the fingertips or parts of the hand.

The design can even further be analysed in terms of *effectiveness*. The effectiveness of the design is closely related to the intuitiveness and therefore it deserves great attention. As a matter of fact, the effectiveness plays a defining role in answering the question of whether or not the purpose of this project is fulfilled: 'to find a new steering interaction that allows the driver to intuitively steer an articulated truck combination, while constantly being aware of the situation'.

Surely, at this stage of the design, the effectiveness cannot be proven. For now, we can only reason and argue. The effectiveness depends on a range of different aspects from the interface.

- Firstly, the effectiveness depends on the driver's ability to understand what information is available and especially what information is crucial. The functionalities and dimensions of the touch panel and the air vortex generators are designed, or still to be designed in more detail, in such a way that the risk of missing critical information is minimal. The idea is that the driver does not need to constantly feel and touch the entire panel. In fact, with only one hand resting on the panel, the driver can be aware of the state of the truck combination, the lane boundaries, and even traffic users on adjacent lanes.

- Secondly, the effectiveness depends on the driver's ability to correctly perceive and understand the information that is given on the panel. The ribbed surfaces and the fixed reference point of the truck help the driver to feel and understand the position of the trailers. The right choice of scaling of the clearance helps the driver to feel the rims and understand the meaning. However, understanding the meaning of out-of-plane rotations of surfaces requires an extra thinking step of translating a position (rotation) into a force. Furthermore, the shapes of the vulnerable traffic users (motorcyclists, cyclists, and pedestrians) are rather arbitrary, so the driver needs practice to learn the meaning of these shapes. Lastly, the sensation of moving surfaces highly contributes to the understanding of how shape and position of a surface change with time. Shear stress applied on the skin not only improves the perception of moving objects, but may also even induce hand movement [29], making it easier for the driver to follow surfaces on the panel.

- Thirdly, the effectiveness depends on the driver's ability to control the position of the walls. The simple and clear stiffness profile of the walls allows the driver to very effectively use feedforward control. The walls give both position feedback and force feedback, and thereby strengthen the driver's perception of the position of the walls. An important consequence of the artificial mechanics of the walls is that the actual dynamics of the truck is not represented through the walls. As reasoned in the previous chapter though, a purely scaled representation of the dynamics through the walls is not preferred.

- Fourthly, the effectiveness depends on the time lag of the actual lateral position of the truck on the position of the walls. Time lag is an inevitable consequence of a second-order system with double integration control. Indeed, due to the steering mechanism, the automated controller must manipulate the steering angle in order to control the lateral position of the truck. For the driver, this time lag translates in the responsiveness of the steering control system. Even though the visual feedback through the windows might be enough for the driver to accept or deal with the time lag, it is desirable to minimize it. There are two options to do so. The first option, which is considered to be the most appropriate, is to design the mechanics of the walls in such a way that the walls move just slowly enough. In other words, the force delivered by the motors is high, but not too high that it becomes uncomfortable for the driver. Another option is to somehow present the pursuit of the lateral position of the truck in the wall, for example by actively controlling the surface roughness or hardness of the wall. The driver then basically receives haptic feedback on the actual position of the truck via the walls.

- Fifthly, the effectiveness depends on whether or not the conditions for lane steering hold. The first condition for lane steering is that there is no need for the driver to control the heading angle or steering angle. After all, this control has been given to the automated controller. The position control of the walls is a zero-order control[3] task. As a consequence, the driver can only control the lateral position of the truck. The second condition is that the assumption about the lane markings actually holds. More specifically, there need to be lane markings present, that can be both detected by the automated controller and seen by the driver.

The fact that the conditions for lane steering are highly critical for the overall effectiveness of the conceptual design, has been the reason to consider at least one alternative to lane steering. As mentioned in the previous chapter, there are possibilities within the concept for free steering. Free steering allows the driver to control the heading of the truck, without the vehicle combination following any particular lane or course. In this case, the driver pushes the walls away as if the walls still continue in the straight forward direction of the truck, with zero heading. The further the driver pushes the walls, the more the heading increases. Figure 55 below depicts three different steering commands with the corresponding change in heading. After the completion of a steering command, the walls take centre position again to represent the current straight forward direction of the truck. This direction serves as a reference for the next steering command. The driver can make a full turn by performing a sequence of steering commands, as shown in Figure 56.

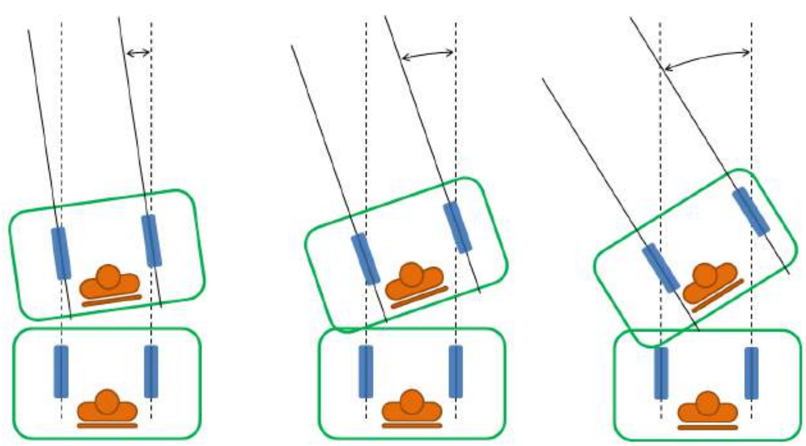


Figure 55. Different steering commands during free steering. The further the driver pushes the walls, the more the heading increases.

[3] Order of control denotes the number of integrations between the human's control movement and the output of the system being controlled. It is the highest derivative in the differential equation. [26]

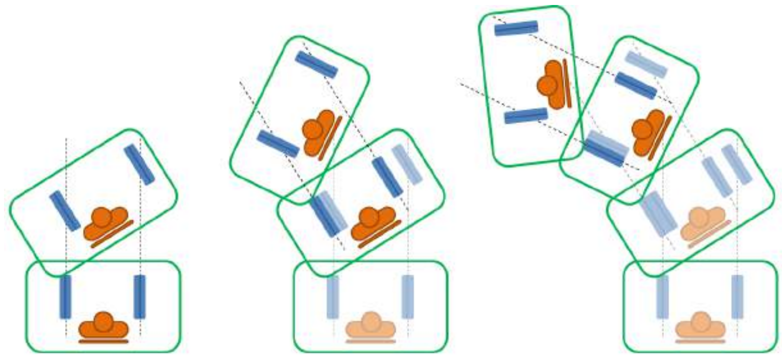


Figure 56. Sequence of steering commands to make a full turn during free steering.

An open question that is left to be answered for free steering is 'When are the walls automatically moved to take centre position?' In other words, 'What determines the end of a steering command?' An intuitive option is to move the walls the moment that the driver lets go of the wall, so when the driver stops touching it. Another option is to move the walls at the end of a certain time interval, for example every 2 seconds. Yet another option is to move the walls every time the truck has travelled a certain distance, for example every 5 meters.

Prototype of the Walls

The purpose of the physical prototype of the walls is threefold. First, it gives the opportunity to see, touch, and hold it, so as to get a sense and 'feeling' of the new interface. It can thereby give inspiration for further possibilities and hints on limitations of the physical configuration. Second, it serves to demonstrate part of the working principle of the walls, both on an office desk and in a real truck. It can thereby help to imagine what the new driving experience would be like. Third, it serves to perform runs in a real truck on a test track in order to observe how real users interact with it. It can thereby give more insight about the comfort, intuitiveness, and effectiveness of the walls.

In accordance with these purposes, the functionality of the prototype has been simplified in multiple ways. First of all, the range of the position of the walls *d* is limited to the corresponding range of the truck within the lane boundaries. In other words, the tyres stay between the lane boundaries and do not cross them. Secondly, stiffness and damping of the walls have been omitted, and simple friction (static and kinetic) is adopted instead. So the driver basically slides the walls without it being attached to a spring, damper, or motor. An important consequence is that the walls cannot take centre position without the driver actually moving it. When the driver leaves the walls in a certain position, the walls will just stay in that particular position. Figure 57 below shows the stiffness profile of the prototype.

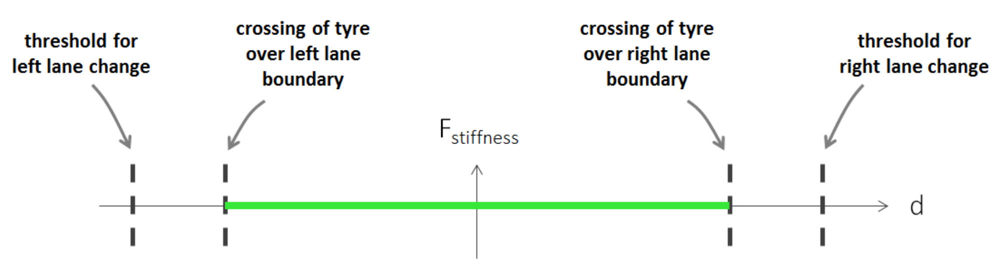


Figure 57. The stiffness profile of the prototype of the walls, showing zero stiffness and a limited range of *d*.

Construction

The simplified functionality and the specific purposes of the prototype have naturally led to a design that is different than the physical design from the previous chapter, yet still based upon it.

Firstly, as the walls are supposed to move together and not individually anymore, the two walls can be connected together to form a U-shape. One piece is easier to handle, and more flexible in terms of orientation and positioning. The U-shape, which is shown in Figure 58, is made of Plexiglas and has been manufactured by a glazier in Gothenburg, Gamlestadens Glasmästari AB. The dimensions are based on not only the conceptual design (see Figure 38), but also on the limited available space in the cab of the test truck. In order to determine the dimensions and range for the prototype, a very first mock-up of the new interface has been made out of cardboard, shown in Figure 59 below.

The thickness of the U-shape was chosen by first just feeling and holding different plastic sheets with different thicknesses at the glazier, then checking the weight[4], and the structural capabilities[5] through rough calculations. There was enough reason for me to believe that the U-shape would hold the lean and push forces, that it would not be too heavy for me to carry, and that the effect of bending on the control of the U-shape would be negligible. Finally, the radius of the curves was kept small, as large radii would make the structure less stiff according to the glazier.

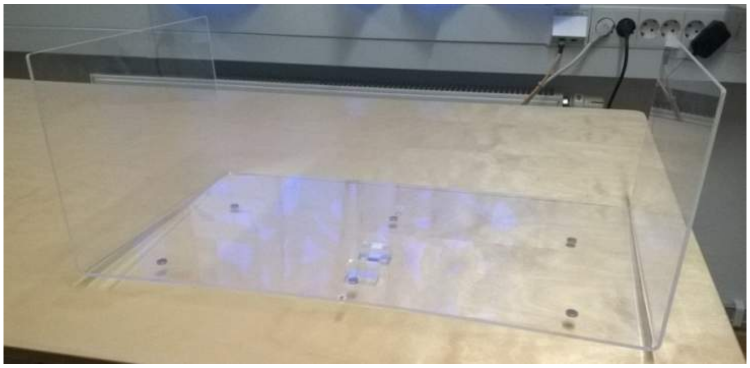


Figure 58. The U-shape as prototype of the two walls, made out of Plexiglas. Dimensions: width 50 [cm], length 30 [cm], height 20 [cm], thickness 0.3 [cm].

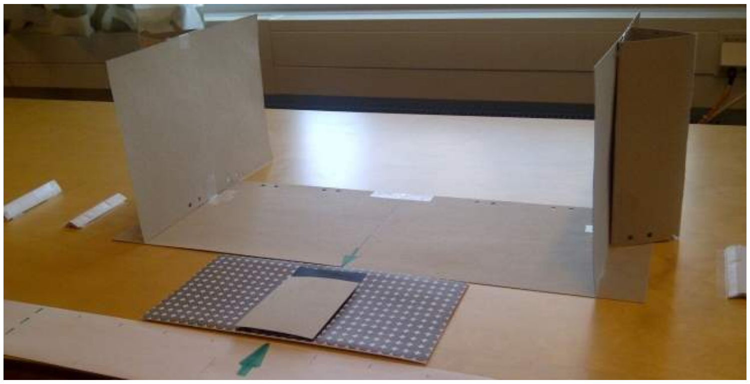


Figure 59. Afirst mock-up of the new steering interface, made out of cardboard.

[4] The weight was estimated to be around about 1 [kg].
[5] Assuming a load of 25 [N] sideward and a total load of 20 [N] downward, the deflections were estimated to be in the order of millimetres, and the stress at the points of connection to be in the order of percentage points of the tensile strength of Plexiglas.

The U-shape is attached on a set of sliders for drawers, as shown in Figure 60 below. The sliders are bought at a DIY (Do-It-Yourself) store in Gothenburg, Clas Ohlson. The particular sliders have been chosen for their flat shape and their direct availability in the store. The sliders are in turn screwed onto a wooden board, which is also bought at Clas Ohlson. A set of 6 magnets is glued both onto the U-shape and the sliders, so that the U-shape can easily be detached and reattached. The magnets on the U-shape are glued in such a way that when the U-shape is flipped, the U-shape is shifted to one side, leaving space for the wrist to lean on the wooden board.

In order to measure the position of the U-shape, a potentiometer is glued onto the wooden board and between the two sliders. The potentiometer is bought from Spectra Symbol at a Swedish distributor of electronics components, Elfa Distrelec[6]. The particular position sensor has been chosen for its simplicity, flatness, and availability. The U-shape makes contact with the potentiometer through a customized pin that I constructed myself, as there were no suitable pins commercially available. The pin and its housing are made of small pieces of plastic and a small spring that ensures continuous contact.

A small plastic block is glued onto the bottom of the U-shape, so that the range of motion can be bounded by a mechanical stop on each side of this plastic block. The stops can easily and quickly be detached and reattached using a Valcro strip that runs along the entire length of the board. Each stop consists of an eraser with a piece of Valcro strip glued onto it.

More photographs and detailed photographs can be found in Appendix J.

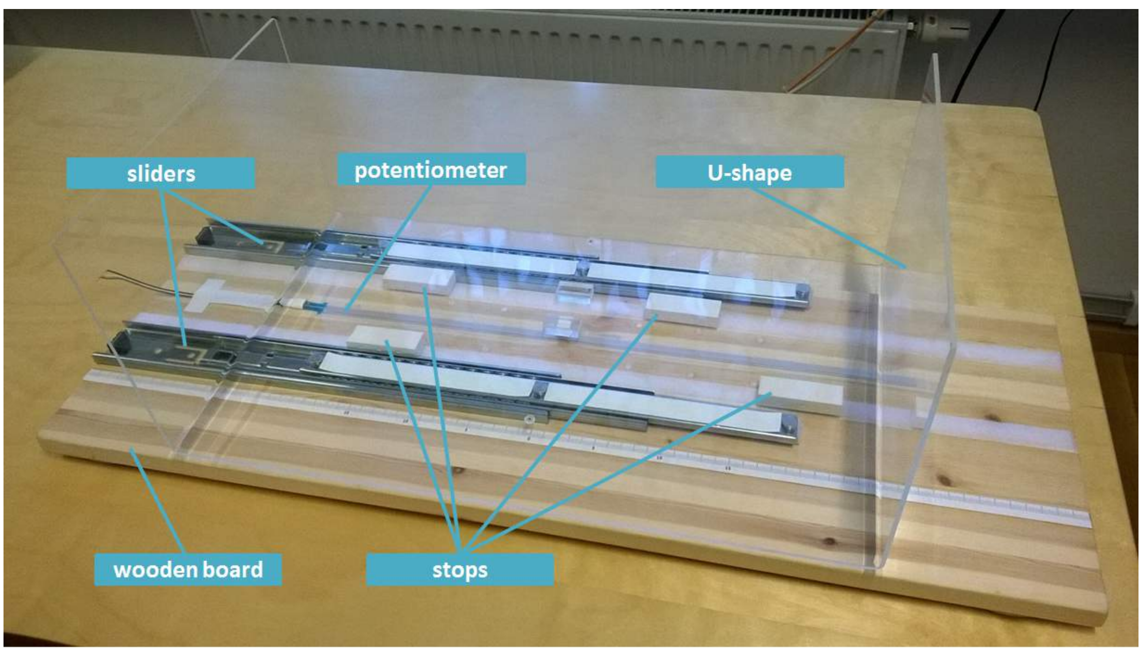


Figure 60. The wooden board with the U-shape, sliders, potentiometer, and mechanical stops.

[6] For specifications of the position sensor for the prototype, see: http://www.spectrasymbol.com/potentiometer/softpot/softpot-diagrams-and-schematics. Manufacturer's article no.: SP-L-500-203-3%-ST. Resistance = 20 [kOhm]. Active Length = 500 [mm].

Testing on the Test Track

The prototype was installed in a test truck in order to perform runs on the test track in Hällered. All runs were performed on the oval-shaped main test track (length 6.2 [km]), during day time with plenty of daylight, on dry roads, and in the presence of a few other test vehicles.

Figure 61. The testing environment. Left: the test track in Hällered. Right: the test truck.

The run plan is shown in Figure 62 below. The test run was performed to get all team members familiar with the procedure and their own tasks, to check whether the recording worked, and to get the driver familiar with operating the new device. After the test run, 6 runs were performed at a speed of 30 [km/h] and then another 6 runs at a speed of 60 [km/h]. During these 12 runs in total, three different ranges of the prototype were adopted: 100, 200, and 300 [mm]. Also, two different contact areas were allowed for the driver to touch: the 'walls', which refer to the vertical parts of the U-shape, and the 'U-shape', which refers to the entire surface of the U-shape, that is the 'floor' and the 'walls'. Finally, a few extra runs were performed to get extra video material and to let other team members drive as well.

Run Plan

Evaluation of Push Steering Walls

Location: Test Track Hällered

Run nr.		Speed [km/h]	Range of device [mm]	Contact area of device
0	test run	30	200	U-shape
1		30	200	U-shape
2		30	200	walls
3		30	300	U-shape
4		30	300	walls
5		30	100	U-shape
6		30	100	walls
7		60	300	U-shape
8		60	300	walls
9		60	200	U-shape
10		60	200	walls
11		60	100	U-shape
12		60	100	walls
13	filming run	30	100,200,300	walls, U-shape

Figure 62. The run plan for the testing.

The test team consisted of 3 people, who each had their own task:

- The **test manager** follows the test protocol and makes sure that all runs are performed and recorded properly. The main tasks include instructing and briefing the team members on the procedures, switching the signal from the prototype on and off between the runs, recording the signal from the prototype on a laptop, video recording the driver on camera, marking the video recordings, and taking notes. The complete test protocol can be found in Appendix K.

- The **driver** operates the U-shape and executes the task given by the test manager. The task is the same for every run:

  - *Start at the left boundary.*
  - *Drive in the middle of the lane.*

  - *Drive next to the right boundary.*
  - *Drive next to the left boundary.*
  - *Drive next to the right boundary again.*
  - *Come back to the middle of the lane.*

  - *Move to the right boundary very fast.*
  - *Move to the left boundary very fast.*
  - *Move to the right boundary again very fast.*
  - *Come back to the middle of the lane very fast.*

  - *Finish at the left boundary.*

  The driver is requested during the runs to try not to look in the mirrors, not to lean heavily on the U-shape, and to relax and enjoy the experience. An additional task is recording signals from the prototype and the truck on a laptop.

- The **safety manager** sits behind the steering wheel and intervenes during the runs whenever necessary. The other task is to maintain the speed that is requested by the test manager. The safety manager should be aware of the limited moving space due to the presence of the prototype.

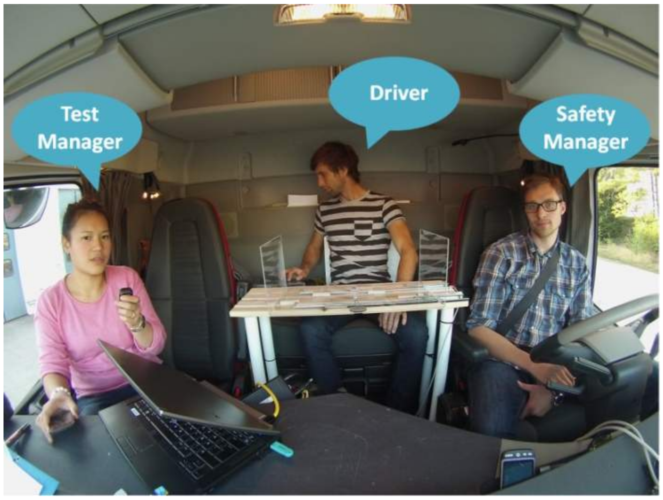


Figure 63. The test team.

The flow chart from Figure 64 below roughly explains how the signal from the prototype is processed in order to control the lateral position of the truck. First of all, the signal from the prototype is sensed by an Autobox[7] named as '1st Autobox'. The laptop that is controlled by the test manager, '1st laptop', receives this signal, records it, and converses it into a signal to be sent to another Autobox named as '2nd Autobox'. The laptop that is controlled by the driver, '2nd laptop', filters this signal, and uses it as a reference for the PID controller[8]. The PID controller, which is based on a steering model, controls the position of the truck by manipulating the steering angle. The signal of the actual lateral position of the truck is also recorded by the '2nd laptop'.

