

Car-following in self-, assisted-, and autonomous driving

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Erstgutachter: Prof. Dr. Hans-Rüdiger Pfister

Zweitgutachter: Prof. Dr. Rainer Höger

Drittgutachter: Prof. Dr. Mark Vollrath  
(Technische Universität Braunschweig)

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## Abstract

In this dissertation the relation between time headway in car following and the subjective experience of a driver was researched. Three experiments were conducted in a driving simulator. Time headways in a range of 0.5 to 4.0 seconds were investigated at 50km/h, 100km/h, and 150km/h under varied visibility conditions and at differing levels of driver control over the car. The main research questions addressed the possible existence of a threshold effect for the subjective experience of time headways and the influence of vehicle speed, forward visibility, and vehicle control on the position of time headway thresholds. Furthermore, the validity of zero-risk driver behavior models was investigated.

Results suggest that a threshold exists for the subjective experience of time headways in car following. This implies that the subjective experience of time headways stays constant for a range of time headways above a critical threshold. The subjective experience of a driver is only influenced by time headway once this critical time headway threshold is passed. Speed does not influence preferred time headway distances in self- and assisted-driving, i.e. time headway thresholds are constant for different speeds. However, in completely automated driving preferred time headways are influenced by vehicle speed. For higher speeds preferred time headways decrease. A reduction of forward visibility leads to a shift in preferred time headways towards larger time headways. Results of this dissertation give credence to zero-risk models of driver behavior.

## Zusammenfassung

In dieser Dissertation wurde der Zusammenhang zwischen der Distanzvariable Time Headway und dem subjektiven Erleben von Autofahrern untersucht. Hierzu wurden drei Experimente in einem Fahrsimulator durchgeführt. Time Headway Abstände im Bereich zwischen 0,5 und 4,0 Sekunden wurden bei 50km/h, 100km/h, und 150km/h, unter verschiedenen Sichtbedingungen in der Fahrumgebung sowie bei verschiedenen Stufen von Fahrerkontrolle über das Fahrzeug untersucht. Die interessierenden Forschungsfragen adressieren die mögliche Existenz eines Schwellenwerteffekts für die subjektive Wahrnehmung von Time Headway und den Einfluss der Fahrzeuggeschwindigkeit, Sicht in der Verkehrssituation und Fahrerkontrolle auf die Position dieses Schwellenwertes. Zusätzlich wurde die Validität von Zero-Risk Modellen der Fahrermodellierung untersucht.

Die Ergebnisse der Dissertation deuten darauf hin, dass ein Schwellenwerteffekt für die Bewertung von Time Headway beim Autofahren existiert. Die subjektive Bewertung von Time Headway ist also für Distanzen über einem kritischen Schwellenwert konstant. Die subjektive Bewertung von Time Headway Distanzen wird erst beeinflusst, sobald dieser kritische Schwellenwert unterschritten ist. Bei der Selbstfahrt und der teilautomatisierten Fahrt hat die Geschwindigkeit des eigenen Fahrzeugs keinen Einfluss auf die Lage des kritischen Schwellenwertes, d.h. der kritische Schwellenwert ist für verschiedene Geschwindigkeiten gleich. Im Gegensatz hierzu ist der kritische Schwellenwert in der vollständig automatisierten Fahrt für höhere Geschwindigkeiten in Richtung kleinerer Time Headway Abstände verlagert. Bei reduzierter Sicht in der Verkehrssituation verschiebt sich der Schwellenwert in Richtung größerer Time Headway Abstände. Die Ergebnisse dieser Dissertation deuten auf die Validität von Zero-Risk Modellen in der Fahrermodellierung hin.

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# 1 Introduction

In this dissertation car-following as a specific case of longitudinal control in car driving was researched. Three experimental studies were conducted to advance the understanding of car following in self-, assisted-, and automated-driving at different speeds and under different visibility conditions. The three studies touch upon different fields of traffic psychological research and the results have implications for driver behavior modeling, the application of advanced driver-assistant systems, and automated driving. In this introductory chapter, a rationale for time headway, as the focal driving parameter of the dissertation, is given. The expected contribution of the conducted research to driver behavior modeling is described afterwards. Next, the significance of this dissertation for the implementation of driver assistant systems and automated driving is summarized. At the end of this chapter the main research questions addressed in this dissertation will be outlined and the rationale for consecutive experiments on the basis of reported results will be given. The subsequent chapters contain the three research articles, each of which reports on one of the three studies in detail. In the last chapter a conclusion of the results of this dissertation is drawn.

Following other cars in traffic is a specific driving task that is examined in this dissertation. In car following, drivers need to maintain a certain distance between their own and a lead vehicle, by controlling the speed of their vehicle and react to changes in speed of the lead vehicle. The distance between two cars can be described in meters. However, while physically meters are the easiest way to describe a distance, this variable neglects another variable that is crucial for the psychological experience of a distance in car following - the speed of the driver's vehicle. Assessing the objective meter distance between two driving cars is psychologically inadequate,

since a distance of 20 meters is perceived differently at 10km/h than at 150km/h. The time headway variable considers this aspect and integrates the psychological perception of distance and speed. Time headway is defined as the time (in seconds) that is needed to reach the temporary position of an object ahead (Evans, 1991). It is calculated by dividing the distance between a vehicle and an object ahead by the speed of the vehicle (Figure 1). If the object ahead is stationary, the time headway expresses the time it takes for the vehicle to pass the object. In car-following where the object ahead is another moving vehicle, time headway expresses the time the driver of the following vehicle has to react to any decrease in velocity of the lead vehicle with an equal decrease in velocity (Taieb-Maimon, & Shinar, 2001).

$$\begin{array}{l}
 \text{Speed} \quad \text{Distance} \\
 50\text{km/h} \quad 27.7 \text{ m} \\
 (13.8 \frac{\text{m}}{\text{s}})
 \end{array}
 = \frac{\text{Distance } (27.7\text{m})}{\text{Speed } (13.8 \frac{\text{m}}{\text{s}})} = \text{Time Headway } 2 \text{ s}$$

Figure 1. Example of time headway calculation for a speed of 50km/h and a distance of 27.7 m.

Therefore, the advantage of time headway over using meters to describe the vehicle to vehicle distance is the fact that time headway incorporates a vehicle's speed and can therefore, in theory, be used by a driver to keep a safe distance to a lead vehicle at different velocities. Due to the nature of the calculation of time headway, it is most useful when the speeds of the following and the lead vehicle are similar. When the following and the lead cars' speeds are dissimilar, the time headway value can change rapidly and is not useful to describe car following, since it does not incorporate the speed of the lead vehicle (for a discussion of time-to-collision as a variable that is useful in these situations see Brackstone, Waterson, & McDonald, 2009; and Vogel, 2003). Due to this fact, observing time headway in real-

life driving can be difficult, as it is influenced by acceleration and deceleration phases of the following and the lead vehicle. Therefore, the ability to choose a preferred headway depends on the vehicle density on the road, the behavior of other road users, as well as the general driving environment (Ayres, Li, Schleuning, & Young, 2001; Gouy, Wiedemann, Stevens, Brunett, & Reed, 2014). Nonetheless, researchers observed that time headways in real life driving are most often found in the range of one to two seconds (Ayres et al., 2001; Shinar, & Schechtman, 2002; Winsum, & Heino, 1996). In studies on time headways of individual drivers, researchers found that time headway is held constant by individual drivers in the range of 40km/h to 70km/h (Winsum, & Heino, 1996) and 50km/h to 100km/h (Taieb-Maimon, & Shinar, 2001). In this dissertation the position of preferred time headways of drivers is systematically researched for self-, assisted-, and automated driving in a driving simulator. Past research has investigated time headway in car following for small speed ranges in settings with multiple interfering variables. Using a simulator to research time headway allows to control for many of the influencing variables found in real life driving observations. Furthermore, time headway distances in car following are examined for a broader speed range than in earlier studies.

Besides the position of a preferred time headway, this dissertation has implications for driver behavior modelling. It is assumed that the subjective experience of a driver determines control parameters of the car (Taylor, 1964; Winsum, 1999). Therefore, a prerequisite to understand a driver's actions is to understand the nature of the relationship between this subjective experience and physical driving parameters. In driver behavior modelling, two types of models are put forward that differ in this relation between subjective experience and driving parameters. In zero-risk models (Näätänen, & Summala, 1994; Summala, 1988), researchers assume that the driving situation rarely causes a change in the subjective state of drivers. For the subjective experience of risk this would mean that drivers control their

car in a way that prevents the occurrence of feelings of risk while driving. In opposition to this, the target-risk or target-task demand models (Fuller, 2005; Wilde, 1982) assume that drivers control their vehicle in a way to hold the experience of a subjective variable constant, i.e. at a target level that is higher than zero. The validity of a driver behavior model not only allows a better understanding of driver behavior, but also helps to design effective traffic safety interventions. The present research contributes to the current body of knowledge on the validity of zero- or target-models for car following.

With the advent of advanced driver assistant systems and automated driving, the subjective experience of the driver does not necessarily influence the driver's control of the car anymore, as it does in self-driving (Taylor, 1964; Winsum, 1999). On the contrary, the relation between subjective experience and driving parameters is reversed, since the assistant system or automation controls the car, driving parameters now influence the subjective experience of the driver. While with today's assistant systems for car following, such as adaptive cruise control, the driver maintains a level of control in that he or she can set a car to car distance, there has been no research on how this car to car distance needs to be adjusted for different speeds and driving environments. This dissertation aims to shed some light on the subjective experience of time headways at different speeds, under different visibility conditions, for self-, assisted-, and automated driving.

To summarize, there are four main research questions that are examined in the three studies of this dissertation:

1. Is there a threshold effect for time headways at different velocities?
2. Is the position of the time headway threshold influenced by velocity?
3. Is there a difference in the position of time headway thresholds between different levels of control over the vehicle?

4. Do differences in forward visibility influence the position of time headway thresholds?

### 1.1 Overview of experiments

To answer these questions, three driving simulator experiments were conducted. In the first experiment (Chapter 2), drivers were presented with time headways ranging from 0.5 to 4.0 seconds (varied in 0.5 second steps) at 50km/h, 100km/h, and 150km/h (24 conditions in total). Participants controlled the steering of their vehicle, while the simulation had longitudinal control to produce constant time headways to the lead vehicle, comparable to driving with a driver-assistant system. Participants were then asked to rate each of the 24 time headway and speed combinations on a 7-point Likert-scale for their subjective experience of risk, task difficulty, effort, and comfort. To compare this data to time headway following in self-driving, participants were also asked to follow a vehicle at 50km/h, 100km/h, and 150km/h while having full control of the car. For this free follow condition, time headway was recorded.

The goal of the first experiment was to replicate the effect of a time headway threshold found by Lewis-Evans, De Waard, and Brookhuis (2010) and to investigate if this effect is stable for different velocities (research question #1). Since the position of the time headway threshold can be deduced from data of the subjective experience of drivers, another research goal was to find out if the threshold position is influenced by different velocities (research question #2). Furthermore, time headways from self-driving were compared to preferred time headways of assisted driving to assess whether drivers prefer different time headways in dependence of their degree of control over their car (research question #3).

Results show that the threshold effect found by Lewis-Evans et al. (2010) is also present in our data. Ratings of subjective variables stayed



constant for large time headways until a threshold was reached. This effect was present at different velocities of 50km/h, 100km/h, and 150km/h (research question #1). The position of the threshold stayed constant for different velocities, although the study design did not allow the identification of a precise location of the threshold (research question #2). Time headways of self-driving were higher than assumed thresholds in assisted driving, and generally higher than expected, varying between 3 and 4 seconds (research question #3). This was attributed to the instruction of participants in the free follow condition, which did *not* ask participants to follow as close as possible while still feeling comfortable, but to follow as they would in real-life driving. With respect to the ratings of the variables subjective experience of risk, task difficulty, effort, and comfort, it was found that all of them correlated significantly with each other.

The second experiment (Chapter 3) was designed on the basis of the results of the first experiment. Three shortcomings of the first study were addressed: First, the inability to exactly pinpoint the time headway threshold was resolved by changing the experimental method for presenting time headways. This change was also made to allow for a higher granularity of presented time headways, increasing accuracy of individual time headway ratings from 0.5 second increments between 0.5 and 4.0 seconds to 0.1 second increments in the same range. Second, the instruction for self-driving was changed to elicit more natural following distances in participants. Third, the number of subjective variables was reduced in light of the high correlations between subjective ratings in the first study to reduce task demands on participants. Further, the two remaining subjective variables, risk and comfort, were researched in a between-subject design to prevent a correlation due to analog presentation of the subjective variables.

In the second experiment, time headways in the range of 0.5 to 4.0 seconds were presented in ascending and descending sequences. As in the

first experiment, participants only controlled the steering, while the speed of the car and thereby the distance to the lead vehicle was controlled by the simulation. Since the results of the first experiment showed that there is a threshold effect for subjective experience of time headways, participants in the second experiment only reported when their comfort or their risk experience changed, i.e. when they crossed the threshold for risk or comfort experience. Through the use of a refined method of limits, it was possible to locate the participants' individual threshold with a precision of 0.1 seconds. Results suggest that the location of the threshold for subjective experience of time headways is not influenced by speed in self- or assisted-driving (research question #2). The threshold positions in self-driving did not significantly differ from threshold positions identified for assisted driving (research question #3).

In the third experiment (Chapter 4) an autonomous car was simulated, to investigate if the results of stable time headway thresholds over different speeds found in the first two studies could also be found in completely automated driving. Since time headway is a variable that is estimated visually, the influence of different levels of visibility on time headways was researched. Drivers were presented with the same time headway range as in the first two experiments (0.5 to 4.0 seconds), with the same granularity of the first experiment, i.e. 0.5 second increments. Since time headway thresholds in the first two experiments were mostly located in the 1 to 2 second range, two extra increments of 1.25 and 1.75 seconds were added to the presented time headways. The resulting ten time headways were presented at 50km/h, 100km/h, and 150km/h, and in three visibility conditions. In the clear visibility condition, participants followed a normal sized passenger car in clear weather (as in experiment 1 and 2). In the fog condition, participants followed the same passenger car but fog occluded parts of the driving environment. In the truck condition, participants followed a truck in clear weather conditions. Participants rated their

subjective level of comfort for the 90 different time headway conditions with a bi-directional haptic lever. The bi-directional nature of the lever allowed to analyze when a rating shifted from e.g., comfortable to uncomfortable, making it easy to identify threshold points of subjective comfort experience.

Results suggest that there is a significant influence of speed on comfort ratings of time headway thresholds in automated driving (research question #2), a result that was not found in the first and second experiment (research question #3). With respect to visibility, results show that reduced visibility led to a preference for larger time headways in all speed conditions (research question #4).

## 1.2 References

Ayres, T. J., Li, L., Schleuning, D., & Young, D. (2001). Preferred time-headway of highway drivers. In *Intelligent Transportation Systems, 2001. Proceedings. 2001 IEEE* (pp. 826-829). IEEE.

Brackstone, M., Waterson, B., & McDonald, M. (2009). Determinants of following headway in congested traffic. *Transportation Research Part F: Traffic Psychology and Behaviour*, *12*(2), 131-142.

Evans, L. (1991). *Traffic safety and the driver*. New York, NY: Van Nostrand Reinhold.

Fuller, R. (2005). Towards a general theory of driver behaviour. *Accident Analysis & Prevention*, *37*(3), 461-472.

Gouy, M., Wiedemann, K., Stevens, A., Brunett, G., & Reed, N. (2014). Driving next to automated vehicle platoons: How do short time headways influence non-platoon drivers' longitudinal control?. *Transportation research part F: traffic psychology and behaviour*, *27*, 264-273.

Lewis-Evans, B., De Waard, D., & Brookhuis, K. A. (2010). That's close enough—A threshold effect of time headway on the experience of risk, task difficulty, effort, and comfort. *Accident Analysis & Prevention*, *42*(6), 1926-1933.

Näätänen, R., & Summala, H. (1974). A model for the role of motivational factors in drivers' decision-making. *Accident Analysis & Prevention*, *6*(3), 243-261.

Shinar, D., & Schechtman, E. (2002). Headway feedback improves intervehicular distance: A field study. *Human Factors*, *44*(3), 474-481.

Summala, H. (1988). Risk control is not risk adjustment: The zero-risk theory of driver behaviour and its implications. *Ergonomics*, *31*(4), 491-506.

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.

Taylor, D. H. (1964). Drivers' galvanic skin response and the risk of accident. *Ergonomics*, 7(4), 439-451.

Vogel, K. (2003). A comparison of headway and time to collision as safety indicators. *Accident analysis & prevention*, 35(3), 427-433.

Wilde, G. J. S. (1982). The theory of risk homeostasis: implications for safety and health. *Risk analysis*, 2(4), 209-225.

Winsum, W. V., & Heino, A. (1996). Choice of time-headway in car-following and the role of time-to-collision information in braking. *Ergonomics*, 39(4), 579-592.

Winsum, W. V. (1999). The human element in car following models. *Transportation research part F: traffic psychology and behaviour*, 2(4), 207-211.

## 2 The Influence of Time Headway on Subjective Driver States in Adaptive Cruise Control

### **Abstract**

There is no agreement on the relation between driving parameters and drivers' subjective states. A linear as well as a threshold relationship for different subjective variables and driving parameters has been put forward. In this study we investigate the relationship between time headway and the ratings of risk, task difficulty, effort, and comfort. Knowledge about this interrelation may advance the development of adaptive cruise control and autonomous driving and can add to the discussion about driver behavior models. An earlier study (Lewis-Evans, De Waard, & Brookhuis, 2010) found a threshold effect for drivers' ratings of subjective variables for time headways between 0.5 and 4.0 seconds at a speed of 50 km/h. This study aims to replicate the threshold effect and to expand the findings to time headways at different speeds. A new measure for criticality was added as a categorical variable, indicating the controllability of a driving situation to give indications for the appliance of time headway in adaptive cruise control systems. Participants drove 24 short routes in a driving simulator with predefined speed and time headway to a leading vehicle. Time headway was varied eight-fold (0.5 to 4 seconds in 0.5 second increments) and speed was varied three-fold (50, 100, 150 km/h). A threshold effect for the ratings of risk, task difficulty, effort, and comfort was found for all three different speeds. Criticality proved to be a useful variable in assessing the preferred time headway of drivers.

### 2.1 Introduction

Time headway is an important variable in the distance keeping algorithms of adaptive cruise control systems (e.g. Desjardins & Chaib-draa, 2011; Swaroop, Hedrick, Chien, & Ioannou, 1994; Touran, Brackstone, &

McDonald, 1999; Winsum, 1999). It is calculated by dividing the distance to a lead vehicle by the speed of the following vehicle, resulting in the time that it takes for the following vehicle to reach the momentary position of the lead vehicle. Since the calculation of time headway incorporates the speed of the following vehicle, it is a variable that can give valid information on distance not only for a specific velocity range, but, at least theoretically, for all possible vehicle velocities in traffic. When vehicle traffic is recorded and time headways are calculated, there is a broad range of observable time headways for self-driving. This is attributed to different traffic states. Sparse traffic for example can lead to large time headways, due to the fact that drivers can freely reach their preferred speed and the speed limit hinders close distances between vehicles, while congested roads lead to smaller time headways (Ayres, Schleuning, & Young, 2001; Neubert, Santen, Schadschneider, & Schreckenberg, 1999). Thus, it is hypothesized that the minimal time headway for self-driving that is considered safe by drivers can only be observed in congested traffic situations. This minimal time headway is suspected to be between 1 and 2 seconds (Ayres et al. 2001). Since in real life traffic many variables, including congestion and speed, have an effect on possible time headway ranges, attempts have been made to systematically research the influence of time headway on drivers' subjective states, such as feelings of risk, task difficulty, effort, and comfort. Therefore, the aim of this study is to systematically research the influence of time headways on the aforementioned subjective driver states. To understand the relation between this distance variable and driver states, we systematically present the driver with a set of time headways. Furthermore we aim to contribute to the development of adaptive cruise control systems and distance keeping in autonomous cars. Since small, i.e., just considered safe, time headways are more often observed in relatively low speeds due to traffic congestion (Ayres, Schleuning, & Young, 2001), we also research if time headway is still useful as a distance variable for higher velocities, by

presenting the range of time headways for 50, 100, and 150 km/h. Since time headway is a variable that is theoretically applicable for different speeds, we expect that the relation between time headway and driver states is constant over all velocities we investigate in the present study.

