UNIVERSITY OF TWENTE

# Headway Performance in the University of Twente Driving Simulator: A validation Study

## Master thesis report

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**January 19, 2013**

# Headway Performance in the University of Twente Driving Simulator: A validation Study

*Master Thesis report*

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January 19, 2013

Amsterdam Zuidoost, the Netherlands

Version 2.3

## Summary

The University of Twente (UT) owns a driving simulator for driving research. As driving simulators are an artificial environment, different from driving on a public road, the question of its similarity to the real world – it's validity – arises.

This research aims to answer the question whether there is physical and behavioural similarity between the UT driving simulator and an instrumented vehicle in the headway attainment and keeping domain.

A test on the physical validity found that the angular size of a virtual lead vehicle at certain distance is on average 32.2% smaller than that of a real lead vehicle seen from a test vehicle. This leads to questions on whether there is a difference between how test participants perceive distance to the lead vehicle in the simulator and on the real road; and whether they will behave to headway instructions in a different way in those two vehicles.

This research on physical validity led to hypotheses on the difference in headway choice between simulator and instrumented vehicle; in headway choice at different speeds; in the time to attain the chosen headway; and in the headway keeping performance.

To test the behavioural validity, tests were performed with 22 participants. Each got into the UT driving simulator and was instructed to attain a certain headway to a lead vehicle, then keep that headway for 15 seconds. The headway instructions were given either in metres or in seconds, at different speeds of the lead vehicle. The same participants also took the same tests in an instrumented vehicle on a public highway. Data on the headway to the lead vehicle was continuously recorded.

The recorded data was then tested with a series of repeated-measures ANOVAs on differences between simulator and instrumented vehicle headway data. No significant main effects on the type of vehicle were found, but there was an interaction between speed and vehicle on the time participants needed to attain an assigned headway. We suspect this difference can attributed to differences in other vehicle's traffic behaviour between the simulated and public highways.

This leads to the conclusion that the University of Twente driving simulator is valid in the headway attainment and keeping domain with regard to the time headway chosen by participants and the headway keeping performance.

# Contents

# 1 Introduction

Driving simulators were first developed to train large numbers of personnel in World War II. Scientists quickly found that driving simulators were useful research tools as well, as they offer the possibility to quickly adapt to different scenarios, to test innovative road and vehicle technologies or layouts, and that all in a controlled and inherently safe environment (Blana, 1996).

However, driving simulators are an artificial environment, which will always be different than the real one. Because of this, drivers might behave differently in a simulator than they would in a real vehicle. This means driver performance measured in a simulator need not be the same as it would be in a natural environment. Validation is the process of checking whether behaviour in a driving simulator is the same as behaviour in a real vehicle on a real road (Blana, 1996; Engen, 2008).

The University of Twente (UT) owns a driving simulator consisting of a mock-up with a car seat, steering wheel, three pedals and a projection screen, in combination with software that manages the projected environment (including traffic) and records and responds to driver input. The UT driving simulator has been used for various types of traffic research. One of these research projects is the CCC[1]-project, sponsored by HTAS[2]. This project aims to develop a Connected Cruise Control system in which a driver receives advice regarding lane, speed and headway. Some experiments in the CCC project, studying participants' response to headway advice, are performed in the UT driving simulator.

The UT simulator has never been validated. This report describes a method for validating the simulator in one specific domain, and the results of this validation.

Section 2 of this report gives some details on what exactly is validation. A small part of our research, on physical correspondence, is presented in section 3. That research is used to formulate the hypotheses on behavioural correspondence, in section 4. In section 5 the methods used for the experiments are presented. Section 6 gives the results of the experiment, and chapter 7 is a discussion on the results and the research as a whole.

Throughout this report the term *simulator* is used to refer to the University of Twente driving simulator, and the term *instrumented vehicle* to refer to an instrumented vehicle driving on a public road in traffic.

## 1.1 Goal

The goal of the research presented in this report is to study the validity of the UT driving simulator for headway attainment and headway keeping research.

## 1.2 Research questions

The general interest of this study is in the physical and behavioural validity of the driving simulator of the University of Twente in the domain where participants are asked to attain and keep a certain headway. The research questions we seek to answer are:

A. In the physical domain:

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[1] Connected Cruise Control
[2] High Tech Automotive Systems

    1. Is there a significant difference in the angular size of the lead vehicle, as viewed by the participant, between the instrumented vehicle and the driving simulator?

B. In the behavioural domain:
    1. Is there a significant difference between the driving simulator and the instrumented vehicle in time or distance headway choice after a headway instruction?
    2. Is there a significant difference in the headway choice at different speeds within one vehicle, and between driving simulator and the instrumented vehicle?
    3. Is there a significant difference between the driving simulator and the instrumented vehicle in time, necessary to attain a certain time or distance headway, between the instrumented vehicle and driving simulator?
    4. Is there a significant difference between the driving simulator and the instrumented vehicle in the keeping of an attained headway between the simulator and the instrumented vehicle?

The method and results of the research in the physical domain are given in section 3. They form the basis for a set of hypotheses on behavioural validity. These hypotheses, their research methods and results are presented in sections 4-6.

# 2 Validation

Up to now, research done in the UT simulator has taken the reactions of participants to be their "natural" reaction, i.e. to be similar as if they were driving in a real car. However it has never been tested whether test persons' behaviour resembles that of their behaviour in an instrumented vehicle on a real road; the simulator has never been validated.

## 2.1 The reason for validation

A driving simulator has many advantages over testing in an existing vehicle on a public road. First and foremost a driving simulator provides a safe environment for driving research. Next to that, the driving simulator can often be easily configured to the specific tests' needs, at low cost. The simulator environment is largely controllable so most external variation sources (e.g. weather, traffic intensity changes) can be eliminated, and as driving simulators are linked to computers they often provide an easy way to collect and process data (Blana, 1996).

However, the driving simulator is an artificial environment that can never be built to fully match the real word (Blana, 1996). This means that there is no certainty that test drivers in a driving simulator behave like they would in a real vehicle on a public road. Thus arises the need to evaluate the driving simulator to see if the behaviour found in simulator studies are valid (Blana, 1996).

Then what is validity? Both Blana (1996) and Elvik (1999) found that there are not only many different definitions but also many different types of validaty, which are discussed in the next paragraph.

One of the key points mentioned in almost any validation study is that it is not possible to qualify a simulator as being valid overall (Blana, 1996; Allen, Mitchell, Stein, & Hogue, 1991; Rolfe, Hammerton-Frasek, Poulter, & Smith, 1970; Leonard & Wierwille, 1975; Godley, Triggs, & Fildes, 2002; Engen, 2008). The validity of a driving simulator can only be studied for a specific task, and this validity at most can be assumed to extend to similar tasks in the same domain (Engen, 2008).

## 2.2 Types of validation

Blana (1996) has written a literature study on driving simulator validation research. He has found different ways to categorize validity. This section describes those categorizations in more detail.

Statistical conclusion validity, theoretical validity, internal validity, and external validity are all properties of a validity study, not of a simulator itself. *Statistical conclusion validity* is the degree to which the numerical results of a study are accurate and reliable. *Theoretical validity* is the degree to which the effects found in a study rely on an explicit theoretical foundation. *Internal validity* is the degree to which the result of an experiment can be attributed to the manipulation of the independent variable, rather than to some other, uncontrolled variable, while *external validity* is the degree to which the results of the study can be generalized to other contexts (Elvik, 1999; Engen, 2008; Tiffin & McCormick, 1965).

Blana (1996) and Godley, Triggs, & Fildes (2002) explain the difference between *absolute* and *relative validity*. Absolute validity is attained when the numerical results of two systems (a driving simulator and a reference system) are the same. When the results are not the same but have a constant ratio, e.g. one system’s results are consistently half that of the other system, then relative validity can be claimed.

Blana (1996) and Engen (2008) distinguish *behavioural* correspondence, between how participants behave in a simulator and the real vehicle, and *physical* correspondence, which is correspondence between the simulator and the real vehicle in e.g. visual size of objects, sounds and dynamic behaviour. Some authors use correspondence interchangingly with validity (and speak of e.g. behavioural validity) (Elvik, 1999; Blaauw, 1982; Godley, Triggs, & Fildes, 2002). Others treat behavioural and physical correspondence as – independent – aspects of the greater concept of validity (Blana, 1996).

Godley, Triggs, & Fildes (2002), citing Triggs (1996), state that researchers often describe that a certain simulator has great fidelity – many physical aspects of the simulator are corresponding to that of a real vehicle – and from that fidelity claim physical validity. However, Blaauw (1982), claims that a more sophisticated driving simulator, and thus greater fidelity, is not always related to greater behavioural validity. The behavioural correspondence is influenced by a lot of factors. There are factors that can make the driving performance in a real-world car different from that in a driving simulator (different visual geometry, vestibular cues, binocular disparity, aural experience etc. – see (Creem-Regehr, Willemsen, Gooch, & Thompson, 2005; Kemeny & Panerai, 2003; Ooi, Wu, He, & others, 2001)). Those are differences that, with effort, can be minimized in order to increase the physical correspondence. There are also differences that cannot easily be eliminated: the inherent danger of being in a fast-moving vehicle within (unpredictable) traffic, the presence and of the test operator, the amount of training time in a real vehicle and a simulator and the difference in perceived workload difference (Blana, 1996; Elvik, 1999). Blana (1996) even suggests that as the driver is aware he is being monitored, results obtained from tests in instrumented vehicles are more likely to resemble simulator driving behaviour than “genuine” road driving behaviour.

The next section describes my research on one of the factors influencing behavioural correspondence that can be altered: the physical correspondence of the driving simulator. The discussion of that research will lead to the formulation of hypotheses on behavioural correspondence of headway attainment and keeping.

# 3 Physical correspondence

To be able to follow a given headway advice, as is the case in the HTAS-CCC project, participants need to be able to estimate their headway, in the unit the advice is given in – usually time or distance. To achieve this in the driving simulator, it is necessary that the headway cues in the simulator correspond to those in a real vehicle. For example, the position of objects relative to the horizon is an important distance cue (Ooi, Wu, He, & others, 2001). However, there are also a lot of uncertainties here. Kemeny & Panerai (2003) argue that both vestibular cues and parallax cues are important in depth perception[3]. Contrast, texture and luminance also play a role in speed perception. On the other hand, Haber & Levin (2001) argue that distance perception is independent of the perceived size of an object, and thus the geometric setup of a simulator is of lesser importance. Creem-Regehr, Willemsen, Gooch, & Thompson (2005) suggest that binocular viewing does not pose a great influence to depth perception. The Known Size-Apparent-Distance-theorem states that "discrete changes in the size of the retinal image of an object whose known size remains constant will be perceived as corresponding changes in the apparent distance of that object" (Epstein, Park, & Casey, 1961).