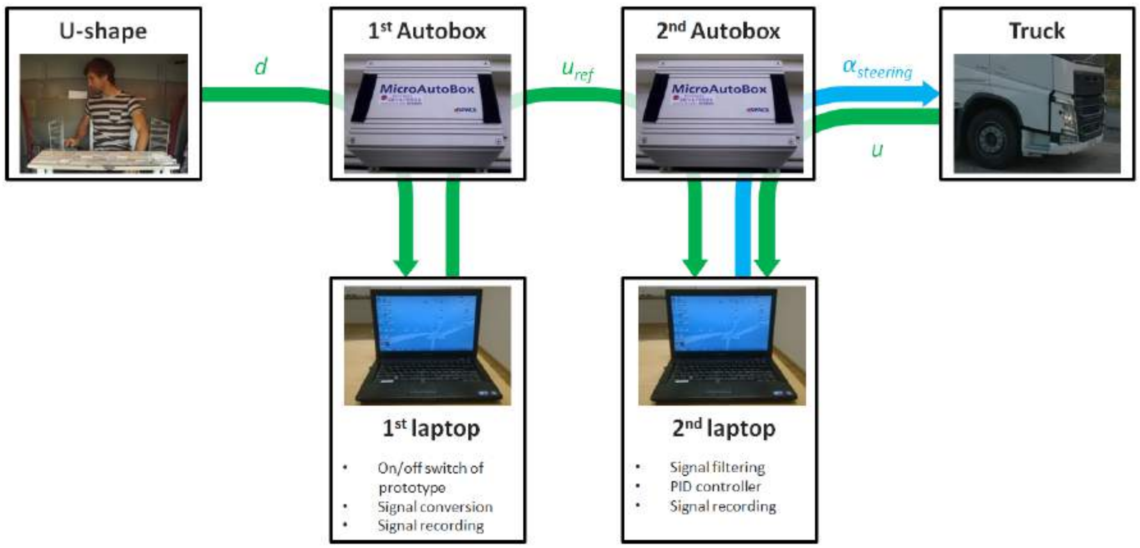


Figure 64. Signal flow chart for testing. The position of the U-shape is sensed, conversed, filtered, recorded, and then used as a reference for the lateral position of the truck.

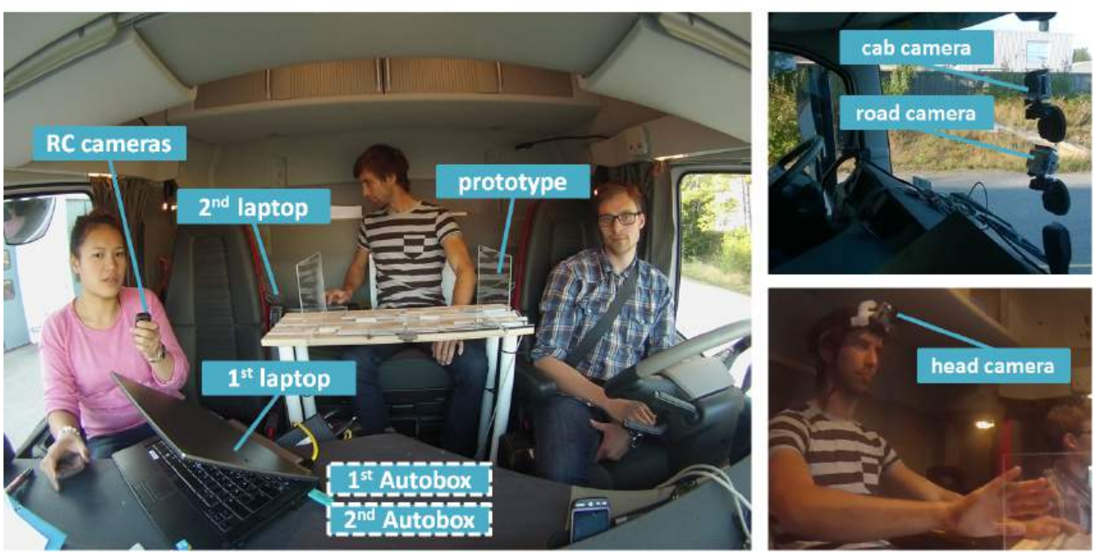


Figure 65. Installation of devices in cab for testing.

[7] A real-time system for performing fast function prototyping.
[8] A proportional-integral-derivative (PID) controller is a control loop feedback mechanism that tries to minimize the error by adjusting the process through use of manipulated variables.

For the purpose of demonstrating the working principle of the walls and getting more insight about the *intuitiveness*, a camera was mounted on the driver's head to capture the driver's view, as shown in Figure 65 above. The stills in Figure 66 below show how the lane boundaries 'move' together with the 'walls' of the U-shape. Even though the stills do not necessarily prove the driver's ability to associate the 'walls' with the lane boundaries, the clear images do strongly suggest that the driver might be able to do so using at least visual information.

The questionnaire that the driver completed afterwards, revealed that it only took a few minutes to understand the principle. He explained that 'when adopting the mindset that the 'walls' were the lane markings, it felt natural' and that it was 'simple to understand'. These statements support the idea that the driver can easily associate the 'walls' with the lane boundaries.

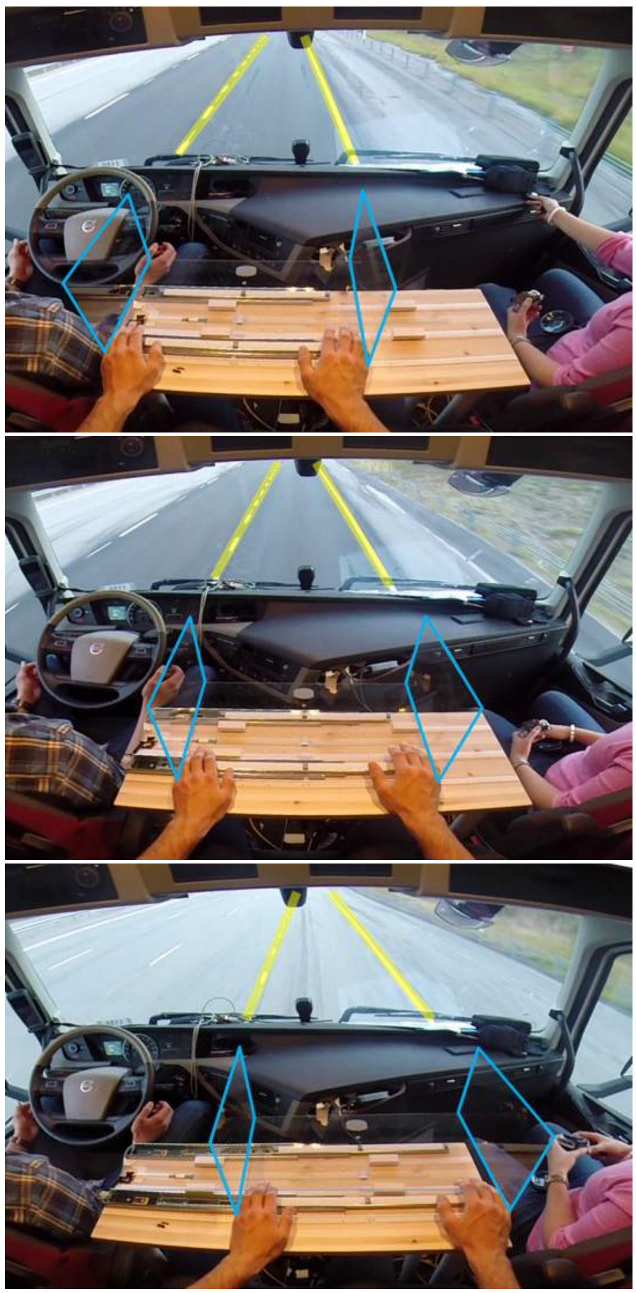


Figure 66. The driver's view during testing. The lane boundaries seem to 'move' together with the 'walls' of the U-shape.

For the purpose of getting more insight about the *comfort* and the *effectiveness*, two cameras were mounted on the front window inside the cab, as shown in Figure 65 above. One camera captured the driver with the prototype, while another camera captured the road. The video recordings allow us to observe the driver carefully and analyse specific aspects of the interaction.

To begin with, from the recordings it seemed that the driver had a comfortable posture. However, in the questionnaire he added that he had bad back support, and that the bed he was sitting on made him bounce. The driver also found it difficult to control the U-shape and hold a certain position when the cab was rolling, especially during aggressive steering manoeuvres. He explained that the U-shape easily moved from the intended position and that he therefore had to use both hands to smoothly make steering manoeuvres. It was easier for him to steer with a large range of the U-shape.

It also seemed that the U-shape together with the board gave sufficient support. The driver continuously leaned on the board during steady position, and sometimes even let go of the U-shape. He seemed to be more comfortable when he was allowed to touch the 'floor' of the U-shape than when he was not allowed to do so. He explained that he liked to rest his hands on the 'floor' and push the 'walls' with one hand while keeping the other on the 'floor'. When the range of the U-shape was small, he sometimes used the 'floor' to move the U-shape. In general, he used the outer side of his hands or his pinkies. Only for fast movements he sometimes used multiple fingertips. The stills in Figure 67 below show common hand positions that the driver used during testing.

Figure 67. Common hand positions of the driver during testing. The driver used mainly the corners of the U-shape as reference and the lower part of the 'walls' to push. Only during the last few runs, when he felt very comfortable and relaxed, he used also higher parts of the 'walls'. Top: the driver is allowed to touch both the 'walls' and the 'floor' of the U-shape. Bottom: the driver is allowed to touch only the 'walls' of the U-shape.

With regard to the mental load, the driver seemed to be relaxed, especially during the second half of the runs when he was talking and laughing. With a few exceptions, he kept his eyes on the road and seemed to be aware of the front surroundings, as he glanced multiple times at road exits or cars passing by. He also glanced a few times at the 2nd laptop when there was a glitch due to loss of signal, and several times at the prototype when he wanted to position the U-shape in the centre. The latter suggests that the driver was not fully aware of the position of the truck in the lane, or that he did not feel sure about it. He confirmed in the questionnaire that he indeed found it difficult to determine the position, especially since he was not able or allowed to use the mirrors.

Lastly, from the synchronous recordings of the two cameras on the front window, it did not seem that there was a time lag to be perceived by the driver. Figure 68 below shows how the lateral position of the truck u followed the filtered reference value u_{ref} that is derived from the steering command. Both graphs reveal that there was a slight time lag. It should be noted though that the relatively big time lag from the lower graph between 60 and 80 [sec] is partly due to a change in curvature. When the driver was asked about the time lag, he responded that he recognized a time lag, but did not mind it much. Also, both the recordings and graphs clearly show the presence of overshoots.

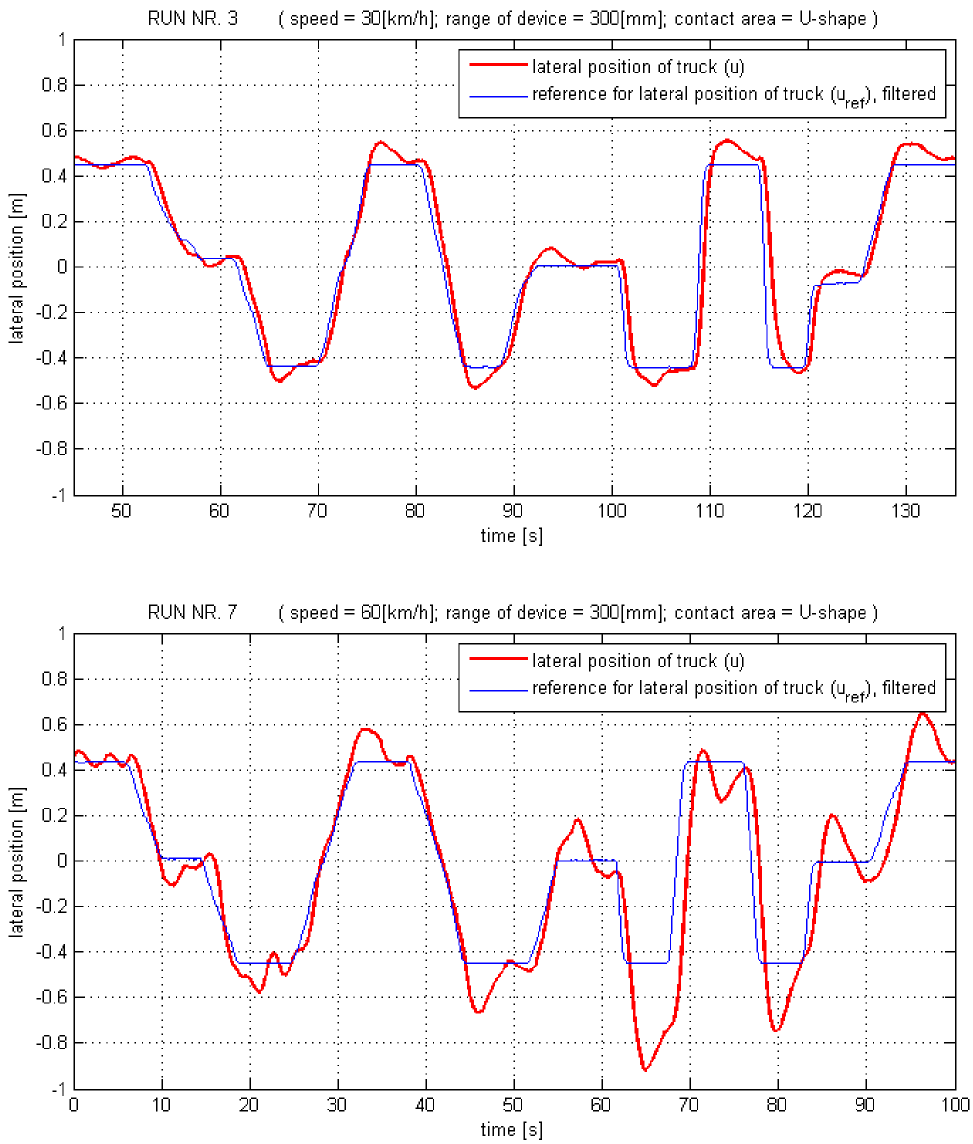


Figure 68. Measured signals of the lateral position of the truck during two test runs, and the filtered reference value that is derived from the steering command.

Overall, the driver was very positive about the new driving experience. He described it as ‘very interesting’, ‘more natural than expected’, ‘intuitive’, and to my own surprise ‘like steering a big ship’. He also said that not seeing overtaking traffic was ‘a bit scary’ and that he missed information about the surroundings. The full questionnaire completed by both Carl-Johan, the driver who performed all runs, and the questionnaire completed by Kristoffer, the second driver who drove for several minutes, can both be found in Appendix L. Carl-Johan and Kristoffer shared similar thoughts on the driving experience. For example, Kristoffer also found it easy to operate and not difficult to understand. He described it as ‘very natural’ and he said that he liked the way he was able to interact. Further, he also missed the mirrors both for determining the position of the truck in the lane and for seeing overtaking cars.

The many glitches that appeared during the runs were a consequence of bad wiring between the prototype and the 1st Autobox. Unfortunately, the glitches were not entirely filtered through the low-pass filter, and the driver’s performance and concentration might therefore have been affected. The bad wiring is considered as one of the main flaws of the prototype. Photographs taken during maintenance can be found in Appendix M. Graphs of an example run with glitches can be found in Appendix N.

A full overview of the notes on the test data and footage can be found in Appendix O.

Prototype of the Active Touch Panel

The purpose of the prototype of the active touch panel is twofold. First, it serves to demonstrate part of the functionality of the panel. It can thereby help to imagine how information from the panel can be felt by the driver. Second, it serves to show the construction of the prototype. It can thereby give more understanding about the high demands and the level of complexity of the panel.

The functionality of the prototype has been simplified in multiple ways. First of all, the information that is presented, is limited to the articulation angle of the 1st trailer and the clearance between the 1st trailer and the road boundaries. Furthermore, the panning function has been removed, which means that there is no need to sense forces that the driver applies on the panel.

The highly simplified functionality of the prototype and the limited availability of hardware products have resulted in a design that is very different than the physical design from the previous chapter, yet still based upon it.

The prototype of the touch panel is a so called flipdots board with slight modifications. Flipdots boards are generally used for instant display of text or images. A flipdots board consists of an array of small discs, that each can be flipped into two positions, ‘on’ and ‘off’. Each disc contains a permanent magnet that is either attracted or repelled by a magnetic field produced by a coil.

Figure 69. Flipdots boards are mechanical displays for text or images [48].

Figure 70. The modified flipdots board. Left: part of the board, with a few modified discs. Right: close-up of a modified disc.

A group of discs is modified as shown in Figure 70 above in order to create specific physical surfaces. Small semi-spheres made of polystyrene (plastic foam) are glued onto one side of the discs. A small groove is made in the semi-spheres, so that the semi-spheres cannot touch any part of the housing or mechanism while flipping. This modification allows the discs to, by being switched 'on' and 'off', basically imitate the first degree of freedom of the pins from the conceptual design, which is the vertical movement.

Due to the low resolution of the flipdots board, the truck combination cannot be presented properly by simply switching on a group of discs, at least not for many articulation angles. Therefore, another way is adopted for presenting the information, using two sets of external surfaces that rest on specific discs that are switched on. The position of the set of surfaces that represent the truck is fixed. The set of surfaces that represent the trailer can rotate around two rotation points. Figure 71 below shows the two sets of surfaces. The surfaces are lightweight and shaped in such a way that a set can be moved in a certain direction by switching specific discs on and off. Figure 72 below illustrates how a set of surfaces is moved by switching on a disc.

According to rough estimations on the available power and force for each disc, it was possible for a disc to turn with the extra inertia of the semi-sphere and to push a set of surfaces. The flipping time of a disc decreased, but for this prototype that was of little or no importance. Unfortunately, it was not possible for a disc to turn with much more inertia than that of the semi-sphere and the set of surfaces. So when a hand is resting on a disc, the disc cannot turn, let alone move a set of surfaces.

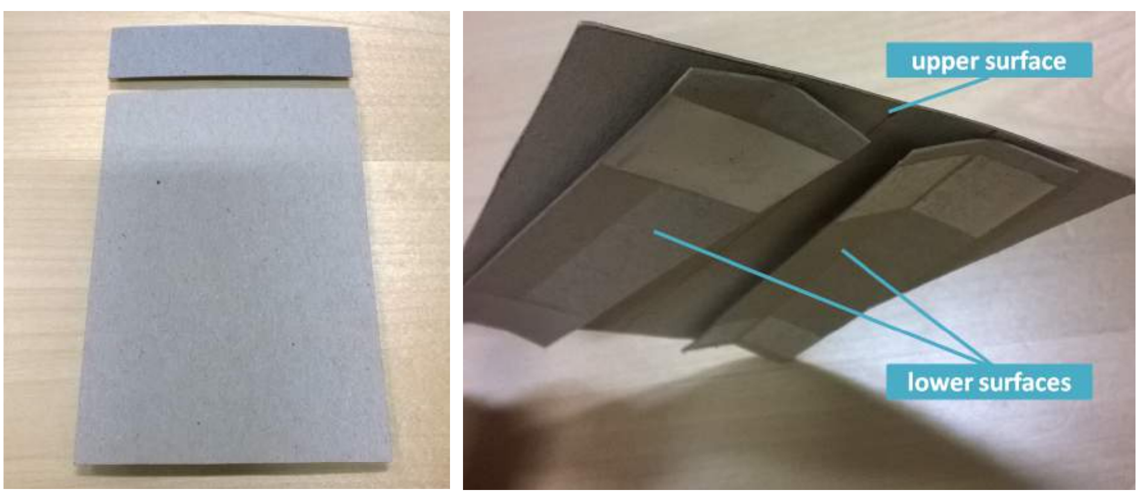


Figure 71. The lightweight external surfaces. Left: the upper surface of the sets that represent the truck and the trailer. Right: the set of surfaces that represents the trailer.

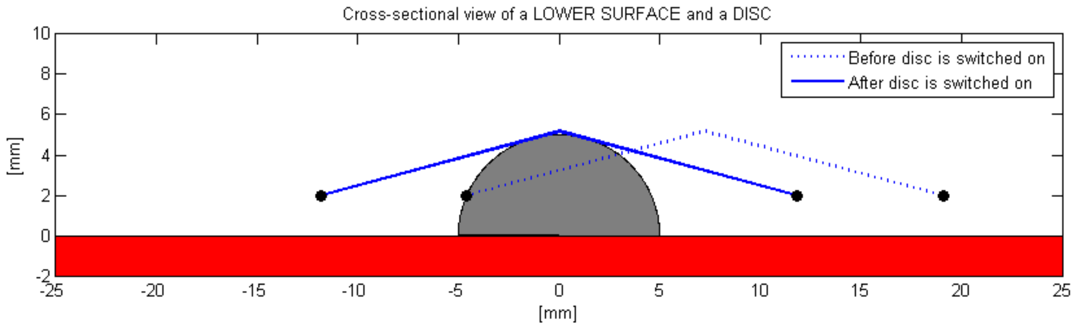


Figure 72. Schematic view of a lower surface and a disc. By switching on the disc, the 'lower surface' is pushed into a new position together with the rest of the set of surfaces.

As explained earlier, the set that represents the trailer can rotate to the left and right around two rotation points. The rotation to the left has been simulated in Matlab in order to determine the dimensions of the external surfaces, and to find out which discs are to be switched on for a specific articulation angle. The rotation to the right is simply a mirrored rotation to the left. Figure 73 below shows the top view of the prototype in the simulation, when the articulation angle is zero.