Apart from implications for the development of adaptive cruise control systems, this study may also add to the discussion about driver behavior modeling and the significance of different subjective variables in traffic psychology. The influence of driving parameters on drivers' subjective states has long been discussed in the traffic psychology research community (e.g. Michon, 1986; Ranney, 1994; Vaa, 2007). As of now there is no agreement on the subjective variables that determine a driver's choice of speed and safety margins or time headway to other road-users and -objects. A number of subjective variables have been researched, e.g., risk (Näätänen & Summala, 1974; Wilde, 1982), comfort (Summala, 2005), effort and task difficulty (Fuller, 2005). A possible reason for the disagreement over which single subjective variable governs drivers' actions may lie in the moderate to high correlation between the aforementioned subjective variables that can be found in traffic psychology research (Lewis-Evans & Rothengatter, 2009; Lewis-Evans et al., 2010; Fuller, 2005; Fuller, McHugh & Pender, 2008). In light of this unresolved disagreement, it seems advisable to measure multiple subjective variables when investigating the influence of time headway on a driver's subjective state. In this study, we assess risk, task difficulty, effort, and comfort, and expect moderate to high correlations between these subjective variables.

In addition to the disagreement over which subjective variable is crucial for drivers' decision making, there is a lack of agreement over the general occurrence and awareness of subjective variables in drivers. By measuring in systematically varied driving situations in this study, we intend to advance the discussion on this topic. A general differentiation between



driver behavior models is the level of awareness and occurrence of subjective variables. For example, Näätänen and Summala (1974; also Summala, 1988) argue in their zero risk model that drivers do not constantly experience risk and that there is no subconscious risk experience when driving their vehicle, but that drivers adjust safety margins while driving to avert risky situations in general. Following this theory, there is generally no occurrence or awareness of subjective risk in drivers. Risk is only infrequently experienced when drivers are pushed towards maladjusted driving behavior due to motivational factors or by actions of other road users, which is considered the exception in normal driving. Contrary to the zero risk model, Wilde (1982) argues in his theory of risk homeostasis that there is a target level of risk that is larger than zero that a driver tries to maintain by adjusting his or her subjective risk through the adjustment of driving parameters. Wilde further hypothesizes that this constant comparison is highly automatized, but can be “called into full consciousness by questioning the individual” (Wilde, 1982, p.210).

Following the zero risk theory, it would be hypothesized that a driver does not report a feeling of risk when asked to assess his subjective state in a normal self-driving condition. Following the theory of risk homeostasis, a driver would report a level of risk in a normal self-driving condition that is larger than zero. In this study, in which a driving parameter, i.e., time headway, is systematically varied, it is therefore of interest if participants report a level of risk in each time headway condition, or if participants only experience risk for certain time headways. If participants do report risk for driving conditions in which time headway is relatively large, this would support the risk homeostasis theory by Wilde (1982). If participants do not report risk for large time headways, this would add to the validity of the zero risk theory by Näätänen and Summala (1974).

There is prior research on the relation between systematically varied time headways and subjective variables. Lewis-Evans, De Waard and Brookhuis (2010) conducted a study investigating the relationship between time headway and the experience of risk, task difficulty, effort and comfort in drivers. They found a threshold effect of time headway. The characteristics of this threshold effect are the following: For large time headways, subjective ratings of risk, task difficulty, effort and discomfort stayed constant until a critical time headway is reached. For all time headways smaller than the threshold time headway, participants' subjective ratings of risk, task difficulty, and effort increased significantly, and ratings of comfort decreased significantly. In the study by Lewis-Evans et al. (2010), participants ( $N = 40$ ) drove in a fixed base driving simulator with a fixed speed of 50 km/h. Participants could not change their speed and only controlled the steering. A lead vehicle was driving ahead of participants' vehicle with an identical speed of 50 km/h. The distance of the lead vehicle was varied eight-fold, resulting in eight different time headways, ranging from 0.5 to 4.0 seconds, varied in 0.5 second increments. At the beginning of each condition, the lead vehicle and the participant's vehicle had a distance of 10 meters at a speed of 0 km/h. The speed was then increased until 50 km/h were reached, while the distance corresponding to one of the pre-defined time headways was set during this acceleration phase. Each condition lasted approximately three minutes. In addition there was a so called free following condition, in which participants had control over their vehicle's speed and were instructed to follow the lead vehicle as close as possible while still feeling comfortable. The simulated road was designed as a typical inner city street.

After each condition in which a single pre-defined time headway was presented, participants rated task difficulty, subjective risk, effort, and comfort for the specific distance on a 7-point Likert scale. Two types of crash risk were also rated by asking participants to indicate the number of

times they would lose control of the vehicle when driving with the given distance, and how often they estimated a loss of control or accident for another driver driving with the same distance in a two month period. For the non-free follow conditions, i.e., when time headways was fixed, participants also rated if they would typically follow a lead vehicle with the same distance on a 7-point scale ranging from 1 = “never” to 7 = “always”. Results showed a threshold relationship between time headway and risk, task difficulty, effort and comfort, in that time headways from 4.0 to 2.0 resulted in consistently low variable ratings and increased ratings for time headways lower than 2.0 seconds.

Regression analyses supported the hypothesis of a threshold for the researched subjective variables with variable ratings showing a significant relationship with time headways of 2.0 to 0.5 seconds ( $\beta = .29$  to  $.61$ ), with no significant relation for time headways of 2.5 to 4.0 seconds ( $\beta = -.17$  to  $.18$ ). Although the threshold point was assumed to lie between 2.0 and 1.5 seconds after descriptive analysis of the data, the split of time headways for the regression analyses was made between 2.5 and 2.0 seconds to be able to use the ratings of 2.0 seconds as the starting point for the regression line for smaller time headways. Ratings of task difficulty, feeling of risk, comfort and effort were moderately to highly correlated with each other ( $r = .41$  to  $.78$ ,  $p < .001$ ), and the mean time headway in the free follow condition was 1.78 seconds ( $SD = .89$ ).

Taking the findings of Lewis-Evans et al. (2010) into account, the present study investigates if a threshold exists for time headway on a set of subjective variables for different speeds. To ensure comparability, we investigated the same subjective variables as Lewis-Evans et al. (2010) did, that is, risk, task difficulty, effort, and comfort. It is hypothesized that the threshold relationship between time headway and risk, task difficulty, effort, and comfort is consistent over different velocities. The threshold was

expected to lie between 2.0 and 1.5 seconds. In line with earlier research, a high correlation between the subjective variables was anticipated (Lewis-Evans & Rothengatter, 2009; Lewis-Evans et al., 2010; Fuller, 2005; Fuller, McHugh & Pender, 2008).

## 2.2 Method

### 2.2.1 Participants

Participants ( $N = 33$ ) were recruited from the student body of the Leuphana University of Lüneburg. The only prerequisite for participation was the possession of a driver's license. 16 participants were female (17 male) with a mean age of  $M = 22.48$  ( $SD = 2.53$ ). Participants owned their drivers' licenses for an average of  $M = 4.92$  ( $SD = 2.59$ ) years and had on average driven  $M = 56,393$  ( $SD = 94,927$ ) kilometers since then. On average participants drove  $M = 7,574$  ( $SD = 8,894$ ) kilometers per year with 48.5% using the car at least once a week. For their participation the students were awarded with test-subject-hours which need to be collected during students' years of study.

### 2.2.2 Materials

A Systems Technology W500 multi-projector fixed-based driving simulator system was used in this study. The passenger cabin, dashboard, steering wheel, and gearshift were taken from an automatic Volkswagen Golf 4, a medium class vehicle. The pedal system consisted of generic driving simulator pedals. The traffic environment was projected onto three screens, each measuring 1.4 x 1.4 meters, which were positioned 2 meters away from the driver's seat. A 7-inch touchscreen was built into the center console at the height of the steering wheel. Curtains enclosed the whole simulator to shut out outside light and dampen ambient sounds. The simulator software was programmed to save data with a frequency of 20Hz.

Analog to the study by Lewis-Evans et al. (2010), 24 “fixed follow” situations were programmed, in which the vehicle speed and distance to another car were fixed. Each of the 24 situations paired one of three velocities (50, 100 and 150 km/h) with one of eight time headways (0.5 seconds to 4 seconds in 0.5 second increments). Each situation had one gentle curve, with right and left curves randomized for every situation. Combinations of time headway and velocity were presented in random order. This was done to counter possible adaptational effects which were found to carry over from automated driving with small time headways to self-driving (Eick & Debus, 2005; Skottke, 2007). Each situation lasted 60 seconds and after each situation the simulator screen was blanked out. The situations were shorter than in the study by Lewis Evans et al. (2010), to keep the length of the experiment reasonable, while still being able to research all 27 conditions in one experimental treatment. Pretests showed that participants are able to rate their subjective experience for conditions of 60 seconds. In contrast to the study by Lewis-Evans et al. (2010), there was no acceleration phase, so the participant’s car and the lead vehicle were driving at their specified speed from the beginning, i.e. the blank screen, to the end of each situation.

Three additional “free follow” conditions were programmed and randomly presented, in which the participants trailed a lead vehicle driving 50, 100 and 150 km/h with full control of their own car. To distinguish free follow from fixed follow conditions, a text was displayed before each free follow condition, informing participants that a free follow condition would start and reminding them to follow the lead vehicle with a distance they would maintain in real-life driving. With the instruction for participants to follow with a distance that resembles their following behavior in real-life driving we aimed for an increase of external validity for following behavior.

In the free follow conditions, the participant's vehicle drove autonomous with a fixed speed (either 50, 100, or 150 km/h) following a lead vehicle with a distance equivalent of a time headway of 4.0 seconds for the first 5 seconds of the situation. After the initial autonomous phase, a short audio signal indicated that the driver now had to take over full control of the pedals and the steering wheel. Control of the vehicle was handed over to the driver 5 seconds after the audio signal. The autonomous phase was added to prevent a loss of velocity and a consequential increase in time headway due to the abrupt start of the situation, especially considering the relatively large time headway. With the help of the autonomous phase, participants had the ability to prepare their desired acceleration/deceleration activity, before taking over control of the vehicle. Every free follow condition lasted 120 seconds and had a gentle curve with left and right curves randomized. Data was recorded for the complete free follow condition, i.e. 120 seconds.

In all conditions, free and fixed follow, participants drove on a two lane road (one lane in each direction), with the lanes separated by dashed lane markings. There was no guard railing on the side of the road. To prevent overtaking, there was oncoming traffic in the opposing lane at random intervals of 5 to 15 seconds. Lane width was 3.60 meters in every situation. There were no objects on the roadside except for sparsely placed trees. Two training conditions were programmed, one free follow and one fixed follow, to help participants get used to driving in the simulator and to make sure that participants were familiar with taking over control of the car in the free follow conditions.

After every condition, participants answered questions (in German) on the touchscreen in the center console about their experience during the condition. In the fixed follow conditions, participants first rated task difficulty, subjective risk, effort, and comfort on a 7-point Likert scale for the distance kept by their car. Next, participants were asked if they would

keep the same distance if they drove on their own, indicated on a 7-point Likert scale with the poles “never” and “very frequently”. To evaluate crash risk participants were then asked how often they would lose control over the vehicle or have an accident if they would drive with the same distance every day for a period of two months. This question was also asked to evaluate the hypothetical crash risk of other drivers, by rewording the question to “How often would another driver have an accident or lose control over the car if he or she drove with the same distance for a period of two months.” Both questions for crash risk (self and other) were answered on a 7-point Likert scale with the poles “never” and “very frequently”.

With the last question, criticality was evaluated. Participants were first asked to give an assessment of the criticality of the distance between the two vehicles, choosing one of five categories followed by a number rating (Neukum, Lübbecke, Krüger, Mayser & Steinle, 2008). The categories and the adjacent numbers were: “nothing noticed” (0), “harmless” (1-3), “unpleasant” (4-6), “dangerous” (7-9), and “uncontrollable” (10). Participants were able to indicate that they found a certain distance to be “unpleasant” and almost “dangerous”, by choosing “unpleasant” and then “6”. The measure of criticality was added to have a categorically anchored question that can give real-life indications for time headways. For the free follow conditions, the questionnaire was the same, except that there was no question whether participants would keep the same distance if they drove themselves.

### 2.2.3 Procedure

After arriving in the driving simulator room, participants were asked to fill out a demographic questionnaire. After this, they sat down in the driver’s seat of the simulator and were asked to adjust their seat, so they could sit comfortably and reached the pedals and the steering wheel. In a short instruction, participants were informed, that they were expected to drive

short routes and that they would answer questions after each drive on the touchscreen in the center console. The two different types of conditions were briefly explained, as “free follow” and “fixed follow” conditions. After this, a first fixed follow training condition was started. Once finished, the researcher explained the operation of the touchscreen questionnaire. After answering the questionnaire, participants were informed about the autonomous phase of the free follow conditions and instructed to keep the same distance to the lead vehicle that they would keep in real world driving. Participants then drove the free follow condition. After answering the questionnaire for the free follow condition, participants were asked if they felt comfortable driving the simulated vehicle and if they had questions concerning the experiment. Next, an individual file, containing all 27 conditions (24 fixed follow, 3 free follow) in randomized order was started. After the last condition was completed, participants received their test-subject hours and were told about the background of the experiment.

### 2.3 Results

To obtain a descriptive impression of the relation between systematically varied time headways and ratings of task difficulty, subjective risk, effort, comfort (recoded), typically follow (recoded), self-, and other- crash probability we plotted the mean ratings of participants (Figure 2) for all eight time headways and the three velocities. It is important to keep in mind that the lowest possible rating for any subjective variable was 1 on a seven point Likert scale. Therefore, there can be no values smaller than 1. Subjective ratings of task difficulty, subjective risk, effort, comfort, as well as self- and other- crash probability stay relatively constant for time headways from 4.0 to 2.0 seconds. For time headways smaller than 2 seconds, subjective ratings increase. Descriptively, it appears that the hypothesized threshold effect can be observed. The threshold effect also appears to be consistent for all three velocities.



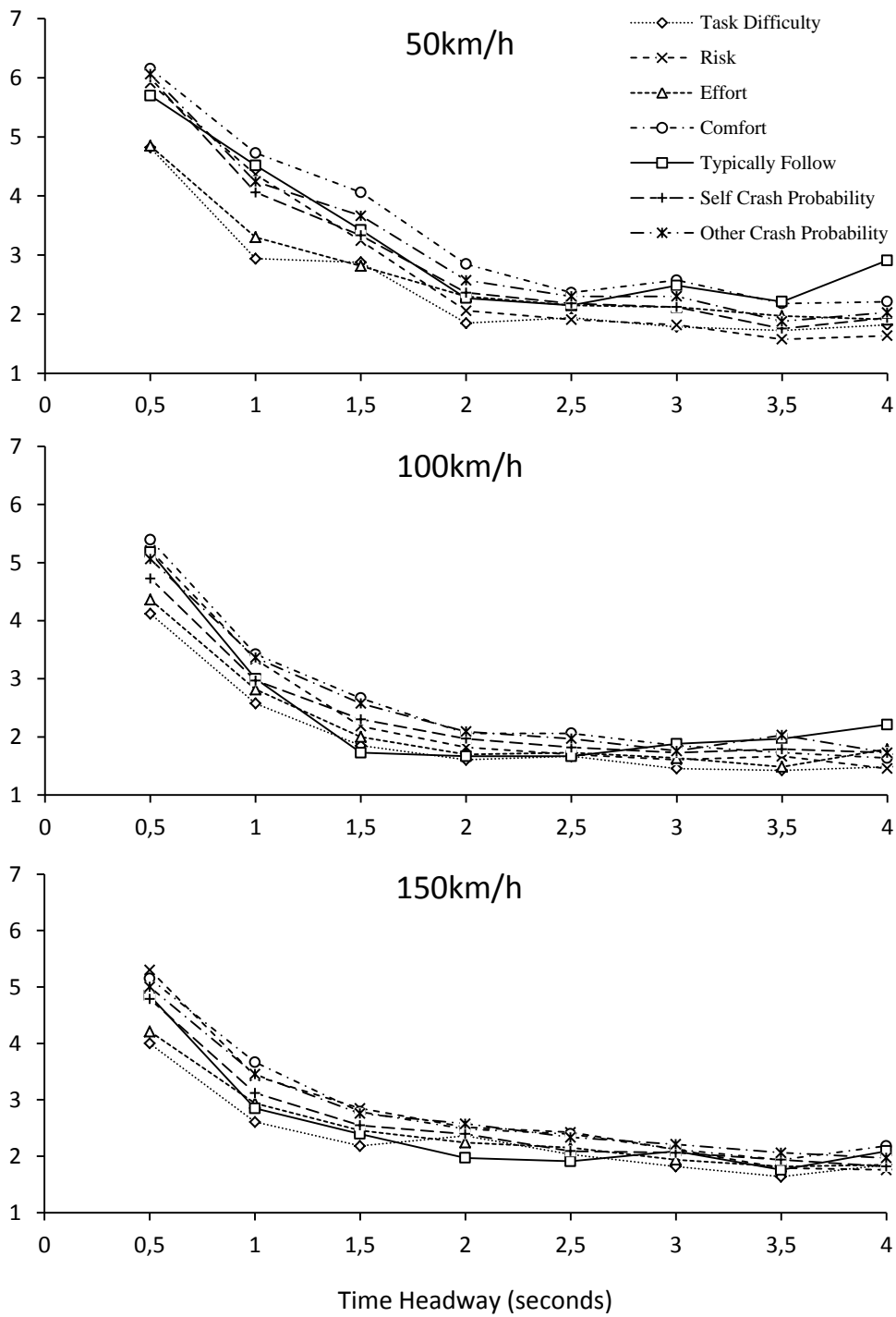


Figure 2. Average ratings of task difficulty, subjective risk, effort, comfort (inverted), typically follow (inverted), and crash probability (self & other) for eight fixed time headways and three velocities.

A second observation can be made from the plotted data: on average the ratings of subjective variables for the large time headway conditions, i.e., 4.0 and 3.5 seconds, are very close to one. Since our goal was to add to the discussion on driver behavior models, we will go into more detail on the ratings of risk, especially for large time headways. Mean ratings of subjective risk are relatively small for time headways of 4.0 seconds for all three velocities. On average participants reported a subjective risk of 1.64 ( $SD = 0.99$ ) for the 50 km/h, 1.45 ( $SD = 0.91$ ) for the 100 km/h, and 1.76 ( $SD = 1.12$ ) for the 150 km/h condition. The anchors on the subjective risk Likert scale were labeled “no risk” and “maximum risk”. When looking at the subjective risk rating for every single participant, it becomes clear that a high number of participants did report “no risk” for the condition with a fixed time headway of 4.0 seconds. For the velocity of 50 km/h, 21 out of 33 participants reported to have experienced no subjective risk, for 100 km/h 24 out of 33, and for the 150 km/h condition with a fixed time headway of 4.0 seconds, 18 out of 33 participants indicated that they did not experience risk by marking the number 1 on the Likert scale.

Since the Likert scales used in this study were only anchored on the poles, criticality was added as a measure that is based on categories. Criticality is plotted in Figure 3 for all time headways and the three researched velocities. As with the other subjective variables, it appears that there is a threshold effect of time headway and the average ratings of criticality. Criticality ratings for time headways from 4.0 to 2.0 seconds stay relatively constant, criticality then increases for subsequent smaller time headways. On average criticality is rated as “harmless” for time headways between 4.0 and 2.0 seconds. In the 50 km/h condition the distance is then rated as unpleasant ( $M = 4.3$ ,  $SD = 1.76$ ) for a time headway of 1.5 seconds. In contrast, criticality was still rated as “harmless” for a time headway of 1.5 seconds for the two higher velocities of 100 and 150 km/h. Time headways of 1.0 seconds are rated as “unpleasant” for all three velocities, and time

headways of 0.5 seconds are rated as “dangerous” for all three presented speeds. In general it appears that over all time headways except the smallest (0.5 seconds) criticality ratings were on average the lowest for the 100 km/h conditions.

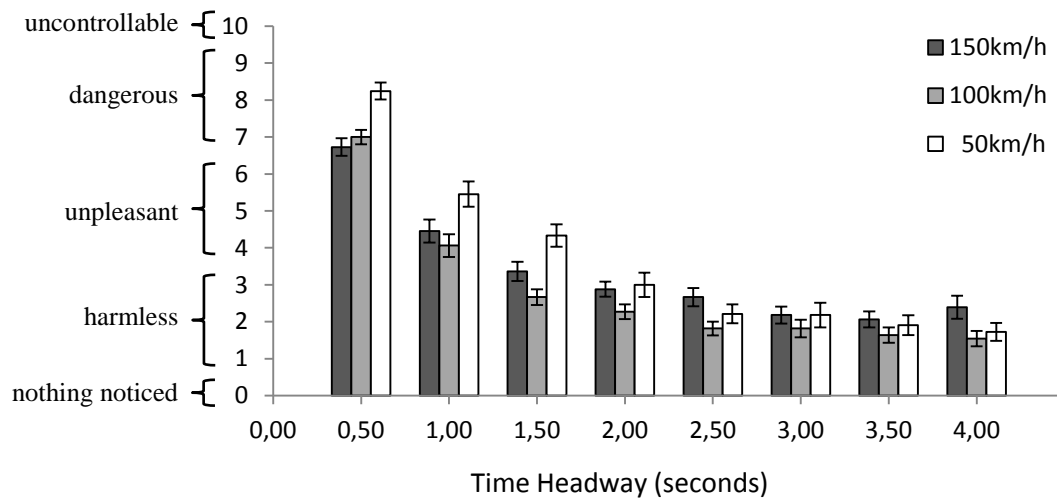


Figure 3. Mean ratings and standard errors of criticality for eight time headways and three velocities.