All in all there are many physical factors that can differ between simulator and real vehicle which could have an influence in headway perception. Therefore, it is interesting to know more about the geometrical differences between the simulator and a real vehicle. The visual size of a leading vehicle as seen from drivers' seat of the simulator and real vehicle was chosen as a research subject.

## 3.1 Method

To measure the physical size of the visual scene, digital photos of the lead vehicle from the driver's position of both the simulator and the instrumented vehicle were analysed.

The relationship of viewing angle $\alpha$, distance $d$ and size (perpendicular to the viewing direction) of an object $w$ is given by $\tan(\alpha/2) = w/2d$, with $d$ and $w$ in (m). By comparing with a reference line of known size and distance, the angle can be calculated not just against a known size in metres, but also against one in pixels on a digital photo.

The instrumented vehicle was placed at several different distances from the lead vehicle. At all these positions, photos of the lead vehicle were taken from the drivers' seat of the instrumented vehicle. The width – the distance between the outsides of the rear wheels – of the lead vehicle was measured on these photos. The distance to the lead vehicle was measured by the instrumented vehicles internal radar[4]. This is the distance to the front bumper; a horizontal distance from the front bumper to the observer's eye needs to be added to this.

In the simulator, the lead vehicle was placed at the same target distances, although it was not always the exact same distance (see Table 1 for the exact distances). The distance to the lead vehicle is again measured to the front bumper of the simulated driving vehicle. However, the simulator consists of part virtual world and part "real" world, in this case a mock-up vehicle. The vendor of the simulator

[3] Our simulator has no vestibular cues, and parallax only in the projection when the vehicle is moving. Moving the head to gain parallax cues, as is possible in the real world, is not possible in our simulator.

[4] At the greatest distance, the distance could not be derived from the radar because there were too many objects – trees, light posts etc. – very close to the road. A distance was taken using a tape measure instead.

stated that they had not calibrated this installation of the simulator and thus could not guarantee whether "virtual" measurements made in the software would line up with the "real" mock-up, which gives even more reason to want to validate this simulator set-up (Steven Wijgerse, Re-lion, e-mail communication, April 2012).

In both the simulator and the instrumented vehicle, the lead car was of the same model (Renault Megane Estate III) and track width (170cm). The virtual car models are from an external 3d object vendor and can be assumed to be accurate (Steven Wijgerse, Re-lion, e-mail communication, April 2012).

## 3.2 Results

Because exact pixel measurements are difficult to take, especially from the photos of the simulator as the projected pixels are so large relative to the vehicle size, it is difficult to determine the exact tire position on the photos. Therefore the pixel widths were measured 4 times by 3 different persons, and the averages were taken.

**Table 1 Measured angular size of instrumented vehicle and simulator**

| Target distance (m) | Vehicle | Reported distance[5] (m) | Measured angular size (°) | Difference in angular size (sim/auto, %) |
|---|---|---|---|---|
| 22 | Inst. veh. | 21.82 | 4.04 | 31.7 |
| | Simulator | 21.55 | 3.07 | |
| 44 | Inst. veh. | 43.95 | 2.10 | 30.8 |
| | Simulator | 43.55 | 1.61 | |
| 66 | Inst. veh. | 66 | 1.40 | 32.1 |
| | Simulator | 65.61 | 1.06 | |
| 88 | Inst. veh. | 90.5 | 1.07 | 34.4 |
| | Simulator | 87.59 | 0.79 | |

As can be seen from Table 1, the difference between the angular size of the lead vehicle in the simulator and the instrumented vehicle is, on average, 32.2%. This means that, at similar distances, lead vehicles look a lot smaller in the simulator than in the real world, as can be seen in Figure 1.

If we scale all the angular sizes from the simulator by multiplying them with the average differential percentage we found (32.3*%), then compare those values to those of the angular size from the instrumented vehicle with a two-tailed t-test, we find that we cannot reject that these numbers are from the same distribution ($t(7)=0.76$, $p=.74$).

[5] For the instrumented vehicle, a Toyota Prius, this is the reported distance from the front of the vehicle. For the distance to the eye, add 2.30 m. For the simulator, the reference point for the reported distance is the front bumper of the virtual vehicle. It is not known what the horizontal front bumper-eye distance of the virtual vehicle (an Opel Astra Police J 5-door) is, but it will be similar to that of the Prius.


**Figure 1 Apparent size of the lead vehicle at 22m from the simulator (left) and from the instrumented vehicle (right). Both photos taken from the drivers seat with the same camera, at the same zoom level.**

## 3.3 Discussion

The numbers found in the previous section state that there is no absolute correspondence or validity in the physical sizes of lead vehicles; however as the angular sizes have a fixed ratio, there is relative validity in the apparent size of the lead vehicle.

The Known Size-Apparent-Distance Hypothesis states that “discrete changes in the size of the retinal image of an object whose known size remains constant will be perceived as corresponding changes in the apparent distance of that object” (Epstein, Park, & Casey, 1961). As the approximate size of a car can be considered to be known under experienced drivers, a smaller retinal image of a lead vehicle, caused by a smaller viewing angle, can lead to an overestimation of the distance to that vehicle. This gives a basis for the idea that participants would overestimate the distance to the lead vehicle, and thus hold a shorter headway to the lead vehicle in the simulator.

# 4 Hypotheses

In the previous section evidence was found in the data and literature to support a hypothesis about the headway drivers will attain in a driving simulator, which can be formulated as the following main hypothesis:

1. *The headway drivers attain in the driving simulator – when given a certain headway instruction – is smaller than that in an instrumented vehicle.*

Several researchers found that drivers drove at a higher speed, or had perceived speeds to be lower in a driving simulator than in an instrumented vehicle (Godley, Triggs, & Fildes, 2002; Kemeny & Panerai, 2003; Colombet, Paillot, Mérienne, & Kemeny, 2011; Jamson, 2000). If a driver underestimates speed but estimates the distance headway to the lead vehicle correctly, the time headway to the lead vehicle will be smaller than the advised time headway, and this effect will increase with speed. In the tests, each participant is instructed to follow a lead vehicle which drives a certain speed (see section Methods). It is to be expected that this tendency of participants to underestimate their speeds will influence their choice of headway to the lead vehicle. I want to test whether this effect exists in any vehicle and is increasing with higher speeds (hypothesis 2a) and whether it is more pronounced in the driving simulator (hypothesis 2b)

2. *a. With increasing speeds, the time headway to the lead vehicle decreases.*
   *b. This will be more pronounced in the driving simulator than in the instrumented vehicle.*

A difference between the UT simulator and a public highway is the behaviour of the other traffic. In the current simulator setup, traffic behaves rather statically; it stays on its lane and never changes speed – see section 5 (Methods) for a more detailed description. Therefore, after a few test rounds, a participant knows what to expect from other traffic. Of course, this is not the case in real traffic, which is more complex (Dingus, et al., 2006). In the instrumented vehicle, a participant has to follow a preceding vehicle – like in the simulator – but also is end responsible for traffic safety and thus his or her own safety – a secondary task not present in the simulator. In order to test whether the difference in behaviour of the other traffic or the responsibility for safety has an effect on the time participants need to attain the assigned headway, the following hypothesis was formulated:

3. *It takes less time to attain a given headway in the driving simulator than in an instrumented vehicle.*

There are many researchers who have researched car following. There are considerable differences in headway keeping between drivers (Ossen, 2008). However, I have not found any basis in literature stating that headway keeping within drivers over time should be different in a simulator and an instrumented car – at least in our test, where both are following a lead vehicle that is driving at a monotonic speed (see Methods). This can be monitored by evaluating the headway keeping performance, as the cumulative (RMS) deviation from the chosen headway over a time period just after the driver states he has attained the advised headway. This leads to the following hypothesis:

4. *The headway keeping performance of drivers who claim to have attained a stable headway to their predecessor in the simulator is not different compared to the instrumented vehicle.*

# 5 Methods

This section describes the method of testing used in the driving experiments. Participants drove both in an instrumented vehicle on a public highway and in a simulator on a simulated highway. This experiment is a within-subject design with repeated measures.

## 5.1 Participants

Twenty-two participants (18 male, 4 female), aged between 27 and 64 years (M: 48.6, SD: 10.3) participated in this research. All participants were employees of the UT and had Dutch as their primary language. Participants were selected to have at least 5 years of driving experience (between 9 and 46 M: 28.7, SD: 10.2) and to have driven at least 10000 km/year annually (between 7500[6] and 27600 km/year, M: 15277; SD: 5476). Each participant drove in both the instrumented vehicle and in the simulator. Participants received a compensation of €50,– for their time when they participated in both tests. Participants were randomized to which of the two tests they took first (10 participants first drove the instrumented vehicle, 12 the simulator). All participants but one had no prior experience in a driving simulator.

## 5.2 Equipment

This section describes the equipment used in the experiments. The next session describes the procedures followed during the experiment.

### 5.2.1 Simulator

The simulator is the University of Twente driving simulator. The simulator consists of a software part and a hardware part.

The driving software is delivered by Re-lion, the product is called “drive”, and the tests were done with version 2.4. In this software package, a scenario can be programmed. The scenario in our tests consists of a 2x2 lane highway. There are four cars in the right lane ahead of the participant that drive at the test speed (80, 100 or 120 km/h as described above), and four cars in the left lane that drive slightly faster. The cars will not switch lanes. The highway is modelled after a Dutch highway, with hectometre signs every 100m, road edge reflectors, light posts, a centre crash barrier, and scenery that consists of greenhouses, plantations and forests. The highway is straight and level, and a slight atmospheric perspective is applied, so that objects in the distance seem faint. The lead vehicle is a different vehicle in each trial.

The hardware consists of a mock-up with a car seat, a steering wheel and three pedals; however as the car was driven in automatic gearbox mode, only the accelerator and brake pedal were used. Around this mock-up, three projection screens are placed, to create a view with a horizontal angle between 180 and 190 degrees, depending on the seating position. Onto the screens, three beamers project the virtual highway. Speakers produce a car sound. The rear view mirror and dashboard in the mock-up are non-functional; the current speed and a rear view mirror were projected on the screen. See Figure 2 for an overview of the simulator in use.

[6] Upon selection, the participants were asked if they drove at least 10000 km annually. After their first test, participants had to fill in a form with age, sex, years of driving experience and annual kilometres driven. Three participants indicated this last value as below 10000 km.


Figure 2 The UT driving simulator set-up. The operator console is behind the mock-up vehicle (to the left, out of picture).

Behind the mock-up is the operator console where the experimenter sits. The participant and experimenter cannot see each other, but they can speak to each other.

### 5.2.2 Instrumented vehicle

The instrumented vehicle is a Toyota Prius XW30 from TNO with automatic gearbox; it has been modified so the distance readings of the internal vehicle tracking radar can be recorded on computer. The lead vehicle was a rented Renault Megane III. The test drives were done on the German A31 Autobahn.

Inside the instrumented vehicle (Figure 3) is a display that shows the time headway to the lead vehicle in seconds. This display was not visible to the participant, only to the experimenter.