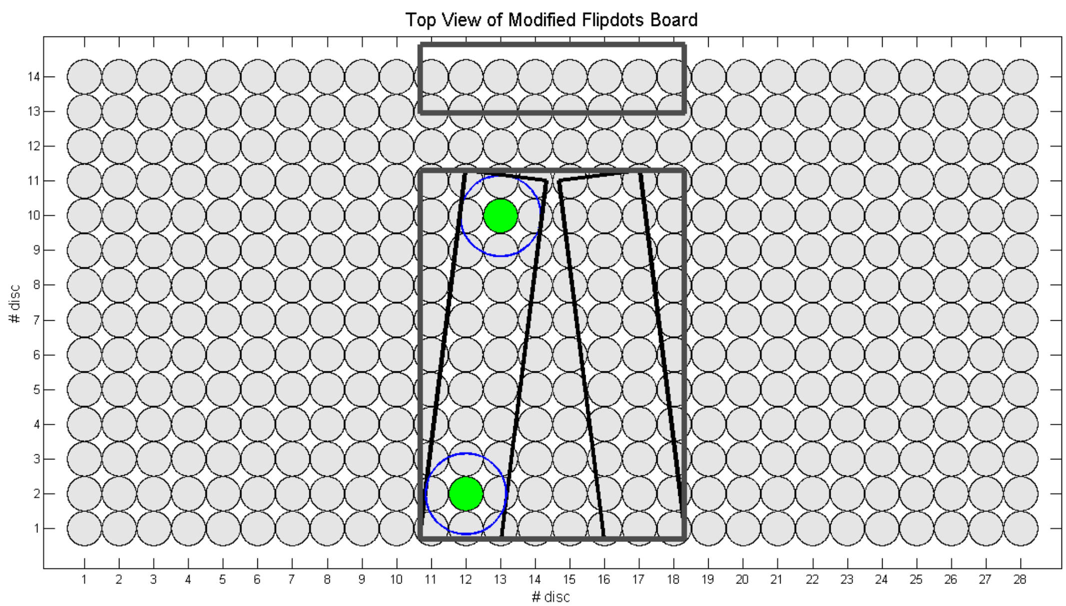


Figure 73. Image from the simulation for the prototype in Matlab. The articulation angle is zero degrees. Two discs, which are indicated with a green dot, are switched on and hold the set of surfaces in position.

The surfaces are dimensioned in such a way that an articulation angle of up to 75 degrees can be made, both to the left and to the right, while minimizing the size of the surfaces and keeping a fair clearance from the discs that are switched off.
The articulation angle can be controlled by switching on one disc that serves as a physical rotation point, and one other disc that pushes the left or right lower surface and holds it in a particular position. This second disc needs to be in the right range from the lower surface to effectively push it. Figure 74 and Table 1 below show the steps for the articulation angle and the corresponding second disc to be switched on.

For example, if an angle of 0.12 [rad] should be made, the discs that correspond to the first 5 pixel coordinates from Table 1 are switched on in that particular order. When the angle should be zero again, the same discs are switched on in the reverse order. So the angles and pixel coordinates from the table do not depend on the direction of movement.

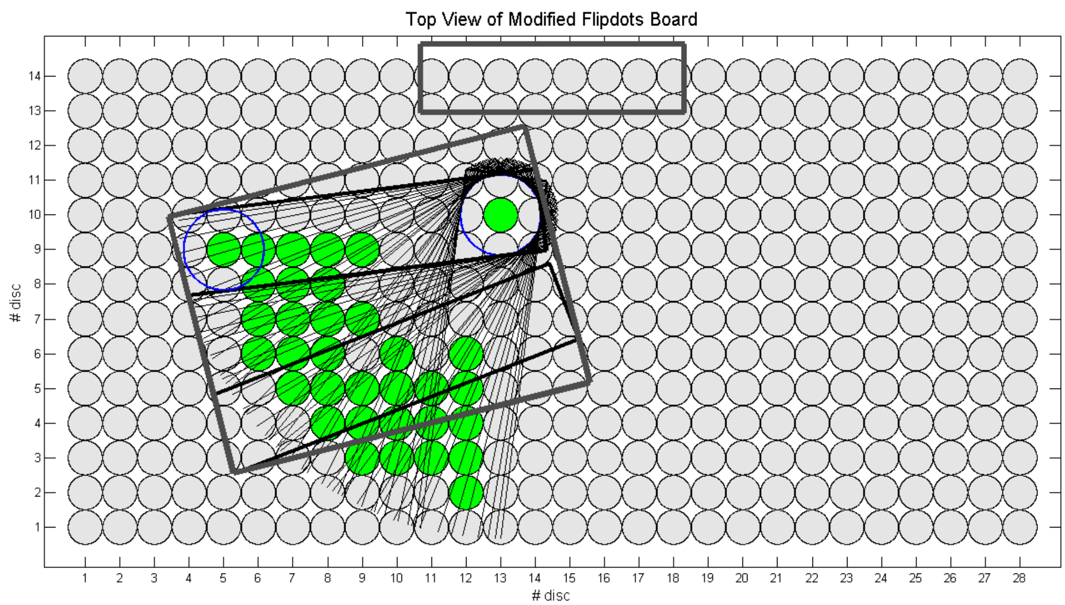


Figure 74. Image from the simulation for the prototype in Matlab. The articulation angle is 75 degrees to the left. In this particular image, all discs that have been switched on to push the lower surface in position, are indicated with a green dot. These discs are not switched on anymore at this moment, except for two discs. To be clear, when a disc is about to be switched on, the previous disc first needs to be switched off. Hence, only two discs are switched on at the same time. The pixel coordinates of the discs, together with the corresponding articulation angle, are given in Table 1 below.

Table 1. Steps for Articulation Angles and Pixel Coordinates for Second Disc

Angle [rad]	Pixel Coordinates [[-],[-]]	Angle [rad]	Pixel Coordinates [[-],[-]]
0.00	[12, 2]	0.75	[7, 5]
0.02	[12, 3]	0.77	[8, 6]
0.04	[12, 4]	0.80	[9, 7]
0.07	[12, 5]	0.86	[7, 6]
0.12	[12, 6]	0.91	[8, 7]
0.15	[11, 3]	0.93	[6, 6]
0.20	[11, 4]	0.98	[7, 7]
0.26	[11, 5]	1.04	[6, 7]
0.28	[10, 3]	1.07	[8, 8]
0.34	[10, 4]	1.12	[7, 8]
0.39	[9, 3]	1.17	[6, 8]
0.42	[10, 5]	1.20	[9, 9]
0.46	[9, 4]	1.25	[8, 9]
0.52	[10, 6]	1.28	[7, 9]
0.55	[9, 5]	1.30	[6, 9]
0.57	[8, 4]	1.32	[5, 9]
0.66	[8, 5]		

Again due to the low resolution of the flipdots board, the road boundaries cannot be properly represented by discs that together form a solid line. Therefore, the road boundaries are represented by only a few discs. The idea is that the driver perceives or derives a line from these few discs. The discs are selected based on a criterion for the distance from the disc to the actual mapped road boundary. Figure 75 below shows an arbitrary left boundary that is represented by two selections of discs, each based on a different criterion. The blue (solid) line is merely a prediction of the line that is perceived or derived by the driver. It is determined using a PCHIP[9] function through the edges of the selected discs.

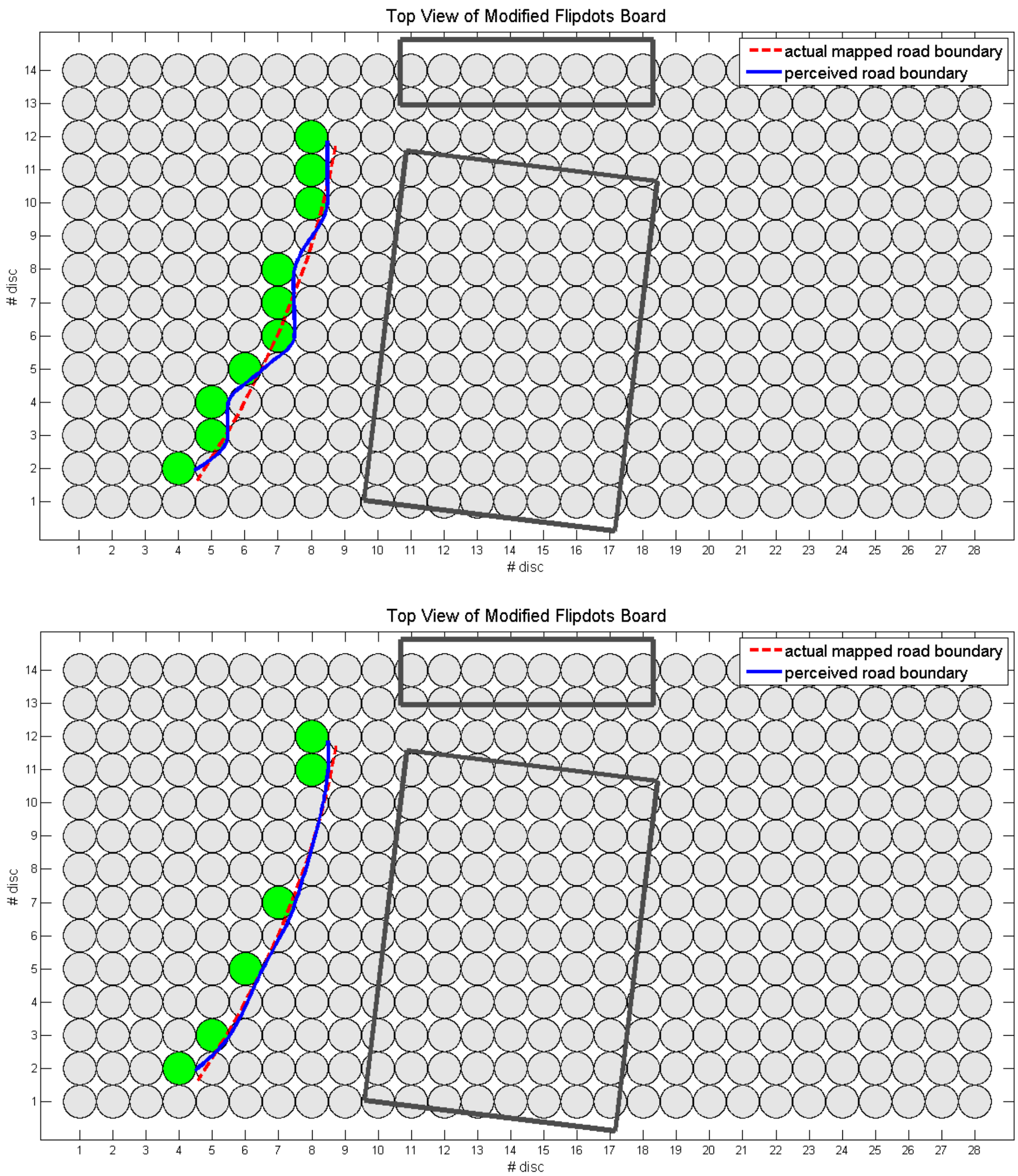


Figure 75. Images from the simulation for the prototype in Matlab. The left road boundary is represented by a selection of discs that are indicated with a green dot. Top: The selection criterion is that the distance from the disc to the actual mapped road boundary is smaller than the distance between the centre of two diagonal discs. Bottom: The selection criterion is that the distance from the disc to the actual mapped road boundary is smaller than half of the distance between the centre of two diagonal discs.

Extra images from the simulation in Matlab can be found in Appendix P.

[9] Piecewise Cubic Hermite Interpolating Polynomial (PCHIP)

Comparison of the New Interface to the Conventional Interface

It is tempting to try to compare the new steering interface with the conventional one in terms of performance, safety, or comfort. To do that properly is however almost impossible and maybe even pointless at this stage of the development. After all, the design has by far not matured yet and has not been given the opportunity to develop into an actual interface that is fine-tuned.

Then again, it is of course possible to study how the new steering interface is *different* from the conventional one. Obviously, it is not only the interface that is different. Instead, it is the entire experience of driving that is different. The differences are mainly on *operational* level and based on the physical interaction with the vehicle through the interface. Where the driver used to control the steering angle of the truck, the driver now controls the lateral position of the truck within a lane. The new interface is thus designed for highly automated driving, where automation allows the truck to follow a lane. Further, where the driver used to turn a steering wheel and get an overload of visual information, the driver now pushes the walls to the side and gets a decent amount of both visual and haptic information. Any differences on *tactical* level depend on the further design of longitudinal control. Where the driver used to constantly choose the speed and distance to other traffic users, the driver now not necessarily needs to do so. For example, automation might allow the driver to only occasionally check the speed or distance. On *strategical* level there is actually no difference between the two interfaces. The driver still chooses the lane and route.

So even though automation is prominently present in the overall experience, it is still the driver that is in control. The driver is always in direct control of the walls, and always operates the walls, even when the walls are simply left in the centre position. There is thus only one mode and there is no need to switch between any modes. The control is still considered to be manual and not supervisory.

As for the physical configuration of the interface in particular, there are a few fundamental differences between the two interfaces. First of all, the steering wheel, the many mirrors and any additional displays or alarms, are replaced by the walls, the touch panel, and the air vibration generators. Furthermore, in order for the driver to get a proper perspective of the view, the driver now sits in the middle instead of on the left or right side.

As for the information presented to the driver, there are also a few fundamental differences. First of all, the visual information is presented in such a way that the driver does not need to take his or her eyes off the road. The walls, which are placed in front of the driver, are seen while keeping the eyes on the road. There are no mirrors to be checked and no displays to be interpreted. The touch panel presents haptic information that complements the visual information, so that the driver can be aware of the situation of both the truck combination and its surroundings. Unlike the conventional interface, the new one presents information about the complete surroundings of the truck, the articulation and position of the trailers, and even the lateral forces acting on the trailers. On the other hand, the road surface and the lateral force acting on the truck are felt only via the seat, and cannot be felt or derived from vibrations and forces from the steering device. Finally, the new interface absolutely requires steer-by-wire technology, unlike the conventional interface.

Altogether, the most significant difference is that the new interface has been designed from the very start for one particular purpose only: to allow the driver to intuitively steer an articulated truck combination, while constantly being aware of the situation.

6. Conclusions

This research has significance and potential value within different areas.

First of all, the research has drawn the design of Human-Machine Interaction into a completely new direction. The new definition of ‘intuitive’ in the context of driving contributes to the common understanding of what ‘intuitive’ means in human-machine interaction. The definition can therefore also be useful and significant for other researchers in the field of HMI. With regard to this research, the definition has been crucial and even essential in the search for a new steering interface and the assessment of different concepts.

Furthermore, this research stimulates research and development of technologies in the automotive industry. After all, the new steering interface facilitates highly automated driving, and therefore also stimulates the development of technologies for highly automated driving. Moreover, the new steering interface requires steer-by-wire technology, and therefore also stimulates further developments of steer-by-wire technologies. In addition, a completely new and intuitive interface that excites and intrigues people, could increase the willingness and acceptance of new technologies.

Finally, the value of this research for road safety can only be reasoned and argued upon. Surely, the new steering interface has been designed to continuously give the driver of an articulated truck combination a high level of situation awareness. However, the question of whether or not the new steering interface is actually able to do so, cannot be answered yet with full certainty. As explained earlier, the design has by far not matured yet and has not been given the opportunity to develop into an actual interface that is ready for implementation in real trucks. Still, this research definitely has the *potential* to bring us closer to preventing road accidents and making roads safer.

7. Recommendations for Further Research

I would like to make recommendations for continuation, extension, and expansion of this research.

First of all, the research can be *continued* by research on improvements and refinements of the new steering interface. One example is research on the possibilities of integrating the walls and the touch panel. The challenge then is to either maintain or replace the functionalities, without compromising the intuitiveness of the interaction. One could try to find a solution by using the space around the driver more effectively. The research can also be continued by further evaluation of for example the functionalities, ergonomics, and dimensions of the conceptual design.

Secondly, the research can be *extended* by research on the implementation of the new steering interface. There are for example consequences for the exterior and interior design of the cab, as the driver sits in the middle and there are no mirrors. There are also consequences for the driver trainings and the safety regulations.

Thirdly, the research can be *expanded* by research on the transferability of the new steering interface to other vehicles, such as passenger cars. It is important to realize that the new steering interface has been specially designed for articulated truck combinations only. So even if the interface can be used in other vehicles, it does not mean that it is the best solution for steering the particular vehicle. In fact, it is strongly recommended to not simply implement the new steering interface in other vehicles. It is also strongly recommended to not simply implement only part of the devices or functionalities of the new steering interface. After all, the interface has been designed as one interface and in such a way that all parts complement each other.

Furthermore, I would like to make strong recommendations regarding the development of the new steering interface in general.

First, the new steering interface should be developed together with other technologies that enable highly automated driving. After all, the effectiveness and reliability of the interface partly depends on for example the available technology for steer-by-wire and detecting lane markings. The design specifications (being the functions, requirements, limitations, and assumptions) of the interface should therefore continuously be determined and updated.

Second, the new steering interface should be developed parallel to a continuous and thorough investigation on new accidents. After all, it is difficult to foresee issues and problems that might arise when the new interface is implemented in real trucks and actually used on the roads. The impact and cause of accidents can be totally different than what we have seen up until today.

8. References

[1] Commission of the European Communities, "European Transport Policy for 2010 - Time To Decide," 2010.

[2] J. Steer, F. Dionori, L. Casullo, C. Vollath, R. Frisoni, F. Carippo, and D. Ranghetti, "A Review of Megatrucks - Major Issues and Case Studies," 2013.

[3] "The Volvo Group Sustainability Report 2012," 2012.

[4] J. Granlund, "Swecos Blogg om Infrastruktur och Trafikdesign - Större Lastbilar Klimatsmart och Trafiksäkrare," 2013. [Online]. Available: http://blogs.sweco.se/infrastruktur-och-trafikdesign/category/projektering/.

[5] J. Aurell and T. Wadman, "Vehicle Combinations Based on the Modular Concept - Background and Analysis," 2007.

[6] Volvo Trucks, "European Accident Research and Safety Report 2013," 2013.

[7] B. Rakic, J. Stegeman, and M. Kind, "Monitoring Traffic Safety - Longer and Heavier Vehicles," 2011.

[8] T. Ehlgen, P. Tomas, and D. Ammon, "Eliminating Blind Spots for Assisted Driving," *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 4, pp. 657–665, 2008.

[9] T. Ehlgen and T. Pajdla, "Maneuvering Aid for Large Vehicle using Omnidirectional Cameras Machine Perception," *IEEE Work. Appl. Comput. Vis.*, 2007.

[10] S. Kawanishi, "Automotive Graphics SoC for 360 ° Wraparound View System," *Fujitsu Sci. Tech. J.*, vol. 49, no. 1, pp. 91–96, 2013.

[11] J. Fagerlönn and H. Alm, "Auditory Signs to Support Traffic Awareness," *IET Intell. Transp. Syst.*, vol. 4, no. 4, p. 262, 2010.

[12] SARTRE, "SARTRE Road Trains Tests with Several Vehicles at High Speed," 2012. [Online]. Available: http://www.sartre-project.eu.

[13] C. Spence and C. Ho, "Tactile and Multisensory Spatial Warning Signals for Drivers," *IEEE Trans. Haptics*, vol. 1, no. 2, pp. 121–129, Jul. 2008.

[14] A. Riener, *Sensor-Actuator Supported Implicit Interaction in Driver Assistance Systems*, 1st Editio. 2009.

[15] Freepik.es, "Títere Foto Gratis," 2015. [Online]. Available: http://www.freepik.es/foto-gratis/titere_342961.htm.

[16] Benson's Lawn and Landscaping, "Complete Lawn Care." [Online]. Available: http://bensonlawn.com/.

[17] M. J. Wang, Y. C. Li, and F. Chen, “How can we design 3D auditory interfaces which enhance traffic safety for Chinese drivers?,” *Proc. 4th Int. Conf. Automot. User Interfaces Interact. Veh. Appl. - AutomotiveUI ’12*, no. c, p. 77, 2012.

[18] K. Lumsden, “Truck Masses and Dimensions - Impact on Transport Efficiency,” no. October. pp. 1–28, 2004.

[19] I. Davydenko, H. Quak, J. de Bes, and K. Verweij, “Longer and Heavier Vehicles in the Netherlands,” 2010.

[20] B. Y. K. E. Maclean and V. Hayward, “Do It Yourself Haptics: Part II - Interaction Design,” *IEEE Robotics & Automation Magazine*, no. March, 2008.

[21] The Vierge, “iMotion Kickstarts Motion Controllers Inspired by ’ Minority Report ' and Oculus Rift,” 2013. .

[22] NS, “Pedestrian Routes for Visually Impaired Travelers,” 2010. .

[23] Zcoches, “Mercedes Benz S Cl 600,” 2014. .

[24] J. J. Gil, I. Díaz, P. Ciáurriz, and M. Echeverría, “New Driving Control System with Haptic Feedback: Design and Preliminary Validation Tests,” *Transp. Res. Part C Emerg. Technol.*, vol. 33, pp. 22–36, Aug. 2012.

[25] D. Göhring, D. Latotzky, M. Wang, and R. Rojas, “Semi-Autonomous Car Control Using Brain Computer Interfaces.” 2013.

[26] D. A. Abbink, “Lecture Slides from The Human Controller.” 2013.

[27] Immersion, “TouchSense Haptic (Tactile) Feedback Technology,” 2014. .

[28] Virtual Technologies Inc., “CyberGlove, CyberTouch, and CyberGrasp,” 2014. .

[29] A. L. Guinan, N. C. Hornbaker, M. N. Montandon, A. J. Doxon, and W. R. Provancher, “Back-to-Back Skin Stretch Feedback for Communicating Five Degree-of-Freedom Direction Cues,” *2013 World Haptics Conf.*, pp. 13–18, Apr. 2013.

[30] R. Sodhi, I. Poupyrev, M. Glisson, and A. Israr, “AIREAL : Interactive Tactile Experiences in Free Air,” *ACM Trans. Graph.*, vol. 32, no. 4, 2013.

[31] B. Phillips, “Bringing Learning to Life : State of the Art Simulation Center Opens at Texas Tech University Health Sciences,” 2010. [Online]. Available: http://www.prweb.com/releases/2010/09/prweb4479024.htm.

[32] YouTube, “Home rink rollerskating,” 2013. [Online]. Available: https://www.youtube.com/watch?v=PQTcMfEiLfQ.