Looking at Figure 2 it appears that the ratings of subjective variables correlate with each other. Hence, multiple Pearson correlations were performed to analyze the relationship between the researched subjective variables. All reported subjective variables on the different time headways and speeds were significantly correlated. For the fixed follow conditions, Pearson’s correlations showed that task difficulty is highly correlated with risk, effort, comfort, rating of criticality, and estimated crash risk for oneself as well as others ( $r = .67$  to  $.87$ ,  $p < .01$ ). Reported risk correlated highly with effort, comfort, rating of criticality, and crash risk for others and oneself ( $r = .80$  to  $.83$ ,  $p < .01$ ). Effort correlated with comfort, rating of criticality, and estimated crash risk for others and oneself ( $r = .67$  to  $.73$ ,  $p < .01$ ). Comfort (recoded) was highly correlated with the rating of criticality and crash risk for others and oneself ( $r = .80$ ,  $p < .01$ ). Ratings of criticality were correlated with crash risk ( $r = .79$  to  $.80$ ,  $p < .01$ ), and crash risk for

oneself correlated highly with estimated crash risk for others ( $r = .95, p < .01$ ). The indication if a participant would follow the lead vehicle with the same distance correlated negatively with the other reported subjective variables ( $r = -.52$  to  $-.66, p < .01$ ).

After calculating the correlation between the ratings of subjective variables, a regression analysis was run separately for each subjective variable and all time headways and velocities. Taking into account the results of the study by Lewis-Evans et al. (2010) and the plotted ratings of the subjective variables and time headway presented in Figure 2 the data was split between the time headways of 2.0 and 2.5 seconds. Multiple regression analyses were then run for subjective ratings of time headways between 4.0 and 2.5 seconds, and subjective ratings of time headways between 2.0 and 0.5 seconds. Regression analyses were also run over all three velocities of 50, 100, and 150 km/h.

The results of these multiple regression analyses are presented in Table 1. Regression analyses revealed no significant relation between time headways of 4.0 to 2.5 seconds and the subjective ratings of participants. This supports the descriptive findings of the plotted data (Figure 2) and the results of Lewis-Evans et al. (2010). Time headways ranging from 4.0 to 2.5 seconds do not significantly influence the ratings of task difficulty, risk, effort, comfort, criticality, and estimated self- and other-crash risk. This result was consistent for all the velocities. There was one exception: Ratings of subjective risk showed a significant relation to time headways from 4.0 to 2.5 seconds for a speed of 150 km/h. It is important to recognize that the regression model can only explain 5% ( $R^2 = .05$ ) of the variance in the ratings of subjective risk for a velocity of 150 km/h.

For time headways ranging from 2.0 to 0.5 seconds a significant ( $p < .001$ ) linear relation between time headways and all ratings of subjective variables was found. Overall, the regression model can explain a moderate

to high percentage of variance in the subjective ratings of participants for time headways of 2.0 to 0.5 seconds. This result was also consistent over all the researched velocities.

Table 1. Regression analyses for ratings of task difficulty, subjective risk, effort, comfort (recoded), crash probability (self & other), typically follow (not recoded), and criticality, for time headways from 4.0 to 2.5, and from 2.0 to 0.5 seconds.

	Time Headway = 4.0 to 2.5			Time Headway = 2.0 to 0.5		
Speed = 50km/h						
	R <sup>2</sup>	Beta	t	R <sup>2</sup>	Beta	t
Task Difficulty	0.00	-0.04	-0.43	0.30 <sup>***</sup>	-0.55	-7.47
Subjective Risk	0.01	-0.11	-1.27	0.52 <sup>***</sup>	-0.72	-11.79
Effort	0.01	-0.07	-0.83	0.26 <sup>***</sup>	-0.51	-6.82
Comfort	0.01	-0.07	-0.79	0.46 <sup>***</sup>	-0.68	-10.59
Self Crash Probability	0.01	-0.11	-1.26	0.45 <sup>***</sup>	-0.67	-10.29
Other Crash Probability	0.02	-0.12	-1.42	0.40 <sup>***</sup>	-0.63	-9.32
Typically Follow	0.02	-0.13	-1.53	0.51 <sup>***</sup>	0.71	11.54
Criticality Rating	0.02	-0.12	-1.41	0.37 <sup>***</sup>	-0.61	-8.67
Speed = 100km/h						
	R <sup>2</sup>	Beta	t	R <sup>2</sup>	Beta	t
Task Difficulty	0.01	-0.08	-0.93	0.35 <sup>***</sup>	-0.59	-8.29
Subjective Risk	0.01	-0.08	-0.91	0.51 <sup>***</sup>	-0.71	-11.63
Effort	0.00	0.00	0.05	0.37 <sup>***</sup>	-0.61	-8.82
Comfort	0.02	-0.15	-1.74	0.52 <sup>***</sup>	-0.72	-11.80
Self Crash Probability	0.00	-0.03	-0.35	0.41 <sup>***</sup>	-0.64	-9.52
Other Crash Probability	0.00	-0.06	-0.72	0.46 <sup>***</sup>	-0.68	-10.44
Typically Follow	0.01	-0.12	-1.32	0.51 <sup>***</sup>	0.72	11.72
Criticality Rating	0.01	-0.09	-1.07	0.58 <sup>***</sup>	-0.76	-13.50
Speed = 150km/h						
	R <sup>2</sup>	Beta	t	R <sup>2</sup>	Beta	t
Task Difficulty	0.01	-0.07	-0.82	0.19 <sup>***</sup>	-0.44	-5.51
Subjective Risk	0.05 <sup>*</sup>	-0.22	-2.56	0.37 <sup>***</sup>	-0.60	-8.65
Effort	0.01	-0.11	-1.25	0.25 <sup>***</sup>	-0.50	-6.60
Comfort	0.01	-0.08	-0.86	0.39 <sup>***</sup>	-0.63	-9.13
Self Crash Probability	0.02	-0.12	-1.41	0.33 <sup>***</sup>	-0.58	-8.02
Other Crash Probability	0.02	-0.15	-1.72	0.35 <sup>***</sup>	-0.59	-8.34
Typically Follow	0.00	-0.02	-0.18	0.36 <sup>***</sup>	0.60	8.60
Criticality Rating	0.01	-0.07	-0.83	0.47 <sup>***</sup>	-0.69	-10.71

\* p < 0.05, \*\*\* p < 0.001.

Time headway for self-driving was calculated for the last 30 seconds of the two minute free follow conditions. Mean time headways were  $M_{50km/h} = 3.06$  seconds ( $SD = 0.85$ ) for the 50 km/h condition,  $M_{100km/h} = 2.96$  seconds ( $SD = 1.20$ ) for the 100 km/h condition, and  $M_{150km/h} = 3.97$  seconds ( $SD = 2.88$ ) for the condition in which the lead vehicle was driving at a speed of 150 km/h. Compared to the results of Lewis-Evans et al. (2010) the time headways in the free following conditions of this study were higher.

## 2.4 Discussion

In this study we investigated the relationship between time headway as a variable for distance calculation of adaptive cruise control and a set of subjective variables. Time headway was systematically varied to investigate the type of relation between time headways and subjective driver states. Additionally, time headways were presented for three different velocities to research if the type of relationship between time headway and subjective variables was constant over different velocities. In line with earlier research, we expected a high correlation between the subjective ratings given by participants. To add to the ongoing discussion on driver behavior models, we analyzed the general occurrence of subjective risk in participants. Furthermore we introduced a measurement of criticality as a categorical rating. Generally, we wanted to contribute to the development of vehicle automation, i.e. adaptive cruise control and autonomous driving.

The main objective of this study was to research the interrelation of time headway and risk, task difficulty, effort, and comfort. Regression analyses support the notion of a general threshold of time headway and subjective variables for 50 km/h. This supports the results of Lewis-Evans et al. (2010). The threshold relationship was also found to be consistent over all three researched velocities. Subsequent time headways ranging from 4.0 to 2.5 seconds did not significantly influence the subjective ratings of drivers. For time headways ranging from 2.0 to 0.5 seconds, the regression analysis

revealed a significant influence of subsequent time headways on the subjective variables. These results indicate that the critical time headway lies between 2.0 and 1.5 seconds. Based on these results, it appears that time headway can provide a good indication for preferred distances in vehicle traffic for different velocities.

Our second hypothesis was that all subjective variables that were measured correlate significantly with each other. The results showed that this is the case. We found moderate to high correlations between all ratings given by participants. Although this result does not help to resolve the disagreement over which single subjective variable is crucial to determine a driver's behavior when controlling a vehicle, it supports earlier findings on drivers' internal affective state (Lewis-Evans & Rothengatter, 2009; Lewis-Evans et al., 2010; Fuller, 2005; Fuller, McHugh & Pender, 2008). The moderate to high correlations appear plausible. A high task difficulty in a given driving situation is likely to accompany a high effort, diminishing comfort and an increased subjective and crash risk. Furthermore, it can be assumed that a driver will not typically follow another vehicle with a distance that is demanding a high level of effort and task difficulty, excites a feeling of subjective risk and crash risk, and is uncomfortable.

A further objective of this study was to add to the discussion about the general occurrence of subjective variables in drivers. While results of a simulator study cannot substitute for research in real traffic, our results show that a majority of drivers in our sample did not report subjective risk for a number of time headways when driving in the simulator. This is in line with the zero risk model by Näätänen and Summala (1974). For the largest time headway of 4.0 seconds, participants indicated that they would typically follow with the equivalent distance, but the majority did not report a subjective feeling of risk. Further research needs to be conducted to explore if these results remain the same in real life driving.



The specific type of interrelation between time headways and subjective variables, named threshold effect in this study, hints to the importance of the adjustment of distance parameters in adaptive cruise control (ACC) and autonomous driving. If even a small gradual change in time headway can lead to a substantial change in drivers' subjective appraisal of a driving situation when time headway falls below the threshold, it is crucial for developers of ACC systems and autonomous vehicles to keep time headways over this threshold. It appears that time headways higher than the threshold do not result in a negative subjective experience for drivers. Large time headways were rated high on comfort, allowing car system developers to utilize a distance of the equivalent of up to 2.0 seconds as a comfort buffer. It is important to keep in mind that time headway is just one of several variables that can be computed for vehicle following. If developers of adaptive cruise control systems decide to use time headway as a variable for distance calculation, it appears advisable to keep the threshold effect in mind.

The measurement of criticality proved to be useful to get an impression of drivers' subjective states. Mean criticality for 50 km/h was rated as unpleasant for time headways lower than 2.0 seconds. For higher speeds, criticality was on average rated as unpleasant for time headways lower than 1.5 seconds. Figure 3 also shows that criticality was rated higher for time headways between 0.5 and 2.0 seconds for the 50 km/h conditions than for the two higher velocities of 100 and 150 km/h. In general, criticality ratings of the 100 km/h conditions were rated lower than for conditions of 50 and 150 km/h conditions, except for the smallest time headway of 0.5 seconds. A possible explanation for this effect could be the roadside design of the simulation. While the lane width that was chosen for this study resembles a highway, the roadside in the simulation had only sparsely placed trees and no guard railing. This design might bear a resemblance to a German country road. Country roads in Germany have a general speed limit of 100 km/h;

speeds of 50 km/h might have been rated as more critical by participants because they are perceived to be too slow for a country road, while speeds of 150 km/h are perceived as being “over the speed limit” for country roads. Looking at the larger time headways in this study, large time headways and resulting high distances to leading vehicles are not rated as critical. This supports the results for ratings of comfort discussed earlier.

The free follow time headways were almost twice as high in this study, compared to earlier results by Lewis-Evans et al. (2010). This shows the importance of participants’ instruction for the free follow condition. While Lewis-Evans et al. instructed participants to follow as close as possible while still feeling comfortable, participants in this study were instructed to follow with the same distance they would keep in real life driving. Since this lead to large time headways, it appears advisable to instruct participants to follow as close as possible while still feeling comfortable.

There are some limitations to the results of this study. It is important to keep in mind that there were no motivational factors induced in participants in this study. It is plausible that drivers would follow with small time headways in real life driving once motivational factors emerge, even though they rate them high on risk etc. and indicate that they would not typically follow this close in this study. This might be the reason for the relatively high time headways in the free follow conditions. These large time headways are not close to the threshold time headway. Furthermore, the duration of free follow conditions was fixed and participants were not allowed to pass the lead vehicle. This might have further inhibited participants to advance the lead vehicle, since there was no time benefit in a small distance to the lead vehicle. Another limitation of this study is the presentation of the questions for subjective ratings. The number of questions that participants had to answer after every condition might have led to response patterns. This possibility has to be kept in mind, especially when

assessing the moderate to high correlation between subjective ratings. Although several questions were recoded, parts of the correlation might be explainable through these response patterns. As reported earlier, there might have been interference in the results for criticality due to the roadway design. To counter this interference it seems advisable to design the roadway compatible with expected speeds. The roadway design of the 50 km/h conditions should therefore be modeled after inner city streets, the 100 km/h condition after country roads, and the 150 km/h condition roadway should be designed like a highway.

With the present study we advanced the current body of literature on the relation of time headway, and subjective driver states. In particular we successfully replicated past research indicating a threshold effect for time headway and risk, task difficulty, effort, and comfort. Moreover, we extended this finding to different velocities. This is important for the design of driver assistant systems and automated driving. We hope that our results can help to build comfortable solutions for distance keeping in adaptive cruise control systems and the acceptance of autonomous vehicles.

## 2.5 References

Ayres, T. J., Li, L., Schleuning, D., & Young, D. (2001). Preferred time-headway of highway drivers. In *Intelligent Transportation Systems, 2001. Proceedings. 2001 IEEE* (pp. 826-829). IEEE.

Desjardins, C., & Chaib-draa, B. (2011). Cooperative adaptive cruise control: A reinforcement learning approach. *Intelligent Transportation Systems, IEEE Transactions on*, *12*(4), 1248-1260.

Eick, E.-M. & Debus, G. (2005). Adaptation effects in an automated car-following scenario. In G. Underwood (Ed.), *Traffic & Transport Psychology. Theory and Application* (pp. 243-255). Amsterdam: Elsevier.

Fuller, R. (2005). Towards a general theory of driver behaviour. *Accident Analysis & Prevention*, *37*(3), 461-472.

Fuller, R., McHugh, C., & Pender, S. (2008). Task difficulty and risk in the determination of driver behaviour. *Revue Européenne de Psychologie Appliquée/European Review of Applied Psychology*, *58*(1), 13-21.

Lewis-Evans, B., De Waard, D., & Brookhuis, K. A. (2010). That's close enough—A threshold effect of time headway on the experience of risk, task difficulty, effort, and comfort. *Accident Analysis & Prevention*, *42*(6), 1926-1933.

Lewis-Evans, B., & Rothengatter, T. (2009). Task difficulty, risk, effort and comfort in a simulated driving task—Implications for Risk Allostasis Theory. *Accident Analysis & Prevention*, *41*(5), 1053-1063.

Michon, J. A. (1986). A critical view of driver behavior models: what do we know, what should we do? In: Evans, L. & Schwing, R.C. (Eds.), *Human behavior and traffic safety* (pp. 485-524). Springer US.

Näätänen, R., & Summala, H. (1974). A model for the role of motivational factors in drivers' decision-making. *Accident Analysis & Prevention*, 6(3), 243-261.

Neubert, L., Santen, L., Schadschneider, A., & Schreckenberg, M. (1999). Single-vehicle data of highway traffic: A statistical analysis. *Physical Review E*, 60(6), 6480.

Neukum, A., Lübbecke, T., Krüger, H.-P., Mayser, C., Steinle, J. (2008). ACC-Stop&Go: Fahrverhalten an funktionalen Systemgrenzen. In Maurer, M. & Stiller, C. (Eds.), 5. *Workshop Fahrerassistenzsysteme (FAS)*, 141-150.

Ranney, T. A. (1994). Models of driving behavior: a review of their evolution. *Accident Analysis & Prevention*, 26(6), 733-750.

Skottke, E.-M. (2007). *Automatisierter Kolonnenverkehr und adaptiertes Fahrverhalten [Automated car following and driving behavior adaptation]*. Hamburg, Germany: Verlag Dr. Kovač.

Summala, H. (1988). Risk control is not risk adjustment: The zero-risk theory of driver behaviour and its implications. *Ergonomics*, 31(4), 491-506.

Summala, H. (2005). Traffic psychology theories: towards understanding driving behaviour and safety efforts. In G. Underwood (Ed.), *Traffic & Transport Psychology* (pp. 383–394). Oxford, UK: Elsevier.

Swaroop, D. V. A. H. G., Hedrick, J. K., Chien, C. C., & Ioannou, P. (1994). A Comparison of Spacing and Headway Control Laws for Automatically Controlled Vehicles<sup>1</sup>. *Vehicle System Dynamics*, 23(1), 597-625.

Touran, A., Brackstone, M. A., & McDonald, M. (1999). A collision model for safety evaluation of autonomous intelligent cruise control. *Accident Analysis & Prevention*, 31(5), 567-578.

Vaa, T. (2007). Modelling driver behaviour on basis of emotions and feelings: intelligent transport systems and behavioural adaptations. In *Modelling driver behaviour in automotive environments* (pp. 208-232). Springer London.

Wilde, G. J. S. (1982). The theory of risk homeostasis: implications for safety and health. *Risk analysis*, 2(4), 209-225.

Winsum, W. V. (1999). The human element in car following models. *Transportation research part F: traffic psychology and behaviour*, 2(4), 207-211.

### 3 The exact determination of subjective risk and comfort thresholds in car following

#### **Abstract**

In this study the location of vehicle to vehicle distance thresholds for self-reported subjective risk and comfort was researched. Participants were presented with ascending and descending time headway sequences in a driving simulator. This so called method of limits of ascending and descending stimuli (Gouy, Diels, Reed, Stevens, & Burnett, 2012) was refined to efficiently determine individual thresholds for stable time headways with a granularity of 0.1 seconds. Time headway thresholds were researched for 50, 100, and 150 km/h in a city, rural, and highway setting. Furthermore, thresholds for self-driving (level 0 automation: NHTSA, 2013) were compared with thresholds for the experience of subjective risk and comfort in assisted driving, similar to adaptive cruise control (level 1 automation). Results show that preferred individual time headways vary between subjects. Within subjects however, time headway thresholds do not significantly differ for different speeds. Furthermore we found that there was no significant difference between time headways of self-driving and distance-assisted driving. The relevance of these findings for the development of adaptive cruise control systems, autonomous driving and driver behavior modelling is discussed.

### 3.1 Introduction

Recent studies suggest that the relation between time headway in car following and the subjective experience of a driver is subject to a threshold effect (Lewis-Evans, De Waard, & Brookhuis, 2010; Siebert, Oehl, & Pfister, 2014). This means that drivers do not experience subjective risk for time headways higher than a specific threshold, while the subjective risk increases significantly for time headways lower than the specific subjective threshold. Studies have also found a consistency of time headway thresholds over different speeds (Siebert et al., 2014). These findings of a threshold effect for time headway and its consistency over different speeds are relevant for the advancement of theoretical issues in traffic psychology, i.e., driver behavior modelling, as well as applied issues such as adaptive cruise control and autonomous driving.

In driver behavior modelling there is a theoretical dispute that can be best observed between so called “zero risk” models (Näätänen & Summala, 1974; Summala, 1988) and “target risk” / “target task difficulty” models (Fuller, 2005; Taylor, 1964). In zero risk models it is generally assumed that drivers choose their path and speed in a way that minimizes their experience of risk. In these models drivers will change the path or speed of their vehicle as soon as any feeling of risk arises no matter how small. Following the “target risk” or “target task difficulty” models however, drivers do not choose their path and speed to completely avoid a feeling of risk or task difficulty. In these “target” models, drivers aim for a target level of risk or task difficulty that is higher than zero. If the driving situation leads to a subjective risk level or a task difficulty that is below the target level, a driver will change the speed and/or path of his vehicle to increase his subjective feeling of risk or perceived task difficulty until the target risk / task difficulty level is reached and vice versa. For the “target” models to be applicable to driving there has to be a level of variance in drivers’ subjective



experience of risk or task difficulty in normal driving situations. Target models do not imply that drivers actively drive in a reckless way where they expect an accident, i.e. that the accident risk is higher than zero, but that their experienced level of general risk / task difficulty is higher than zero. Following the “zero risk” models there should be very little variance in the subjective feeling of risk, because following this theory, drivers will avoid risky situations thereby maintaining a constantly low level of subjective risk.