Figure 3 Interior of the instrumented vehicle: Driver's side (left) and passenger side (right). Visible on the passenger side is the laptop that recorded the radar data and the small display that shows headway to the lead vehicle (on the dashboard), with cover so the driver cannot see this.

All sessions on the highway were held during daytime, in off-peak hours, in fair weather (sunny or overcast, with a dry road surface.

## 5.3 Procedure

The tests in the instrumented vehicle and in the simulator were set up to resemble each other as much as possible. This section first describes the general outline of a test driving session, and then describe the specifics of driving in an instrumented vehicle and in the simulator.

In this report, a "session" means one test session with a participant in either the simulator or the instrumented vehicle. Each session consisted of 21 "trials". In each trial the participant was given one headway assignment. The participant tried to attain that headway, and when he/she thought he/she had attained the assigned headway, signalled this to the experimenter. At the same time, the participant tried to maintain the attained headway for a certain time period, after which the experimenter signalled the participant the trial has ended and the next trial would be started.

Each test driving session, both in the simulator and in the instrumented vehicle, was split up in different trials. The general idea of a trial is that there is a (real or simulated) lead vehicle that the participant has to follow. The participant was then given an assignment to attain a certain headway. Whenever the participant thought he/she has achieved the assigned headway in a stable manner (i.e. not losing or gaining headway), he/she signalled this to the experimenter; this moment is called *attainment time.* After attainment time, the participant tries to keep the chosen headway until a signal sounded or the experimenter signalled this; this is at least 15 seconds after attainment time. Then the trial ended and the next trial can begin.

The sessions were divided in three blocks with the lead vehicle driving either 80, 100 or 120 km/h. Within each of these blocks, 7 trials were held; three trials where the participant was asked to attain a headway in seconds (1, 1.5, or 2s), three trials where the participant was asked to attain a headway in metres (the equivalent of 1, 1.5 or 2s for that speed, see Table 2) and one trial where the participant was asked to attain a headway as they normally would do themselves.

**Table 2 Advised distance headways as a function of the underlying time headway at different speeds.**

| Time headway | Headway distance (m) | | |
|---|---|---|---|
| | **80 km/h** | **100 km/h** | **120 km/h** |
| 1s | 22 | 28 | 33 |
| 1.5s | 33 | 42 | 50 |
| 2s | 44 | 56 | 67 |

The order of the three blocks was randomized, as is the order of the 7 trials within each block. Participants thus received trials in a different order in the simulator and in the instrumented vehicle.

Each session started with an explanation of the procedure during the test session and few training trials before the actual trials were started. Halfway during the 21 trials, the participants could take a break if they desired so. The experimenter gave no feedback on how well the participants performed during the session or between the two sessions of the same participant.

During the session, data was continuously recorded on the speed of the vehicle and the distance of the (instrumented or virtual) vehicle to the lead vehicle, as well as the moments in each trial where an instruction was given, where the participant thought he/she had attained the assigned headway and the end of the trial.

### 5.3.1 Simulator

As the experimenter started a trial the participant was placed at the highway at no speed, then asked to keep the accelerator pedal pressed until the speed is matched with that of the lead vehicle[7]. After a few seconds, a pre-recorded message instructed the participant to attain a certain headway to the lead vehicle – as described above. When the participant thought he/she had attained the given assignment, he/she had to push the horn button on the steering wheel. 30 seconds later the trial ended and the experimenter started the next trial.

Data on the speed and the distance to the lead vehicle were recorded by the computer at 10Hz. The moment the pre-recorded message was given and the moment the participant signalled he/she had attained the given headway were recorded as well.

[7] It was our goal to make a “flying start”, where the test subject is placed onto the highway at the test speed, but we could not make this work in time for the experiments.

### 5.3.2 Instrumented vehicle

All participants were picked up near their workplace in the instrumented vehicle. The experimenter sat in the passenger seat. The session started with a short instruction on the working of the car (some participants had never driven an automatic gearbox vehicle). There the participant drove to the German A31 highway via local roads and a 100km/h limited access road. This drive lasted about 20 minutes, and gave the participant the possibility to familiarize him/herself with the instrumented vehicle. When the A31 was reached, the tests began. The experimenter instructed the driver of the lead vehicle over two-way radio to drive one of the experiment speeds, supported by his/her cruise control; the participant could hear this instruction.

The experimenter asked the participant to increase the distance to the lead vehicle until the headway was over 3 seconds. The participant did not know that the start headway was 3 seconds. Then, the experimenter gave the instruction to attain a certain headway to the lead vehicle and marked this in the computer. When the participant thought he/she had attained the given assignment, he/she spoke this out loud to the experimenter who marked it in the computer. Meanwhile, the participant maintained his or her distance to the lead vehicle for at least 15 seconds, until the experimenter instructed the participant the trial was over.

Because the sessions were held on a public highway with other traffic, the drivers of which were unaware there an experiment was being conducted, participants were instructed they themselves are responsible for safe traffic behaviour and that safety is more important than the experiment. The traffic could also interact with the experiment. The experimenter aborted and restarted a trial whenever the lead vehicle had to brake or the lead vehicle released the cruise control, or when another car cut in between the instrumented vehicle and the lead vehicle.

Data on the speed and the distance to the lead vehicle were recorded by the experimenter's computer at 50Hz. The moments the experimenter gave the assignment to the participant, the participant thought he/she had attained the given headway and when the experimenter instructed that the 15s period where the headway should be kept stable is over were logged on the computer as well.

## 5.4 Design

By using participants that perform the same tests in both the instrumented vehicle and the simulator, the within-subject variance can be measured, instead of the between-subject variance. This has the advantage of greater statistical power with a lower number of participants (Minke, 1997). The experiment is thus a within-subject design with repeated measures.

The independent variables are:

- *Assignment speed*: The speed of the lead vehicle (3 levels: 80, 100 or 120 km/h)
- *Assignment headway*: The assigned headway (3 levels: 1, 1.5 or 2 s; the actual assignment is given either in seconds or in metres, see section 5.3)
- *Assignment unit*: The unit in which the assignment is given (two levels: distance in seconds or metres[8])

[8] No unit is given if the headway assignment is "drive as you would normally". These cases were not used in the statistical tests.

- *Vehicle*: The vehicle driven during that test session (two levels: instrumented vehicle or driving simulator)

The following dependent variables were measured and compared:

- *Time headway*: The distance from the front of the instrumented vehicle to the rear of the lead vehicle, expressed in seconds – based on the speed of the lead vehicle. Time headway is a performance metric for how well participants can estimate assigned distances (given in metres or seconds) and attain that distance (hypotheses 1, 2a 2b).
- *Time to attainment*: The time from the moment the assignment is given to the moment the participant thinks he/she reached the assigned headway (*attainment time*). It is a performance metric for how long participants take to perform the initial part of the assignment (hypothesis 3)
- *Headway keeping performance*: The maintaining of the headway accuracy over a time period of 15 seconds. The absolute estimation error of headway accuracy is calculated as the root mean square (RMS) of the deviations from the chosen headway at attainment time with a 10 Hz sampling frequency[9]. It is a performance metric for how well participants can keep a chosen headway – independent of whether the chosen headway is the assigned headway (hypothesis 4).

The hypotheses will be tested on the available data using repeated-measures ANOVA (General Linear Model) in the SPSS statistics package.

[9] See Appendix A.4 for a more in-depth description of how the headway keeping performance is calculated.

# 6 Results

This section describes the results of the statistical tests, per dependent variable. The last subsection lists some of the observation made during the trials which could not be caught in the data. In the next section, conclusions are drawn from these results.

Data for some of the trials was unusable. This was caused by a number of factors, such as errors in data storage, participants taking a headway beyond the detection range of the instrumented vehicle's radar (about 160 metres), or it being impossible to detect which of the radar signals was the right one. See appendix A.5 for a detailed specification of data that was unusable, the reason why it became unusable and how it was handled.

All hypotheses were tested with repeated measures ANOVA. Values that were unusable (for 19 trials, on a total of 462 trials, or 4.1%) were replaced with their column averages, i.e. the average over all participants for that particular test – see appendix A.5. This generally provided more significant results than with the unusable data left out, but the main effect was never found significant when a test with unusable data left out was not significant.

The contrasts used were polynomial; the reason is that no "control group" levels were used. Instead, the independent variables that had 3 levels were variables that had cardinal levels (*assignment headway*, *assignment speed*); the independent variables that had nominal levels (*vehicle*, *assignment unit*) had just 2 levels, in which the highest-order polynomial – linear – just serves to show a difference – quadratic or higher-order polynomials have no meaning here.

In the results below, all significant main effects and interactions found are mentioned, as well as insignificant results that have an effect in the accepting or rejecting of the hypotheses.

## 6.1 Time headway (hypotheses 1, 2a, 2b)

Hypothesis 1 and 2 were tested by analysing time headway. Both were tested in a repeated measures ANOVA with the independent variables *vehicle* (with two levels: instrumented *vehicle* and simulator), *assignment speed* (with three levels: 80, 100, 120 km/h), *assignment headway* (with 3 levels: 1, 1.5; 2s), and *assignment unit* (with two levels: metres, seconds) as within-subject variables.

Mauchly's test indicated the assumption of sphericity had been violated for *assignment headway* $\chi^2(2)=7.467$, $p<.05$; and for the interaction between *assignment unit* and *assignment headway* $\chi^2(2)=13.016$, $p<.005$. Degrees of freedom were corrected using Greenhouse-Geisser-corrected estimates of sphericity; for *assignment headway* $\varepsilon=.762$; for the interaction between *assignment unit* and *assignment headway* $\varepsilon=.676$.

There was no significant main effect of v*ehicle* on time headway chosen, with $F(1,21)=1.642$, $p>.05$. There are also no interaction effects involving *vehicle*. This means hypothesis 1 (*The headway drivers attain in the driving simulator – when given a certain headway instruction – is smaller than that in an instrumented vehicle*) is rejected: no significant effect of *vehicle* on the time headway was found.

There was no significant main effect of *assignment speed* on time headway chosen, with $F(2,42)=1.105$. $p>.05$. This means hypothesis 2a (*With increasing speeds, the time headway to the lead vehicle decreases.*) is rejected.

As hypothesis 2b (*This*[10] *will be more pronounced in the driving simulator than in the instrumented vehicle*) builds on 2a, it has to be rejected as well.

The main effect of *assignment unit* on time headway was significant, with F(1,21)=7.952, p<0.05. Participants took a much longer time headway to their predecessor if the *assignment unit* was metres (M: 1.93s, SD: 1.46) then when the assignment was given in seconds (M: 1.18s, SD: 0.71). A quick post-hoc analysis on the data for time headway, where the headway instruction was either in seconds or in metres was performed. On average, participants underestimated the headway by 20% when the headway advice was given in seconds, while they overestimated the headway by 31% when it was given in metres. This effect occurred both in the instrumented vehicle (18% underestimation with instruction in seconds/19% overestimation with instruction in metres) and in the simulator (22% underestimation (s)/44% overestimation (m)).