[33] campanianotizie.com, “Giornata nazionale del braille, tavola rotonda a Piedimonte Matese,” 2015. [Online]. Available: http://www.campanianotizie.com/attualita/caserta/108448-giornata-nazionale-del-braille-tavola-rotonda-a-piedimonte-matese.html.

[34] Wellness Pour Tous, “Le yoga est-il adapté à la femme enceinte ?,” 2014. [Online]. Available: http://www.wellnesspourtous.com/tag/yoga-2/.

[35] verdadessuprimidas.blogspot.se, “Remote Control Toy Cars 2015,” 2015. [Online]. Available: http://verdadessuprimidas.blogspot.se/2015/01/remote-control-toy-cars-2015.html.

[36] Top Best Massage Chair, “Fujita KN9003 Massage Chair Review,” 2014. [Online]. Available: http://www.topmassagechairreviews.com/2014/09/fujita-kn9003-massage-chair-review_26.html.

[37] Sam Sports Services, “L.F. Pro Arm Extension,” 2015. [Online]. Available: http://www.esamsports.com/products-page/selectorized-machines/l-f-pro-arm-extension/.

[38] Audet & Partners, “Da Vinci Surgical Robot Investor Lawsuit Alleges Misleading Statements by Intuitive Surgical Share,” 2014. [Online]. Available: http://audetlaw.com/da-vinci-surgical-robot-investor-lawsuit-alleges-misleading-statements-intuitive-surgical/.

[39] TUDelft, “Aristotle’s Lantern and 3D Printing: TU Delft Researcher Presents Prototypes of Two New Medical Devices,” 2015. [Online]. Available: http://www.tudelft.nl/en/current/latest-news/article/detail/de-lantaarn-van-aristoteles-en-3d-printen-tu-delft-onderzoeker-presenteert-prototypen-van-twee-nieu/.

[40] StrangeRacer.com, “Dangerous Sports - Motorcycle Racing,” 2015. [Online]. Available: http://www.strangeracer.com/content/item/152253.html.

[41] B. Cooper, “Piano Player - the Cooper Piano Blog,” 2011. [Online]. Available: http://www.cooperpiano.com/piano-player-blog/bid/61589/Why-Tune-a-Piano-Even-If-Not-Playing-It.

[42] M. Sato, I. Poupyrev, and C. Harrison, “Touché : Enhancing Touch Interaction on Humans, Screens, Liquids, and Everyday Objects,” no. c. 2012.

[43] TAP Plastics, “Cast Acrylic Clear,” 2015. [Online]. Available: http://www.tapplastics.com/product/plastics/cut_to_size_plastic/acrylic_sheets_super_thick_clear/510.

[44] Shock Graphic, “Plexiglass - support & photo imprimée,” 2015. [Online]. Available: http://shock-graphic.be/nos-produits/plexiglass-aluminium/.

[45] C. Rye, “Organic Solar Concentrator Discovery at MIT,” 2008. [Online]. Available: http://solarpowerauthority.com/organic-solar-concentrator-discovery-at-mit/.

[46] Aceize, “3D Table Top Display from X-Men,” 2007. [Online]. Available: http://www.aceize.com/node/286.

[47] NHS Choises, “Protect Your Ears from Loud Music,” 2015.

[48] designboom.com, “Interactive High Speed Flip Dot Display by Breakfast,” 2012.

Appendices

Appendix A. Visual Systems and Technologies for Situation Awareness during Driving

Appendix B. Audial Systems and Technologies for Situation Awareness during Driving

Appendix C. The Haptic Senses

Appendix D. Haptic Systems and Technologies for Situation Awareness during Driving

Appendix E. Alternative Steering Devices

Appendix F. Morphologic Charts for Concepts

Appendix G. Key Points of Concepts

Appendix H. Motivation for Scores in the Rating Chart, and Explanation of Rating Criteria

Appendix I. Scores from Rating Chart per Group of Criteria

Appendix J. Photos of Prototype of Walls

Appendix K. Test Protocol

Appendix L. Questionnaires on Driving Experience during Testing of Prototype of Walls

Appendix M. Photos of Testing of Prototype of Walls

Appendix N. Example Run with Glitches (Run Nr. 5)

Appendix O. Notes on Test Data and Test Footage

Appendix P. Images from Simulation of Flipdots Board

Appendix A. Visual Systems and Technologies for Situation Awareness during Driving

The interface for visual feedback currently consists of window screens, mirrors and possibly additional displays. The feedback can be a real 3D view, a flat 2D video image, or a flat 2D graphical image. There are European legal requirements for the field of view[10].

Figure A 1. Visual feedback in the Volvo FH is given through windows, mirrors and an additional display in the dashboard.[11]

Advantages and Drawbacks of Visual Feedback

The most important advantage of visual feedback is that it gives spatial information. Furthermore, drivers are already used to rely (almost) totally on visual cues.[12]

The most important drawback of visual feedback is that, in order to be effective, it needs to be seen by the driver. If feedback from different directions is given simultaneously, the driver needs to choose which direction to look at. One of the risks is that there is too much visual feedback available. An overload of information can cause stress and loss of situation awareness. Another risk is that the driver is distracted by one cue or by one source of feedback, and therefore misses other important visual feedback. An additional drawback of 2D images is that it is difficult to perceive depth.[12]

Visual Feedback on State of Surrounding

The window screens together with the mirrors provide the most important visual feedback on the state of the surrounding. A major drawback of mirrors is that the size is limited, because it obstructs the view through the window. Furthermore, distorted images of convex mirrors or video systems

[10] European Union, *Directive 2003/97/EC of the European Parliament and of the Council*, vol. 2003, no. 807. 2004.
[11] H. Danielsson and E. Höcke, “Future Layout of Visual Information in Trucks,” Chalmers University of Technology, 2013.
[12] K. Borre and R. Larsson, “Low Speed Maneuvering Aids For Long Vehicle Combinations,” Chalmers University of Technology, 2012.

have the risk that distance is overestimated. Finally, the view can be heavily disturbed by sunlight reflections in the mirror and on window screens, or by interior lighting reflections on the window screens.[13,14]

Warning systems are generally based on audial feedback, but some are supported with visual feedback. One example is Volvo's Lane Changing Support, which uses a warning sound in combination with a red flashing light. Video systems that show an image of the rear or side view of a vehicle are widely available[15,16]. Generally, one or more exterior cameras are mounted on the vehicle and one display is mounted in the cab near the driver. The system can function as a replacement for the mirrors[13], or it can function as a supplement to the mirrors[15,16].

Although video systems improve the visibility and are adopted easily[17,18], there are also many issues. First, is it is difficult for the driver to judge heights and distances, because the image is flat and possibly distorted. Secondly, the system may need time to adjust to brightness when for example driving out of a building. Thirdly, the view can be blocked by dirt, snow or rain[16]. Finally, it can be a challenge for the driver to understand exactly where the camera is mounted[17].

An image from a bird's eye view, that is the top view, can improve the understanding of positioning. The image can be constructed by transforming and combining omnidirectional images, which are taken from the sides of the vehicle. The main issue is that the captured area is limited by the resolution and the image tends to be blurred. Recently, Fujitsu Semiconductor has developed a 360° wraparound view system that projects the image on a virtual 3D curved surface, and converts it into an image as seen from an arbitrary point of view. The driver can change the point of view and the system provides a seamless view. However, the technology is new and it has only been tested on cars.[19,20,21]

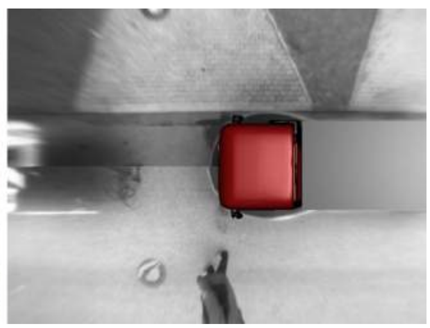


Figure A 2. Images from a video system for the rear view[22] (left) and for a bird's-eye view[19] (right).

[13] S. Pardhy, C. Shankwitz, and M. Donath, "A Virtual Mirror for Assisting Drivers," *IEEE Intell. Veh. Symp.*, pp. 255–260, 2000.
[14] TMC, "Future Driver Vision - Equipment User Expectations for Vision when Driving Heavy Trucks," no. March, pp. 1–3, 2004.
[15] Volvo Trucks, "VOLVO TRUCKS Rearview Mirrors, Exterior Vision Cameras, Lane Changing Support," 2014.
[16] Health and Safety Execute, "Safe Manoeuvring," 2014.
[17] See footnote 12 on previous page.
[18] C. Lee, A. Kourtellis, P. Lin, and P. Hsu, "Rearview Video System as Countermeasure for Trucks ' Backing Crashes - Evaluating the System ' s Effectiveness by Controlled Test," *Transp. Res. Rec.*, vol. No. 2194, pp. 55–63, 2010.
[19] T. Ehlgen and T. Pajdla, "Maneuvering Aid for Large Vehicle using Omnidirectional Cameras Machine Perception," *IEEE Work. Appl. Comput. Vis.*, 2007.
[20] T. Ehlgen, P. Tomas, and D. Ammon, "Eliminating Blind Spots for Assisted Driving," *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 4, pp. 657–665, 2008.
[21] S. Kawanishi, "Automotive Graphics SoC for 360 ° Wraparound View System," *Fujitsu Sci. Tech. J.*, vol. 49, no. 1, pp. 91–96, 2013.
[22] T. M. Ruff, "Evaluation of Systems to Monitor Blind Areas Behind Trucks Used in Road Construction and Maintenance : Phase 1," 2003.

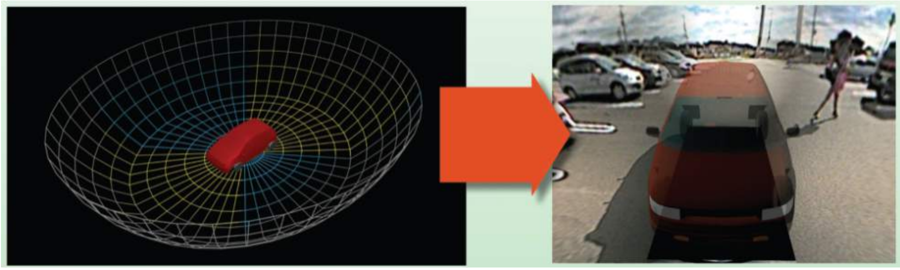


Figure A 3. Images from the 360 Degrees Wraparound View System[23].

Visual Feedback on State of Vehicle

The most obvious way to visually indicate the state of the vehicle is from a bird's-eye view. A recent study[24] showed that a head up display that shows the trailer's predicted trajectory during reversing, leads to smoother steering behaviour and an increase of predictability of steering actions. However, the degree of stress that the participants experienced during reversing is not affected by the display. Additional corridors can also be displayed, that indicate the predicted trajectory of both the trailer and the truck[25]. When the vehicle has multiple trailers, the predicted trajectory may become difficult to visualise.

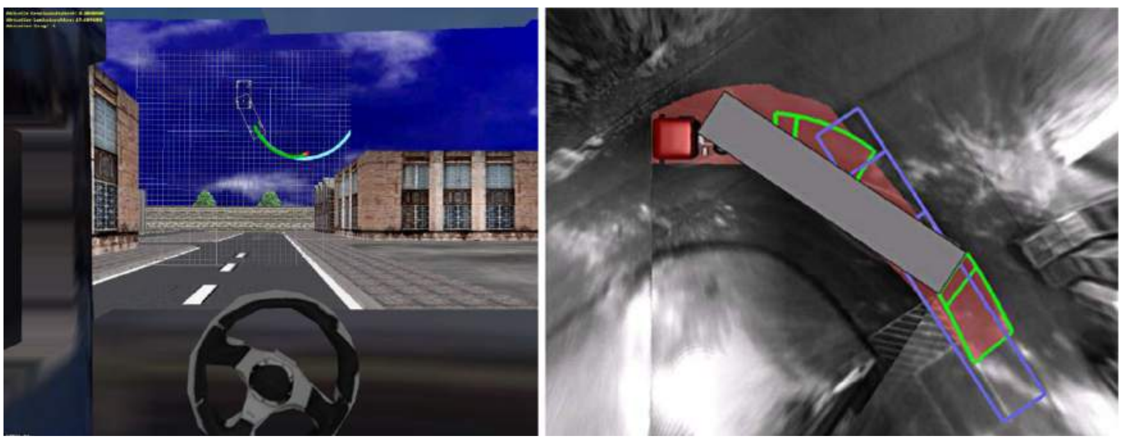


Figure A 4. Images that show the predicted trajectory of only the trailer[24] (left) and the predicted trajectory of both the truck and the trailer[25] (right).

[23] Fujitsu, "The Worlds First 360 Wraparound View System for Automotive Applications."
[24] Z. Dieter, D. Polock, and P. Wojke, "Steering Assistance for Backing Up Articulated Vehicles," *Syst. Cybern. Informatics*, vol. 1, no. 5, pp. 101–106, 2003.
[25] See footnote 20 on previous page.

Appendix B. Audial Systems and Technologies for Situation Awareness during Driving

The interface for artificial audial feedback consists of one or more speakers. The feedback can be arbitrary sounds (beeps or tones), auditory icons (imitating or highly-recognizable sounds) or speech sounds (spoken words). Auditory icons and speech have shown to be equally effective, but speech is language dependent. Arbitrary sounds are less effective and annoying. It is important that the sound is clear, unambiguous and that it is not a redundancy of information.[26,27]

Advantages and Drawbacks of Audial Feedback

The most important advantage of audial feedback is that it cannot be shut off voluntarily, unless the system is actually turned off. Also, the feedback can be sent from every (spatial) direction, without the driver needing to move his head or body. Furthermore, responding to audial feedback is natural and leads to a short perception-reaction time.[27,28]

The most important drawback of audial feedback is that there is a risk of annoyance. The level of annoyance depends on the acoustic properties, the level of urgency/danger, and the rate of false alarms[28]. False alarms can also affect the trust and understanding of the system[29]. Finally, there is a risk that the feedback is drowned out by other sounds or noise[30].

Audial Feedback on State of Surroundings

Only a limited amount of audial feedback from other road users is available directly to the driver.
Most modern vehicles are featured with one or more warning systems that are mainly based on audial feedback. Examples include Lane Change Warning (LCW), Lane Departure Warning (LDW), Forward Collision Warning (FCW), and Backup Warning (BW). Warning systems have shown to help the driver to become aware of the position of the vehicle in the travel lane and the surrounding traffic. However, the effectiveness of these warning systems is limited, because they give little or no information about what or where the danger is.[26,29,31]

One solution might be a spatial sound system that gives information about the location and movement of other road users. It uses recognizable sounds that imitate the road user, making it easy to associate the sound with the type of road user (e.g. pedestrian, child, cyclist, motorcyclist, car, or truck). Spatial sound information is still new in the automotive industry. The research that has been conducted has shown improvement on performance and driver satisfaction[26,27].

[26] J. Fagerlönn and H. Alm, "Auditory Signs to Support Traffic Awareness," *IET Intell. Transp. Syst.*, vol. 4, no. 4, p. 262, 2010.
[27] M. J. Wang, Y. C. Li, and F. Chen, "How can we design 3D auditory interfaces which enhance traffic safety for Chinese drivers?," *Proc. 4th Int. Conf. Automot. User Interfaces Interact. Veh. Appl. - AutomotiveUI '12*, no. c, p. 77, 2012.
[28] J. Fagerlönn, "Urgent alarms in trucks: effects on annoyance and subsequent driving performance," *IET Intell. Transp. Syst.*, vol. 5, no. 4, pp. 252–258, Dec. 2011.
[29] E. Nodine, A. Lam, W. Najm, B. Wilson, and John Brewer, "Integrated Vehicle-Based Safety Systems," 2011.
[30] See footnote 7 two pages back.
[31] Mobileawareness.com, "Visionstat Plus Backup Camera & Sensor System For Trucks," 2014. [Online]. Available: http://www.mobileawareness.com/visionstat-plus/visionstat-plus-backup-camera-sensor-system-trucks/.

The estimation of the time distance to another road user is improved by using looming sounds that increase in intensity as the distance between the two road users decreases[32].

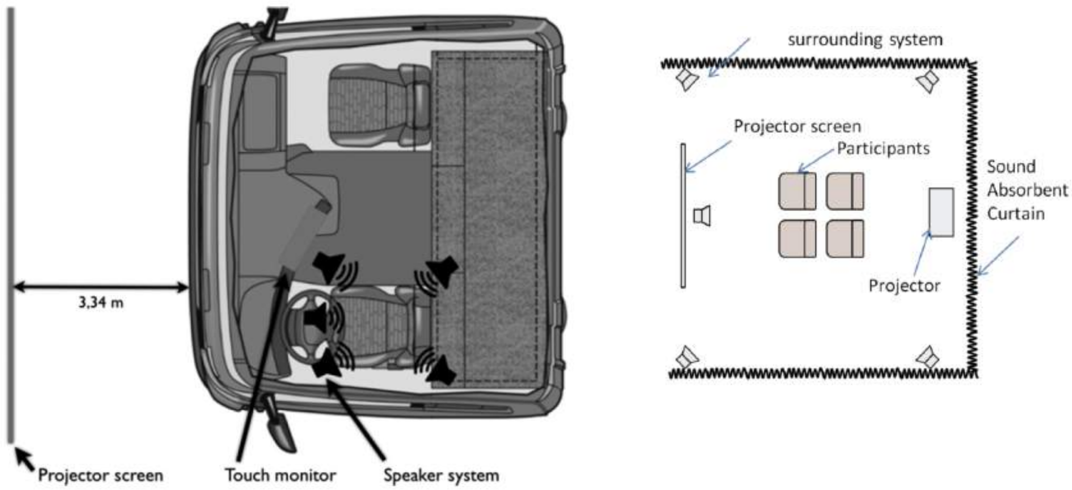


Figure B 1. Experimental set up of two studies on spatial audial feedback[33,34].

Audial Feedback on State of Vehicle

Only limited research has been conducted on audial feedback on the state of the vehicle.
A study on an assistance system for backing up articulated vehicles[35] shows positive results. The system assists the driver by giving advice during the whole manoeuvre of backing up. The frequency gives information about the speed of the articulation angle, the loudness gives information about the articulation angle itself, and a speech sound gives information about whether to turn the wheel left or right. The assistance turned out to be very helpful to the driver. Keeping an angle was relatively easy for the participants, but reaching a specific angle was much more difficult.

---

[32] R. Gray, "Looming Auditory Collision Warnings for Driving," *Hum. Factors J. Hum. Factors Ergon. Soc.*, vol. 53, no. 1, pp. 63–74, Feb. 2011.
[33] See footnote 26 on previous page.
[34] See footnote 27 on previous page.
[35] E. Balcerak, J. Schikora, P. Wojke, and D. Zobel, "Maneuver-Based Assistance for Backing Up Articulated Vehicles," *IEEE Conf. Robot. Autom. Mechatronics, 2004.*, vol. 2, pp. 1066–1071, 2004.

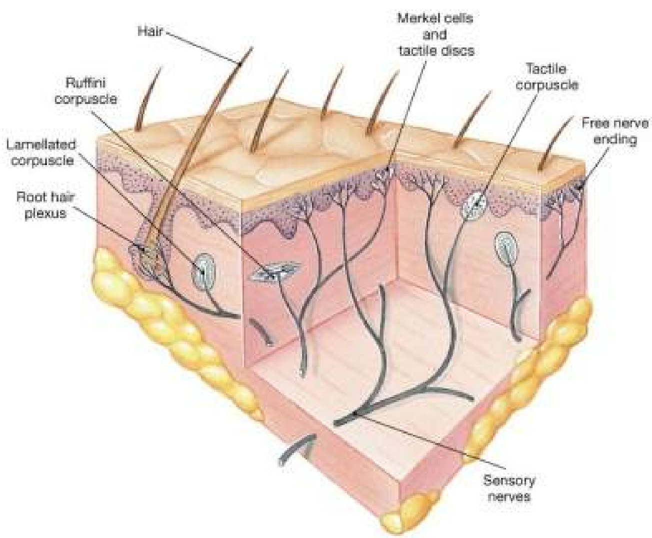
Appendix C. The Haptic Senses

The haptic senses allow us to physically feel our own body and our environment. There are two kinds of haptic senses: the tactile sense and the proprioceptive sense.

The **tactile** sense is sometimes called “touch” and it is one of the five traditional senses (the others being sight, hearing, taste, and smell). We use this sense to perceive for example texture, surface roughness, hardness, shear stress, wetness, tickles, and pain. Tactile sensors are located in the skin (cutaneous) and they can detect pressure, vibration, temperature and electric voltage.[36,37]

The **proprioceptive** sense is one of the less known senses. We use this sense to perceive for example weight, inertia, shape, body movements, and body posture. Sensors in the tendon detect forces, whereas sensors in the muscle detect position and velocity. The proprioceptive sense should not be confused with the vestibular senses, with which we perceive body (head) motion and acceleration. Unlike all other senses, the haptic senses are closely coupled with the motor function. After all, very often we use the same body part to actor manipulate as with which we sense haptic cues.[36,38]

The haptic senses are of fundamental importance in everyday life to function and communicate. For example, we use our haptic sense to stand and walk, to reach and grasp for something, or to write and talk.



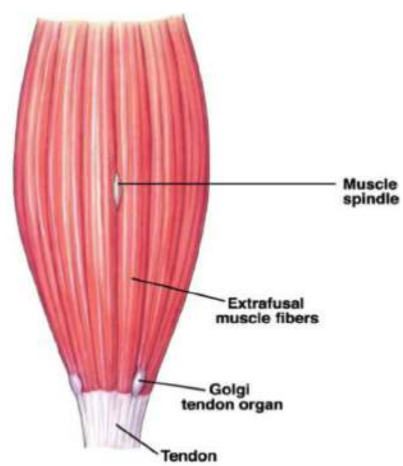


Figure C 1. Tactile sensors in the skin[39] (left); proprioceptive sensors in the muscles and tendons[40] (right).