The findings of a threshold effect for the influence of time headway on the subjective experience of risk (Lewis-Evans et al., 2010; Siebert et al., 2014) give credence to zero risk models. If a driver does not experience subjective risk up until an individual threshold, there is no variance in subjective risk experience before the threshold. Therefore, a driver cannot use subjective risk to select a time headway respectively distance to another vehicle that he likes to keep. The threshold effect further presumes a significant increase in subjective risk for time headways lower than the individual threshold. In theory, the target level of risk could be located in this area. This, however, is unlikely for two reasons; the sharp increase in the subjective risk experience would either lead to a very large target level of risk, or would require very frequent and precise control of time headway. Furthermore it was shown by Siebert et al. (2014) that drivers experience time headways lower than the threshold as unpleasant, making it unlikely that drivers would choose a time headway that is lower than the subjective threshold.

Consequentially the existence of a threshold effect and the resulting assumption of the validity of the zero risk models can lead to the dichotomization of the subjective risk experience of drivers. A researcher therefore does not need to ask “how much risk is experienced?” but is allowed to ask “is risk experienced or not?”.

Apart from a general threshold effect, there is evidence for a consistency of individual time headways over different speed conditions (Ayres, Li, Schleuning, & Young, 2001; Siebert et al., 2014; Taieb-Maimon & Shinar, 2001; Winsum & Heino, 1996). This study aims to replicate these findings of constant individual time headways over different driving speeds for a broader speed range with an efficient and precise method that can alleviate some confounding interference of existing study designs.

Besides theoretical issues, the existence of a threshold effect of time headway on the subjective experience of a driver is meaningful to applied issues as well. As discussed earlier, drivers will change their path or speed once they experience subjective risk when they drive themselves. With the adoption of advanced driver assistance systems, such as adaptive cruise control (level 1 automation), and the emergence of level 3 automation in vehicles (NHTSA, 2013) the task of changing the vehicle's speed and its resulting distance to other road users is carried out by the vehicle itself. In level 1 automation, drivers might decide not to use a system that does not adhere to subjective time headway thresholds. In level 3 automation systems the problem of not-individually adjusted time headway can be much more dangerous. Level 3 automation allows the driver to be distracted from the driving task and just requires occasional control. This might lead to situations in which a driver refocuses on the driving task after being distracted, perceiving the car to car distance as risky, and taking over control of the car in a hasty and dangerous way. Furthermore, perceiving a level 3 automation system as risky, can lead to a decline in trust in the system and general disuse of the system (Parasuraman & Riley, 1997). Taking into account the subjective experience of the driver will therefore be a prerequisite for the adoption and frequent usage of automation systems of different levels. This will be especially important in the initial usage phase, where users have not adjusted the system for their subjective preference.

Accurately identifying the location of the time headway threshold for an experience of subjective risk could therefore help to design the automation to stay above said threshold. This higher than personal threshold headway can help to build trust and prevent a feeling of subjective risk in the driver, thereby increasing the use of such systems (Muir, 1994; Pereira, Beggiano, & Petzoldt, 2015), preventing dangerous takeover situations by the driver, and lowering the number of traffic accidents.

In the location of the time headway threshold rests another important research question for the application of advanced driver assistant systems. What is the relation between time headways of drivers when they have full control of the car (level 0 automation), compared to time headway thresholds in automated driving (level 1 automation and higher)? An earlier study by Lewis-Evans et al. (2010) suggests that time headways of self-driving are congruent with time headway thresholds of subjective risk experience in driving with adaptive cruise control (level 1 automation). This study aims to replicate these findings of a high correlation of time headways in self-driving and driving with an adaptive cruise control.

Apart from subjective risk, which helps to locate the absolute boundaries of what is an acceptable distance in car following, it is also important to locate the range of distances that drivers feel comfortable to keep (Marsden, McDonald, & Brackstone, 2001; Stanton & Young, 2005), as comfortable time headways might differ from non-risky thresholds. In earlier studies, subjective risk and comfort experience were investigated together in a within subject design and risk and comfort ratings showed a significant and high correlation (Lewis-Evans et al., 2010; Siebert et al., 2014). While Lewis-Evans et al. (2010) argue that the correlation of different subjective variables might be a sign for an underlying construct that is rated, they also support an effort to try and separate subjective variables. We therefore used a between-subject design for the two subjective variables. This can also help

to counter a possible response bias, stemming from the presentation of the two subjective variables together.

For theoretical as well as applied issues, it is of further interest to identify the threshold location as precisely as possible. The studies on time headway thresholds by Siebert et al. (2014) and Lewis-Evans et al. (2010) were designed to research a broad range of time headways (0.5 to 4.0 seconds), but had a very low spatial resolution of only 0.5 seconds time headway. This study utilizes a finer resolution of the time headway variable by using an enhanced type of the psychophysics method of limits. The basic principle of this method is to present a participant with ascending and descending sequences of stimuli to locate a stimuli specific threshold. The details of this method are explained in the methods section. The precise knowledge of individual time headway thresholds in level 1 automation due to the use of our method, allows us to compare this threshold to self-driving thresholds, which can be measured as precise.

### 3.2 Aims of this Study

In the simulator study by Lewis-Evans et al. (2010) participants were presented with eight different time headways ranging from 0.5 to 4.0 seconds divided in 0.5 second time headway steps at a speed of 50 km/h. The different time headways were each presented for approximately 180 seconds in a random order. Participants had control over the steering wheel, while the distance to another car was controlled by the simulator, resulting in the different time headways. For every time headway, participants rated their subjective risk, task difficulty, effort, and comfort on a 7-point Likert scale. The study by Siebert et al. (2014) had a similar design with two added speed conditions of 100 and 150 km/h. The duration of each time headway condition was shortened to 60 seconds. The division of the time headway space in 0.5 second increments in both of the studies might have suppressed some of the variance in subjective ratings, since even a seemingly small

time headway change of 0.5 seconds is equivalent to a change in the vehicle to vehicle distance of 6.9 meters (50 km/h), 13.9 meters (100 km/h), or 20.8 meters (150 km/h) respectively.

While our current study investigates the same time headway range (0.5 to 4.0 seconds) as the preceding studies, the variation of the time headway variable was modified. This resulted in a higher resolving power of 0.1 time headway seconds compared to 0.5 time headway seconds of earlier studies. The spatial resolution of this refined design is equivalent to a finely graduated vehicle to vehicle distance of 1.39 meters for 50 km/h, 2.78 meters for 100 km/h, and 4.17 meters for 150 km/h. Furthermore, to be able to locate the individual time headway threshold of a participant more efficiently, the so called “method of limits” was used (Brecher, 1934; Fechner, 1860; Fletcher & Wegel, 1922; Gouy, Diels, Reed, Stevens, & Burnett, 2012, 2013). This was done since the randomized presentation of time headways in the range of 0.5 to 4.0 seconds with a resolution of 0.1 seconds would have resulted in 36 different time headway situations for every speed condition. The method of limits provided us with a tool to more efficiently pinpoint a participant’s individual time headway threshold with a fine resolution of 0.1 seconds. This time headway threshold position was used as the dependent variable in our study.

The method of limits belongs to the methods developed in the field of psychophysics founded by Gustav Theodor Fechner (1860). Psychophysics link physical quantities, e.g., intensity of light or weight, to the subjective experiences produced by these quantities in humans, e.g., perceived brightness or heaviness. The method of limits was designed to locate absolute sensory thresholds. It was used by Fletcher and Wegel (1922) and further developed by Gerhard Brecher (1934) to locate sensory thresholds of audio signals. In his study Brecher played a sequence of sounds of different frequencies to participants, starting with either a very low or a very high

frequency. When starting with a low frequency, the frequency increased until participants reported that they heard something, i.e., had a hearing sensation. When starting with a high frequency, the frequency was decreased until participants reported that they did not hear a sound anymore, i.e., that there was no hearing sensation anymore. Each increasing or decreasing frequency sequence was repeated five times and the points of transition from hearing to non-hearing (sensation to no sensation) or non-hearing to hearing (no sensation to sensation) were noted. So called “transition points” were then calculated by taking the average of the two physical stimuli that represented sensation and no sensation in a sequence, and vice versa. The transition point for a decreasing sequence therefore lies in the middle of two frequency points that were presented, i.e., the frequency where a participant still heard a tone and the frequency where a participant did not hear a tone anymore. The reasoning behind this is that since a researcher cannot exactly pinpoint where the shift from sensation to no sensation occurred, the mean between the two stimuli is used. While this recalculation of transition points does not influence the resulting average that is the threshold, it is important for the understanding of sole transition points (Gescheider, 1997). Brecher then calculated the mean of the frequency of the 10 transition points as a hearing threshold for the frequency of audio signals.

Analog to Brecher’s sequences of increasing and decreasing frequencies, we programmed sets of ascending and descending time headway sequences in the driving simulator called “fixed follow” conditions. Using a time headway range of 0.5 to 4.0 seconds, an ascending sequence started with a fixed time headway distance of 0.5 seconds to another car. After 20 seconds the car driving ahead accelerated for one second leading to an increase in time headway of 0.5 seconds and so resulting in a new time headway of 1.0 seconds. Time headway increased in 0.5 second steps up to the maximum time headway of 4.0 seconds. In the descending sequence, participants were

presented with a time headway of 4.0 seconds that decreased in 0.5 second steps to the minimum time headway of 0.5 second (top of Figure 1). The time headways were fixed, since participants could not use the gas or brake pedal to influence their speed and therefore all presented time headways could not be changed. The time headway change of 0.5 seconds, either in ascending or descending order, was labelled a “large scale sequence”, because, as explained earlier, it represents a large change in the vehicle to vehicle distance. The order of ascending and descending large scale sequences are presented at the top of Figure 4.

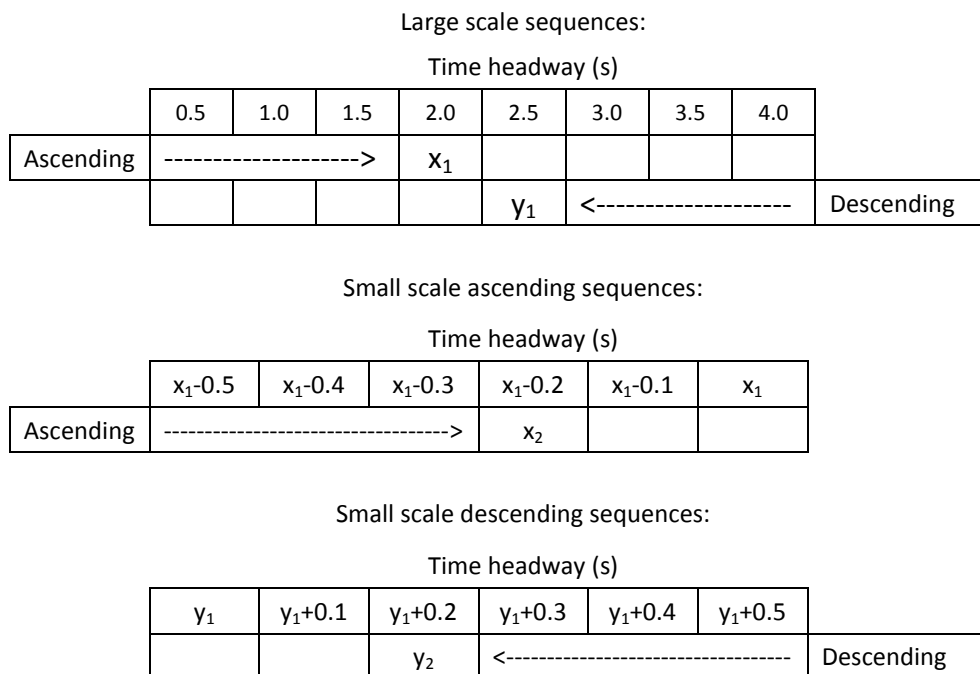


Figure 4. Experimental design of large and small scale time headway sequences. A participant’s report of a transition is labelled as  $x_i$  for ascending sequences and  $y_i$  for descending sequences.

The experimental design of ascending and descending time headway sequences is similar to two studies by Gouy et al. (2012, 2013), who varied time headway between 0.1 and 2.5 second, using ascending and descending 0.1 second steps. Each time headway step was presented for 5 seconds. The speed of the lead vehicle and the participants’ car was fixed at

approximately 110 km/h and not varied. Participants did not have control over the steering wheel during ascending and descending time headways.

To research if comfort thresholds differ from risk thresholds, participants were randomly assigned to either a “comfort” or a “risk” group. Participants in the comfort group were instructed to monitor their subjective comfort in the driving situation with a special focus to the vehicle to vehicle distance. Participants were further instructed to immediately report a change in their comfort experience, i.e., when their experience of the vehicle to vehicle distance changed from comfort to discomfort or from discomfort to comfort in the fixed follow conditions, by addressing the experimenter. Participants were instructed to use the word “now” (“Jetzt” in German) to indicate this point, although this was not enforced and participants sometimes used different words to indicate that a threshold was reached.

Participants assigned to the risk group were instructed to monitor their subjective experience of risk, also with a focus on the vehicle to vehicle distance. As in the comfort group, participants in the risk group were instructed to report changes in their subjective experience of risk, i.e., when their experience of the vehicle to vehicle distance changed from risky to not risky or the other way around in the fixed follow conditions, by saying “now” (“Jetzt”).

Since participants only reported a change in their subjective risk or comfort experience, the risk and comfort reports are binary, i.e. participants in the risk group are either reporting risk or no risk, while participants in the comfort group report comfort or a lack of comfort. Assignment to either comfort or risk group was used as a between-subject independent variable in this study.

The report of a change of a participant’s subjective risk or comfort allows us to assess the subjective experience of said participant. It is important to distinguish this self-report of a participant’s subjective



experience from the direct observance of risk or comfort, or any form of specific crash risk. Strictly speaking, we do not measure risk or comfort, but we measure *reported risk* and *reported comfort*.

To be able to locate time headway thresholds on a scale of 0.1 time headway seconds, each “large scale sequence” was followed by a “small scale sequence”. The small scale sequence presented time headways in 0.1 second increments starting with the time headway of the large sequence that was presented before a participant reported a change in his subjective experience (see Figure 4). As in the large scale sequences, time headways were fixed and could not be influenced.

Analogue to the study by Lewis-Evans et al. (2010), a free follow condition was programmed to allow participants to set their preferred time headway by themselves by adjusting their speed. Adhering to the design of the fixed follow conditions, there were ascending and descending free follow conditions. In ascending free follow conditions, the scenario started with a vehicle to vehicle distance of 0.5 seconds time headway. Participants then increased the distance by decelerating their vehicle until they felt comfortable respectively did not experience risk anymore. In the descending free follow conditions the scenario started with a time headway of 4.0 seconds. Participants then decreased the distance until they did not feel comfortable anymore respectively experienced risk. The average of the two time headways of ascending and descending free follow conditions was calculated as the free follow time headway threshold. The type of control over the vehicle, labelled free follow or fixed follow condition, was used as a within-subject independent variable in this study.

To investigate the influence of speed on time headway thresholds, fixed and free follow conditions were presented at 50, 100, and 150 km/h.

In this study the influence of the independent variables speed, control, and type of subjective experience on time headway thresholds of drivers

was researched. Speed was varied three-fold within subjects (50, 100, 150 km/h), control was varied two-fold within subjects (free follow, fixed follow), and subjective experience was varied two-fold between subjects (risk group, comfort group).

### 3.2.1 Hypotheses

Based on the results from Lewis-Evans et al. (2010) and Siebert et al. (2014), we expected the mean time headway threshold for the subjective experience of risk and comfort to be located between 1.5 and 2.0 seconds.

Adding to this, we expected that the thresholds would be constant over different speed conditions, i.e., that different speeds do not significantly influence the threshold locations as in the study by Siebert et al. (2014).

We further expected a high positive correlation between individual time headway thresholds of 50 and 100km/h, 100 and 150km/h, and 50 and 150km/h, indicating a stability of individual time headway thresholds over different speeds.

Furthermore, we hypothesized that the threshold for the experience of comfort would be higher than the threshold for the experience of risk, i.e., that the comfort group would report a loss of a subjective feeling of comfort at a higher time headway than the risk group would report a subjective experience of risk.

We additionally hypothesized that individual time headway thresholds of fixed and free follow conditions would correlate positively significantly, i.e., if a participant's individual threshold in fixed follow driving is relatively small, it will also be relatively small in free follow driving.

### 3.3 Method

#### 3.3.1 Participants

38 participants were recruited at the Leuphana University Lüneburg as a convenience sample. All recruited participants completed the experiment. 20 participants were female and 18 participants were male. As the only prerequisite, participants had to be in possession of a valid driver's license. Participants had a mean age of  $M = 24.11$  years ( $SD = 4.6$ ) and held their driver's license on average for  $M = 6.59$  ( $SD = 4.41$ ) years. Participants estimated that they drove  $M = 4142.24$  ( $SD = 6966.08$ ) kilometers per year on average. 11 participants owned a car, while 27 did not own a car. Students were awarded with test-subject hours for the duration of the experiment, which need to be collected during students' years of study. 20 participants were assigned to the comfort group (10 female, 10 male), 18 participants were assigned to the risk group (10 female, 8 male). After the experiment was conducted, participants were told about the purpose of the experiment and could leave their e-mail address to get informed about the results of the study.

#### 3.3.2 Materials

The experiment was conducted in the fixed base driving simulator at the Institute of Experimental Industrial Psychology at the Leuphana University Lüneburg. The driving simulator cabin was taken from a Volkswagen Golf 4 GTI, a medium class vehicle. The steering wheel (taken from a Golf 4 non-GTI model) was connected to the base of a Logitech G25 Racing wheel. The pedals used in the study were generic gaming pedals from Logitech. The simulator cabin was taken from a car with automatic transmission, therefore the simulated car had an automatic gearbox. To simulate the driving environment, the SCANeR Studio driving simulation software version 1.3 from Oktal was used. The driving environment was

projected on to three screens in front of the driving cabin, each screen had a size of 1.4 x 1.4 meters. The outer screens were positioned in an angle of 120° to the center screen. The driver seat was positioned 2 meters from the center screen, resulting in a horizontal field of view of approximately 110° and a vertical field of view of approximately 30°. The physical eye height of the participants was approximately 1.25m (with a small influence of the height adjustment of the driver seat). The simulated eye height was fixed at 1.25m. The simulated car model was a Citroën C4. The simulator is pictured in Figure 1. To shut out ambient sounds and light, curtains surrounded the cabin and the projection screens. The test supervisor sat behind the cabin in the corner of the simulator room, controlling the simulation from outside of the participant's field of view. Simulation sounds (engine and wind) were produced from two speakers in front of the cabin. Simulation data was saved to a plain text file with the help of a python script with a frequency of 20 Hz. The speedometer of the cabin was turned off for the whole experiment. This was done to not distract participants, since they were asked to focus on the distance to the leading vehicle for the whole sequence of 20seconds.

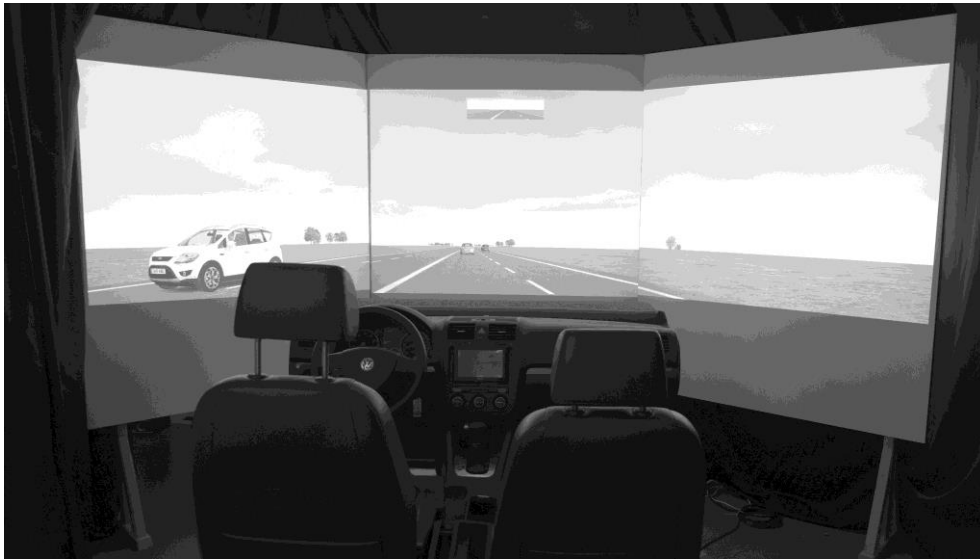


Figure 5. Fixed base driving simulator and simulated driving environment of the 100km/h condition.