The main effect of *assignment headway* on the chosen headway was significant, with F(1,525;32.023)=88.538, p<.001. Contrasts found a linear effect with F(1,21)=117.251, p<.001. This means that participants indeed take longer headways when the *assignment headway* is longer. See Table 3 for the mean headway taken at different *assignment headway*s.

A 2-way interaction effect between *assignment unit* and *assignment headway* was found to be significant with F(1,353;28,410)=4.028, p<.05 (Figure 4). The effect of *assignment headway* on time headway was affected by the *assignment unit*. See Table 3 for the means of the different *assignment headway* and *assignment unit* groups. I performed three two-tailed t-tests on the two *assignment unit* groups – one test for each *assignment headway*, testing the two *assignment headway* groups – to see whether their means could be from the same distribution; this was found to be not the case, see

Table 4, even while α was Bonferroni-corrected to 0.017 (=0.05/3).

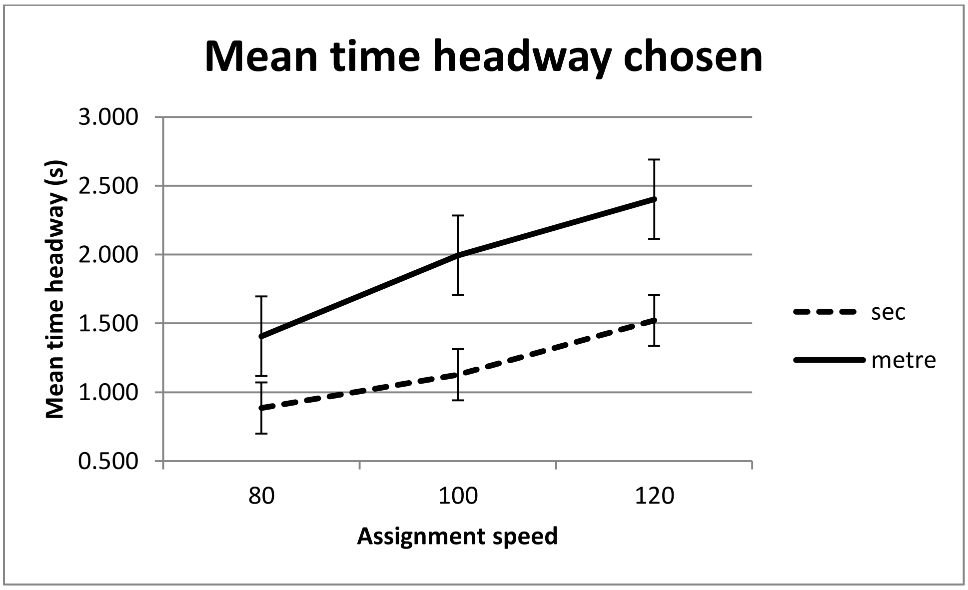


**Figure 4 Interaction between assignment unit and assignment headway on the mean time headway chosen. The time headway chosen is larger when the assignment is in metres, and is increasing with increased assignment highway.**

[10] *This* being the effect suggested in hypothesis 2a, namely that with increasing speeds, the time headway to the lead vehicle decreases.

**Table 3 Mean time headway (in seconds) for the different assignment units and assignment headways; Standard deviation in parentheses**

| | | Assignment headway | | | |
|---|---|---|---|---|---|
| | | 1s | 1.5s | 2s | Overall |
| Assignment unit | s | 0.86 | 1.13 | 1.52 | 1.18 |
| | | (0.53) | (0.67) | (0.80) | (0.71) |
| | m | 1.41 | 1.99 | 2.40 | 1.93 |
| | | (0.99) | (1.43) | (1.68) | (1.46) |
| | Overall | 1.15 | 1.56 | 1.96 | 1.56 |
| | | (0.84) | (1.20) | (1.38) | (1.21) |

**Table 4 t-values and probability of distributions having the same mean (p) per assignment headway (two tailed paired t-test)**

| | 1s | 1.5s | 2s |
|---|---|---|---|
| t | -5.48 | -6.09 | -4.59 |
| p | <.001 | <.001 | <.001 |

## 6.2 Time to attainment (hypothesis 3)

The attainment time (hypothesis 3: *It takes less time to attain a given headway in the driving simulator than in an instrumented vehicle*) was tested in a repeated measures ANOVA with the *vehicle*, *assignment speed*, *assignment headway* and *assignment unit* as within-subject variables.

Mauchly's test indicated the assumption of sphericity had been violated for *assignment speed*, $\chi^2(2)=6.586$, $p<.05$. Degrees of freedom for *assignment speed* were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=.781$).

There was no significant main effect of *vehicle* on time to attainment: $F(1,21)=3.812$, $p>.05$ – but close to the significance boundary at $p=.064$.

A significant interaction was found between *vehicle* and *assignment speed*: $F(2,42)=8.067$, $p<.005$. I performed a series of three post-hoc two-tailed t-tests on the two vehicles, one for each *assignment headway* group. With the α-level Bonferroni-corrected to a conservative 0.017 (=0.05/3), This showed that there was no difference between vehicles in the time to attainment at 80 km/h, ($t(105)=-1.30$, $p=.10$) and at 120 km/h ($t(105)=0.48$, $p=.69$). However, at 100 km/h ($t(105)=-5.02$, $p<10^{-5}$), there was a significant difference between vehicles in time to attainment – see Table 5 and Figure 5.

The main effect of *assignment speed* on time to attainment was significant: $F(2,42)=30.133$, $p<10^{-3}$. The higher the *assignment speed*, the longer the time to attainment was. See Table 5 for the means per *assignment speed* group. Contrasts also revealed a linear effect for *assignment speed*, with $F(1,21)=15003.364$, $p<10^{-4}$.

**Table 5 Mean time to attainment (in seconds) for the different *assignment speed* and vehicle groups; Standard deviation in parentheses**

| | | Assignment speed | | | |
|---|---|---|---|---|---|
| | | 80 | 100 | 120 | overall |
| Vehicle | Auto | 30.46 | 38.27 | 39.66 | 36.13 |
| | | (11.46) | (20.29) | (18.66) | (17.70) |
| | Sim | 28.35 | 29.97 | 40.47 | 32.93 |

| | | | | |
|---|---|---|---|---|
| | (14.90) | (16.74) | (16.74) | (17.02) |
| overall | 29.40 | 34.12 | 40.06 | 34.53 |
| | (13.33) | (19.05) | (17.73) | (17.74) |

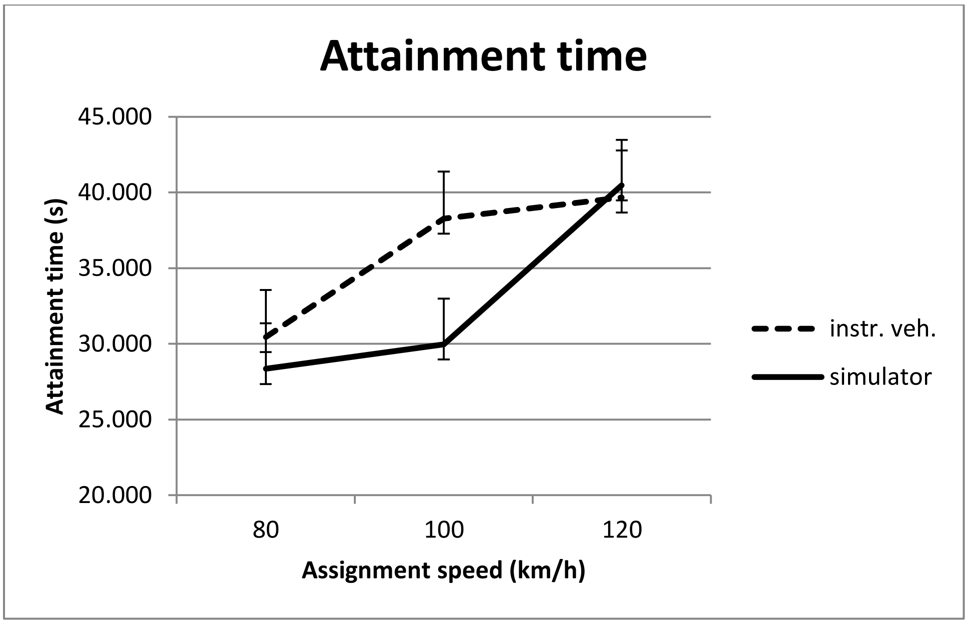


**Figure 5 Time to attainment by vehicle at different assignment speed groups. At 80 and 120 km/h the mean attainment times are roughly the same for both vehicles, but at 100 km/h attainment time is much higher for the instrumented vehicle than for the simulator.**

## 6.3 Headway keeping performance (hypothesis 4)

The headway keeping performance (RMS of estimation error, hypothesis 4) was tested in a repeated measures ANOVA with the *vehicle*, *assignment speed*, and *assignment headway* as within-subject variables.

There was no significant main effect of *vehicle* on headway keeping performance, with $F(1,21)=2.125$, $p>.05$. This means that hypothesis 4 (*The headway keeping performance of drivers who claim to have attained a stable headway to their predecessor in the simulator is not different compared to the instrumented vehicle*) cannot be rejected; there is no significant difference between the performance in the instrumented vehicle (M: 0.147, SD: 0.134) and the simulator (M:0.208, SD: 0.399) with regard to the estimation error.

The main effect of *assignment headway* is significant for the headway keeping performance: $F(2,42)=15.443$, $p<.001$. Contrasts reveal the effect is linear: $F(1,21)=22.838$, $p<.001$. At larger *assignment headway*s, the RMS of estimation error increases, which means the headway keeping performance decreases, see Table 6.

**Table 6 Mean Headway keeping performance (RMS of estimation error) the different assignment headways. A lower score denotes a better performance. Standard deviation in parentheses**

| Assignment headway | | | |
|---|---|---|---|
| 1s | 1.5s | 2s | Overall |
| 0.13 | 0.19 | 0.22 | 0.18 |
| (0.17) | (0.31) | (0.37) | (0.30) |

## 6.4 Observations

During the tests some – anecdotal – observations on the behaviour of participants were made which I want to share with the reader.

Most participants were interested in "how well they performed", i.e. how good they were in keeping to the *assignment headway*. While this was not a subject of my research – the interest lies in the differences between vehicles – a log was kept on participants' behaviour, based on the observations of instruments during the experiments. The log was often one or two lines of shorthand such as "time less than half of assigned, distances more than double". Participants received their performance after having done tests in both vehicles[11]. It was often striking how much the log lines of the two tests were similar. There were only two participants where I had the idea that they really performed differently in the driving simulator and instrumented vehicle.