[36] D. A. Abbink, “Lecture Slides from The Human Controller.” 2013.
[37] A. Riener, *Sensor-Actuator Supported Implicit Interaction in Driver Assistance Systems*, 1st Editio. 2009.
[38] B. Y. K. E. Maclean and V. Hayward, “Do It Yourself Haptics: Part II - Interaction Design,” *IEEE Robotics & Automation Magazine*, no. March, 2008.
[39] M. J. Malachowski, “Receptors in the Skin,” 2002. [Online]. Available: http://fog.ccsf.cc.ca.us/~mmalacho/anatomy/Skin/Sensors.html.
[40] Quizlet.com, “CNS: Spinal Cord,” 2015. [Online]. Available: https://quizlet.com/31562130/cns-spinal-cord-flash-cards/.

Appendix D. Haptic Systems and Technologies for Situation Awareness during Driving

The interface for haptic feedback depends on what type of stimuli it generates. The type of stimuli can be electrical, thermal or mechanical[41]. Up until now, researchers have only focused on using haptic feedback via surfaces that are in direct contact with the human[42].

Advantages and Drawbacks of Haptic Feedback

The most important advantage of haptic feedback is that it can be sent and sensed effectively from every (spatial) direction, without the driver having to move the head or body. In fact, it can give even more spatial information than audial feedback. While audial feedback gives spatial information with respect to one part of the human body (the head), haptic feedback can give spatial information with respect to all parts of the human body. Also, haptic feedback is required for shared control between the operator and the automation[41,43].

The most important drawback of haptic feedback is that no universal language has been developed yet[41]. The main challenge is thus to communicate exactly the right information, using haptic feedback that is easy to identify and to recognize, without excessive training[42]. It may be helpful to continuously give haptic feedback, instead of only occasionally, and let it become part of the normal and routine operation. The driver would then be able to develop a mental model for the feedback, which would lead to familiarity and trust. A recent study[44] has proven this beneficial effect of continuous haptic feedback on spatial awareness.

Furthermore, haptic feedback is capable of informing about the space close to the body (also called 'peripersonal space'), but it is less capable of informing about the space farther away from the body (also called 'extrapersonal space'). Some influential researchers[42] believe that audial feedback and visual feedback are therefore more appropriate to inform about the surroundings of a vehicle.

Finally, the resolution required for haptic feedback to be effective, is limited, especially compared to visual feedback[41].

Haptic Feedback on State of Surroundings

Feedback about the road surface is to some extent given through vibrations in the cabin. These vibrations are partly transferred to the driver via the steering wheel and the seat. Rumble strips are a road safety feature that is based on this principle[45]. Lane Departure Warning (LDW) systems imitate rumble strips by vibrating the seat. There are only a few systems such as these widely available[46,47].

[41] See footnote 37 on previous page.

[42] C. Spence and C. Ho, "Tactile and Multisensory Spatial Warning Signals for Drivers," *IEEE Trans. Haptics*, vol. 1, no. 2, pp. 121–129, Jul. 2008.

[43] F. Flemisch, J. Kelsch, C. Löper, A. Schieben, J. Schindler, and M. Heesen, "Cooperative Control and Active Interfaces for Vehicle Assistance and Automation," in *Fisita World Automotive Congress*, 2008, no. 2.

[44] J. Morrell and K. Wasilewski, "Design and evaluation of a vibrotactile seat to improve spatial awareness while driving," *2010 IEEE Haptics Symp.*, pp. 281–288, Mar. 2010.

[45] NZ Transport Agency, "Rumble Strips Information Sheet," 2009.

[46] Wabco, "OnLane," 2014. [Online]. Available: http://www.wabco-auto.com/advanced-driver-assistance-systems/onlane-ldws/.

[47] Bendix, "Lane Departure Warning (LDW) System by Bendix CVS," 2012.

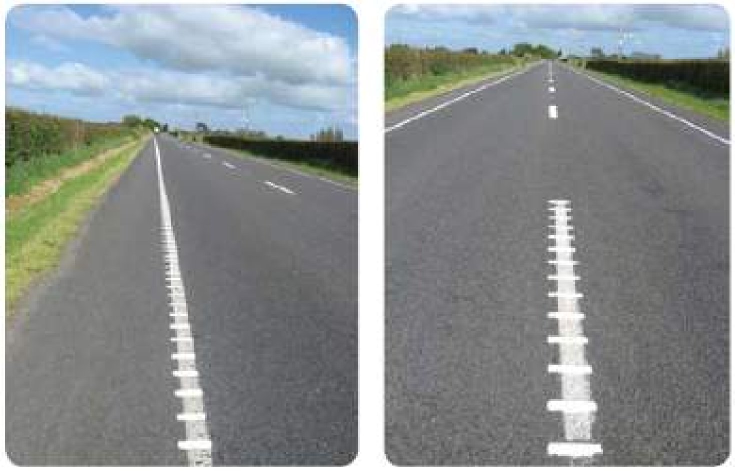


Figure D 1. Rumble strips are a road safety feature that warn or alert the driver[48].

Within the SAFELANE project, there is also a Lane Departure Avoidance (LDA) system under development. This system uses vibrations on the steering wheel as warning, and torques on the steering wheel as correction.[49]

Haptic Feedback on State of Vehicle

The currently available haptic feedback is limited to forces that are acting on the truck. The driver can feel longitudinal forces from both the seat and seatbelt, and lateral forces from both the seat and the steering wheel. The forces that are felt from the steering wheel are directly linked to the lateral forces acting on the front axle. Only limited or no information about the position of the trailers or the forces that are acting on the other axles is available to the driver through the seat.

A project group has recently been working on an assistance system for cornering (forward and backward) articulated vehicles[50]. This system has been proven to prevent unsafe steering commands by setting bounds on the range of the steering wheel according to the position of the vehicle. In this case, haptic feedback on the position of the trailers is thus given indirectly.

Haptic Feedback Systems for Road Vehicles

Only a limited number of systems provide haptic feedback on the surroundings of a truck or on the state of the truck. These systems are either already available on the market, still under development, or studied as part of a research project. However, there are other systems that provide haptic feedback for road vehicles in general. These systems are mainly aimed at usage in passenger cars.

Systems that give the driver haptic feedback for lateral control of the vehicle are widely adopted in passenger cars. The most common examples are the Lane Departure Warning (LDW) system and the

---

[48] See footnote 45 on previous page.

[49] A. Amditis, M. Bimpas, G. Thomaidis, M. Tsogas, M. Netto, S. Mammar, A. Beutner, N. Möhler, T. Wirthgen, and S. Zipser, "A Situation-Adaptive Lane-Keeping Support System: Overview of the SAFELANE Approach," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 617–629, 2010.

[50] J. Morales, A. Mandow, J. L. Martínez, A. J. Reina, and A. García-Cerezo, "Driver Assistance System for Passive Multi Trailer Vehicles with Haptic Steering Limitations on the Leading Unit.," *Sensors (Basel).*, vol. 13, no. 4, pp. 4485–98, Jan. 2013.

Lane Change Warning (LCW) systems. The feedback is either given as vibrations in the seat[51], the steering wheel[52,53], or the seat belt[54]. Systems that give the driver haptic feedback for longitudinal control of the vehicle are less common. The systems generally use vibrations[55] or an upward force[56] as warning, and a force on the pedal(s) as correction[55,56].

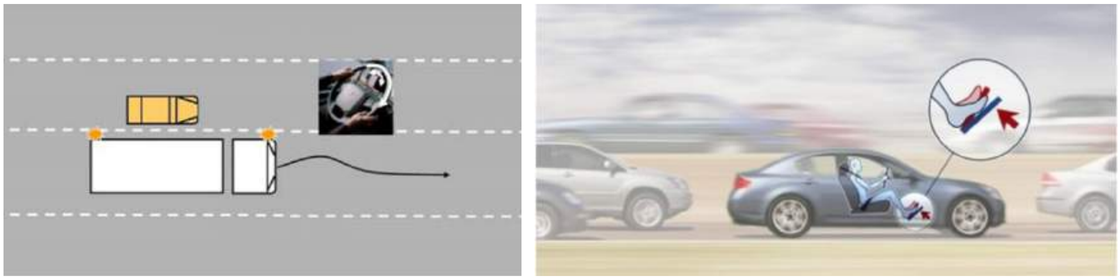


Figure D 2. Lane Departure Avoidance system that both warns and corrects the driver through the steering wheel[57] (left); a vibration or a force on the pedals can warn or even correct the driver[55] (right).

Researchers have conducted studies on new systems that provide tactile feedback to the driver at different locations of the body. Systems that require an additional device to be attached to the driver's body, such as a waist belt, are not taken into consideration. It is reasonable to assume, like Spence and Ho[58], that drivers are not willing to wear additional devices for comfort reasons.

An elaborated literature study by Riener[59] has shown that feedback to the driver's back or bottom, via the driver's seat, can effectively transfer directional information, mapping information, information about the surrounding traffic conditions, and guiding information for navigation. In addition, feedback to the driver's feet, via the sole or top of the shoe, can effectively transfer information about location and movement.

In general, the interface is a discrete display that consists of an array of vibrating elements. The number of vibrating elements depends on the resolution that is required to represent a certain location (e.g. front), direction e.g. (from left to right), or pattern (e.g. U-turn). However, the vibrating elements are not necessarily arranged in an array. For example, AT&T is developing a navigation system that uses a steering wheel to which vibrating elements are attached[60,61]. The vibrations simulate a motion pattern in the direction of the turn. The motion is faster and stronger as the curve is approached. A study[62] has proven that the system stimulates the driver to keep eyes on the road.

[51] Citroën, "Citroën C4 - Modern and Innovative Equipment for Relaxed Driving," 2014.
[52] BMW South Africa, "BMW 3 Series Sedan - Lane Departure and Lane Change Warning," 2014.
[53] Audi, "Audi Active Lane Assist," 2012.
[54] Citroën, "New Citroën C4 Picasso and Citroën Grand C4 Picasso," 2013.
[55] S. Abuelsamid, "Continental Introduces Force Feedback Accelerator Pedal," 2014.
[56] Nissan, "Nissan Distance Control Assist System," 2014.
[57] A. Polychronopoulos and A. Beutner, "The Safelane Adaptive Lane Keeping Support System."
[58] See footnote 42 two pages back.
[59] See footnote 37 three pages back.
[60] AT&T Labs Research, "Haptic Steering Wheel and Other Cloud-Based Services Showcased by AT&T Researchers," 2012.
[61] D. D'Orazio, "Haptic Feedback Steering Wheel Gives GPS Directions With Vibrations (Hands-On)," 2012.
[62] D. Talbot, "AT&T Reinvents the Steering Wheel," *MIT Technology Review*, pp. 22–23, 2012.

Figure D 3. Small actuators are placed in an array on the bottom of the seat to give spatial information[63].

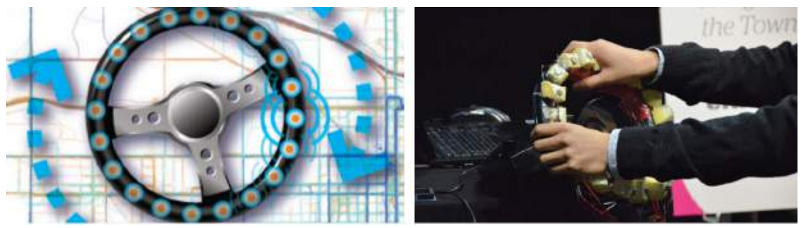


Figure D 4. Small actuators are placed on the steering wheel to simulate a motion[64,65].

Haptic Interaction for Non-Driving

Although the focus of this study is on systems for driving tasks, there are other promising haptic systems for non-driving tasks that are worth mentioning. In general, the purpose of these systems is to control infotainment systems.

Continental has recently developed a touchpad that gives tactile pulses when a menu field is reached or when an option is selected by the driver.
Several companies, both automotive (e.g. BMW and Toyota) and non-automotive (Microsoft, Harman and Neonode), are working on gesture control systems. The systems recognize certain hand gestures, hand movements, nods, or winks. The unique aspect of gesture-based control is that there is no contact between the driver and the device.

Figure D 5. Haptic systems for non-driving tasks. Continental's touchpad with haptic feedback[66] (left); Harman's gesture control system[67] (centre); Neonode's gesture-and-touch-sensitive steering wheel[68] (right).

[63] See footnote 44 three pages back.
[64] See footnote 60 on previous page.
[65] See footnote 61 on previous page.
[66] Continental, "Study : Next Generation Touchpad with Haptic Feedback Makes Control Tasks Easier and Safer," 2013.
[67] www.AutoChunk.com, "Future Tech Facial Expressions and Gestures to Control Car's Functioning," 2012.
[68] NY Daily News, "Neonode Banks on Touch- Sensitive Steering Wheel to Let Drivers Use In-Car Entertainment," 2013.

Appendix E. Alternative Steering Devices

In general, the steering device for trucks (and cars) is a steering wheel. However, there are many alternative steering devices being researched. The purpose of these alternative steering devices has not necessarily been to give the driver awareness, but mainly to either improve the steering performance, or to simply explore new possibilities for the steering interaction.

For example, a study on a steering control aid for backing up articulated vehicles[69], has successfully used a joystick. Some concept cars have adopted another steering device, mostly a joystick or a yokes. Under certain circumstances, people with disabilities are allowed to drive cars that are adapted with an alternative steering device, such as a joystick, a mini steering wheel, a tiller, or a foot pedal[70,71,72,73,74,75].

Figure E 1. Mercedes' joystick for the SCL600 concept car[76] (left); GM's yoke for the Hy-wire concept car[77] (right).

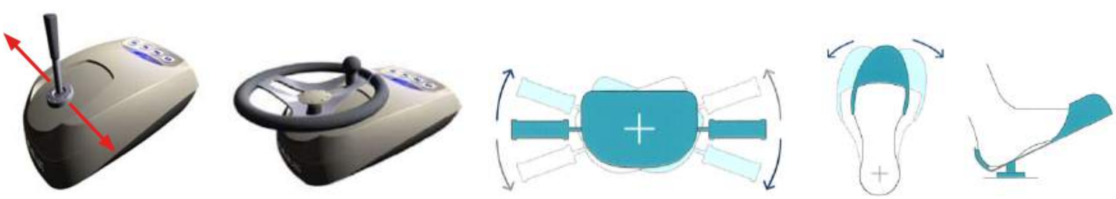


Figure E 2. Alternative steering devices for disabled people. A joystick[70] (left), a mini steering wheel[70] (second from left), a tiller[71] (second from right), and a foot pedal[71] (right).

[69] B. Widrow and M. M. Lamego, "Neurointerfaces: Applications," *Proc. IEEE 2000 Adapt. Syst. Signal Process. Commun. Control Symp. (Cat. No.00EX373)*, vol. 3, pp. 441–444, 2000.
[70] Space Drive, "SpaceDrive Driving Aids for Motor Vehicles," 2005.
[71] Steering Developments Limited, "Hi-Tech Driving Systems," 2011.
[72] Y. Murata and K. Yoshida, "Automobile Driving Interface Using Gesture Operations for Disabled People," vol. 6, no. 3, pp. 329–341, 2013.
[73] J. J. Gil, I. Díaz, P. Ciáurriz, and M. Echeverría, "New Driving Control System with Haptic Feedback: Design and Preliminary Validation Tests," *Transp. Res. Part C Emerg. Technol.*, vol. 33, pp. 22–36, Aug. 2012.
[74] M. Wada and F. Kameda, "A Joystick Car Drive System With Seating in a Wheelchair," *2009 35th Annu. Conf. IEEE Ind. Electron.*, pp. 2163–2168, Nov. 2009.
[75] J. Östlund, "Joystick-Controlled Cars For Drivers With Severe Disabilities," 1999.
[76] Zcoches, "Mercedes Benz S Cl 600," 2014.
[77] T. Harris, "How GMs Hy-wire Works," *HowStuffWorks*, 2014.

Joystick

The base of the stick pivots either in one direction (2-way) or two directions (4-way)[78,79]. A steering device requires only one degree of freedom for lateral control (steering left and right), which means that a 2-way joystick suffices. If the stick serves as a complete driving device, it also requires the second degree of freedom for longitudinal control (accelerating and braking). The latter joystick replaces the steering wheel and the pedals, but poses the risk of interference of longitudinal and lateral control[79,80].
The most important advantage is that it uses the flexibility and dexterity of the wrist and fingers. It is found that a joystick provides even more control over curves than a steering wheel[81]. It is thus possible to obtain a high precision and adopt a small range of motion.
The most important drawback is that movements of the driver's body during certain manoeuvres (e.g. hard braking) can induce unintended movements on the joystick[78,80]. An important risk is that the high precision and the small range of motion can be tiresome for the driver[80]. Finally, regarding the passive safety, the mounting of the stick should give way readily if the driver hits it[79].

Touch Screen

Touch screens are now only used or studied in the field of gaming and vehicle tele-operation. The input can be a movement on the screen (e.g. a virtual steering wheel[82,83]), one point on the screen (e.g. a joypad[84]), or a sequence of points on the screen that form a trajectory[84,85].
The main advantage is that any movement on the screen can be programmed as an input. Furthermore, the fingertips are the most sensitive areas of the skin.
The main drawback is that it can only provide feedback at points where it is touched at that moment.

Figure E 3. Ridge Racer DS is a game in which the car is steered with a virtual steering wheel[83].

[78] See footnote 73 on previous page.
[79] See footnote 75 on previous page.
[80] B. Peters and J. Östlund, "Joystick Controlled Driving for Drivers with Disabilities," 2005.
[81] E. C. Haas and M. Kunze, "The Effect of a Vehicle Control Device on Driver Performance in a Simulated Tank Driving Task," 2001, pp. 143–146.
[82] A. Srinivasan, "Nintendo Files Patent for Touch Screen Steering Wheel on DSi," 2010.
[83] "A Look Into Video Games: Ridge Racer Inequality," 2012.
[84] T. Fong, B. Glass, and C. I. S. Saic, "PdaDriver: A Handheld System for Remote Driving," 2003, vol. 2003.
[85] T. Sekimoto, T. Tsubouchi, and S. Yuta, "A Simple Driving Device for a Vehicle - Implementation and Evaluation," 1997, pp. 147–154.

Gesture Recognition

Strictly spoken, all body parts can make a gesture that is detected as a control input. However, assuming that the driver is in a comfortable seating position, the most reasonable body parts to make gestures are the hands, the arms, and the head. A recent study[86] showed that gestures made by the lower arm and the wrist allow for better control than gestures made by the forefinger or the upper arm. The study also shows that the steering performance using gestures is similar to using a steering wheel.

The most important advantage is that any recognizable gesture can be programmed as being an input. Furthermore, the gestures can be comfortable and natural for the driver. Finally, the driver does not have to hold or touch any device.

The most important drawback is that the commands from the driver, and only from the driver, need to be detected effectively[87]. Also, if the driver needs to give continuous command, it can be tiresome. Finally, the body parts that make the gesture need to be in line-of-sight of the sensor[88].

Figure E 4. GestureDriver detects gestures as input for steering left and right[89].

Voice Command

There is very little or no research conducted on voice commanded steering.

The most important advantage is that the driver does not have to make any movements with this body, besides his mouth, to give a control input. However, the driver still needs to look sideways and thereby move his head or body.

The most important drawback is that the commands from the driver, and only from the driver, need to be detected effectively[86]. Also, if the driver needs to give continuous command, it can be tiresome. Furthermore, feedback cannot be provided through the same interface.

Brain-Computer Interface (BCI)

A brain-computer interface detects electrophysiological signals from the brain[90]. These signals serve as input for lateral and longitudinal control[90,91]. Several studies are held at this moment to investigate the possibilities of brain-controlled vehicles. Preliminary results show that the accuracy and reliability need significant improvements before it can operate within open traffic[90,92].

---

[86] Y. Murata and K. Yoshida, "Proposal of an Automobile Driving Interface Using Gesture Operation for Disabled People," no. 4, pp. 472–478, 2013.

[87] D. Hausen, B. Conradi, A. Hang, F. Hennecke, S. Kratz, S. Löhmann, H. Richter, A. Butz, and H. Hussmann, "Ubiquitous Computing - Hauptseminar Medieninformatik SS 2011," 2011.

[88] T. Fong and C. Baur, "Advanced Interfaces for Vehicle Teleoperation: Collaborative Control , Sensor Fusion Displays , and Remote Driving Tools," pp. 77–85, 2001.

[89] T. W. Fong, F. Conti, S. Grange, and C. Baur, "Novel Interfaces for Remote Driving - Gesture, Haptic and PDA." pp. 300–311, 02-Mar-2001.

[90] D. Hood, D. Joseph, and S. Sridharan, "Use of Brain Computer Interface to Drive: Preliminary Results," 2012, no. c, pp. 103–106.

[91] D. Göhring, D. Latotzky, M. Wang, and R. Rojas, "Semi-Autonomous Car Control Using Brain Computer Interfaces." 2013.

[92] See footnote 72 two pages back.

The most important advantage is that the driver does not have to make any movements to give a control input. However, the driver still needs to look sideways and thereby move his head or body. The most important drawback is that the system first needs to be calibrated for each driver. The system needs to learn specific brain patterns from the driver and it needs to ignore extraneous signals such as distractive or random thoughts[93,94]. Furthermore, an important issue is that it cannot provide feedback through the same interface. Finally, the driver needs to wear the device on his head.

Figure E 5. Emotive's Epoc neuroheadset detects electrophysiological signals from the brain[94].