The simulated driving environments were modelled after a generic German city road, a rural road, and a highway. The city road environment consisted of two lanes with one lane reserved for oncoming traffic. The two lanes were divided by a dashed line. Each lane of the city road was 3m wide, and the road was modelled after the “Regelquerschnitt 9,5” or RQ9,5, which is a standard of road construction in Germany. The roadside consisted of an adjacent sidewalk and generic inner city buildings. The rural road had four lanes, two in each direction with a solid line separating traffic of different directions and a dashed line separating lanes for same direction traffic. Each lane of the rural road was 3.25m wide, and modelled after the German road construction standard RQ20. The rural road environment had randomly placed trees and rural buildings on the side of the road. The highway environment was modelled after the German road construction standard RQ33, and consisted of six lanes with three lanes in each direction. There was a central barrier dividing traffic of different directions, and dashed lane markings dividing traffic lanes of the same direction. Each lane was 3.5m wide. There were randomly placed trees next to the highway. In all driving

environments there was only minimal curvature and no slope. Objects in all three traffic environments, i.e., buildings and trees, were placed with a minimal distance of 20 meters to the traffic lanes. There were gentle curves in every traffic environment and there was no cross traffic or pedestrians. All simulated vehicles adhered to traffic rules, did not overtake and drove 1-5% slower than the participants' car and the leading vehicle. Distances between simulated vehicles, other than the participant's and the lead vehicle, were programmed as a minimum of two seconds, to prevent a carryover effect from observed time headways in traffic to the time headway of participants (Gouy, Wiedemann, Stevens, Brunett, & Reed, 2014).

Ascending and descending fixed follow large scale and small scale scenarios as well as ascending and descending free follow scenarios for all three different speeds were preprogrammed. Every time headway step, small scale or large scale lasted 20 seconds, while each change in time headway lasted one second. The order of the scenarios was randomized for every participant with the help of the built in script of the SCANeR software as well as external python scripting.

The choice of a driving simulator as a research tool leads to the question of the generalizability of the data acquired in this study. It has to be stated that every driving simulator system is different, using a unique combination of simulation software, vehicle hardware, and projection size. With this caveat in mind, the validity of a driving simulator is broadly characterized by two types of validity: absolute / physical validity, which describes the accuracy with which the physical properties of real life driving are presented in the simulation; and relative / behavioral validity, which is given when different experimental conditions lead to the same behavioral changes of a driver when comparing real life and simulated driving (Godley, Triggs, & Fildes, 2002; Yan, Abdel-Aty, Radwan, Wang, & Chilakapati, 2008).

While we did not assess the absolute validity of our simulation, we used a projection with a large field of view and chose a natural eye-height of the participant. A large field of view allows for good speed perception, while a natural simulated and physical eye-height can prevent misjudgment of distances in simulators (Kemeny, & Panerai, 2003). Results of a study by Purucker, Ruger, Schneider, Neukum, and Farber (2014) suggest that longitudinal distances between vehicles are perceived as more critical in simulated than in real-life driving. This effect could help to explain discrepancies between the relatively large time headways found in simulator studies (Lewis-Evans et al., 2010; Siebert et al., 2014) and relatively small time headways found in car following in real-life driving (Brackstone, Sultan, & McDonald, 2002, Brackstone, Waterson, & McDonald, 2009). Therefore, results from our driving simulator may not have absolute validity, i.e. time headway thresholds from this study might not be directly translatable to time headway thresholds in real life driving.

For relative validity of results on vehicle to vehicle distance in simulators, not many results can be found. Yan et al. (2008) found that results on following distance on approach to intersections show the same effects in real life and simulated driving. Risto and Martens (2014) found differing time headways dependent on instructions and reproduced this effect in a driving simulator. This indicates relative validity of driving simulators for time headway perception. Results from studies on relative validity of other driving variables, such as speed and lateral control of the vehicle indicate a relative validity of driving simulators (Bella, 2008; Carsten, & Jamson, 2011).

### 3.3.3 Procedure

After filling out a demographic questionnaire and receiving their group specific instruction, participants were presented with a training session in the driving simulator that consisted of two parts. In the first part of training, participants familiarized themselves with the control of the simulator by driving on an inner city, a rural, and a highway road. The roads were similar to the roads used later in the experiment described in the “materials” section. The second part of the training session consisted of a descending and an ascending time headway sequence presented at the speed of 100 km/h. Participants were instructed to report a change in their experience of comfort respectively risk with regard to the vehicle to vehicle distance. There was no other traffic apart from the participants’ and the leading vehicle in the training sessions. Since the wording of the instruction for reporting a change in subjective experience can have an influence on participants’ reports, it is quoted in full in German and then translated into English. The text in square brackets contains instructions for the researcher.

“Vor dir fährt ein anderes Auto und der Abstand zu diesem Auto wird sich schrittweise verändern. Der Abstand ist zu Beginn entweder sehr klein und wird dann größer, oder er ist sehr groß und wird dann kleiner. Beurteile nur den Abstand und nicht das Abbremsen oder Beschleunigen des Fahrzeugs. Hast du hierzu fragen? [Falls Fragen, noch mal erklären] In dieser Situation wird der Abstand sehr groß sein. Sag mit bitte Bescheid, sobald du den Abstand als risikoreich empfindest. [Warten auf Rückmeldung von Proband, aufsteigende Bedingung laden wenn keine Fragen] In dieser Situation wird der Abstand zu Beginn sehr klein sein. Sag mir bitte Bescheid sobald du den Abstand nicht mehr als risikoreich empfindest.“



In English:

“There is a car in front of you, and the distance to this car will change in steps. In the beginning the distance is either very small and gets bigger, or is very big and gets smaller. Please only judge the distance and not the deceleration or acceleration of the vehicle. Do you have any questions? [If there are questions, explain again] In this situation the distance will be very big. Please tell me when you perceive the distance as risky. [Wait for report from participant, load ascending condition if there are no questions] In this situation the distance will be very small in the beginning. Please tell me when you perceive the distance as not risky anymore.”

This initial instruction for the risk group is from the training session. For the comfort group two sentences were changed, the sentence “Please tell me when you perceive the distance as risky.” was changed to “Please tell me when you perceive the distance as not comfortable anymore”, the sentence “Please tell me when you perceive the distance as not risky anymore” was changed to “Please tell me when you perceive the distance as comfortable”.

The same instruction was repeated for the small scale sequences in the training. The instruction was repeated again before the main part of the experiment, where a sentence about other cars on adjacent lanes was added, informing participants that other traffic would stay on their respective lanes. Participants were not informed how to interpret “risk” or “comfort”, i.e. risk and comfort were not defined for the participants.

When participants indicated that they felt capable driving the simulator and that they understood the task of reporting a change in their subjective risk respectively comfort experience, the main part of the experiment was started.

In the main part of the experiment, participants were first presented with the fixed follow conditions, i.e., with the ascending and descending time headway sequences of all three speeds in a randomized order. The first sequence, ascending or descending, was always a large scale sequence with a change of time headway in 0.5 second increments. This large scale sequence was then always followed by a fine graduated small scale sequence of the same speed and direction (ascending or descending). The small scale sequence started at the time headway step of the large scale sequence that was presented to the participant before he or she reported a transition (Figure 4). The procedure in the small scale sequences was the same as in the large scale sequences. When participants reported a change in their experience of risk respectively comfort, the sequence was stopped and the experimenter wrote down the condition time at which a participant reported a transition in his or her subjective experience. This was done to be able to later extract the time headway distance at the transition point from the simulator data.

After the presentation of the 12 fixed follow sequences, participants were presented with the 6 free follow sequences. As explained earlier, free follow conditions were also presented as ascending and descending conditions, i.e., conditions started with a large time headway distance of 4.0 seconds or a small time headway distance of 0.5 seconds to another vehicle. In contrast to the fixed follow conditions, participants had full control of the car in the free follow conditions. In descending free follow sequences, starting with a time headway of 4.0 seconds, participants were instructed to decrease the distance to the leading car until they experienced risk (risk group) or did not experience comfort anymore (comfort group). In ascending free follow sequences, starting with a time headway of 0.5 seconds, participants were instructed to increase the distance between their vehicle and the leading vehicle until they did not experience risk anymore (risk group) or experienced comfort (comfort group). Ascending and

descending sequences were presented for the same three speeds as in the fixed follow conditions (50, 100, 150 km/h). As in the fixed follow conditions, participants were instructed to immediately indicate when they had reached a distance where their subjective experience of the vehicle to vehicle distance changed. Each sequence lasted as long it took for the participant to reach his or her individual transition point upon which he or she informed the experimenter. The experimenter then wrote down the simulation time and stopped the scenario.

After the last free follow condition participants were informed about the background of the experiment and were given their test-subject hours.

### 3.4 Results

To calculate the transition points of the fixed and free follow condition, the simulation data along with noted scenario times was used. The time headway values of the transition points were located by matching the condition time at which a participant reported a transition with the simulation data. Transition points as well as demographic data were then transferred to an SPSS 22 file. Since we cannot know where exactly a transition from, e.g., no risk to risk between the time headways of, e.g., 2.0 and 1.5 seconds in a descending large scale sequence occurred, researchers have used the mean between the two stimulus steps of a sequence as an estimated transition point, 1.75 seconds in this example (Gescheider, 1997). We therefore recalculated the transition points of the fixed follow conditions in SPSS to reflect the time headway at which a transition occurred. For large scale descending sequences, 0.25 time headway seconds were subtracted from transition points, while in large scale ascending sequences 0.25 seconds were added to the transition point. For the small scale descending

sequences 0.05 seconds were subtracted, and 0.05 seconds were added for small scale ascending sequences.

Estimated transition points of the ascending and descending fixed follow sequences of the small scale are presented in Figure 6. Mean transition points of descending sequences were generally higher than the transition points of the ascending sequences.

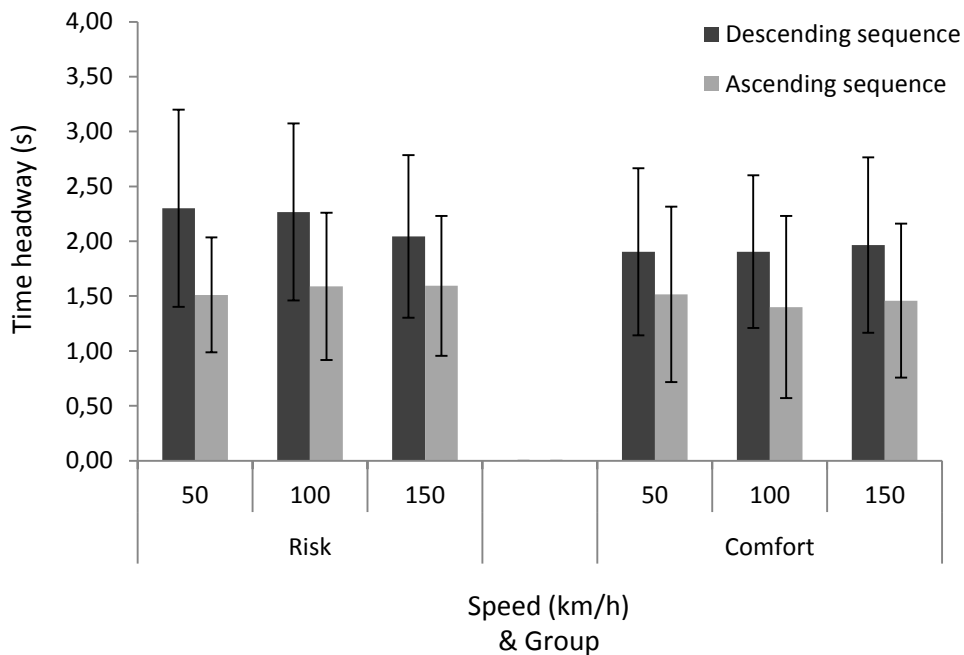


Figure 6. Mean estimated small scale transition points and standard deviations of the descending and ascending sequences.

After the recalculation of the transition points, threshold values were calculated. The threshold values were computed as the average of the estimated transition points of an ascending and a descending sequence of the same speed and the same scale.

Mean small scale threshold values for different speeds of the risk and comfort groups are presented in Figure 7. The time headway thresholds that were calculated with the large scale sequences were very similar to the

thresholds calculated using the small scale and are therefore not presented here.

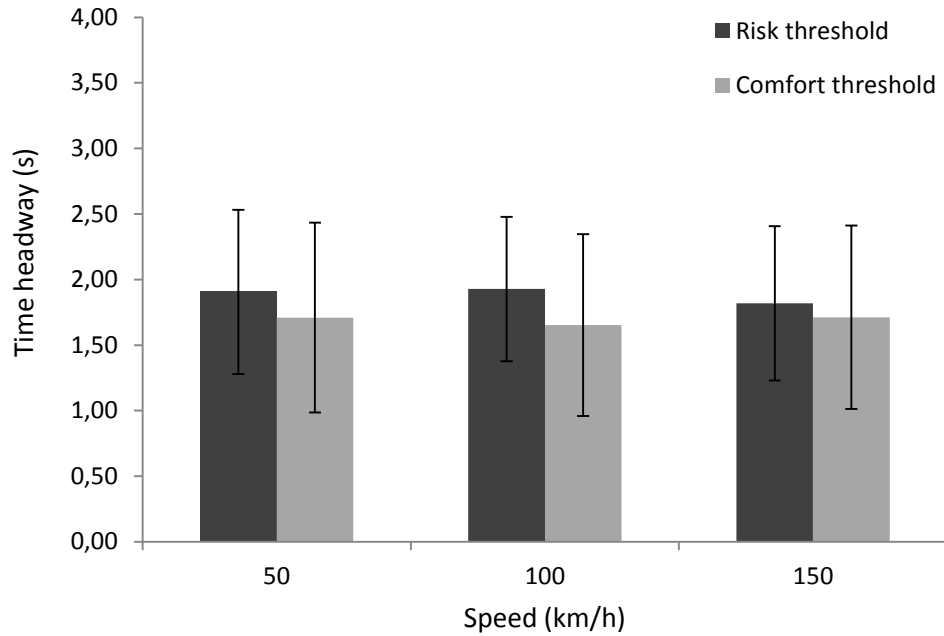


Figure 7. Mean time headway thresholds and standard deviations in the fixed follow condition of the risk and comfort group for different speed conditions calculated with the small scale sequences.

Threshold means are all located between 1.5 and 2.0 seconds (see Table 2 and Table 3). Descriptively it appears that there is very little difference between time headway thresholds of the different speed conditions for the small scale sequences.

Table 2. Mean time headway thresholds (in seconds) and Pearson correlations of the risk group (n = 18) for three different speeds and fixed and free follow conditions.

	<i>M</i>	<i>SD</i>	1	2	3	4	5	6
1 Fixed follow risk threshold 50km/h	1.91	0.63						
2 Fixed follow risk threshold 100km/h	1.93	0.55	.85**					
3 Fixed follow risk threshold 150km/h	1.82	0.59	.81**	.90**				
4 Free follow risk threshold 50km/h	1.99	0.67	.76**	.58*	.68**			
5 Free follow risk threshold 100km/h	1.85	0.72	.78**	.68**	.74**	.78**		
6 Free follow risk threshold 150km/h	2.00	0.70	.78**	.68**	.79**	.73**	.92**	

\* $p < .05$ , \*\* $p < .01$

Table 3. Mean time headway thresholds (in seconds) and Pearson correlations of the comfort group (n = 20) for three different speeds and fixed and free follow conditions.

	<i>M</i>	<i>SD</i>	1	2	3	4	5	6
1 Fixed follow comfort threshold 50km/h	1.71	0.73						
2 Fixed follow comfort threshold 100km/h	1.65	0.69	.82**					
3 Fixed follow comfort threshold 150km/h	1.71	0.70	.81**	.79**				
4 Free follow comfort threshold 50km/h	1.88	0.93	.88**	.91**	.79**			
5 Free follow comfort threshold 100km/h	1.98	1.24	.78**	.87**	.75**	.94**		
6 Free follow comfort threshold 150km/h	1.80	0.68	.85**	.78**	.87**	.83**	.82**	

\*\* $p < .01$

The equivalent mean threshold values of the risk group expressed in meters (m) are 26.47 m ( $SD = 8.44$ ) in the 50 km/h condition, 53.55 m ( $SD = 14.87$ ) in the 100 km/h condition, and 75.81 m ( $SD = 23.81$ ) in the 150 km/h condition. In the comfort group the mean threshold vehicle to vehicle distance was 23.75 m ( $SD = 9.81$ ) in the 50 km/h condition, 45.90 m ( $SD = 18.76$ ) in the 100 km/h condition, and 71.35 m ( $SD = 28.38$ ) in the 150 km/h condition. These meter-distance thresholds are presented in Figure 8.

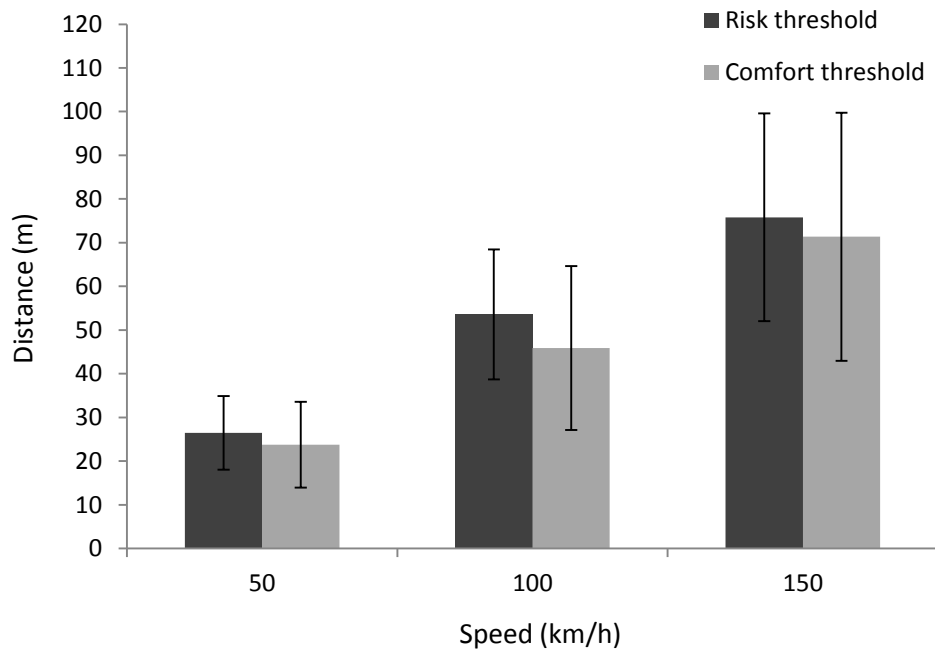


Figure 8. Mean distance thresholds in meters and standard deviations in the fixed follow condition of the risk and comfort group for different speed conditions calculated with the small scale sequences.

A Pearson correlation showed that individual time headway thresholds of the small scale sequences in the fixed follow condition correlated significantly with each other over the different speed conditions (see Table 2 and Table 3). Individual time headways for the different speeds are plotted in Figure 9 for the risk and comfort group combined.