Part of the trials involved participants taking a headway "as they normally would do themselves". It was interesting to see here that participants often took a headway of about 2 to 3 seconds here, while in the driving towards the A31 autobahn – when the tests had not started – participants took a much smaller headway – often 0.8 to 1.5 seconds, just as other traffic did. This confirms the remark from (Blana, 1996) that participant behaviour in an instrumented vehicle is very different from naturalistic driving and might be closer to their behaviour in a simulator.

Some participants were better in following up the headway advice than others. One participant – who first took the test in the real vehicle – when instructed to take a 1s headway at 120 km/h, instead took a headway of about one tenth of that, and somewhere during that time coming to a time headway of 0.1071s, which equals 3.57 metres. When given an instruction of 67m (the equivalent of 2s) at the same *assignment speed*, the participant took a distance that was well outside the radar range and which was estimated by the experimenter at 400 metres. The next week this same participant, before doing the driving simulator tests, had self-reflected that the headway he/she took during the 1s test must have been far too short. However, in the 120 km/h / 1s trial in the simulator, the participant again took a headway which was – at the shortest – 5.32 metres or 0.16s. On the 67m instruction, the headway at one point was 433m, over 6 times the instructed headway – this happened after self-reflection on the chosen headways in the instrumented vehicle. Apparently, the prior knowledge of this participant's own error did not influence the participant's behaviour to correction of that error.

Overall, the experimenter had the impression that almost all participants did not perform well in following up on headway instructions in either length or time, deviating 50% or more on at least one of the *assignment unit*s – and doing consistently so between vehicles. There were only a few participants that, in general, kept within 25% of the instructed headway in both time and distance instructions. This also accounts for the large standard deviations found.

[11] Under the promise they wouldn't speak about their performance to their colleagues for the duration of the tests, to not influence other participants.

# 7 Discussion

This concluding section lists each of the hypotheses and gives an interpretation of the results, and concludes with a general discussion.

## 7.1 Time headway

The first hypothesis was:

1. *The headway drivers attain in the driving simulator – when given a certain headway instruction – is smaller than that in an instrumented vehicle.*

This hypothesis, that states that headway in the driving simulator is smaller than in the instrumented vehicle, is not supported by the data. In fact, no significant difference in the time headway choice between vehicles was found.

This is surprizing, given the finding of our research in physical validity that cars in the simulator have a smaller angular size. Given the Known-Size-Apparent-Distance-theorem (Epstein, Park, & Casey, 1961) we would expect people to be able to estimate distances based on the size of a known object.

There are a few possible explanations for the similarity in time headway between vehicles. A first explanation is that the Known-Size-Apparent-Distance-theorem can only be applied so strictly that the direct change of angular size implies a change in distance, but that a certain angular size alone does not give a basis for distance estimation. A second explanation is that there are multiple effects that happen to work together and produce the right headway. For example; if drivers overestimate the distance to the lead vehicle (caused by it having a smaller angular size than a real vehicle has at the same distance), and at the same time overestimate their speed in the simulator and thus take a higher headway than they would take if they had correctly estimated their speed, then the combination of those two misestimations produces a correct headway. However, (Godley, Triggs, & Fildes, 2002; Kemeny & Panerai, 2003; Colombet, Paillot, Mérienne, & Kemeny, 2011; Jamson, 2000) state that simulator drivers underestimate their speed; thus making this explanation highly unlikely. A third explanation is that the angular size is not the only way for people to estimate the distance to their predecessor. It would be an interesting subject for further research to see whether the results found in the simulator still hold when the angular size of preceding vehicles is corrected. If the known-size-apparent-distance-theorem is the only way to estimate distance, this would mean participants would take longer headways in the simulator compared to those found in this research. However, it is probable that drivers take other methods of estimating distance, such as the time needed between the predecessor and oneself passing a certain point, as information on the headway. In this case, altering the angular size of the lead vehicle will not produce much change in headway taking from our research.

There was a significant effect of the *assignment unit* on time headway; participants chose a larger headway when the *assignment unit* was metres than when the *assignment unit* was seconds. This happened in both vehicles. This reproduces the findings from Taieb-Maimon & Shinar (2001) that found a difference between headway estimation in metres and seconds. Risto & Martens (2012) hypothesized that *time based instructions lead to headways that are smaller than instructed* (their hypothesis H3a) and that *distance based instructions lead to headways larger than instructed* (their hypothesis H3b). They could not confirm their hypotheses, but our research shows that these hypotheses hold.

There also was a significant effect of the *assignment headway* on the chosen headway. This means that participants do take the headway assignment as an important factor in their headway choice, indeed taking a larger headway when a larger headway is instructed.

The second hypothesis consists of two parts. They are:

2. *a. With increasing speeds, the time headway to the lead vehicle decreases.*
   *b. This will be more pronounced in the driving simulator than in the instrumented vehicle.*

Hypothesis 2a had to be rejected: There was no significant effect of *assignment speed* on the time headway chosen. From literature, we expected that an effect of *assignment speed* on time headway would be more pronounced in the driving simulator, due to drivers underestimating their speeds in a driving simulator. Due to the effect in hypothesis 2a not being present, reject hypothesis 2b.

Hypotheses 2a and 2b were founded on two assumptions; that simulator drivers underestimate speed (Godley, Triggs, & Fildes, 2002; Kemeny & Panerai, 2003; Colombet, Paillot, Mérienne, & Kemeny, 2011; Jamson, 2000) and that they correctly estimate headway (see section Hypotheses). If we indeed assume that simulator drivers underestimate their speed in simulators we would expect a huge error increase in distance estimation with increasing speeds in the simulator. In our tests we found no difference between headway estimation between the driving simulator and instrumented vehicle.

However, in the discussion on distance and speed estimation for hypothesis 1, we found we could not make any claims from this research alone about the speed and distance estimation of participants. Participants always followed a lead vehicle driving at a certain speed, never were asked to pick a certain speed on their own, reason why there is no data on speed estimation of participants in this simulator. Further research, e.g. asking drivers to attain a certain speed in a free-driving scenario could shed more light on this subject.

## 7.2 Time to attainment

The third hypothesis is:

3. *It takes less time to attain a given headway in the driving simulator than in an instrumented vehicle.*

There is no significant effect of *vehicle* on the time to attainment.

While effort was taken to make the differences in tests between vehicles small, the differences that existed potentially have had a large effect on time to attainment. A participant in the simulator starts from a standstill and has to accelerate and match his/her speed to that of the lead vehicle, just before or sometimes while an instruction is received. A participant in the instrumented vehicle receives a headway instruction at about the same speed as the lead vehicle, at distances of at least 3 seconds.

In the driving simulator, there is no interference from traffic from the other lane. On the public highway, a 3 second headway means another car sometimes tries and cuts in between the lead and instrumented vehicles[12]. Participants needed to be aware of this other traffic.

Therefore, it was surprising that no main effect between vehicles was visible in the data. However, there was a trend (p=.064), indicating the tendency for longer attainment times for instrumented vehicles compared to simulators.

An interaction effect was found between *assignment speed* and *vehicle*. At 80 and 120 km/h there was no significant difference in time to attainment between the vehicles. Yet at 100 km/h, the time to attainment in the simulator was significantly shorter than in the instrumented vehicle, see Figure 5.

A possible explanation could be the following. The amount of interference with other traffic seemed to be a function of speed difference. At very low differential speeds there was almost no interference, neither at high differential speeds – the faster vehicle overtook the slower. However, at moderate differential speeds the participant also had to spend a lot of attention to other traffic which wanted to overtake or needed to be overtaken. At 80 km/h the speed difference with trucks was low, to passenger vehicles relatively high; at 120 km/h this was the opposite. But at 100 km/h the speed difference to both vehicle types was moderate; we drove faster than most trucks and slower than most passenger vehicles. The assumption is that at 100 km/h a relatively large part of participant attention went to traffic other than the lead vehicle compared to at other speeds, which could explain that the time to attainment is different from that in the simulator at that speed.

Another explanation is that participants who underestimated their headway and took large headways over about 160 m “fell off the radar”; these trials were removed. This happened more at higher *assignment speed*s, which could bias the values at higher speeds more than at lower speeds. However, other reasons for trial rejection happened more at the lower *assignment speed*s. In the instrumented vehicle data, 5 trials were omitted at 80 and 100 km/h each, 8 trials were omitted at 120 km/h (of 132 trials per *assignment speed* where a headway instruction was given). This omission of higher-distance trials hardly seems to offer an explanation.

All in all, a significant difference in the attainment time was found when looking at the interaction between *assignment speed* and *vehicle*. This means hypothesis 3 cannot be rejected, especially not for the *assignment speed* of 100 km/h. This can be explained by combining the findings of (Dingus, et al., 2006) that real traffic is more complex than simulated traffic with the assumption that the traffic complexity difference between a simulator and instrumented vehicle in our test setup was much greater at speeds between that of truck traffic and that of most car traffic – in this case 100 km/h – than at the other *assignment speed*s. One way to test this is to either make the traffic in a simulator more like that on a real highway, or instead to the instrumented vehicle tests on a closed test circuit with other vehicles behaving like those in the simulator, such that no overtaking is necessary.

A significant effect of *assignment speed* on time to attainment was found: at larger *assignment speed*s, the time to attainment was longer. This could be explained by that at higher *assignment speed*s, drivers need to cover a longer distance to the lead vehicle to get to the *assignment headway*

[12] If this happened, the trial was aborted and re-taken.

– from a longer headway. This longer distance needs to be covered at the same speed difference, so the time necessary to get to the lead vehicle is longer.

## 7.3 Headway keeping performance

The fourth hypothesis is:

4. *The headway keeping performance of drivers who claim to have attained a stable headway to their predecessor is the same in the simulator as in the instrumented vehicle.*

There is no significant effect of *vehicle* on the headway keeping performance. This means that hypothesis 4 cannot be rejected.

A highly significant effect of *assignment headway* on headway keeping performance was found. At larger headways, the headway keeping performance decreases. This might be caused by that at higher *assignment headway*s, the lead vehicle is further away, making precise adjustment of that headway more difficult.

## 7.4 General discussion

We found a considerable difference between the angular size in the two vehicles; the lead vehicle looked smaller in the simulator than in the instrumented vehicle. One could say there is no absolute but only relative physical correspondence on angular size. This all makes it even more striking there is so much correspondence in behaviour between the two vehicles. The angular size might not be the only way to determine the distance to a predecessor: One could also think of speed estimation from peripheral view, vestibular cues, and visual motion estimates etc. as factors influencing speed estimation.

We did not find a main difference in headway attainment and headway keeping performance and headway changes relative to speed changes between the instrumented vehicle and the simulator. An interaction effect was found between *assignment speed* and *vehicle* on the time to attainment; further investigation found a significant difference in the time to attainment, where at 100 km/h the time to attainment was much larger in the instrumented vehicle than in the simulator; while at 80 and 120 km/h these differences are not significant. The other significant main or interaction effects that were found were not related to the differences in *vehicle*.

A subject for further research would be what happens if the simulator was set up to show vehicles in the correct angular size. We suspect this would not make much difference and participants will keep the same headway, but a large influence of the angular size would be shown if participants then estimate vehicles to be much closer and thus keep longer headways.