Other Steering Devices

Researchers have proposed other steering devices for vehicles. One example is a conventional steering wheel that can slide from left to right[95]. The purpose is to effectively control a four-wheel independent steering vehicle. Sliding the steering wheel corresponds to pure translational motion. This system and interface is not yet tested in a real vehicle, but simulator tests show positive results. Another example is a device that has strong similarities with the yoke from GM's Hy-wire[96]. The difference is that this device is operated by only one hand. The device is not yet tested in a real vehicle. Simulator tests show that the driving performance using this device is similar to using a conventional steering wheel with pedals.

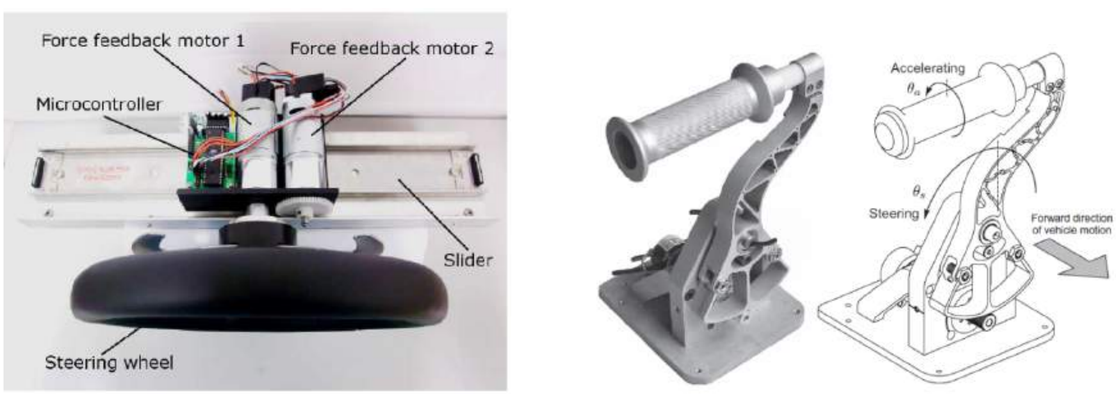


Figure E 6. A steering wheel that can slide, extends the input possibilities to a four-wheel steering vehicle[95] (left); a new device that shows strong similarities with the yoke from GM's Hy-wire (right)[96].

[93] Neurogadget.com, "Honda Creates Brain-Reading Driving Hat," pp. 1–8, 2011.
[94] See footnote 91 from previous page.
[95] T. L. Lam, S. Member, and H. Qian, "Omnidirectional Steering Interface and Control for a Four-Wheel Independent Steering Vehicle," vol. 15, no. 3, pp. 329–338, 2010.
[96] See footnote 73 from three pages back.

Appendix F. Morphologic Charts for Concepts

Design Characteristics - Concept 1. PUSH-STEERING

steering command (INPUT 1)	proprioceptive control			actuator (body part)		
	force	position	velocity	finger(s)	hand(s)	fore arm(s)
	direction					
	rotation	translation				

information about articulation (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction				reference				
	rotation	translation		top	bottom	inside/outside (left/right)		steering direction	cabin	1st trailer	2nd trailer	road boundaries

information about lateral forces (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about traffic users (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about road layout (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

Design Characteristics - Concept 2. DOUBLE-THUMB-STEERING

steering command (INPUT 1)	proprioceptive control			actuator (body part)		
	force	position	velocity	finger(s)	hand(s)	fore arm(s)
	direction					
	rotation	translation				

information about articulation (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction				reference				
	rotation	translation		top	bottom	inside/outside (left/right)		steering direction	cabin	1st trailer	2nd trailer	road boundaries

information about lateral forces (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about traffic users (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about road layout (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

Design Characteristics - Concept 3. DOUBLE-WRIST-STEERING

steering command (INPUT 1)	proprioceptive control			actuator (body part)		
	force	position	velocity	finger(s)	hand(s)	fore arm(s)
	direction					
	rotation	translation				

information about articulation (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction				reference				
	rotation	translation		top	bottom	inside/outside (left/right)		steering direction	cabin	1st trailer	2nd trailer	road boundaries

information about lateral forces (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about traffic users (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about road layout (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

Design Characteristics - Concept 4. SINGLE-WRIST-STEERING

steering command (INPUT 1)	proprioceptive control			actuator (body part)		
	force	**position**	velocity	finger(s)	**hand(s)**	fore arm(s)
	direction					
	rotation	translation				

information about articulation (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	**position**	velocity	pressure	vibration	temp.	electric voltage	**finger(s)**	hand(s)	arm(s)	chest	back
	direction			direction				reference				
	rotation	**translation**		top	bottom	inside/outside (left/right)		steering direction	**cabin**	1^{st} trailer	2^{nd} trailer	road boundaries

information about lateral forces (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	**pressure**	**vibration**	temp.	electric voltage	**finger(s)**	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	**inside/outside (left/right)**						

information about traffic users (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	**pressure**	**vibration**	temp.	electric voltage	**finger(s)**	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	**translation**		top	bottom	**inside/outside (left/right)**						

information about road layout (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	**pressure**	**vibration**	temp.	electric voltage	**finger(s)**	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	**translation**		top	bottom	**inside/outside (left/right)**						

Design Characteristics - Concept 5. ELBOW-STEERING

steering command (INPUT 1)	proprioceptive control			actuator (body part)		
	force	position	velocity	finger(s)	hand(s)	fore arm(s)
	direction					
	rotation	translation				

information about articulation (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)					
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back	
	direction			direction				reference					
	rotation	translation		top	bottom	inside/outside (left/right)		steering direction	cabin	1st trailer	2nd trailer	road boundaries	

information about lateral forces (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about traffic users (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about road layout (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

Design Characteristics - Concept 6. ONE-ARM-CONTROL

steering command (INPUT 1)	proprioceptive control			actuator (body part)		
	force	position	velocity	finger(s)	hand(s)	fore arm(s)
	direction					
	rotation	translation				

information about articulation (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction				reference				
	rotation	translation		top	bottom	inside/outside (left/right)		steering direction	cabin	1st trailer	2nd trailer	road boundaries

information about lateral forces (OUTPUT 2a)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about traffic users (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

information about road layout (OUTPUT 2b)	proprioceptive feedback			tactile feedback				sensor (body part)				
	force	position	velocity	pressure	vibration	temp.	electric voltage	finger(s)	hand(s)	arm(s)	chest	back
	direction			direction								
	rotation	translation		top	bottom	inside/outside (left/right)						

Appendix G. Key Points of Concepts

	CONCEPT 1. Push-Steering	CONCEPT 2. Double-Thumb-Steering	CONCEPT 3. Double-Wrist-Steering	CONCEPT 4. Single-Wrist-Steering	CONCEPT 5. Elbow-Steering	CONCEPT 6. One-Arm-Control
	(picture)	(picture)	(picture)	(picture)	(picture)	(picture)
Keypoints	1 hand for steering, 1 hand for feedback	2 thumbs for steering, 2 arms for feedback	2 hands for steering, 2 arms for feedback	3 fingers for steering, 3 fingers for feedback	2 elbows for steering, 2 hands for feedback	1 arm for steering and feedback
	non-continuous feedback (active feeling)	continuous feedback (passive feeling)	continuous feedback (passive feeling)	continuous feedback (passive feeling)	non-continuous feedback (active and passive feeling)	continuous feedback (passive feeling)
	hand for steering or feedback is flexible	arms move together	hands move together	freedom of arm position	hands move independently from each other	fingers move together in pairs
Steering command:	hands move physical 'walls' to left/right (position control)	thumbs move together to left/right (position control)	hands move together to left/right (position control)	wrist rotates relative to lower arm (position control)	elbow presses outwards (force control)	finger pair presses/moves inwards
Feedback articulation:	feel and follow surface of mechanical device or active touch panel with hand and fingers	follow mechanical device with arms	-	follow mechanical device with fingers	follow mechanical device with wrists	feel mechanical device with hand and arm (skin stretch)
Feedback forces:	feel and follow surface of mechanical device or active touch panel with hand and fingers	feel pressure along length of arms	feel pressure/vibration along length of arms	feel pressure/vibration on fingertips	follow mechanical device with thumbs and pinkies	feel pressure on hand and arm
Feedback road boundaries:	feel and follow surface of mechanical device or active touch panel with hand and fingers	feel pressure/vibration along length of arms	feel pressure/vibration along length of arms	feel pressure/vibration on proximal finger parts	feel and follow surface of mechanical device with index finger and ring finger	feel pressure/vibration on hand and arm
Feedback traffic:	feel surface/vibration on mechanical device or active touch panel with hand and fingers	feel pressure/vibration along length of arms	feel pressure/vibration along length of arms	feel pressure/vibration on second finger parts	feel pressure/vibration on fingertips of index finger and ring finger	feel pressure/vibration on hand and arm
Advantages	push-steering is intuitive (direct relation front-axle to own body)	large area available for feedback	large area available for feedback	all motion is relative, so freedom of posture	fingertips are most sensitive area	all motion is relative, so freedom of posture
	freedom of choosing which hand to use for steering	passive feeling, no need to explore	passive feeling, no need to explore	fingertips are most sensitive area	mainly passive feeling, only little need to explore	total freedom of entire non-steering arm
	freedom of choosing which hand to use for feedback		arms are continuously supported	passive feeling, no need to explore		freedom of choosing which finger to use for steering
	freedom of posture		arms do not move			
	opportunities for highly autonomous driving (if walls represent road boundaries)		absolute and clear representation of steering angle (no scaling)			
Disadvantages	active feeling, exploring is necessary	limited angle to represent 2nd articulation angle	only indirect information about articulation and road	limited area available for feedback	limited area available for feedback	device needs to be worn
	arms are not continuously supported	little freedom of posture	limited freedom of posture	probably device(s) need to be worn	little freedom of posture	limited support for steering arm
		limited support of arms supported	locating traffic users requires extra thinking		limited support possible	
Risks	missed information, especially on traffic	steering with precision is difficult	incorrect perception of location of traffic users	incorrect perception of direction	shoulder strain	incorrect perception of direction
		continuously forced position is uncomfortable				tickles on hand palm
		confusion of steering command due position of hands				pain due to frequent skin-stretch
Notes	position of hands is flexible, so feedback also needs to be flexible	prototype could be attached to hands and arms	symmetry	left finger represents same trailer as corresponding right finger	one hand for each trailer	prototype could use plates
	prototype would be mechanical device, with discrete points of feedback (not a continuous touch panel)	symmetry		skin-stretch can be applied	middle fingers and thumbs can freely move on surface	direction could be made dependent on orientation
	walls can be any size			direction could made dependent on orientation	prototype could be a rotating disk underneath wrists	

Appendix H. Motivation for Scores in the Rating Chart, and Explanation of Rating Criteria

	RATING CRITERIA	CONCEPT 1 Push-Steering unweighed score	CONCEPT 2 Double-Thumb-Steering unweighed score	CONCEPT 3 Double-Wrist-Steering unweighed score	CONCEPT 4 Single-Wrist-Steering unweighed score	CONCEPT 5 Elbow-Steering unweighed score	CONCEPT 6 One-Arm-Control unweighed score
	Safety						
Driver is safe from injury and pain during normal driving. E.g. no sharp edges, no hard objects near head, no parts sticking out to torso or head, no electric shocks	**operational safety**	5 *no reason for injury*	5 *no reason for injury*	5 *no reason for injury*	5 *no reason for injury*	5 *no reason for injury*	1 *skin could be stretched excessively*
There are possibilities for passive safety features. E.g. room for airbag, collapsible parts, minimal number of (large) objects in front of driver	**passive safety possibilities**	1 *large object in front of driver*	1 *horizontal bar and rail in front of driver*	3 *large object could pass the driver sideways*	5 *no large objects, no fixed objects*	3 *small objects in front of driver*	5 *no large objects, no fixed objects*

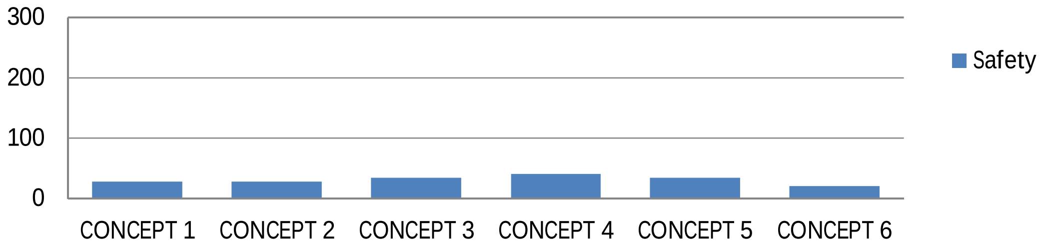
	RATING CRITERIA	CONCEPT 1 Push-Steering unweighed score	CONCEPT 2 Double-Thumb-Steering unweighed score	CONCEPT 3 Double-Wrist-Steering unweighed score	CONCEPT 4 Single-Wrist-Steering unweighed score	CONCEPT 5 Elbow-Steering unweighed score	CONCEPT 6 One-Arm-Control unweighed score
	Comfort						
Precision of control (force or position) is comfortable for driver. E.g. sufficient range, comfortable amount of play, no fatigue, no strain	**precision comfort for giving command**	5 *small rotation, but large translation of arm*	2 *limited rotation of thumb*	3 *limited rotation due to "inner" wrist*	5 *full rotation of wrist*	1 *low precision of upper arm force*	4 *up-and-down movement of finger*
Posture when giving command is comfortable. E.g. no awkward posture, no fatigue, no strain, no (large) influence of feedback, sufficient support	**body comfort, when giving command**	3 *arms move easily sideways, support between steering commands is possible*	2 *wrist rotation (feedback) can affect thumb position, only limited support of arm is possible*	4 *wrist is very flexible, both lower arms are supported and remain straight*	5 *wrist is very flexible, support of lower arm is possible*	1 *wrist rotation (feedback) can affect force of elbow, very limited support of arm is possible*	5 *fingers move (or apply force) up and down easily, support of part of lower arm is possible*
Posture when receiving feedback is comfortable. E.g. no awkward posture, no fatigue, no strain, sufficient support	**body comfort, when receiving feedback**	3 *fingers can be stretched or bent, limited support of arm is possible*	1 *wrists and lower arms can be in an awkward position*	5 *both arms are supported and remain straight*	4 *individual fingers move up and down easily, support of lower arm is possible*	1 *wrists and lower arms can be in an awkward position*	2 *skin-stretch can be awkward, support of part of lower arm is possible*
Driver can move arms and hands to a certain extent when giving command. E.g. multiple options of articulation, independent arm movements (left/right)	**freedom of posture, when giving command**	4 *multiple options for articulation of arm, fingers can move freely*	1 *thumbs must rotate together, fingers can move a little*	1 *wrists must rotate together and cannot translate, fingers can move a little*	5 *thumb can move a little, upper and lower arm and entire other arm can move freely*	2 *only elbows can rotate a little*	5 *fingers can move a little, complete freedom of (i) upper and lower arm and (ii) entire other arm*
Driver can move arms and hands to a certain extent when receiving feedback. E.g. minimal forced positions or articulations	**freedom of posture, when receiving feedback**	4 *multiple options for articulation of fingers and wrist*	1 *forced orientation of hands and forced articulation of wrist, fingers can move a little*	1 *complete fixation of lower arms, fingers can move a little*	3 *forced articulation of 3 left fingers, complete freedom of (i) upper and lower arm and (ii) entire other arm*	2 *forced articulation of wrists and most fingers, only elbows can rotate a little*	5 *fingers can move a little, complete freedom of (i) upper and lower arm and (ii) entire other arm*
Driver can choose which body part to use when giving command. E.g. left or right body part, hand palm or back of hand, choice of fingers	**freedom of which body part to use when giving command**	5 *fingers, hand palm, back of hand, or lower arms*	2 *left or right thumb*	2 *left or right wrist*	1 *only one wrist*	1 *only left or right elbow*	3 *one of two fingers*
Driver can choose which body part to use when receiving feedback. E.g. left or right body part, choice of area of body part to sense with, choice of fingers	**freedom of which body part to use when receiving feedback**	5 *left or right fingers, any combination of fingers*	1 *hands and lower arms, including prescribed areas*	1 *lower arms, prescribed areas*	1 *specific fingers, including prescribed areas*	1 *wrists and specific fingers, including prescribed areas*	1 *handpalm and lower arm, prescribed areas*

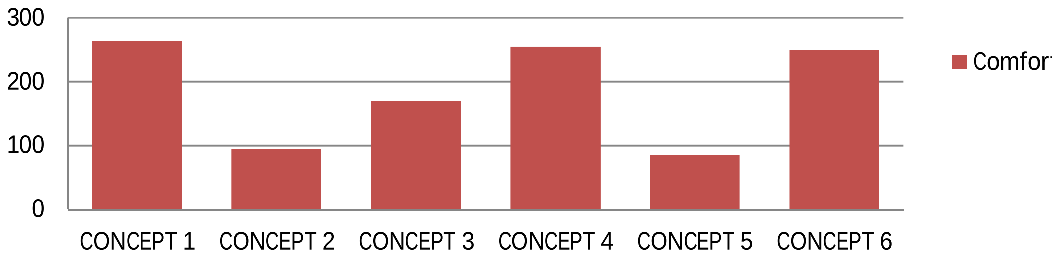
	RATING CRITERIA	CONCEPT 1 Push-Steering unweighed score	CONCEPT 2 Double-Thumb-Steering unweighed score	CONCEPT 3 Double-Wrist-Steering unweighed score	CONCEPT 4 Single-Wrist-Steering unweighed score	CONCEPT 5 Elbow-Steering unweighed score	CONCEPT 6 One-Arm-Control unweighed score
	Intuitiveness						
Driver understands well how command affects steering direction or lateral position. E.g. resemblence of direction, no (large) influence of posture, no (large) influence of feedback	**representation of steering command**	5 *position and movement of walls give clear indication about position and movement of tractor*	1 *orientation of thumbs can be heavily affected by position of arms (feedback)*	5 *angle of wrists closely ressembles actual steering angle*	2 *orientation of wrist depends on position of lower and upper arm*	4 *direction of force corresponds to either the steering direction or the opposite (push-steering)*	2 *orientation of hand depends on position of lower and upper arm*
Driver understands where trailers are positioned w.r.t. tractor. E.g. fixed reference, minimal scaling	**representation of information about vehicle articulation**	5 *fixed reference; feedback cues represent exactly actual articulation*	5 *fixed reference; feedback cues represent exactly actual articulation*	1 *fixed reference; actual articulation can only be derived from other cues*	3 *non-fixed reference; scaling is necessary*	2 *2 non-fixed references; scaling is necessary*	2 *non-fixed reference; high scaling is necessary*
Driver understands how critical the lateral forces on the trailers are. E.g. preferably force or pressure feedback, clear distinction of trailers, clear distinction of direction, no (large) influence of posture, no (large) influence of feedback	**representation of information about lateral forces**	3 *position feedback; clear distinction of trailers and direction*	5 *pressure feedback; clear distinction of trailers and direction*	4 *pressure feedback; little unclear distinction of trailers*	1 *vibration feedback; unclear distinction of trailers; perception of direction depends on orientation of hand*	3 *position feedback; distinction of trailers depend on relative position of hands*	2 *pressure feedback; perception of direction depends on orientation of hand*
Driver understands how large the distance between the vehicle and the road boundaries is. E.g. preferably position feedback, clear distinction of side (left or right), clear distinction of location along the vehicle length, no (large) influence of posture, no (large) influence of feedback	**representation of information about road boundaries**	5 *position feedback; clear distinction of side and location*	3 *pressure feedback; little unclear distinction of location*	3 *pressure feedback; little unclear distinction of location*	1 *pressure feedback; unclear distinction of location; perception of side depends on orientation of hand*	4 *position feedback; only one location per trailer, distinction of location also depends on relative position of hands*	2 *pressure feedback; little unclear distinction of location; perception of side depends on orientation of hand*
Driver understands how critical the state of other traffic users w.r.t. the truck is. E.g. clear distinction of location, clear distinction of velocity (including direction)	**representation of information about traffic users**	5 *clear distinction of location and velocity*	4 *unclear distinction of velocity*	4 *unclear distinction of velocity*	1 *unclear distinction of location and velocity*	3 *unclear distinction of velocity; little unclear distinction of location, also depends on relative position of hands*	2 *unclear distinction of velocity; perception of location depends on orientation of hand*
Driver continuously perceives feedback. E.g.active or passive feeling	**continuity of information**	2 *active feeling, driver must move around to explore*	5 *passive feeling*	5 *passive feeling*	5 *passive feeling*	5 *passive feeling*	5 *passive feeling*

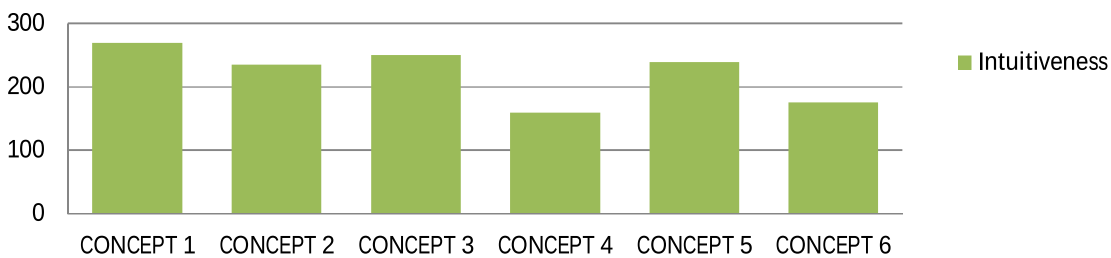
	RATING CRITERIA	CONCEPT 1 Push-Steering unweighed score	CONCEPT 2 Double-Thumb-Steering unweighed score	CONCEPT 3 Double-Wrist-Steering unweighed score	CONCEPT 4 Single-Wrist-Steering unweighed score	CONCEPT 5 Elbow-Steering unweighed score	CONCEPT 6 One-Arm-Control unweighed score
	Accessibility						
Driver can easily access the seat and take sitting position. E.g. minimal amount of devices that need to be folded in, minimal amount of devices very close to the driver	**accessibility from driver's side**	4 *devices are in front of driver*	1 *devices are on both sides of driver*	1 *devices are on both sides of driver*	5 *no obstructions*	2 *devices are placed next to both elbows*	5 *no obstructions*
Driver is not physically attached to any (large) device. E.g. no large sleeve to be worn	**absence of devices to be attached to body**	5 *no devices to be attached to body*	4 *lower arms and hands must take specific position*	4 *lower arms must take specific position*	1 *small devices to be attached to both hands*	2 *devices to be attached (??) to wrists*	1 *medium-sized device to be attached to one hand*