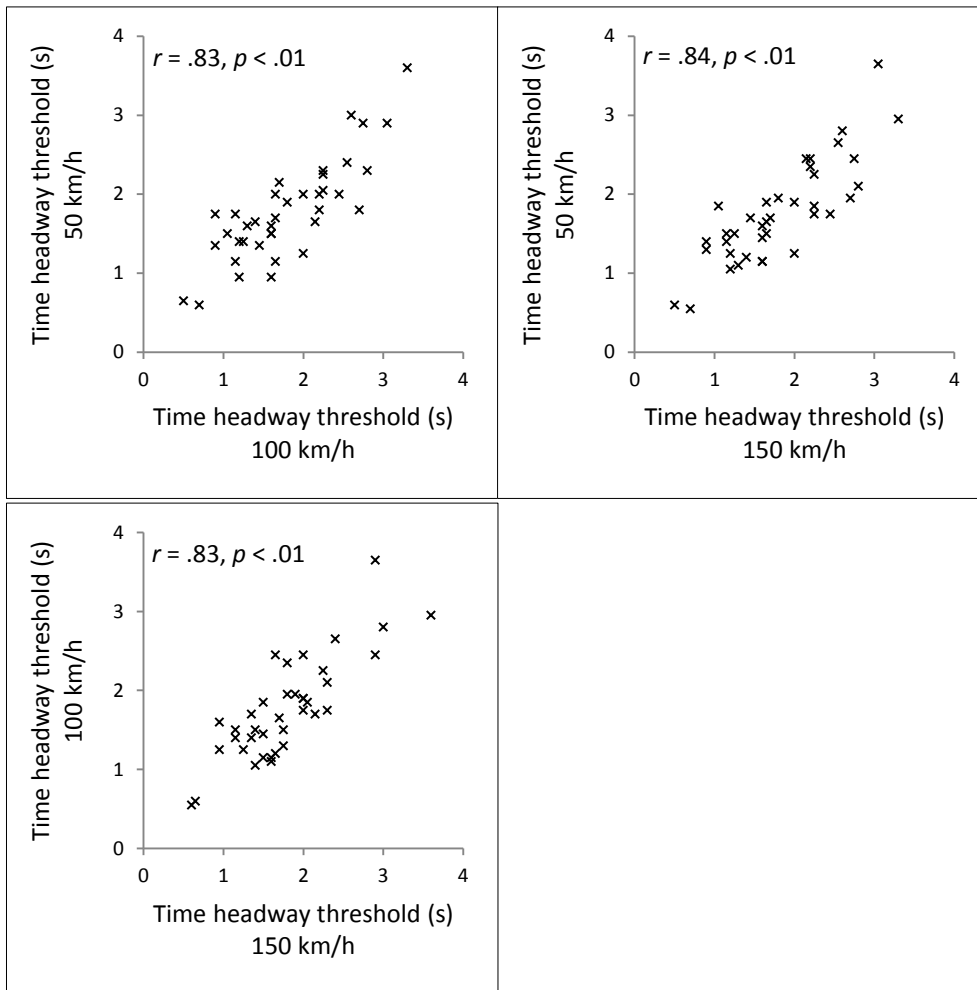


Figure 9. Individual time headway thresholds of the fixed follow condition for different speeds and the resulting correlation between them (comfort and risk group combined).

Time headway thresholds of the free follow conditions, i.e., when participants had full control of the car, are presented in Figure 10, the exact time headway values can be found in Table 2 and Table 3. Descriptively it appears that there is little influence of the speed condition on time headway thresholds in the free follow condition.



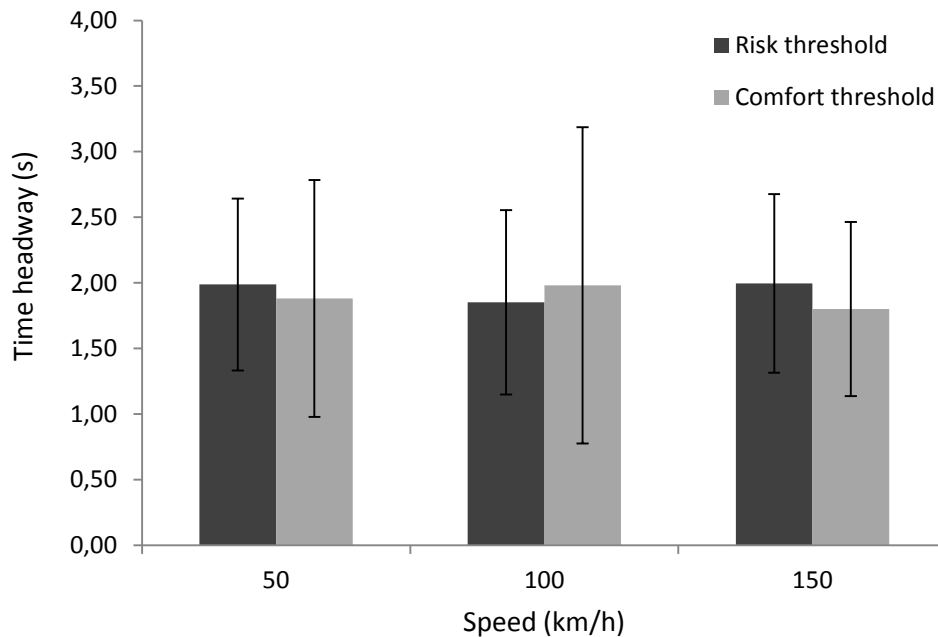


Figure 10. Mean time headway thresholds and standard deviations in the free follow condition of the risk and comfort group for different speed conditions calculated with the small scale sequences.

Calculating a Pearson's correlation for time headway thresholds for the free follow conditions shows a significant relation between time headway thresholds of different speeds (see Table 2 and Table 3).

Time headways thresholds of the free follow conditions (Figure 10) appear to be very similar to time headway thresholds observed in the fixed follow conditions (Figure 7). Fixed and free follow conditions of different speeds correlated significantly in the risk group (Table 2,  $r = .58$  to  $.79$ ,  $p < .01$  to  $.05$ ) and in the comfort group (Table 3,  $r = .75$  to  $.91$ ,  $p < .01$ ).

To test the influence of the independent variables on time headway thresholds, a three-way ( $3 \times 2 \times 2$ ) repeated measures mixed analysis of variance (ANOVA) was performed, with the factors speed (within-subjects; 50 km/h, 100 km/h, 150 km/h), group (between-subjects; risk group vs. comfort group), and follow condition (within-subjects; free vs. fixed). There was no significant main effect for speed, i.e., there is no significant

influence of speed on the time headway thresholds of participants ( $F_{(2, 72)} = 0.21, p = .81, \eta_p^2 = 0.01$ ). There was also no main effect for the group participants were in, i.e., there is no significant difference in time headway thresholds between the risk and the comfort group ( $F_{(1, 36)} = 0.32, p = .58, \eta_p^2 = 0.01$ ). The influence of the follow condition, i.e., the comparison of time headway thresholds of the fixed and free follow condition did just fail to be significant ( $F_{(1, 36)} = 4.10, p = .05, \eta_p^2 = 0.10$ ).

### 3.5 Discussion

In this study we investigated the thresholds for subjective risk and comfort experience in car following. We used a refined version of the method of limits to determine time headway thresholds similar to the studies by Gouy et al. (2012, 2013). Time headway was presented in ascending and descending sequences to locate participants' individual risk respectively comfort thresholds for different speeds. Self-reported risk and self-reported comfort were assessed in a between-subject design to avoid response biases. Before conducting the experiment, we proposed hypotheses about the location of time headway thresholds in general, of individual thresholds, thresholds over different speeds, and between the risk and comfort group.

Our first hypothesis stated that mean time headway thresholds for the experience of risk and comfort would be located between 1.5 and 2.0 seconds. Our results (Figure 7 & Figure 10) add to the growing evidence of a mean threshold for subjective experience between 1.5 and 2.0 time headway seconds in simulated driving (Lewis-Evans et al., 2010; Siebert et al., 2014). Since absolute validity was not assessed for our simulator, these results are not directly transferable to real-life driving.

In our second hypothesis we assumed that there would be no significant difference in time headway thresholds over the different speed conditions,

i.e., that speed has no significant influence on time headway thresholds. Figure 8 shows participants' thresholds as the meter distance, and it can be seen that meter-wise, the thresholds for different speeds are very different. When transferred to time headway thresholds (Figure 7) this difference disappears. A repeated measures mixed ANOVA did not show a significant difference between time headway thresholds of different speed conditions. This result indicates a general validity of time headway as a variable in car following. Participants were not aware that the distance sequences that were displayed in the experiment were varied in 0.5 respectively 0.1 seconds time headway increments. Still, our results show that participants experience and rate distances in car following by their equivalent time headway value.

With our third hypothesis we assumed that individual time headway thresholds would correlate positively and significantly over different speeds, e.g., that a participant with a relatively low threshold in the 50 km/h condition would also have a relatively low threshold in the 100 and 150 km/h condition. We found that individual thresholds correlate significantly with each other over different speed conditions (Figure 9).

In our fourth hypothesis we expected time headway thresholds in the comfort group to be higher than in the risk group. We found that there is no significant difference between thresholds of the risk and comfort group. Furthermore, Figure 7 shows that, while not significant, mean thresholds are actually higher in the risk group than in the comfort group. This could be interpreted as there still being a feeling of comfort present for time headway distances at which an experience of risk is reported. Why is that? Our assumption of higher comfort thresholds was based on the idea that a driver would lose his feeling of comfort before he or she would experience risk. While the results of our study do not support this assumption, the results might be influenced by a flaw in our study design. As explained earlier, participants were presented with ascending and descending sequences of

time headways. While the presentation of sequences was randomized, there might be a cognitive difference in monitoring risk and comfort in participants. The variables used are different in that risk is a negative experience, while comfort is a positive experience. In a descending sequence a participant in the risk group is anticipating an emerging feeling of risk, while a participant in the comfort group is anticipating the disappearance of comfort. This contrast is switched for ascending time headway sequences and should therefore, theoretically level out. As the mean transition points of ascending and descending series plotted in Figure 6 show, this effect is more pronounced in the descending sequences, leading to the observed effect of higher thresholds in the risk group compared to the comfort group. Due to this effect, the question about a possible underlying variable posed by Lewis-Evans et al. (2010) has to be left unanswered.

In our fifth hypothesis we assumed that individual time headways of the free and the fixed follow condition would correlate positively and significantly. While individual time headways of the free and fixed follow conditions correlate significantly, a comparison of the fixed and free follow condition just failed to show a significant difference between the two groups. This is an indication that participants prefer for example small time headways in both the fixed and free follow condition, but that thresholds still differ between the fixed and free follow condition. For the development of level 3 automation in vehicles, our results suggest that self-driving thresholds can give an indication for thresholds in automated driving. However, it is important to keep in mind that distance thresholds in ACC have been shown to be influenced by the amount of system use (Pereira, Beggiato, & Petzoldt, 2015) and we did not control for prior ACC use in our study.

Overall our results suggest that level 1, 2, and 3 automation vehicles need to adapt to the individual driver's time headway threshold. While the

results for our first hypothesis show that the mean time headway threshold lies between 1.5 and 2.0 seconds, individual thresholds can be found outside of this range (Figure 9). Individual thresholds of the free follow conditions, i.e. level 0 automation, correlate significantly with thresholds of the fixed follow conditions, i.e. level 1 automation. Since individual thresholds in our study are also consistent over a broad range of speeds, it is in theory possible to extrapolate from an individual self-driving threshold at a single speed to individual thresholds for level 1 automation driving at different speeds.

There are several limitations to this study. While there is evidence for a general comparability of preferred time headways of real world and simulated driving, we did not test the absolute and relative validity of our specific driving simulator setup. Our results for time headway thresholds can therefore be influenced by differences between simulated and real-life driving, such as the lack of real crash risk in a driving simulator (Risto & Martens, 2014) and differences in criticality ratings of time headways in simulated and real-life driving (Purucker et al., 2014). The effect of underestimated criticality in simulated driving might explain the comparatively large time headways found in this study, compared to the relatively small time headways found in real-life driving (Brackstone, Sultan, & McDonald, 2002, Brackstone, Waterson, & McDonald, 2009). Nevertheless, we argue that while the precise time headway threshold value might change for real life driving (absolute validity), it would still be constant over different speeds (relative validity). Another limitation of this study is the lack of speed differences between the lead and the following car. In real life driving, drivers need to constantly accelerate and decelerate when following another vehicle, leading to complex speed adjustment patterns (Brackstone, Sultan, & McDonald, 2002). Since the speed of the participants' vehicle and the lead vehicle was fixed, these patterns were not present in our study. Furthermore, the surrounding traffic in our study

adheres to a minimum following distance of two seconds, which is higher than individual time headways found in our study and in real life driving (Knospe, Santen, Schadschneider, & Schreckenberg, 2002).

As discussed earlier, self-reported risk and self-reported comfort do not necessarily equate the subjective experience of risk and the subjective experience of comfort. Reported risk and reported comfort thresholds from the fixed follow conditions do not differ significantly from the experienced thresholds of the free follow conditions in which participants had complete control over the car. This could be interpreted as an indication for the validity of using self-reported experiences in lieu of more directly measuring subjective experience. This comparison just failed to show a significant difference, so more research into this is needed.

For future studies it seems advisable to balance the order of free follow and fixed follow conditions so a possible effect of sequence can be controlled. Our two stage utilization of the method of limits proved to be an efficient method to identify participants' thresholds. Presenting all time headway thresholds between 0.5 and 4.0 seconds with a resolution of 0.1 seconds would have resulted in 36 experimental conditions. With our two stage approach participants were on average presented with only 18.35 conditions before a threshold was found. Our advanced method therefore allows researching a broader time headway range compared to the study by Gouy et al. (2012, 2013) without increasing the number of experimental conditions. Results show that it is important to consider possible effects of the chosen variable for threshold detection, as the valence of the variable appears to influence ascending and descending sequences differently.

For future application of the two stage method of limits, as well as the classic method of limits it is important to vary the starting points of each ascending and descending sequence. In this study we used fixed starting points for the time headway sequences, 0.5 and 4.0 seconds, to research the

same time headway range as in preceding articles (Lewis-Evans et al., 2010; Siebert et al., 2014). In hindsight it seems advisable to vary time headway sequence starting points, since starting a sequence out of the researched range can help to mitigate possible errors of expectation (Gescheider, 1997). The only downside of this variation is a small increase in the number of conditions presented, deviating from the 0.5 second increments (4.0, 3.5, 3.0 ...) in presented headways should not influence headway thresholds.

Further improvement to the two stage approach might be possible by using a mix of psychophysical methods. The two stage method of limits provides two transition point reports from each participant, one for the small scale descending, and one for the small scale ascending sequence. To increase the number of transition points, it would be possible to first use the method of limits large scale sequences, to determine a first estimate of an individual's transition point, and to then use the so called staircase method with smaller increments, in which the direction of the stimulus sequence is switched when a transition is reported. This would increase the number of transition points and would in theory provide a more exact transition point estimate. Gescheider (1997, p.50-51) provides a more thorough explanation of this method.

The results of this study for the programming of autonomous cars lie in the stability of time headways for different speeds. While participants show inter-individual differences in time headway thresholds, intra-individual time headway thresholds are constant over a range of speeds. Further research on the influence of external factors on time headway thresholds, such as weather, traffic, and type of vehicle that is followed is needed to form a coherent model for time headway thresholds in autonomous driving. The influence of personality traits on individual time headway thresholds was also not controlled for in this study. Research has shown that following behavior can be influenced by individual factors in self-driving (Heino, van

der Molen, & Wilde, 1996; Ohta, 1993), this could also influence time headway thresholds in automated driving. Since there are no differences in velocity between the lead and the participant's vehicle in this study, the influence of differences in velocity between two vehicles and the resulting occurrence of non-zero time to collision should be researched. Frequent usage of adaptive cruise control can over time have an influence on time headway distance thresholds (Pereira et al. 2015), and just observing other cars driving with relative short time headways, in so called platoons, also temporarily influences preferred time headway distances in drivers (Gouy et al., 2014). Driving automated in platoons furthermore changes a driver's time headway in the subsequent self-driving (Skottke, Debus, Wang, & Huestegge, 2014). These findings and their possible interaction with time headway thresholds at different speeds need to be researched in more detail.



### 3.6 References

Ayres, T. J., Li, L., Schleuning, D., & Young, D. (2001). Preferred time-headway of highway drivers. In *Intelligent Transportation Systems, 2001. Proceedings. 2001 IEEE* (pp. 826-829). IEEE.

Bella, F. (2008). Driving simulator for speed research on two-lane rural roads. *Accident Analysis & Prevention, 40*(3), 1078-1087.

Brackstone, M., Sultan, B., & McDonald, M. (2002). Motorway driver behaviour: studies on car following. *Transportation Research Part F: Traffic Psychology and Behaviour, 5*(1), 31-46.

Brackstone, M., Waterson, B., & McDonald, M. (2009). Determinants of following headway in congested traffic. *Transportation Research Part F: Traffic Psychology and Behaviour, 12*(2), 131-142.

Brecher, G. A. (1934). Die untere Hör-und Tongrenze. *Pflüger's Archiv für die gesamte Physiologie des Menschen und der Tiere, 234*(1), 380-393.

Carsten, O., & Jamson, A. H. (2011). Driving simulators as research tools in traffic psychology. *Handbook of traffic psychology, 87-96*.

Fechner, G. T. (1860). Elemente der Psychophysik. *Breitkopf und Härtel, Leipzig*.

Fletcher, H., & Wegel, R. L. (1922). The Frequency—Sensitivity of Normal Ears. *Physical review, 19*(6), 553.

Fuller, R. (2005). Towards a general theory of driver behaviour. *Accident Analysis & Prevention, 37*(3), 461-472.

Gescheider, G. A. (1997). *Psychophysics: The Fundamentals* (3rd ed.). Mahwah, N.J.: L. Erlbaum Associates.

Godley, S. T., Triggs, T. J., & Fildes, B. N. (2002). Driving simulator validation for speed research. *Accident analysis & prevention, 34*(5), 589-600.

Gouy, M., Diels, C., Reed, N., Stevens, A., & Burnett, G. (2012). Preferred time headway assessment with the method of limits. In J.-F. P. P. V. Mora, & L. Mendoza (Eds.), *European Conference on Human Centered Design for Intelligent Transport Systems*: 87-93.

Gouy, M., Diels, C., Reed, N., Stevens, A., & Burnett, G. (2013). Preferred or adopted time headway? A driving simulator study. In *Proceedings of the International Conference on Ergonomics & Human Factors*, M. Anderson, Ed (pp. 153-159).

Gouy, M., Wiedemann, K., Stevens, A., Brunett, G., & Reed, N. (2014). Driving next to automated vehicle platoons: How do short time headways influence non-platoon drivers' longitudinal control?. *Transportation research part F: traffic psychology and behaviour*, 27, 264-273.

Heino, A., van der Molen, H. H., & Wilde, G. J. (1996). Differences in risk experience between sensation avoiders and sensation seekers. *Personality and individual differences*, 20(1), 71-79.

Kemeny, A., & Panerai, F. (2003). Evaluating perception in driving simulation experiments. *Trends in cognitive sciences*, 7(1), 31-37.

Knospe, W., Santen, L., Schadschneider, A., & Schreckenberg, M. (2002). Single-vehicle data of highway traffic: Microscopic description of traffic phases. *Physical Review E*, 65(5).

Lewis-Evans, B., De Waard, D., & Brookhuis, K. A. (2010). That's close enough—A threshold effect of time headway on the experience of risk, task difficulty, effort, and comfort. *Accident Analysis & Prevention*, 42(6), 1926-1933.

Marsden, G., McDonald, M., & Brackstone, M. (2001). Towards an understanding of adaptive cruise control. *Transportation Research Part C: Emerging Technologies*, 9(1), 33-51.

Muir, B. M. (1994). Trust in automation: Part I. Theoretical issues in the study of trust and human intervention in automated systems. *Ergonomics*, 37(11), 1905-1922.

Näätänen, R., & Summala, H. (1974). A model for the role of motivational factors in drivers' decision-making. *Accident Analysis & Prevention*, 6(3), 243-261.

NHTSA (2013). US Department of Transportation Policy on Automated Vehicle Development, p4. See <http://www.nhtsa.gov/About+NHTSA/Press+Releases/U.S.+Department+of+Transportation+Releases+Policy+oo+Automated+Vehicle+Development>

Ohta, H. (1993). Individual differences in driving distance headway. *Vision in vehicles*, 4, 91-100.

Parasuraman, R., & Riley, V. (1997). Humans and automation: Use, misuse, disuse, abuse. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 39(2), 230-253.

Pereira, M., Beggiato, M., & Petzoldt, T. (2015). Use of adaptive cruise control functions on motorways and urban roads: Changes over time in an on-road study. *Applied Ergonomics*, 50, 105-112.

Purucker, C., Rüger, F., Schneider, N., Neukum, A., & Färber, B. (2014, July). Comparing the perception of critical longitudinal distances between dynamic driving simulation, test track and Vehicle in the Loop. In *Advances in human aspects of transportation. Proceedings of the 5th AHFE Conference. Krakau, Polen* (Vol. 19, No. 23.07, pp. 421-430).

Risto, M., & Martens, M. H. (2014). Driver headway choice: A comparison between driving simulator and real-road driving. *Transportation research part F: traffic psychology and behaviour*, 25, 1-9.

Siebert, F. W., Oehl, M., & Pfister, H. R. (2014). The influence of time headway on subjective driver states in adaptive cruise

control. *Transportation research part F: traffic psychology and behaviour*, 25, 65-73.