This research shows that for experiments in the headway domain, there is little difference in the headway keeping behaviour between the University of Twente driving simulator and an instrumented vehicle in the time headway, headway keeping performance and headway estimation error. The simulator can said to be valid in these fields. We found a difference between the instrumented vehicle and the simulator in the time to attain a headway. The assumption is that this stems from differences in behaviour of other traffic near the simulator and instrumented vehicles. Further research may provide the answer to this.

This research showed the validity of the University of Twente driving simulator in the headway keeping domain. Based on these results, prior studies performed for the CCC project in the simulator, based on headway performance may be considered valid compared to instrumented vehicle tests on the real road.

# Bibliography

Allen, R., Mitchell, D., Stein, A., & Hogue, J. (1991). *Validation of Real-time Man-in-the-loop Simulation.*

Blaauw, G. (1982). Driving experience and task demands in simulator and instrumented car: a validation study. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 24*(4), 473-486.

Blana, E. (1996). *Driving Simulator Validation Studies: A Literature Review.* Leeds: Institute of Transport Studies, University of Leeds.

Colombet, F., Paillot, D., Mérienne, F., & Kemeny, A. (2011). Visual scale factor for speed perception. *Journal of Computing and Information Science in Engineering*, 041010.

Creem-Regehr, S., Willemsen, P., Gooch, A., & Thompson, W. (2005). The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual environments. *Perception*, 191-204.

Dingus, T., Klauer, S., Neale, V., Petersen, A., Lee, S., Sudweeks, J., et al. (2006). *The 100-car naturalistic driving study, Phase II-results of the 100-car field experiment.*

Elvik, R. (1999). *Assessing the validity of evaluation research by means of meta-analysis.* Oslo: Institute of Transport Economics, Norwegian Centre for Transport Research.

Engen, T. (2008). Use and validation of driving simulators. *PHD Thesis*. Norwegian University of Science and Technology.

Epstein, W., Park, J., & Casey, A. (1961). The current status of the size-distance hypotheses. *Psychological Bulletin, 58*(6), 491.

Godley, S., Triggs, T., & Fildes, B. (2002). Driving simulator validation for speed research. *Accident analysis & prevention*, 589-600.

Haber, R., & Levin, C. (2001). The independence of size perception and distance perception. *Attention, Perception, & Psychophysics*, 1140-1152.

Jamson, H. (2000). Driving simulation validity: issues of field of view and resolution. *Proceedings of the Driving Simulation Conference*, (pp. 57-64).

Kemeny, A., & Panerai, F. (2003). Evaluating perception in driving simulation experiments. *Trends in Cognitive Sciences*, 31-37.

Leonard, J., & Wierwille, W. (1975). Human performance validation of simulators: theory and experimental verification. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (pp. 446-456). SAGE Publications.

Minke, A. (1997). Conducting repeated measures analyses: Experimental design considerations. In *Annual Meeting of the Southwest Educational Research Association, Austin* (pp. 23-25).

Ooi, T., Wu, B., He, Z., & others. (2001). Distance determined by the angular declination below the horizon. *Nature*, 197-199.

Ossen, S. (2008). *Longitudinal driving behavior: theory and empirics.*

Re-lion. (2012, June 28). E-mail conversation with Steven Wijgerse, Re-Lion.

Risto, M., & Martens, M. H. (2012). Time and Space: The difference between following time headway and distance headway instructions. *Manuscript submitted for publication.*

Rolfe, J., Hammerton-Frasek, A., Poulter, R., & Smith, E. (1970). Pilot response in flight and simulated flight. *Ergonomics*, 761-768.

SWOV. (2010). SWOV-Factsheet: Volgtijd en verkeersveiligheid.

Taieb-Maimon, M., & Shinar, D. (2001). Minimum and comfortable driving headways: Reality versus perception. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 43*(1), 159-172.

Tiffin, J., & McCormick, E. (1965). *Industrial psychology.* Englewood Cliffs, NJ: Prentice-Hall.

Triggs, T. (1996). Some critical human factors issues and challenges in simulation and training. *Simtect*, (pp. 21-26).

# Appendix A Data path and data manipulations

This appendix describes the path of the data, and manipulations therein, between the driving simulator and instrumented vehicle on one side and the statistics package, SPSS, on the other side.

Data from both the instrumented vehicle and the simulator were stored on a computer, and then read in into MATLAB. The instrumented vehicle data needed manual input to select the right data. Then, both datasets were output in a format that was ready for input into SPSS, where it was read in to do statistical tests that accept or reject our hypotheses; see Figure 6.

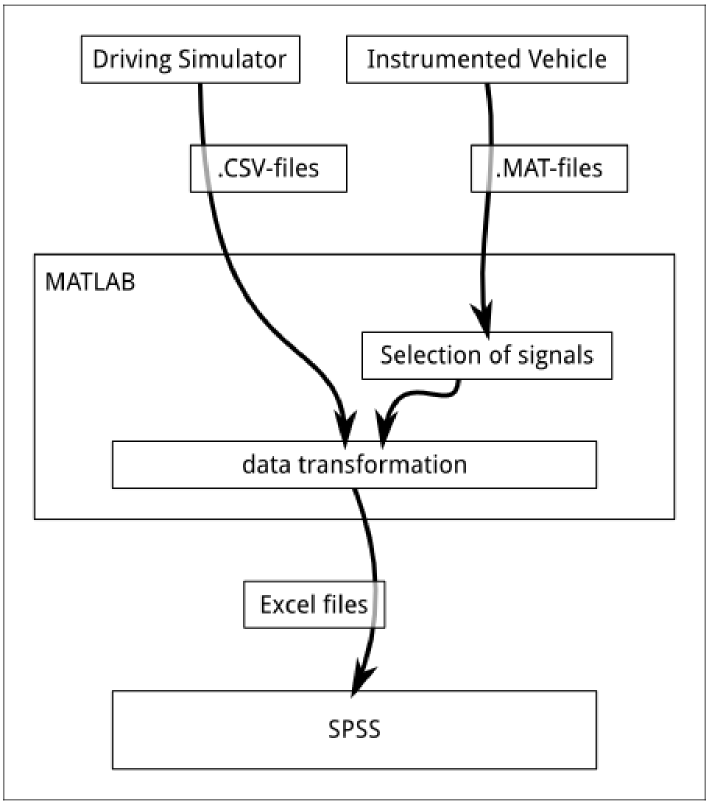


Figure 6 Data path between vehicles and SPSS

In this section, I take "a test" to mean one session with a participant, which consists of 21 "trials". In each trial the participant is given one headway assignment, tries to attain that headway, signals to the experimenter that he/she thinks he has attained the assigned headway, then tries to maintain that headway for 15 seconds, after which the experimenter signals the participant the trial has ended. For a full explanation of what happens in the driving simulator and instrumented vehicle, see section 5.3.

## A.1 Data gathering in the driving simulator

Data gathering in the driving simulator was done mostly automatic. The test operator starts each trial in the simulator program from an operator console, and has no interaction with the participant or simulator until a beep is heard signalling that the participant has finished the sub-test. The test operator then ends the trial on the operator console and starts the next participant.

From the moment the driving simulator is started to the moment it ends, the simulator records data to a comma separated file (CSV), at 10 Hz, or 10 lines per seconds. A sample of simulator CSV data is shown in Figure 7.

```
46.200000,101.425730,-0.166827,-0.467936,2070.313477,9.9623899459839,27.777778
46.300000,101.389256,-0.004570,-0.475228,2073.599609,9.9164915084839,27.777778
46.400000,101.388343,-0.004564,-0.480816,2076.885010,9.8713254928589,27.777778
46.500000,101.371354,-0.082680,-0.484705,2080.170410,9.8261594772339,27.777778
46.600000,101.325630,-0.110345,-0.486894,2083.454834,9.7819700241089,27.777778
,,,,,,,4
46.700000,101.282715,-0.098859,-0.487414,2086.737793,9.7392454147339,27.777778
46.800000,101.246953,-0.076271,-0.486608,2090.019531,9.6977415084839,27.777778
```

Figure 7 Data sample from a simulator .csv file

The simulator CSV data consists of eight columns, separated by commas. The columns are listed in Table 7.

Table 7 Data columns in simulator CSV file

| Column | Column name | Description |
|---|---|---|
| **1** | Time | Time passed since trial start (s) |
| **2** | Speed | Speed of simulated vehicle (km/h) |
| **3** | acceleration | Longitudinal acceleration (unit unknown) |
| **4** | lateralOffset | Distance from lane centre (unit unknown) |
| **5** | distanceOnSpline | Distance covered since experiment start (m) (experiment starts at 500m) |
| **6** | followingDistance | Distance to lead vehicle (front bumper to rear bumper) (m) |
| **7** | carInFrontSpeed | Speed of lead vehicle (m/s) |
| **8** | marker | See text for explanation |

At certain moments a special marker line is added to the CSV, where only the 8$^{th}$ column has data filled in, for an example see the 6$^{th}$ line of Figure 7. The values of these markers have a specific meaning; see Table 8 for an explanation.

Table 8 Simulator CSV marker values

| Marker | Meaning |
|---|---|
| **1** | Start of experiment, start of logging |
| **2** | 3 seconds after headway assignment starts playing |
| **3** | Unused |
| **4** | Participant has pressed “horn” button, meaning he/she thinks he/she has attained the assigned headway |
| **5** | 30 seconds after marker 4; beep plays; wait for experimenter to end trial |

One CSV file is being created per trial, 21 per test. Each participant received its own directory. The directory and file are named as PP<participant number>/<speed>_<assignment>.csv, where <speed> is the speed of the lead vehicle in km/h and assignment is the assignment in either seconds or metres, or “zelf” if the participant had to choose their headway as they would normally do themselves; for example “PP10/100_56m.csv” for the file wherein participant 10 received a headway assignment of 2 seconds, the unit was in metres and the speed was 100 km/h[13].

### A.1.1 Data manipulations

The following manipulations were made to the simulator data:

- Participant 19, when given the 120/zelf assignment, after 90.6 s from experiment start, deviated from the right lane for a period of 0.5 seconds (5 lines). The simulator software recorded the distance to the lead vehicle and the lead vehicle speed as “infinity”. Both were altered to become the linear interpolation of the corresponding values just before and just after this moment.
- Participant 4 did something similar when given the 120/33m assignment, except that after 98.1s the headway suddenly jumped to about 2400 metres for 1.0 second (10 lines). The correction was made in a similar manner.

Next to this, participant 12 experienced a case of simulator sickness, and asked to be relieved after having done 11 trials. This participant did perform all the tests in the instrumented vehicle.

## A.2 Data gathering in the instrumented vehicle

Data gathering in the instrumented vehicle was a much more manual task than in the simulator.