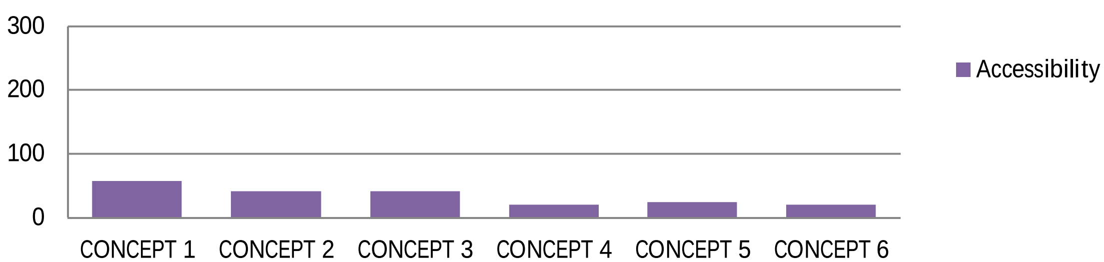
		CONCEPT 1	CONCEPT 2	CONCEPT 3	CONCEPT 4	CONCEPT 5	CONCEPT 6
		Push-Steering	Double-Thumb-Steering	Double-Wrist-Steering	Single-Wrist-Steering	Elbow-Steering	One-Arm-Control
	RATING CRITERIA	unweighed score	unweighed score	unweighed score	unweighed score	unweighed score	unweighed score
	Originality						
The steering commands are unlike any other steering command related to existing steering E.g. minimal similarities with joystick, minimal similarities with yoke	**originality of giving command**	5 *indirect steering of front wheels by directly positioning tractor*	2 *similarities with position controlled joystick*	2 *similarities with position-controlled joystick*	1 *strong similarities with position-controlled joystick*	4 *similarities with lean-steering of motorcycle*	3 *similarities with pressure pad e.g. in yokes of concept cars*
The feedback perception is unlike any other feedback perception from existing control devices. E.g. minimal similarities with exoskeleton, minimal similarities with tactile warning systems	**originality of feedback**	3 *similarities with interactive touch screen*	1 *similarities with exoskeleton and tactile warning systems*	1 *similarities with tactile warning systems*	2 *similarities with exoskeleton and tactile warning systems; precise and small-scale cues*	3 *similarities with exoskeleton and interactive touch screen*	5 *skin-stretch is not widely used*

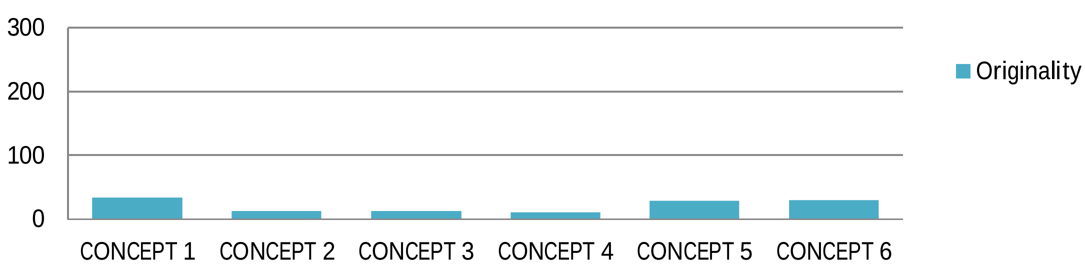
Appendix I. Scores from Rating Chart per Group of Criteria











Appendix J. Photos of Prototype of Walls

Figure K 1. The U-shape in regular position. The range of motion is bounded at 10 [cm] to the right (top) and 10 [cm] to the left (bottom).

Figure K 2. The U-shape is placed in flipped position. The range of motion is bounded at 10 [cm] to the right (top) and 10 [cm] to the left (bottom).

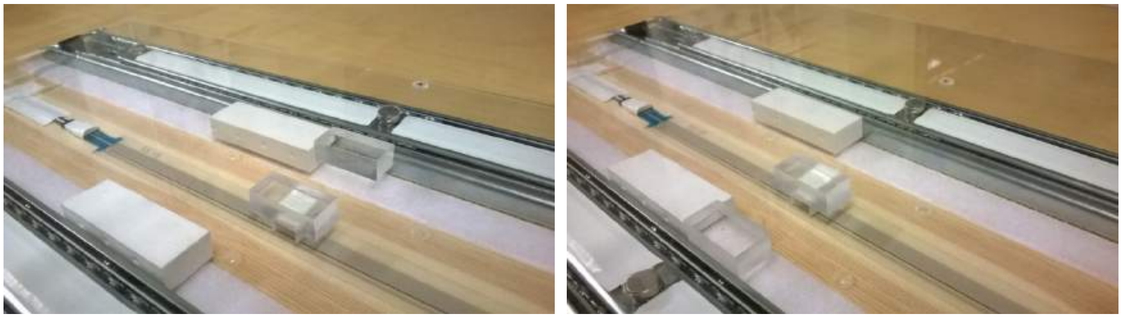


Figure K 3. The range of motion of the U-shape is bounded by mechanical stops. The small plastic block hits a stop, with the U-shape in regular position (left) and in flipped position (right).

Figure K 4. Each stop consists of a white eraser with a piece of Valcro strip glued onto it.

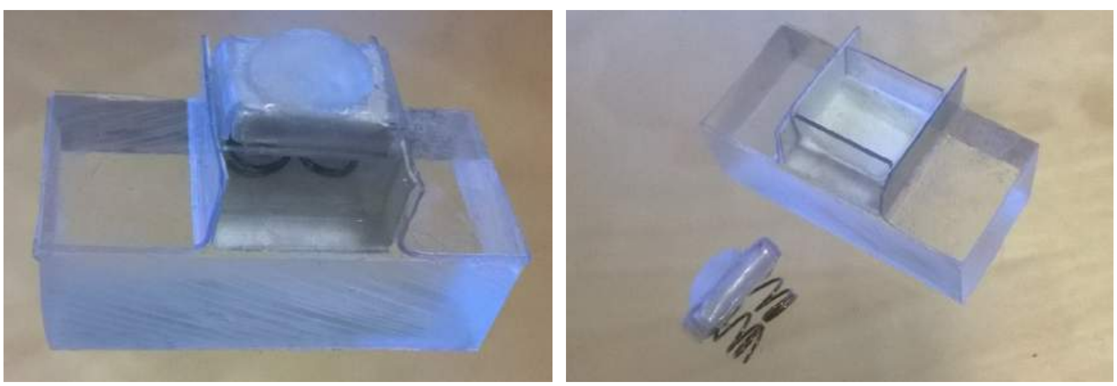


Figure K 5. The U-shape makes contact with the potentiometer through a customized pin. The pin and its housing are made of small pieces of plastic and a small spring that ensures continuous contact.

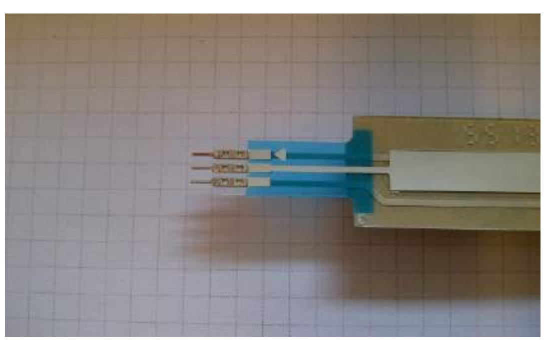


Figure K 6. The end of the simple, small, and flat potentiometer on a background of squared paper (5x5 [mm]).

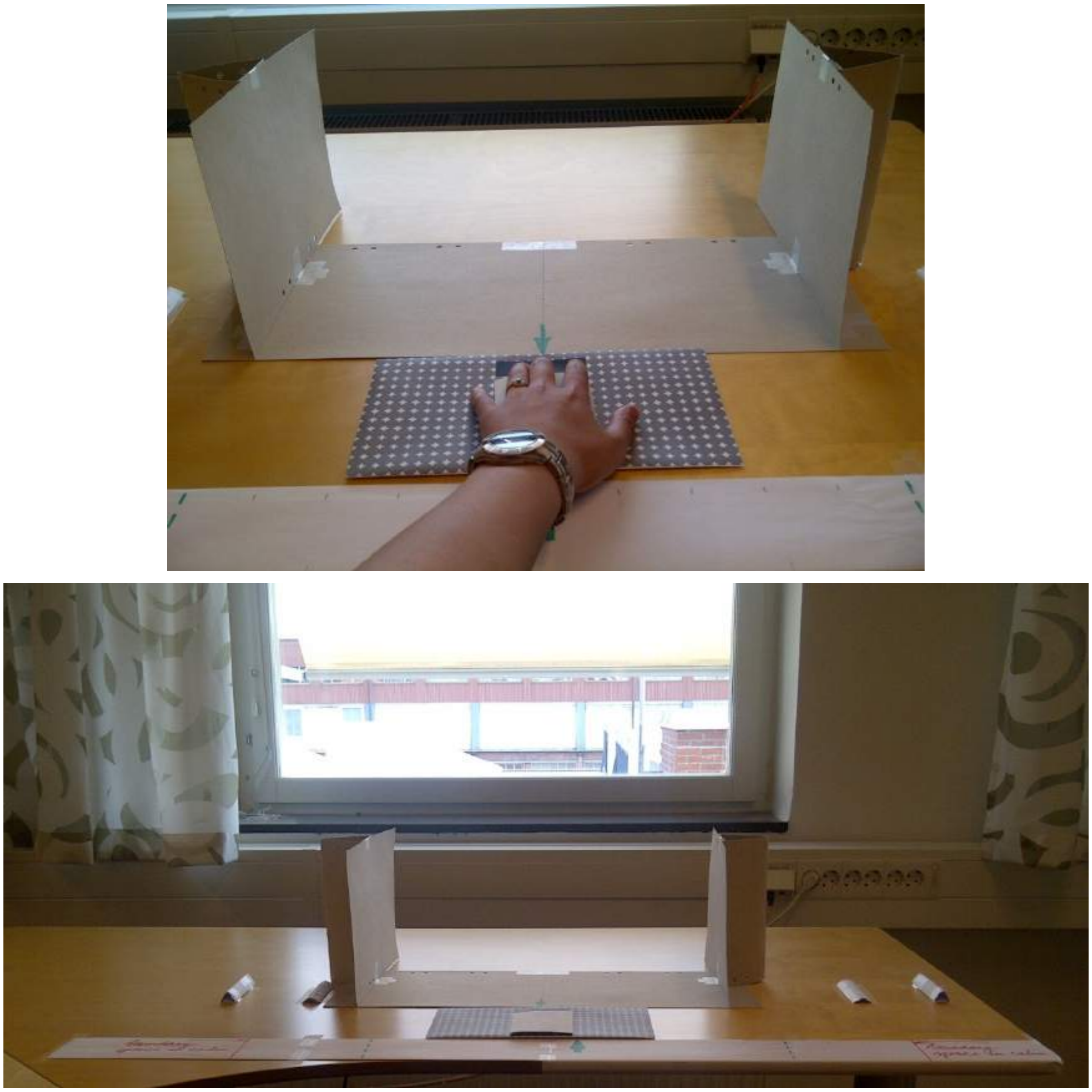


Figure K 7. A first mock-up of the new steering interface that was made out of paper and cardboard, was used to determine the dimensions and range for the prototype.

Test Protocol

Before the runs:

- Brief DRIVER and SAFETY MANAGER on the runs, the procedure, and the instructions
- Adjust wooden board/table to DRIVER's preferences
- Mount cameras
- Connect power supply cables and communication cables
- Start ControlDesk
    - Determine 'Lane Width' and 'Truck Width', and enter value in ControlDesk
        - Check if 'Lane Width' can be kept constant for all runs
    - Determine 'Output_limit DAC', 'Output_min DAC' and 'Output_max DAC', and enter value in ControlDesk
        - Update the SAFETY MANAGER about 'Input_min DAC' and 'Input_max DAC'
    - Check if 'Conversion' needs to be adjusted in ControlDesk
    - Determine 'Wiring side' and select side in ControlDesk
    - Apply trigger rules for Recorder in ControlDesk
- Open document 'Notes on Execution of Runs (during testing).docx'

For <u>EVERY</u> run:

- Set mechanical stops according to 'Range of device'
- Enter value of 'Position_max WALLS' in ControlDesk
- Give instruction to SAFETY MANAGER to attain and maintain the speed
- Give instruction to DRIVER regarding 'Contact area of device'
- Start recording cameras
- Mark test: 'Run nr.' , 'Speed', 'Range of device', 'Contact area of device'
- Start recording Autobox A
- Start triggered recording Autobox B
    - Press F9 button (start of recording)
    - Press 'START' button (application of marker)
- Ensure that DRIVER executes task correctly
    - Ensure that at the end of a run DRIVER positions U-shape at the left boundary
- Stop recording Autobox B
    - Press 'STOP' button
    - Write any comments in document 'Notes on Execution of Runs (during testing).docx'
- Stop recording Autobox A
    - Name and save data
- Stop recording cameras

After the runs:

- Check the data recordings
- Check the camera recordings
- Close ControlDesk, detach cables, demount cameras, and unload all hardware from the cabin
- Conduct the survey with DRIVER, using the questionnaire

Questionnaire on Driving Experience

Evaluation of Push Steering Walls
Test track Hällered, 17 September 2014

Driver: Carl-Johan Hoel

Did you like it?
Yes, it was relaxing not having to focus on normal steering all the time and just make minor adjustments when you want to.

How did it feel?
It felt very different from normal driving. More like driving a big ship. And less demanding since you don't need to steer all the time.

Was it difficult to understand?
No, very simple. It just took a few minutes to get used to pushing which way meant going in which direction. But when adopting the mindset that the walls were the lane markings, it felt natural.

Was it difficult to operate?
It felt natural. Only sometimes it was a bit difficult knowing where you were in the lane, especially since I didn't look in the mirrors. The left and rightmost positions were easy to find, but it was more difficult to judge your position in between. Some kind of force feedback could maybe be an evolution.

Were you physically comfortable using it?
Yes, it felt good. Though when the cab was rolling a lot from evasive maneuvers, the sliding mechanism also moved so you had to hold it. So some more friction could be good.

Were you mentally comfortable using it?
Yes, after getting used to the system it felt intuitive to use it.

Did you trust the system?
The input device itself felt good. Then there were glitches and problems with the lane following that made me a bit nervous. But that is of course natural for a prototype. And when the glitching problem was solved and we had been driving for a while, it felt quite safe.

How did you feel about not looking in the mirrors?

It made it difficult to judge where you are in the lane. And not seeing overtaking traffic is a bit scary. If not using the mirrors, more information about the surroundings should be presented to the driver.

How did you feel about not controlling the speed?
That felt good, no problems.

Do you have a preference for the value of the 'Range of device'?
I preferred a large range, at least the +/- 100 mm. That made me feel more in control, whereas the shorter range felt too jerky.

Do you have a preference for the 'Contact area of device'?
I liked resting my hands on the moveable "floor" of the plate. And then pushing the walls to make adjustments. Partly because then the hand not pushing the wall helped stabilize the movement. Otherwise it is tricky to make a smooth movement when the cab is rolling. But this is also related to me sitting at the bed with bad back support, making me bounce around a lot. Probably it would be better in a normal seat.

Do you have any suggestions for the design?
As mention above, some more friction in the system to make it more stable and easy to control when the truck is moving. And maybe some type of force feedback/dents in the motion range to inform you about where you are in the lane.

Do you have any further comments?
It was very interesting to try this new way of driving. And it felt more natural than I had expected.

Questionnaire on Driving Experience

Evaluation of Push Steering Walls
Test track Hällered, 17 September 2014

Driver: Kristoffer Tagesson

Did you like it?
Yes, I think that having the possibility to interact also with an "autonomous" can be very usable. I also liked the way I was able to interact.

How did it feel?
Rather natural. If you just thought of the walls as lane-markings then is was very natural. You just pushed them away.

Was it difficult to understand?
No.

Was it difficult to operate?
No, easy. A child could do it.

Were you physically comfortable using it?
Yes. No problem with that.

Were you mentally comfortable using it?
Yes. Before I tested it I was a bit nervous about how it would feel. Bu already after a few seconds that was long gone.

Did you trust the system?
100%. But it would be good to operate speed also.

How did you feel about not looking in the mirrors?
It was hard to tell exactly where in the lane that the truck was positioned without looking in the mirrors. I also did not see cars overtaking from behind. So I missed the mirrors.

How did you feel about not controlling the speed?
It was ok in the test as we had someone doing that. But that would be important in a real implementation.

Do you have a preference for the value of the 'Range of device'?
I only tested one setting.

Do you have a preference for the 'Contact area of device'?
Somewhere low so I can lean and relax my arms. When I held high on the walls I had to tens my arms.

Do you have any suggestions for the design?
The idea of controlling the lateral position in lane was superb. One thing to improve would be the size. It literally uses up all the space you have in front of you.

Do you have any further comments?
I was impressed by how good it worked.

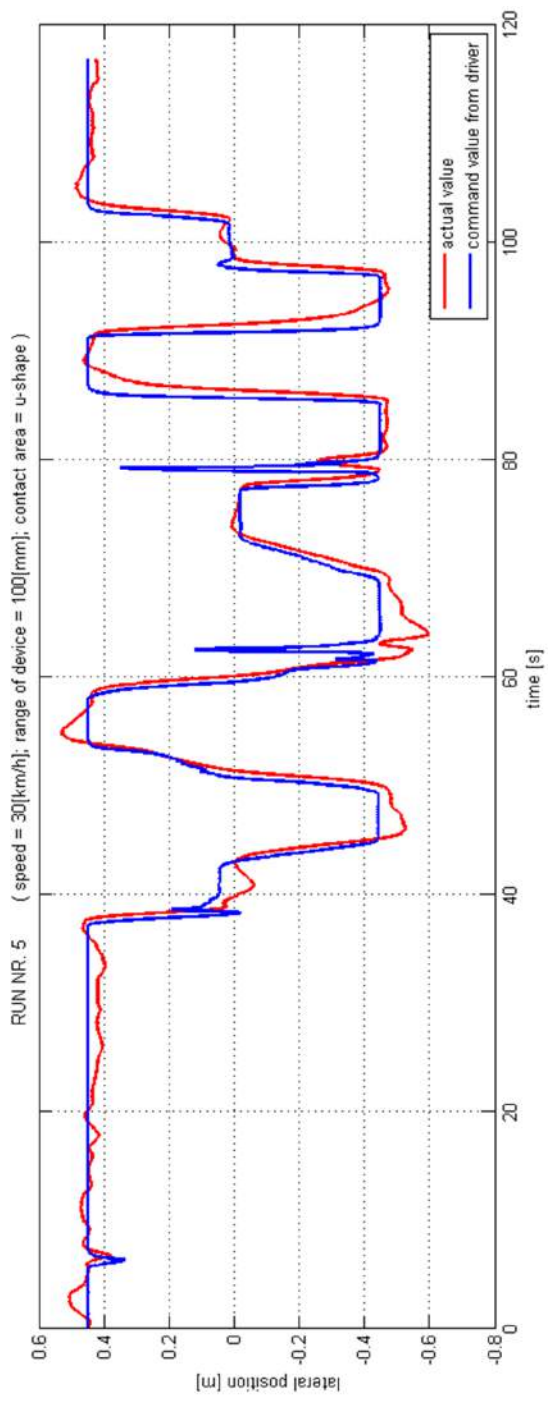
Appendix M. Photos of Testing of Prototype of Walls

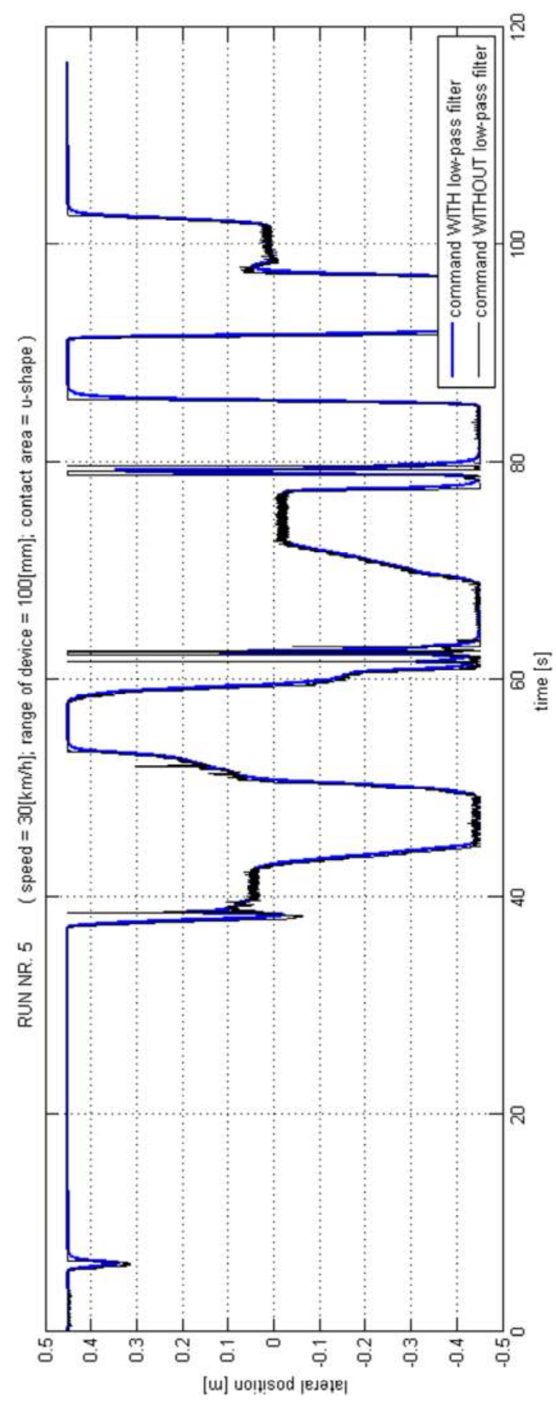
Figure N 1. Maintenance on the wiring of the prototype was performed between test runs.