Skottke, E. M., Debus, G., Wang, L., & Huestegge, L. (2014). Carryover effects of highly automated convoy driving on subsequent manual driving performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 56(7), 1272-1283.

Stanton, N. A., & Young, M. S. (2005). Driver behaviour with adaptive cruise control. *Ergonomics*, 48(10), 1294-1313.

Summala, H. (1988). Risk control is not risk adjustment: The zero-risk theory of driver behaviour and its implications. *Ergonomics*, 31(4), 491-506.

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.

Taylor, D. H. (1964). Drivers' galvanic skin response and the risk of accident. *Ergonomics*, 7(4), 439-451.

Winsum, W. V., & Heino, A. (1996). Choice of time-headway in car-following and the role of time-to-collision information in braking. *Ergonomics*, 39(4), 579-592.

Yan, X., Abdel-Aty, M., Radwan, E., Wang, X., & Chilakapati, P. (2008). Validating a driving simulator using surrogate safety measures. *Accident Analysis & Prevention*, 40(1), 274-288.

## 4 Automated driving and preferred distances in car-following – the influence of time headway, speed, and visibility

### **Abstract**

While the introduction of completely autonomous cars promises lower accident numbers, a main requirement for wide use of autonomous cars will be the acceptance by drivers. In this study a crucial variable for the acceptance of autonomous cars, the vehicle to vehicle distance expressed in time headway, was researched in a driving simulator. Research has shown that time headway distances, perceived as comfortable in self-driving and assisted driving with adaptive cruise control, remain constant over a range of different speeds. This study aims to test these findings for fully automated driving. Since time headway is perceived visually, the driving situation was varied to understand the influence of visibility on the subjective comfort of the driver in an autonomous driving situation. In a within-subject design, drivers followed a passenger car in clear weather conditions, the same passenger car in fog which occluded parts of the traffic environment, as well as a truck that occluded the lane ahead, also in clear weather condition. Subjective comfort of drivers in each condition was rated with a haptic rating lever.

Results suggest that comfortable time headway following distances in autonomous driving are not constant over different speeds, but that these distances decrease with increasing speed. Reduced visibility generally led to a shift in comfortable following distances towards larger headways. An interaction of speed and visibility was found, at 50km/h participants rated following a truck as less comfortable than following a normal sized vehicle in fog. However, this effect was not present in the 100 and 150km/h conditions. These results have implications for the introduction of autonomous cars and their time headway adjustments in reduced visibility

conditions. Possible explanations for the distance increase of comfortable following distances under impaired visibility will be discussed.

#### 4.1 Introduction

Past research suggests that time headway is a variable held constant by individual drivers in self-driving (Siebert, Oehl, & Pfister, 2014; Siebert, Oehl, Bersch, & Pfister, 2017; Winsum, & Heino, 1996), and the individual choice of time headway has been related to the drivers' awareness of risk and comfort (Lewis-Evans, de Waard, & Brookhuis, 2010). However, there has been no research on the influence of longitudinal vehicle to vehicle distances of completely autonomous cars on the subjective experience of drivers so far. Therefore, the aim of this study is to test how results of constant time headway following from self- and assisted driving translate to autonomous driving. The validity of a preference for constant time headway following in autonomous cars is important for two reasons - it would mean that the complete secession of control by the driver of the car does not alter the effect of preferred constant time headways found in self- and assisted-driving, and it would allow car manufacturers to program autonomous cars to follow at a constant time headway over a broad speed range.

A second objective of this study is to investigate the effect of different visibility conditions on preferred following distances in autonomous driving. Since time headway is a variable that is visually perceived, resulting from an estimation of the vehicle to vehicle distance divided by an estimation of the vehicle speed, the accuracy of an individual's time headway estimation depends on the visibility condition of the driving situation. Car following under adverse visibility, such as following a truck or following a passenger car in a foggy driving environment has been studied for self-driving, and we hope to extend this research to fully autonomous driving.

#### 4.1.1 Constant time headway following

Researchers have found that drivers follow other vehicles with a constant time headway at different speeds, and prefer constant time headway following to non-constant following when presented with a number of time headways at different speeds. In a simulator study, Winsum and Heino (1996) found that drivers follow with constant time headways for a speed range of 40 to 70km/h. Siebert et al. (2014) and Siebert et al. (2017) found no influence of speed on ratings of subjective risk and comfort when drivers were presented with constant time headways at 50, 100, and 150km/h in a driving simulator. In real life driving, Ayres, Li, Schleuning, and Young (2001) found time headways of highway drivers to be constant for speeds in the range of roughly 30 to 100km/h, and Taieb-Maimon and Shinar (2001) found that drivers maintain constant time headways for speeds between 50 and 100km/h in real life driving.

Due to the methodology of their studies, the results of Siebert et al. (2014) and Siebert et al. (2017) also have implication for adaptive cruise control systems. In their experiments, participants were presented with a range of stable time headways that they were asked to rate for their subjective experience of risk and comfort. Relatively stable time headways are also present in adaptive cruise control, where a distance is maintained by the automation, while the driver steers the vehicle. The results of Siebert et al. (2014) and Siebert et al. (2017) indicate that constant time headways for different speeds are preferred in assisted driving, where drivers only control steering, but not the speed and vehicle to vehicle distance between their car and the lead vehicle. While the preferred time headway differs between individual drivers, in simulated as well as in real-life driving preferred headways are most often found in the range between one and two seconds.

#### 4.1.2 Driving in fog

Winsum (1999) postulates in his mathematical model of human car following that a reduced visibility in the driving environment due to fog or rain should in theory lead to an increase in time headway “as an increase of the safety margin to compensate for later detections of decelerations of lead vehicles” (p. 209). However, researchers have found conflicting results for following behavior during fog. While in some studies drivers increase their time headway, in other studies drivers follow closer when the visibility in the driving situation is reduced due to fog. In traffic psychology research, two main perceptual effects of fog on driver perception have been identified that influence following behavior, an overestimation of the vehicle to vehicle distance, and an underestimation of a driver’s own vehicle speed. Furthermore, two theories about behavioral adaptation to following in fog have been put forward. Studies exploring these four effects are presented in the following.

For general distance estimation, Ross (1967) found that participants overestimate the distance to objects in fog. She argues that this is an effect of reduced contrast due to the foggy environment. Reduced contrast occurs under normal visibility as earth’s atmosphere scatters sunlight leading to reduced contrast of objects in the far distance (O’Shea, Blackburn, Ono, 1994), an effect that is similar to reduced contrast in fog. For specific distance estimation for vehicles, Cavallo, Colomb, and Dorè (2001) found that the vehicle to vehicle distance is on average overestimated by 60% by participants in nighttime fog. Their study was conducted in a fog chamber and the lead vehicle was represented only by its rear lights. The overestimation of distance was reproduced by Buchner, Brandt, Bell, and Weise (2006). In theory, this perceptual effect leads to shorter time headways in car following, as the vehicle to vehicle distance is



overestimated and drivers drive closer to the lead vehicle than they think and would under normal visibility conditions.

For vehicle speed estimation, Snowden, Stimpson, and Ruddle (1998) found that the speed perception of drivers is altered when the contrast of the driving environment is reduced due to fog. In simulated driving, participants drove faster when trying to match a target speed when fog was introduced in the driving environment. Distler and Bülthoff (1996) found that a reduced contrast of the road texture lowered the estimated speed of vehicles in a driving simulator study. Sotiropoulos, Seitz, and Seriès (2014) found that reduced contrast leads to reduced speed estimations of moving gratings, a finding that can be applied to driving, where a reduction of contrast of the driving environment due to fog can be considered analogue to reduced contrast in gratings. Horswill and Plooy (2008) found that reduced contrast in a driving simulation leads to a reduction in speed discrimination and generally to the underestimation of speeds. Since time headway is calculated by dividing the vehicle to vehicle distance by the speed of the ego-vehicle, an underestimation of speed leads to an overestimation of time headway. In theory, this perceptual effect therefore also leads to shorter time headways.

While the effects of an overestimation of the vehicle to vehicle distance and an underestimation of speed would accumulate and lead to shorter time headways and higher speeds in fog, research suggests that drivers adapt their following behavior when driving in fog. Sumner, Barguley, and Burton (1977) observed that drivers reduce speed on the freeway when visibility is reduced due to fog. A similar effect was found in a study by Al-Ghamdi (2007), where drivers reduce their speed in dense fog (visibility < 50m). Trick, Toxopeus, and Wilson (2010) found that older drivers' reduction of speed when driving in fog is higher than the speed reduction of younger and more inexperienced drivers. Mueller and Trick (2012) found that both novice and experienced young drivers reduce their speed in a driving

simulator when visibility was reduced due to fog, but that this effect is more pronounced for experienced young drivers. This behavioral adaptation to driving in fog would generally lead to increased time headways. However, there are studies that suggest that not all drivers change their following behavior in fog in the same way.

Van der Hulst, Rothengatter, Meijman (1998) found that drivers generally compensate for reduced visibility with decreased driving speed and increased time headway following distances. While this result appears to be in line with the presented results by other researchers, Van der Hulst et al. also found that when participants were motivated to drive at high speeds, they followed the lead vehicle with relatively small time headways, despite the reduced visibility. They postulate that these small time headways in reduced visibility conditions are counterbalanced by a heightened alertness. Results by Vivoli, Bergomi, Rovesti, Carrozzi, and Vezzosi (1993) appear to confirm this hypothesis. Vivoli et al. found an increase in epinephrine excretion in truck drivers that drove long distances when they had to drive in reduced visibility weather conditions due to fog. The excretion of epinephrine has been associated with a stressful driving task (Aronsson & Rissler, 1998; Evans, 1994). A related effect has recently been found in a study by Pekkanen, Lappi, Itkonen, and Summala (2017), where drivers increased the visual sampling rate when following at small time headway distances. These results suggest that drivers follow close when driving in fog if they are motivated to do so. Another possible explanation for some drivers following close to the lead vehicle in fog is put forward by researchers that argue that close following during fog allows drivers to better identify the lead vehicle's speed and the distance to it.

Broughton, Switzer, and Scott (2007) found that when driving during fog with visibility distances of 90 meters or less with 50 and 80km/h, drivers' following behavior can be classified into two categories, "laggers"

and “non-laggers”. Laggards follow a lead vehicle with a very high distance that does not allow them to see the lead vehicle due to the fog. Non-laggers follow closer to the lead vehicle within the visibility range. Caro, Cavallo, Marendaz, Boer, and Vienne (2009) argue that this close following allows drivers to better identify relative motion of the lead vehicle, which has been shown to be problematic during fog (Horswill & Plooy, 2008; Kang, Ni, & Andersen, 2008). These results suggest that the visibility distance that is reduced due to fog can lead to an additional effect of dichotomizing drivers in laggards and non-laggers.

In summary, drivers underestimate their own speed, and overestimate the vehicle to vehicle distance when driving in fog due to a reduced contrast of the driving environment. Some drivers adjust to fog by lowering their speed and increasing the vehicle to vehicle distance. If the visibility reduction is very high, such as in dense fog, some drivers follow close to the lead vehicle to maintain eye contact to the lead vehicle. The same close following also occurs when drivers are motivated to follow closely.

#### 4.1.3 Driving behind larger vehicles

Apart from reduced visibility of the driving environment due to weather, forward visibility can also be reduced when following large vehicles such as trucks or busses. Empirical results for changes in car following due to the lead vehicle’s size are mixed and the influence of vehicle size on following behavior is not well understood.

Evans and Rothery (1976) did not find a difference in following distance for the size of the lead vehicle, when the size was varied by the length of the rear-bumper. In their laboratory experiment the lead car was presented on colored slides. Wasielewski (1981) found that time headway in free flowing traffic increases with the size of the lead vehicle, with the largest headways found for trucks as lead vehicles in real life observations on a freeway.

Green and Yoo (1999) found that time headway increases by 10% when participants followed a truck in a driving simulation compared to a normal sized car. Duan, Li, and Salvendy (2013) found a similar effect for a speed of 45km/h, where time headways increased when following a truck compared to following a normal sized car, but this effect disappeared for a speed of 90km/h. Sayer, Mefford, and Huang (2000) found an opposing effect. In their study, participants in an instrumented vehicle followed closer to light trucks than to normal sized cars, an effect also found by Brackstone, Waterson, and McDonald (2009) for trucks and vans.

While the direction of the effect of lead vehicle size is debated, Sayer et al. (2000) and Brackstone et al. (2009) put forward a hypothesis that could help explain effects of lead vehicle size, a freeing up of mental resources due to a reduction in monitoring needs. They argue that since the view on the rest of the traffic is occluded, drivers' vehicle to vehicle distance maintenance is focused on the leading vehicle, resulting in a very simple following strategy that allows for closer following. This hypothesis stands in contrast to the results of higher alertness (Van der Hulst et al., 1998) and increased visual sampling (Pekkanen et al., 2017) during close following. Another theory on decreased headways when following large vehicles was put forward by Harb, Radwan, Yan, and Abdel-Aty (2007). It postulates that decreased headways are a result of discomfort when following a large vehicle. In their theory, drivers follow close because they want to pass the larger vehicle as fast as possible. Following this theory, the absence of the possibility to take over would minimize the effect of decreased time headways when following large vehicles.

#### 4.1.4 Using a haptic lever for feedback on subjective experience in driving

In this study, participants rated their subjective comfort for a given time headway by using a bi-directional haptic lever. Different subjective variables have been used as dependent variables when participants are asked to rate their subjective experience of different time headways. Earlier studies have shown that subjective variables highly correlate with each other when time headways are rated (Lewis-Evans et al., 2010; Siebert et al., 2014). In this study, comfort was chosen as the dependent variable because it can easily be described in a positive and negative valence by the words comfort (German: angenehm) and discomfort (German: unangenehm). This is not the case for other possible dependent variables such as risk, where a new word is needed for a positive valence (risky vs. safe).

Furthermore, in contrast to earlier studies on time headway, a bi-directional haptic lever was used instead of single items likert-scales used by Lewis-Evans et al. (2010) and Siebert et al. (2014). An advantage of the haptic lever as a rating method is the simultaneous evaluation of the vehicle to vehicle distance, compared to a retrospective rating by a subsequent questionnaire. Additionally, the lever allows the participants to keep their eyes on the leading vehicle while rating the vehicle to vehicle distance since the lever can be adjusted without looking at it. The lever used in this study has been positively evaluated for linearity of ratings in a pre-test with 24 participants, replicating the results of an earlier study by Wolfgang Vehrs (1986) on a prior model of the lever. A study by Charlton, Starkey, Perrone, and Isler (2014) showed that participants are able to rate the risk of a traffic situation by using a haptic risk-meter, similar in function to the lever used in this study.

#### 4.1.5 Goals of this study

In this study, the forward visibility of drivers was systematically varied at different speeds in a driving simulator. The simulated car was driving autonomously, i.e. lateral and longitudinal control was performed by the simulation, driving did not require driver input. To assess the impact of different time headways and reduced visibility on the subjective experience of the participants in car following situations, drivers indicated their subjective level of comfort by moving a bi-directional haptic lever with their right hand. Participants were then presented with different vehicle to vehicle distances and the lever position was recorded continuously for these different distances. There was no motivating factor introduced for drivers to follow close to the lead vehicle. Furthermore, the visibility range of the fog condition was kept high to prevent effects of laggings and non-laggings.

Based on the literature review of results on vehicle to vehicle distance in self- and assisted-driving, we expected the following in completely automated driving:

1. Speed does not influence the comfort ratings for specific time headways.
2. Reduced visibility leads to a decrease in comfortable ratings for distances when compared to the clear visibility condition.
3. Following a truck is rated as less comfortable than following a normal sized car in a foggy environment due to the underestimation of speed and the overestimation of vehicle to vehicle distance in the fog condition.

## 4.2 Method

In this paragraph the study design, the sample, the driving simulator and the driving environment will be described. Afterwards, the procedure during the experiment will be explained, before the haptic lever, and the processing of its data will be presented.

### 4.2.1 Experimental design

In this experiment visibility was varied threefold (clear vs. truck vs. fog), speed was varied threefold (50km/h vs. 100km/h vs. 150km/h), and time headway was varied tenfold (0.5 vs. 1.0 vs. 1.25 vs. 1.5 vs. 1.75 vs. 2.0 vs. 2.5 vs. 3.0 vs. 3.5 vs. 4.0). The extra 0.25 second increments between 1.0 and 2.0 seconds were added to more finely represent typical time headways found in earlier studies. The resulting 90 experimental conditions were grouped in 9 blocks, each block consisting of a randomized order of ten time headways for the same visibility and speed. These 9 blocks were then randomly presented to participants. All participants were presented with the 90 experimental conditions in a within-subject design.

Each experimental condition lasted 10 seconds, and each experimental block lasted about 100 seconds. There were short pauses of about 2-3 seconds between the conditions within each block, and longer pauses of 20-30 seconds between blocks, when a new block was loaded into the driving simulation software.

### 4.2.2 Participants

39 participants took part in this study. Due to technical difficulties with the scaling lever 4 participants were excluded from the analysis. All values reported in this paper are based on the sample of the 35 participants where no technical difficulties occurred. Of these 35 participants, 17 were female and 18 were male. Participants had a mean age of  $M = 22.46$  years ( $SD =$

5.84). All participants were in possession of a valid driver's license, that they had acquired an average of  $M = 12.80$  years ( $SD = 13.80$ ) before the study. On average, participants estimated to drive  $M = 8820.57$  kilometers per year ( $SD = 18902.6$ ) with a minimum of 20 and a maximum of 100000 kilometers. The average accumulated driving experience of the participants was  $M = 108546.29$  kilometers. About one third of the participants owned a car, and more than 50% of the participants used their own or another car at least once a week. The car type most used by the participants was a compact car. 34 participants were right-handed, with one participants being ambidextrous. Participants were recruited from the student body of the Leuphana University Lüneburg as a convenient sample. For their participation, participants were given "study-subject hours" that they have to acquire during their time at the university.

#### 4.2.3 Driving simulator and driving environment

The study was conducted in a fixed-base driving simulator at the Leuphana University Lüneburg. The simulator cabin was from a Volkswagen Golf 4 GTI with automatic transmission. The steering wheel, taken from a non GTI Golf 4 model, was connected to the base of a G25 Racing Wheel from Logitech, the pedals were generic Logitech pedals. To simulate the driving environment, SCANeR Studio Driving Simulation Software version 1.4 from Oktal was used. The driving environment was projected on to three screens in front of the simulator cabin for a total resolution of 3072x768 pixels with three video projectors. Each single screen had a size of 1.4 x 1.4 meters. The outer screens were positioned at an angle of 120° to the center screen. The driver seat was positioned 2 meters from the center screen, resulting in a horizontal field of view of approximately 110° and a vertical field of view of approximately 30°. The physical and simulated eye height of the participants was 1.25m. The simulated car model was a compact car, a Citroën C4. The speedometer of the simulator was inactive during the



experiment. In the front of the cabin, two speakers were used to play simulation sounds. Curtains surrounded the simulator cabin to block external sound and light. Simulation data was saved with a frequency of 20 Hz. The test supervisor sat behind the cabin, controlling the simulation from outside the field of view of the participant.

Three driving environments were programmed for this study, with each environment representing a road type where a speed of 50, 100, or 150km/h could be expected. The 50km/h driving environment resembled an inner city road with one lane in each direction. The speed limit in German inner cities is typically 50km/h. A small number of inner city buildings were placed at the road side. Road width and lane markings were modelled after the Regelquerschnitt 9,5, a German road standard. The 100km/h driving environment was modelled after a German rural road, with two lanes in each direction, with opposing lanes divided by a solid line. The typical speed limit on German rural roads is 100km/h. There were a small number of buildings and trees on the side of the road, and road width and lane markings were modelled after Regelquerschnitt 20. The 150km/h condition was modelled after a German “Autobahn”, a highway road where the advised speed is 130km/h, but generally there is no enforced speed limit. In this condition there were three lanes in each direction, and opposing traffic was separated by a guard railing. A small number of trees was placed on the side of the road. Lane width and road markings were modelled after Regelquerschnitt 33. Each environment had only minimal road curvature, no slope, and sparse oncoming traffic. There were no side-streets in any of the road environments and there was no cross traffic by pedestrians. Road side buildings and trees had a minimal distance of 20meters to the side of the road. All simulated cars drove with a fixed speed and were programmed to adhere to all traffic rules and to stay in their lanes. The participant’s vehicle and the lead vehicle always drove in the right-most lane.