The instrumented vehicle is a Toyota Prius XW30 which has been modified so the distance readings of the internal vehicle tracking radar can be recorded on the computer. The vehicle tracking radar - a standard feature on all Toyota Priuses with adaptive cruise control (ACC) - already does some pre-processing on the reflected radar signals. The data stream gives information of up to 8 different “targets”; i.e. distinctive features. Data for each of those targets are i.a. distance and deviation from the vehicle’s central axis. Sometimes less than 8 features are detected.

The target data is recorded from the vehicles internal CAN bus via a data link to the laptop of the experimenter via a software suite, “dSPACE ControlDesk”. This data suite allows the experimenter to see the distances of the 8 targets in real time, and to modify a so-called “marker” value, which is recorded along with the radar data.

For each trial, the experimenter asks the participant to increase the distance to the lead vehicle; whenever the headway is over 3 seconds, the experimenter gives the instruction to attain a certain headway to the lead vehicle, and increases the marker value by one (I will call this “start time” from now on). When the participant thinks he/she has attained the assigned headway (“attainment time”), he/she says this aloud to the experimenter who again increases the marker value. After at least 15 seconds, the experimenter again increases the marker value (“end time”), instructs the participant to increase his/her distance to the lead vehicle so the next test can begin, and increases the marker value twice again.

The marker value thus continuously increases throughout the test. The value of the marker $m$ can be calculated as $m=(b-1)*5+n$; where $b$ is the number of the trial (in the order the tests are taken) and $n$ a status within the test, as given in Table 9. Note that it is not so much the value of the marker that is interesting, but the moment the value of the marker changes.

[13] A headway of 2 seconds at 100 km/h is 56 m.

Table 9 Instrumented vehicle marker values.

| Value of n mod 5 | Meaning |
|---|---|
| **0** | Ready to start trial |
| **1** | Start time - assignment given |
| **2** | Attainment time – participant thinks he/she has attained the assigned headway |
| **3** | End time - At least 15 seconds after n=2; end of trial |
| **4** | - |
| **5** | Ready to start next trial (equals to 0) |

Sometimes, a trial cannot be completed. This can have various causes, such as a vehicle cutting in between the instrumented and lead vehicles, or the lead vehicle approaching a slower vehicle in front of him, while it is not possible for both the instrumented and lead vehicle to switch lanes at the same time. In that case, the experimenter waits until the conditions for a trial are favourable, he decreases the marker so *n* modulo 5 is zero again and repeats the test.

Because the experimenter was ready to increase the marker value at the signal of the participant, a bump in the road would sometimes cause him to accidentally click the laptop's touchpad and increase the marker. He then would immediately decrease the marker value again. I will explain later why this is not a problem. Next to the laptop, the experimenter had a cheat sheet for each test showing the order of the trials and the required marker values – this had a spot for notes if anything remarkable happened (such as increasing the marker early), and a spot for marking the number of radar reflection the experimenter thought was the right one (called "slot" in Figure 8. A sample of such a cheat sheet is in Figure 8.

PP 24 Weer:

| | | adv geg | ok | 15 sec | | slot | opmerkingen |
|---|---|---|---|---|---|---|---|
| 1 | 120 | 1 | 2 | 3 | 1.5s | | |
| 2 | 120 | 6 | 7 | 8 | 1s | | |
| 3 | 120 | 11 | 12 | 13 | zelf | | |
| 4 | 120 | 16 | 17 | 18 | 2s | | |
| 5 | 120 | 21 | 22 | 23 | 67m | | |

Figure 8 Example of instrumented vehicle cheat sheet - only top 5 rows of a total of 21 are shown

The laptop could only store up to 700 seconds of vehicle and marker data at a time, enough for about 7 trials or less if trials had to be repeated or there was the need to wait for favourable traffic conditions. Data was saved in so-called .MAT-files, stored in separate directories for each participant, as “PP<participant number>/pp<participant number> <trial start>tm<trial end>.mat”. For example: The file “PP5/pp5 8tm14.mat” holds the 8th to 14th trial taken by participant 5.

## A.3 Signal selection in MATLAB

After the raw data from the simulator and instrumented vehicle are saved on a computer, they are read into MATLAB. Before it could be transformed to the desired output signal, the right radar signal had to be selected from the instrumented vehicle data. After some experimentation, I opted to take a visual approach: All the headway radar data for one trial is shown on the screen, and then I visually inspect the data to select the right signal.

A selection program called Part3[14] was built in MATLAB that shows the radar data in chunks of one trial each. An annotated example of what the program shows is visible in Figure 9.

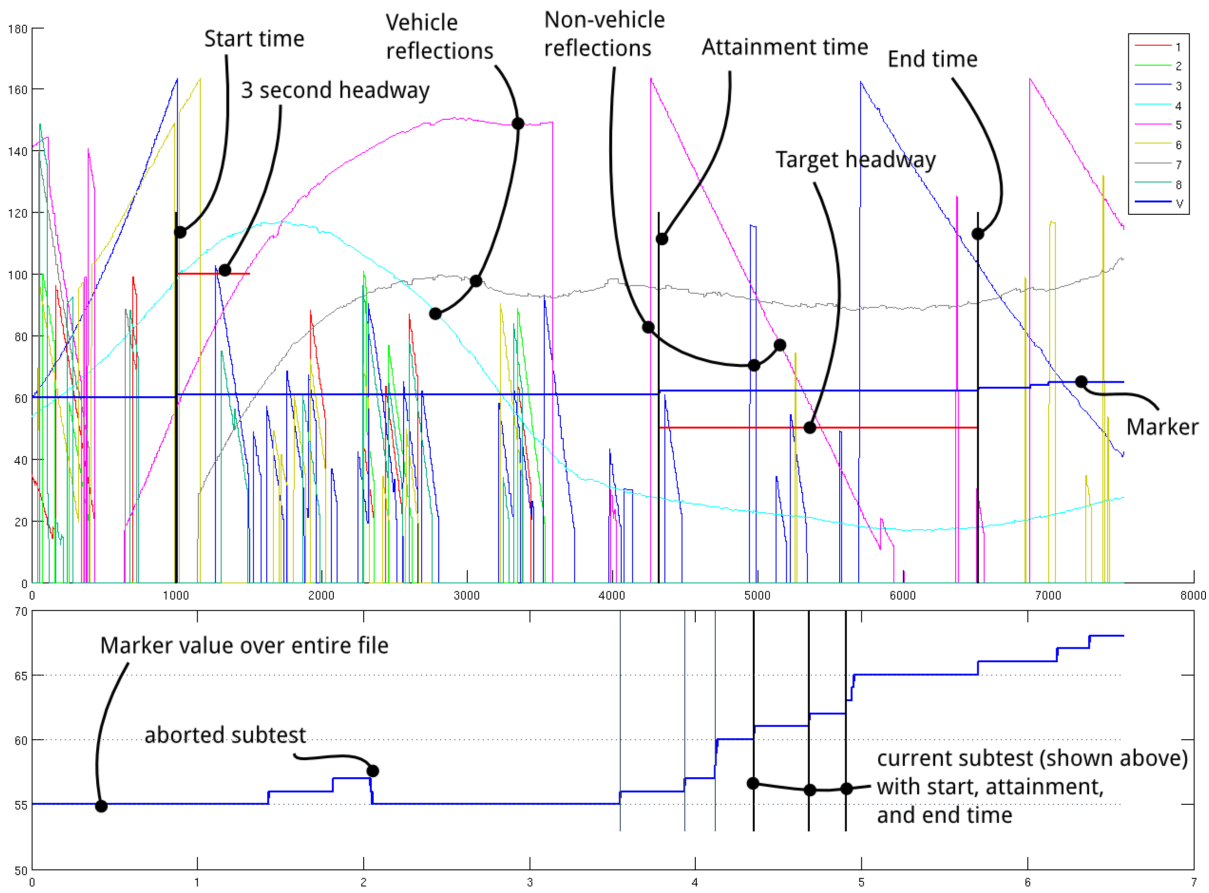


Figure 9 MATLAB script Part3: radar selection screen, annotated.

The lower section of the Part3 program, shown in Figure 9, shows the marker value for the entire .MAT-file, which contains a few trials. The vertical axis is the value of the marker, the horizontal axis time (in s*100). Overlaid over the marker, as 3 vertical lines, are the three distinctive moments for

14 The set of MATLAB scripts I wrote are called: Part1 (instrumented vehicle file analysis), Part1sim (simulator data import), Part2 (analysis of marker value changes), Part3 (Radar data import and selection), and Part5 (Data transformation and output). Part3 is the only program that needs manual input. Functionality from an originally planned Part4 was implemented in Part5; thus Part4 was never written.

this trial (based on the marker value): start time, attainment time and end time. Similarly, in grey, these three moments are shown for the previous trial.

The marker value can decrease if a trial is aborted or an error is made, such as is visible at left in the bottom section of Figure 9. The Part2 program only takes the last moment where the marker goes to a certain value as a distinctive moment, so any prior increases with corresponding decreases are ignored.

The upper section of the Part3 program, shown in Figure 9, shows the radar headway signals from one trial – and the 10 seconds before and after. The horizontal axis is time (in s/100); the vertical axis is headway (in m) and marker value. Overlaid on this are, as black vertical lines, the start, attainment and end time; in blue, the value of marker; as red horizontal lines, protruding from the *start time* line, a line that shows 3s headway (the start time headway), and a line between *attainment time* and *end time* that shows what the headway to the test vehicle should have been. In this case, the headway should have been 1.5s or 50m at a lead vehicle speed of 120 km/h.

The coloured thinner lines in Figure 9 are the radar reflections. The lines have different gradients. Note that the gradient of a line resembles the relative speed between the radar target and instrumented vehicle, and thus that objects (vehicles) traveling in the same direction have a relatively flat gradient compared to stationary objects (decreasing gradient) or vehicles traveling the other way (sharp decreasing gradient).

Visible is that the cyan (line 4, see legend of Figure 9), grey (7), magenta (5, only on the left half) and blue and yellow (3 and 6, only before start time) lines are somewhat smooth lines with varying gradients. Those are the radar reflections which probably resemble vehicles, while the shorter spikes and lines with a very steep gradient resemble reflections from signs, bridges, lamp posts or opposing vehicles (on the other side of the central divider).

From experience I found that the radar can detect objects up to about 160 metres, but only at a relatively small angle. This means that objects in the same lane (such as the lead vehicle) can be measured up to a few centimetres distance, but objects with a nonzero lateral distance – such as vehicles in another lane or signs in the soft shoulder) have a minimum measurement distance of roughly 15 metres. Any line that crosses trough the x-axis is an object that passes the instrumented vehicle or is passed by it[15]. Lines "disappearing" (becoming zero) close to the x-axis are probably also passing or being passed by the instrumented vehicle, but at a nonzero lateral distance. In Figure 9 only the reflections 4 and 7, and in smaller parts of the graph, 5 (left half) and 3 and 6 (before *start time*) look like they could be a vehicle reflection. From those, we disregard the reflections that are visible only part of the time. Of the remaining two lines (4 and 7), the grey 7 appears near the x axis (it overtook us), thus only 4 can be our lead vehicle. Confirmation of my belief that signal 4 is the right one is that the distance from signal 4 is at almost exactly 3 seconds at *start time*, and has an almost flat gradient (i.e. we are following that car with almost the same speed) between *attainment*

[15] Due to the small radar beam angle, theoretically an object within a few metres will only be detected if it is in the same lane at about bumper height, and thus, if it has a steep (negative) gradient the instrumented vehicle will crash into it. Yet there are numerous short (<100ms) reflections in the 0.1-3m range – maybe these are reflections from cracks in the road or bugs in front of the car.