Figure N 2. Kristoffer Tagesson (left) and Syarifah Siregar (right) driving with the prototype in extra test runs.

Figure N 3. An extra camera was mounted on the window in the ceiling of the cab.

Appendix N. Example Run with Glitches (Run Nr. 5)





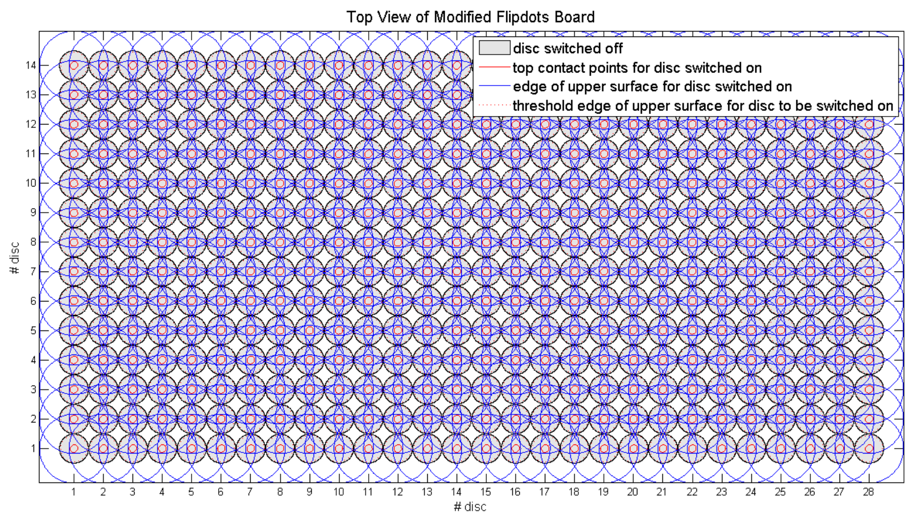
Appendix O. Notes on Test Data and Test Footage

Run nr.	Speed [km/h]	Range of device [mm]	Contact area of device	Notes on executions of runs (during testing on track)	Notes on footage and data (after testing on track)	Selected footage for presentation	Run nr. on video marker	Recording data Autobox A (Syarifah's Autobox)	Recording data Autobox B (CJ's Autobox)
0 test run	30	200	U-shape	CJ: cabin moves and so board moves, he needs to get used to it.	CJ: Cab is rolling and the table (U-shape) is moving too, so it's not stuck where I left it. CJ keeps his eyes on the road, leans on the table, CJ seems to use the corners of the U-shape as reference, uses the lower part of the walls, pushes with the outer surface	fast little movements delay <0.5 s CJ seems to understand it	0	recdata_exptrack_001.mat	014_test30kph_P1_I0p4_D2p5_withLP
1	30	200	U-shape	Board lost contact at 230 s	Maintenance: connection cables are taped to board CJ keeps his eyes on the road CJ 4,2,1 cm off centre with walls CJ uses outer surfaces of both hands, at the middle height of the walls	KT is texting, maintenance	1	recdata_exptrack_002.mat	015_realTest_30kph.mat
2	30	200	walls	For short seconds board lost contact	General: everybody had to get used to the shaky movements, once or twice signal loss/glitch Glitches are appearant in recdata_exptrack, but also to some extent (time delay) in CJ's mfile where you only see small peaks. CJ keeps his eyes on the road, CJ uses outer surface of both hands, at the lower part of the walls CJ beginning 3 cm off centre, but at the end very accurate	CJ at the end pushes the wall with all fingertips, higher than during the rest of the run	2	recdata_exptrack_003.mat	016_realTest_30kph.mat
3	30	300	U-shape	For short seconds board lost contact CJ forgot task Restart at 160 s. Mark 6 times Wrong position_max (100 instead of 150)	G: a lot of signal loss, CJ forgot the task, stop M: attempt to fix connection CJ keeps his eyes on the road, feels comfortable to leave the walls during control and look away at a table CJ puts hands practically in the corners, touching both floor and walls CJ 2 cm off centre, also very close to centre	KT has arms crossed, relaxed maintenance	4	recdata_exptrack_004.mat	-
				Extra Loss of contact is fixed now...?	G: very clear graphs CJ glanced at the U-shape in the beginning CJ uses fingertips a lot, uses the corners of the U-shape mainly, touching both floor and walls CJ first very close to centre, then 3 cm off centre	very clear graphs, footage for perfect testrun	4b	recdata_exptrack_005.mat	017_realTest_30kph.mat
4	30	300	walls	-	G: truck tried to follow exit lanes for a couple of seconds CJ 2.5,1,3 cm off centre CJ keeps his eyes on the road, looked at the ushape for 1 second CJ keeps hands at middle height or lower, sometimes uses multiple fingertips		5	recdata_exptrack_006.mat	018_realTest_30kph.mat
5	30	100	U-shape	Very jerky	G: glitches at several points CJ less than 0.5 cm off centre, very accurate CJ keeps his eyes on the road CJ keeps hands very low, uses floor to lean and to move, also uses pinkies to move,	KT is texting; high frequency oscillations of steering wheel (noise multiplied)	-	recdata_exptrack_007.mat	019_realTest_30kph.mat
6	30	100	walls	Heavy loss of contact board	G: a lot of glitch, by the end decided to fix glitch again CJ just over 1 cm or less off centre CJ tries to keep eyes on the road, but is distracted by glitches and shaking cab CJ keeps hands low, uses outer surface of hands only (pinkies), uses U-shape also to deal with the shaking cab		8	recdata_exptrack_008.mat	020_realTest_30kph.mat
				Tried to fix loss of contact again Much better	CJ: it's much harder with a small range (100mm) G: very short glitches did not seem to be picked up as input for the vehicle, so they are don't appear in CJ's graphs. CJ 1.5 off centre, after very close to centre CJ keeps his eyes on the road CJ leans a lot on the table, keeps hands low, uses pinkies, barely touches the floor, clearly uses both walls to control position of U-shape		8b	recdata_exptrack_009.mat	021_realTest_30kph.mat

7	60	300	U-shape	-	G: High overshoots in graphs G: loss of signal, glitches, seem to have been fixed permanently CJ is very relaxed and confident CJ less than 1cm off centre CJ keeps eyes on the road CJ uses floor with one hand and wall with other hand, middle height or even higher part of wall; also leans on the floor during steady position	very clear graphs, footage for perfect testrun	-	recdata_exptrack_011.mat	023_realTest_60kph.mat
8	60	300	walls	-	no useful content		9		-
				-	G: High overshoots in graphs, sometimes doesn't even seem to reach right steady-state value CJ feels very comfortable leaving the U-shape and even leaning on it while in being still in control CJ: It feels quite good, it feels quite comfortable CJ 3.5, then less than 1 cm off centre CJ looks at Kristoffer several times while talking to him, or keeps his eyes on the road CJ leans on the table when not moving the U-shape, uses both hands to control the movements, uses pinkies, or multiple fingertips to move, higher part of the walls	CJ feels very comfortable, even uses just one hand, laughs, talks	9b	recdata_exptrack_012.mat	024_realTest_60kph.mat
9	60	200	U-shape	-	CJ about 1cm or less off centre CJ everytime glances ot the U-shape to take centre position, glances at computer and at radio that makes noise for a second CJ leans on the table and rests both hands on the floor, moves board with multiple finger tips, at middle height, while keeping one hand on the floor	CJ is aware the traffic situation (car from road exit), stays calm and acts confidently	11	recdata_exptrack_013.mat	025_realTest_60kph.mat
10	60	200	walls	-	G: truck clearly oscillates around steady requested position, change of curvature influences how well and fast the truck follows the input CJ less than 1cm off centre CJ everytime looks at the U-shape when taking centre position, looks at computer for a couple of seconds, glances at a possible exit CJ uses both hands at middle or high height to control the movement, leans on table during steady input, pinkies mainly and sometimes multiple finger tips		12	recdata_exptrack_014.mat	026_realTest_60kph.mat
11	60	100	U-shape	-	G: glitches appeared again, change of curvature influences how well and fast the truck follows the input CJ less than 1cm off centre, despite multiple glitches CJ everytime glances at the U-shape to take centre position, looks at computer because of glitches, keeps eyes on the road, glances at stopping car at road exit CJ leans on table, fingertips on floor in the corners, moves board with multiple finger tips, at high height; only touches (higher parts of) walls when moving the U-shape.		13	recdata_exptrack_015.mat	027_realTest_60kph.mat
12	60	100	walls	-	CJ 0.5cm or less off centre CJ everytime glances at the U-shape to take centre position, looks several times at computer (because truck doesn't follow properly because of curvature change) CJ leans on table during steady input, pushes with mainly pinkies, for fast movements also uses other finger tips, keeps other pinky against wall at low height		14	recdata_exptrack_016.mat	028_realTest_60kph.mat

Run nr.	Speed [km/h]	Range of device [mm]	Contact area of device	Notes on executions of runs (during testing on track)	Notes on footage and data (after testing on track)	Selected footage for presentation	Run nr. on video marker	Recording data Autobox A (Syarifah's Autobox)	Recording data Autobox B (CJ's Autobox)
13a filmrun 001				Shots, tried to fix loss of contact permanently	handcam: testmanager view, roofcam in view roofcam: setup, team trucksidecam: setup	'-' means useless		recdata_exptrack_010.mat	
					handcam: driver shot from low angle, side angle, glitches on steering wheel, back sidetruck view, testmanager view, driver front shot from low angle, driver view high angle and low angle roofcam: - trucksidecam: sunset at 1.30, glitches				
13b filmrun 002					handcam: - headcam: driver view, sudden lane change manoeuvre				
13c filmrun 003					cabcam/roadcam: CJ is very comfortable, laughs, makes aggressive manoeuvres				
13d filmrun 004					groundcam1: go to 2.40 groundcam2: go to 1.00 handcam:				
					-				
14a extrarun 001 (Syarifah)					CJ: (There is a delay, do you like it?) I don't mind. cabcam: adjusting range at 6.40, fast left/right movement at 6.00 roadcam: -	'-' means useless			
14b extrarun 001 (Kristoffer)					Kristoffer: Cool!; If you start thinking like you want to push the lines, then it will become more clear. CJ: Yes, exactly. It was a bit confusing in the beginning, but after a while I think it was very natural. Just think of it as sort of lines, then it's fine. But first I was thinking like 'this is the truck', then it's confusing Kristoffer: I like it more than I was hoping for. And it feels like something very big is moving. cabcam: Kristoffer is waving roadcam: -				
14c extrarun 001 (other track)					G: camera has trouble detecting the lane when the lane width is too large (~6m) cabcam/roadcam: - handcam: test manager view (only until 1.00)				
15a setup 001				Truck width (outer edge of tyre to outer edge of tyre) is 247 cm. Tyres on outer edge of lane markings: -45cm...+45cm. So in ControlDesk 'Lane Width = 3370mm' and 'Truck Width = 2470mm Negative sign on track (left/right). Simple fix is to change wiring side to RIGHT.	very short camera check without device	'-' means useless			
15b setup 002					-				
15c setup 003					roofcam: setup trucksidecam: Kristoffer's head sticking out to check the camera				

Appendix P. Images from Simulation of Flipdots Board



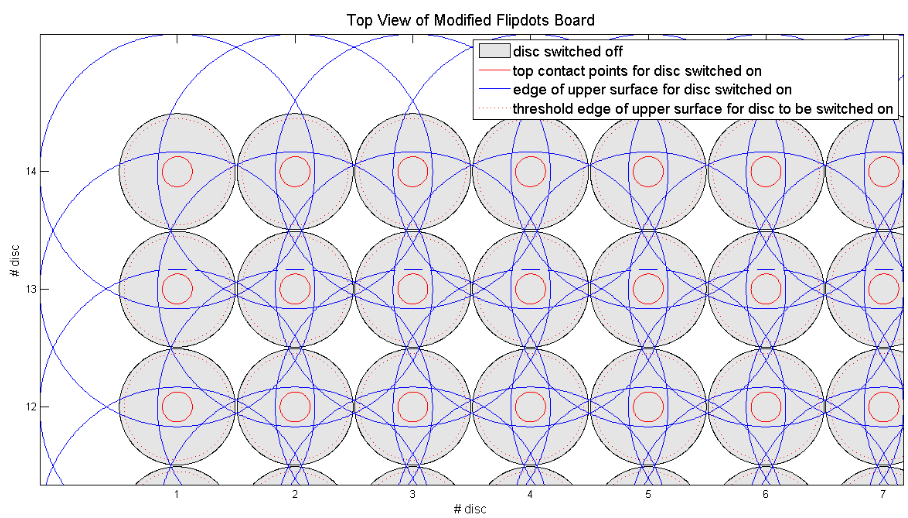


Figure R 1. The simulated flipdots board (top), without any set of surfaces on it, and a zoomed-in image (bottom). The guidelines are used to determine which discs are to be switched on for a specific articulation angle.

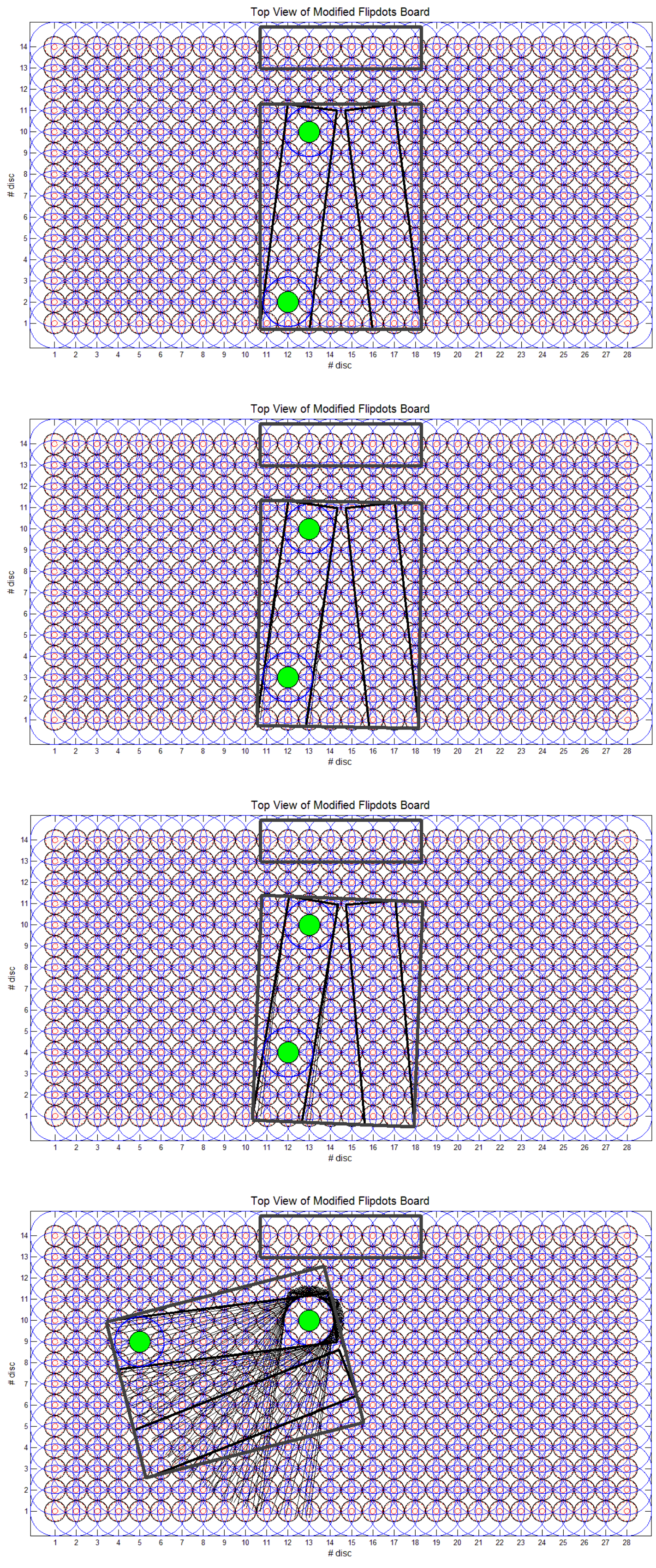


Figure R 2. The simulated flipdots board with the two sets of surfaces. Two discs that are switched on, hold the set of surfaces in position, for an articulation angle of 0, 0.02, 0.04, and 1.32 [rad] (from top to bottom).

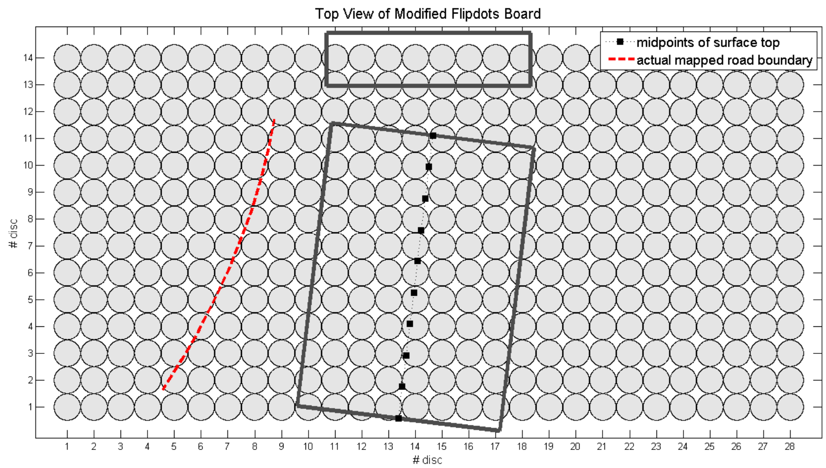


Figure R 3. The road boundary that is mapped on the flipdots board, is in fact a line that is constructed by a few points. These points lie at a chosen distance from the midpoints on the upper surface.

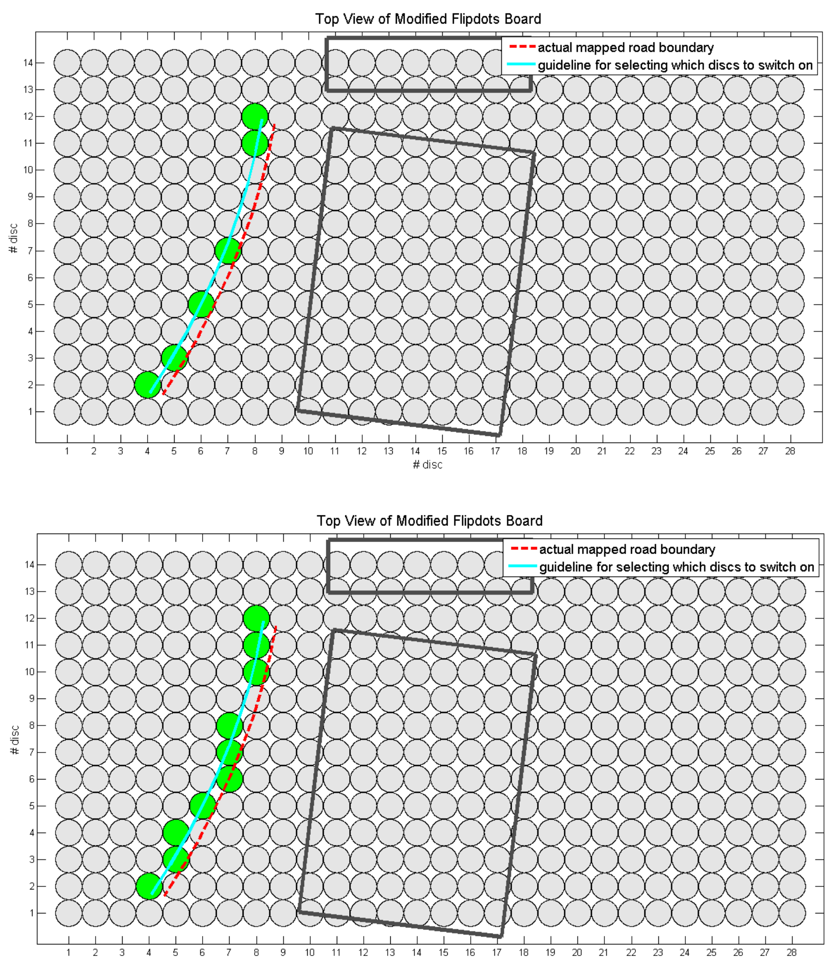


Figure R 4. The centre of the discs that represent the road boundary, are at a close distance from the cyan guideline. The maximum distance is set using a criterion, that can be for example strict (top) or less strict (bottom).