*time* and *end time*, as per the assignment. Another confirmation is that I noted down signal 4 on my cheat sheet for this trial[16].

### A.3.1 Data omissions and manipulations

Table 10 lists the radar signal for each trial. However, there are a few cases where there is a deviation from the above procedure:

- Sometimes, the participant chose a headway to the lead vehicle that was over 160 metres[17], and the radar could not track the lead vehicle. In those cases, I marked an estimate of the attained headway on my cheat sheet, but in the end I omitted those results. Those cases are marked in Table 10 as "U (O)".
- Sometimes, the radar tracked the lead vehicle in two signals, changing between them. I built a "multisignal"-option into the Part3 program that allows to select different signals at start, attainment and end time. The change between signals never happened between attainment and end time. This was fortunate, as it allows the headway of the RMS of deviation from attained/target headway (hypothesis 4) to be calculated from one signal. Cases where the tracking happened in multiple signals are marked as M<signal at start time><signal at attainment time><signal at end time> in Table 10.
- Sometimes, the experimenter accidentally started a trial at the wrong marker value. I built an option to increase or decrease the marker value for a certain trial for such occasions. Cases where this was necessary are marked as (-<x>) or (+<x>) in Table 10, where <x> is the amount the marker value needed to be decreased or increased, respectively.
- Sometimes, the marker value was accidentally decreased and again increased during the experiment – e.g. due to a bump in the road. Normally, the Part2 program only takes the last time the marker changes to a certain value as the "right" place for the marker. In cases where the marker was changed down, I had to manually edit the marker value so the accidental changes were no longer present.
- In two cases, I could not discern clearly between the radar signals. This was marked with "U" in Table 10.
- One file with a series of 7 trials was not saved correctly and consequently was unusable. Those cases are the empty cells under participant 16 in Table 10.

[16] During the driving test, the laptop screen in front of the experimenter shows the distance to the up to 8 trials. By estimating the distance to the lead vehicle and matching this to one of the radar reflections a few times during a trial, I know which of the radar reflections is the one corresponding to the lead vehicle.

[17] The furthest assignment headway is 2 s at 120 km/h = 67m.

**Table 10 Selected radar signal for instrumented vehicle. Trials are in the order that they were taken on the road. See text for explanation. A light red background means no signal could be selected.**

| Participant / Trial | 2 | 4 | 5 | 6 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 22 | 23 | 24 | 25 | 26 | 27 | 28 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 4 | 6 | 4 | 4 | 4 | 3 | 4 | 4 | 6 | 3 | 3 | 6 | 3 | 3 | 8 | 5 | 4 | 6 | 4 | 3 | 3 | 3 |
| 2 | 4 | 6 | 4 | 4 | 4 | 3 | 4 | 4 | 6(-2) | U (O) | 3 | 6 | 3 | 3 | 8 | 5 | 4 | 6 | 4 | 3 | 3 | 3(-1) |
| 3 | 4 | M633 | 4 | 4 | 1 | 3 | 4 | 4 | 6(+2) | U (O) | 3 | 6 | 3 | 3 | 8 | 5 | 4 | 6 | 4 | 3 | 3 | 3(+1) |
| 4 | 5 | 5 | 4 | 4 | 1 | 3 | 4 | 4 | 6 | 6 | 3 | 6 | 3 | 3 | 8 | 5 | 4 | 6 | 4 | 3 | 3 | 3 |
| 5 | U | 5 | 4 | 4 | 1 | 3 | 4 | 4 | 6 | 6 | 3 | 3 | 3 | 3 | 8 | 3 | 4 | 6 | 4 | 3 | M344 | 3 |
| 6 | 5(-5) | 5 | 4 | 4 | 1 | 3 | 4 | 4 | 6 | U (O) | 5 | 3 | 3 | 3 | 8 | 3 | 4 | 6 | 4 | 3 | 3 | 3 |
| 7 | 5(+5) | 5 | 4 | 4 | 1 | 3 | 4 | 4 | M622 | 6 | 5 | 3 | 3 | 3 | 8 | 5 | 4 | M433 | 4 | 3 | 3 | 3 |
| 8 | 5 | 7 | 3 | 4 | 1 | 2 | 4 | 4 | 3 | U (O) | 5 | 3 | 3(-2) | 3 | 5 | 5 | 4 | 8 | 4 | 4 | 3 | 3 |
| 9 | 5 | 4 | 3 | M433 | 1 | 2 | 4 | 4 | 3 | 4 | 5 | 3 | 3(+2) | 3 | 5 | 6 | 4 | 8 | 4 | 4 | 3 | 3 |
| 10 | U | 6 | 3 | 3 | 1 | 6 | M411 | 4 | 3 | 4 | 5 | 3(-2) | 3 | 3 | 4 | 6 | 4 | 8 | 4 | 4 | 3 | 3 |
| 11 | M544 | 8 | 8 | 6 | 3 | 6 | 1 | 3 | 3 | M433 | 5 | 3(+2) | 3 | 4 | 4 | 6 | U (O) | 8 | 4 | 4 | 3 | 3 |
| 12 | M344 | 8 | 8 | 6 | 3 | 6 | 1 | 3 | 3 | 3 | | 3 | 3 | 4 | 3 | 6 | 5 | 8 | 4 | 4 | 3 | 3 |
| 13 | 4 | 8 | 8 | 6 | 3 | 6 | 4 | 3 | 3 | 3 | | 3 | 3 | 3 | 3 | 6 | 5 | 8 | 4 | 4 | 3 | 3 |
| 14 | 4 | 8 | 8 | 6 | 3 | 6 | M488 | 3 | 3 | 3 | | 3 | 3(-2) | 3 | 3 | 6 | U (O) | 3 | 3 | 4 | 3 | 3 |
| 15 | 4 | 8 | U (O) | 6 | 5 | 6 | 8 | 3 | M533 | 3 | | 3 | 6 | 3 | 3 | 7 | U (O) | 3 | 3 | 4 | 3 | 6 |
| 16 | 4 | 8 | 4 | 6 | 5 | 6 | 8 | 3 | 3 | 3 | | 3 | 3 | 3 | 3 | 7 | 6 | 3 | 3 | 4 | 3 | 3 |
| 17 | 4 | 8 | 4 | 6 | 5 | 6 | 8 | 3 | 3 | 3 | | 3 | 5 | 3 | 3 | 7 | M344 | 1 | 3 | 4 | 3 | 3 |
| 18 | 4 | 8 | 4 | 6 | 5 | 6 | 8 | 3 | 3 | 3 | | 3 | 5 | 3 | 3 | 7 | U (O) | 4 | 3 | 4 | 3 | 3 |
| 19 | 4 | 8 | 4 | 6 | 5 | 6 | 8 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 7 | 6 | 4 | 3 | 4 | 3 | 3 |
| 20 | 4 | 6 | U (O) | 6 | 5 | 8 | 8 | 3 | 3 | 3 | 3 | 3 | 4 | 3 | 3 | 7 | 6 | 4 | 3 | 4 | 3 | 4 |
| 21 | 3 | 6 | 3 | 6 | 3 | 8 | 8 | 3 | 3 | 3 | M388 | 5 | 4 | 7 | 3 | 7(+5) | 6 | 4 | 3 | 4 | 3 | 4 |

## A.4 RMS calculation

After the signal selection we know the headway to the lead vehicle from start time to end time for each trial for both the instrumented vehicle and the driving simulator. However, we need different data to test our hypotheses. The dependent data necessary for the different hypotheses are listed in Table 11.

Table 11 Data needed for hypothesis testing

| Hypothesis | Necessary data |
|---|---|
| **1** | Headway at attainment time (THW) |
| **2** | Headway at attainment time (THW) |
| **3** | Time to attainment: time between start and attainment time (TTR) |
| **4** | Headway keeping performance: root mean square of deviation from the headway at attainment time, calculated over the 15 seconds after attainment time (RMS) |

The way of obtaining the first two data types (for hypotheses 1-3) are straightforward. Below I will explain the exact procedure for the Root Mean Square.

The root mean square of the deviation from headway at attainment time (RMS) is a metric for how well participants can keep their vehicle at a fixed, self-chosen, headway. It only takes into account the deviation from the headway at attainment time, that is, the headway at the moment that the participant was confident they held the assigned headway – even if it was far from correct – and not the deviation from the assigned and the actual headway. The RMS has the property of always being positive; it is only a metric for the amount, not for the direction of deviation.

The RMS is calculated as

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{150}\left(b - h_{\frac{i}{10}}\right)^2}$$

where $b$ is the headway in seconds at start time; $h$ the headway at instant $\frac{i}{10}$s after start time and $n$ the number of discrete instances of time.

I opted to take data samples at a 10 Hz interval as it was the lowest common sampling interval of the simulator and instrumented vehicle. Samples were taken 15 seconds after start time, making 150 samples per trial.

## A.5 Output and omission handling

For each of the participants, for each trial, we have thus obtained 3 data values: THW (needed to test hypotheses 1 and 2), TTR (3) and RMS (4). These are written to 3 excel files, one per data type. The excel file has one row per participant and one column per trial. The first column and first row are headers, listing the participant number and trial name, respectively. Thus the file has 43 columns: 1 header column, 21 columns for the instrumented vehicle and 21 columns for the simulator, in that order. The 21 columns for each vehicle consist of three blocks of 7 columns for the lead vehicle speeds of 80, 100 and 120 km/h, in that order. Each of these blocks then consists of first three columns for the headway assignment of 1, 1.5, and 2 seconds, given in seconds, then a column where the user could select his/her own headway and then three columns for the headway assignment of 1, 1.5, and 2 seconds, given in metres. Note that the order of the trials in these files is not the same order as given in Table 10, where the order the tests were taken is used.

However, not all data points are available, due to factors described earlier in this appendix; e.g. inability to select the right radar signal, participant taking a too long headway or getting simulator sickness. In those cases we can chose to omit the data point. The ANOVA method used in the statistical analysis expects full matrices, and upon omitted values will remove entire rows or columns. Therefore I also took the approach of replacing unavailable values with their column averages (over existing data points).

I ran the statistical tests with both data variants (unavailable data omitted and replaced by column averages). No main effects were found significant in one version that were not significant in the other. Therefore, I chose to use the variant with the column averages, as the greater number of data used made the tests more credible.