Screenshots of the three visibility conditions are shown in Figure 11. The lead vehicle in the clear condition was a compact car, the lead vehicle in the truck condition was a truck, and the lead vehicle in the fog condition was the same compact car as in the clear condition. The fog in the fog condition was set to a range of 200 meters.



Figure 11. Screenshots of the center projection of the three visibility and three speed conditions for a time headway of 2 seconds: fog & 50km/h (left), truck & 100km/h (middle), clear & 150km/h (right).

#### 4.2.4 Procedure

After participants arrived at the simulator, they filled out a short demographic questionnaire and were then seated in the driver's seat of the simulator. The experimenter then explained the use of the simulator, and participants' task in the experiment. The instruction for using the rating lever was as follows (translated from German):

“Today you will be shown multiple driving situations in the driving simulator. During these situations, you do not need to control the car, as the car drives by itself. You do not need to steer, brake, or accelerate. Next to you there is a lever that can be moved in two directions, to the front and to the back. You will feel a light resistance that tries to automatically move the lever to a middle position. The lever position at the maximum front position represents “uncomfortable” (German “unangenehm”), the middle lever position represents “neutral” (German “neutral”), and the maximum back position is “comfortable” (German “angenehm”). Now take the lever into your hand and familiarize yourself with it by moving it to the front and the

back multiple times. Now try some lever positions without looking at the lever. In the following you will see multiple consecutive driving situations. Please indicate the intensity of your feelings toward the distance to the lead vehicle, by adjusting the lever between “comfortable”, “neutral”, and “uncomfortable” and keeping the lever in this position for the whole driving situation. Please only rate the distance to the lead vehicle and not the other traffic or the driving environment.”

A figure with the lever positions with the “comfortable”, “neutral”, and “uncomfortable” position was shown to participants during the explanation of the lever positions. This part of the instruction was followed by a short training in which the experimenter instructed the participant to imagine a positive, a negative, and a neutral event and use the lever to rate his or her feelings during this event. The participant was then reminded to focus their gaze on the driving situations and not on the lever and the first block of driving situations was started.

#### 4.2.5 Comfort rating lever

Participants rated their subjective experience of the vehicle to vehicle distance on a bi-directional haptic lever (Figure 12). The lever used in this study is an adapted version of the “Vehrs-Hebel” (engl. “Vehrs-Lever”), developed by Wolfgang Vehrs (1986) for the non-verbal rating of stimuli. The lever consists of a heavy base that connects to a height-adjustable box that houses the mechanics of the lever. The lever-arm protrudes out of the top end of the box, with an orthogonally placed handle at the top. The arm can be moved linearly in a space of 15cm, allowing a movement of the lever for 7.5cm from its middle position to each edge of the box. Inside the box, there are two springs that keep the lever-arm in a middle position when no force is applied, a 9Volt battery for powering the lever, and a potentiometer. The potentiometer translates any lever movement into a change in voltage that corresponds to a specific lever position. Through an analog digital

converter, the voltage value is measured and transferred into a digital value that is readable by a computer with a frequency of 20 Hz. The lever was placed under the driving simulator cabin, with the lever arm protruding out of the middle console in front of the gearstick. Tests on the use of the lever for ratings of subjective experiences by Vehrs (1986) as well as a pretest ( $N = 24$ ) by the authors of this study suggest that participants are able to express their subjective experience accurately with the help of the lever. The direction of valence of lever ratings was chosen for two reasons. First, a movement away from the body resembles the pushing of a negative object away from oneself, while the movement of pulling something towards the body has a more positive connotation. It is therefore more natural to have “uncomfortable” ratings defined as a lever push away from the body, and “comfortable” ratings as a pulling movement toward the own body. Second, since time headways for a given speed are represented as gaps between the participant’s vehicle and the lead vehicle, the lever movement could in theory just copy this gap between the two vehicles. In this case, the lever would present the position of the lead vehicle, if it is far away from the participant, the lever can also be set further away, if it is close, the lever is close too. Defining the lever ratings in a way that prohibits this “copying” of the lead vehicle position with the lever helps to prevent this effect.



Figure 12. The adapted model of the Vehrs lever used in this study.

#### 4.2.6 Analysis

The raw data output of the lever was processed before any calculations were conducted. This was done in two steps, first, data length was adjusted to eliminate unintended lever ratings, and second, voltage data was transferred into a value of physical lever position expressed as a percentage.

The elimination of data was necessary due to the study design and the use of the lever as a rating method. Different time headway conditions in this study were shown for 10 seconds each, and 10 conditions followed each other consecutively. Participants were instructed to rate the vehicle to vehicle distance by moving the lever to a certain position, and to hold this position until the vehicle to vehicle distance changed, i.e. a new time headway condition started. Due to this design, participants started each condition (except the first) with the lever position of the preceding condition. The lever position of the first seconds of each condition therefore does not represent a rating of the vehicle to vehicle distance, but consists of lever movement from the old position to the new intended rating. This

required an adjustment of the temporal length of the recorded data for analysis. To ensure that no intended lever ratings were excluded, the standard deviation of all ratings in this study was plotted, including each condition and each participant, resulting in one average of standard deviation for 10 seconds of rating. These 10 seconds were consecutively shortened in 0.5 second steps starting from the beginning, until there were only the last 0.5 seconds of the condition left. The resulting data (Figure 13) shows that standard deviation in the lever data decreases as the first few seconds of each condition are eliminated.

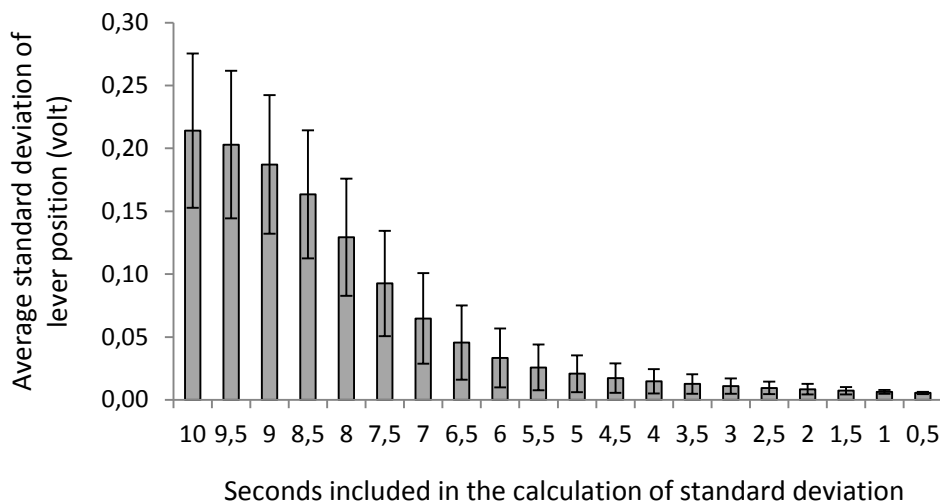


Figure 13. Average standard deviation of voltage output of the lever for different condition times, reduced by 0.5 second increments from the start of the condition (error bars show the standard deviation).

Analyzing the data in this way reveals that the lever movement, expressed as its standard deviation, is high in the beginning of each condition, but decreases rapidly until it stays relatively stable after 5 seconds into the conditions. Since participants were instructed to hold the lever position once they had made their rating, it can be assumed that the majority of participants require about 5 seconds to arrive at the intended lever position. Due to this, the lever data of the first five seconds of each condition is not

included in the calculation of the lever position. Only the last 5 seconds (100 data points) of each condition are averaged and used as the lever rating for a given condition.

After this adjustment of data length and the calculation of the average, the resulting average voltage value was transferred into the physical lever position as a percentage value. A “neutral” lever rating, i.e. the lever is positioned in the middle, results in a 50% value. A “comfortable” lever rating, i.e. a participant pulls the lever as close toward herself as possible, results in a 0% rating. An “uncomfortable” rating where a participant pushes the lever as far away as possible from himself results in a 100% rating.

All rating data was analyzed by a three-way (3x3x10) repeated measures analysis of variance (ANOVA), with visibility (within-subjects; clear vs. fog vs. truck), speed (within-subjects; 50km/h vs. 100km/h vs. 150km/h), and time headway (within-subjects; 0.5 vs. 1.0 vs. 1.25 vs. 1.5 vs. 1.75 vs. 2.0 vs. 2.5 vs. 3.0 vs. 3.5 vs. 4.0) as the independent variables. Apart from general average differences in comfort between different visibility and speed conditions, comfortable and uncomfortable ratings of time headways can be distinguished due to the design of the rating lever. This is possible since a lever position lower than 50% indicates a rating of a time headway as comfortable, while a position higher than 50% indicates that a time headway was perceived as uncomfortable. This approach of dichotomizing comfortable and uncomfortable ratings therefore supplemented the ANOVA.

### 4.3 Results

To test the experimental variation of time headways, the influence of time headways on comfort ratings will be presented first. After this, results on the influence of different speeds on general comfort ratings of time headways will be presented, followed by the results for different visibility conditions. A more detailed analysis of the influence of speed and visibility on the transition point from comfortable to uncomfortable ratings of time headways via the lever will be presented at the end of this section. All reported data on lever ratings was processed according to the procedures described in Chapter 4.2.6.

#### 4.3.1 Influence of time headway on comfort ratings

We assume that the larger a time headway is, the more comfortable it is perceived. The data provides evidence that time headways were successfully perceived as more comfortable the larger they were (Figure 14). Since Mauchly's Test revealed a violation of the assumption of sphericity for the main effect of time headway ( $\chi^2(2) = 480,07, p < .01$ ), Greenhouse-Geisser corrected degrees of freedom were used ( $\epsilon = .18$ ). Time headway conditions were significantly different ( $F_{(1.65, 56)} = 88.88, p < 0.01, \eta_p^2 = .72$ ).

#### 4.3.2 Influence of speed on comfortable time headways

We assumed that speed does not influence comfort ratings for specific time headways. The influence of speed on comfort ratings was tested in a three-way ANOVA, comparing speed as one of the factors at 50, 100 and 150 km/h. Since Mauchly's Test revealed that the assumption of sphericity had been violated for the main effect of speed ( $\chi^2(2) = 8.92, p < .012$ ), Greenhouse-Geisser corrected degrees of freedom were used ( $\epsilon = .81$ ). There was a significant main effect of speed on comfort ratings of time headways ( $F_{(1.62, 54.98)} = 42.22, p < .01, \eta_p^2 = .55$ ). For nearly all time



headways, participants rated following at lower speeds as more uncomfortable than following at higher speeds (Figure 14). Mean lever ratings in the clear visibility condition (top of Figure 14) are highest for the 50km/h condition, followed by the ratings of the 100km/h condition, with the 150km/h condition rated as the most comfortable with the lowest lever ratings on average. This difference in ratings can also be observed for the fog and the truck condition, where time headways of lower speeds are rated as more uncomfortable when compared to the same time headways at higher speeds.

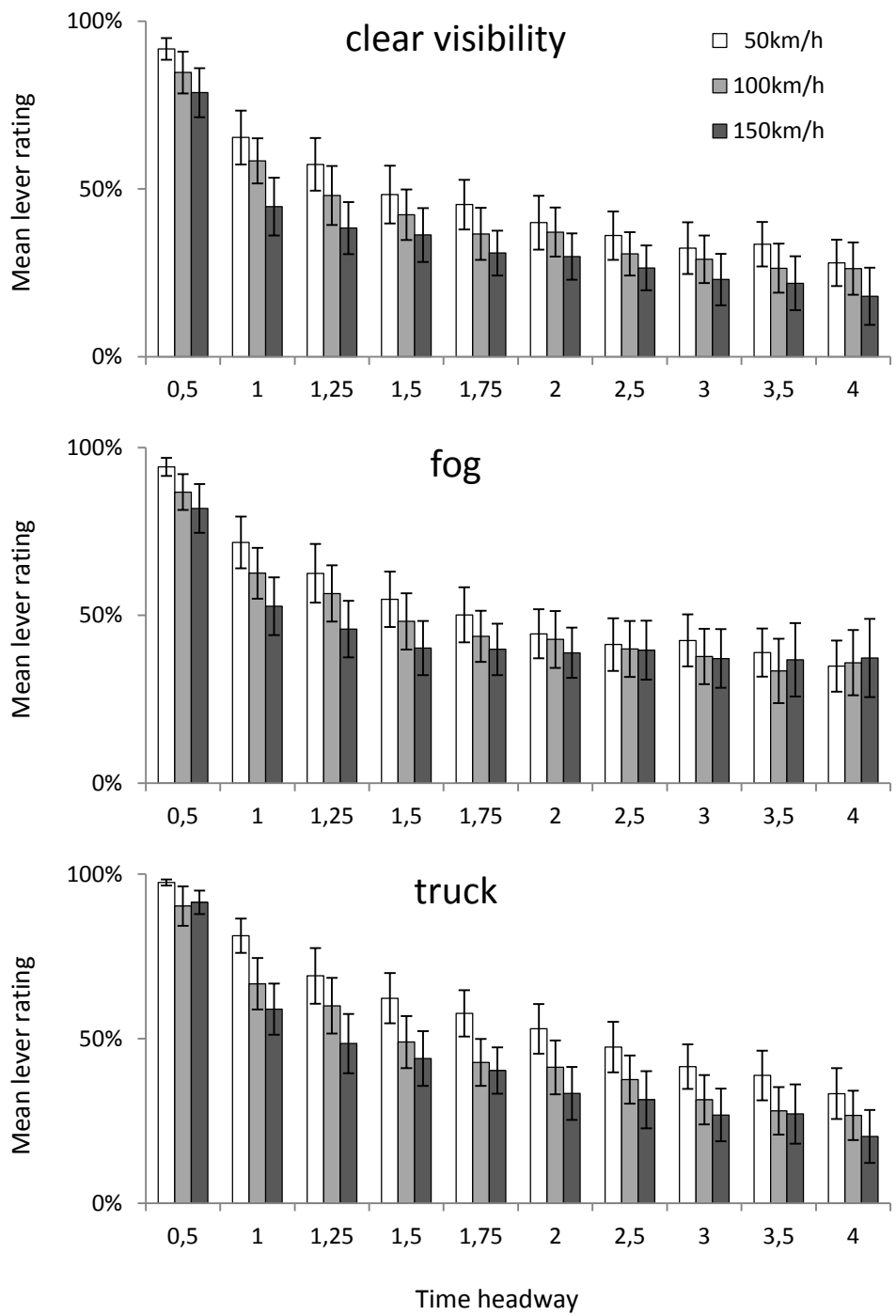


Figure 14. Mean lever ratings for different time headways at 50, 100, and 150km/h and three visibility conditions (error bars show the 95% confidence interval).

Post-hoc tests using Bonferroni correction for multiple comparisons revealed significant differences between lever ratings of all three speed conditions (all  $p < .01$ ). Other effects of this ANOVA will be presented in the next chapter.

#### 4.3.3 Influence of visibility on comfortable time headways

We hypothesized that reduced visibility leads to a decrease in comfort ratings of time headways when compared to clear visibility. To test the influence of visibility on comfort ratings, three visibility conditions (clear vs. fog vs. truck) were compared as one factor in a three-way ANOVA. There was a significant main effect of visibility on comfort ratings of time headways ( $F_{(2, 68)} = 16.87, p < .01, \eta_p = .33$ ). As Figure 15 reveals (this is the same data presented in Figure 14, but rearranged for better comparability of the visibility conditions), for most time headways driving behind a truck is, in fact, less comfortable than driving behind a normal-sized vehicle. Participants furthermore rate time headways as less comfortable in foggy environment than in clear visibility.

Additionally, driving behind a truck was assumed to be even less comfortable than following a normal sized car in a foggy environment. Descriptively, the most comfortable visibility condition is following a normal sized car in clear visibility conditions, followed by driving behind a normal sized car in a foggy environment, with the least comfortable visibility condition following a truck, except for time headways  $\geq 3$ . Mean lever ratings for the speeds of 100 and 150km/h show the same pattern of influence of visibility on comfort for small time headways.

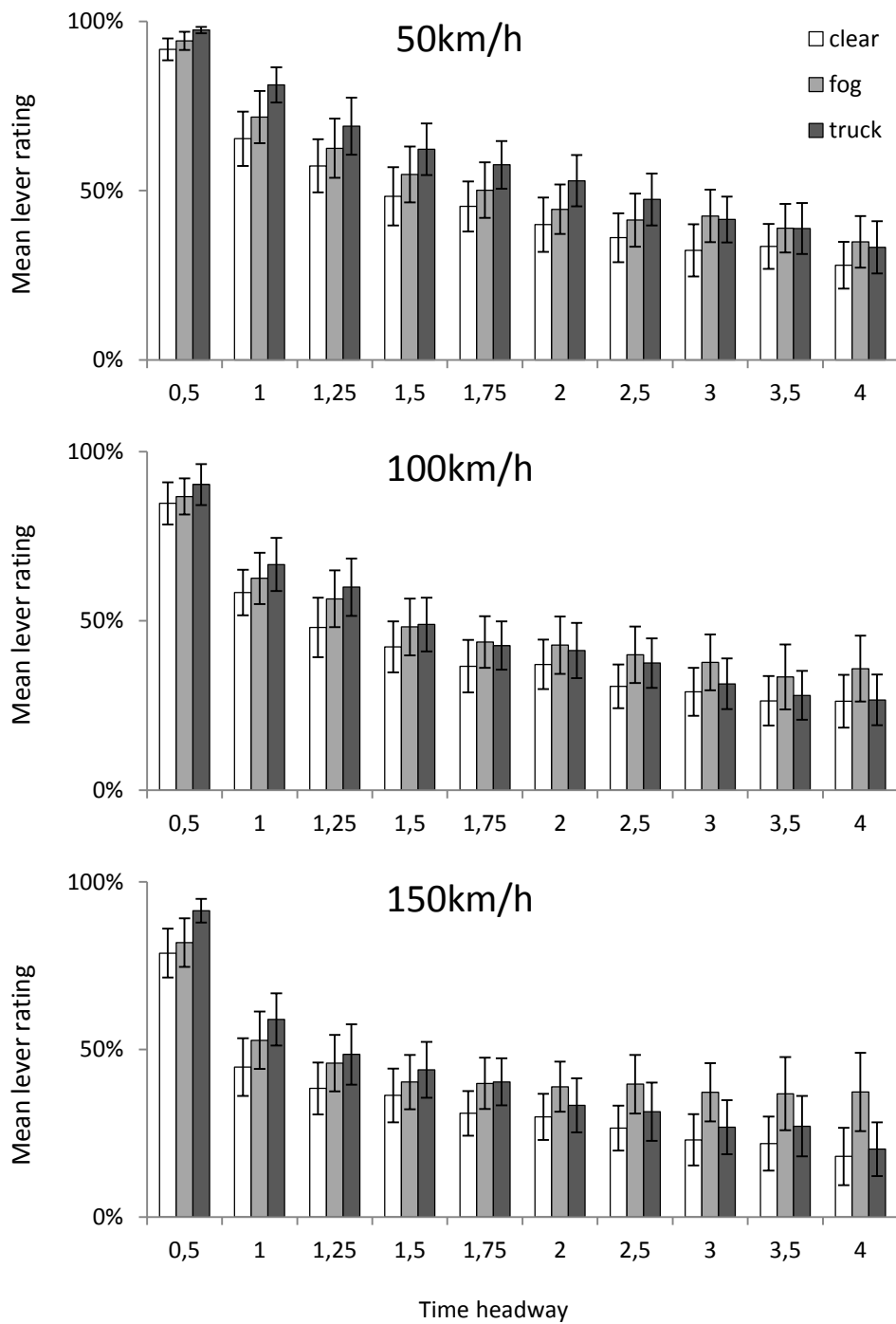


Figure 15. Mean lever ratings for time headways at different visibility and speed conditions (error bars show the 95% confidence interval).

An additional effect of reduced visibility can be observed for large time headways in the fog condition. While mean lever ratings for the clear and

truck visibility conditions indicate more comfort with increasing time headways, the comfort ratings for the fog condition remain more constant even when time headway increases. Large time headways are therefore more uncomfortable in a foggy environment than in the truck or clear visibility condition, contrary to the effect found for smaller time headways. Descriptively, this effect is most pronounced for the 150km/h condition.

Post-hoc tests using Bonferroni correction for multiple comparisons revealed significant differences when comparing the clear visibility condition to the truck and the fog condition. Lever ratings in the clear visibility condition are significantly smaller than in the truck and the fog condition (both  $p < .01$ ). There was no significant difference found between ratings of the truck and the fog condition ( $p = 1.0$ ).

#### 4.3.4 Interaction of visibility and speed

The ANOVA revealed a significant interaction for the influence of visibility and speed on comfort ratings ( $F_{(4, 136)} = 2.86, p = .026, \eta_p^2 = .078$ ). An interaction graph with a shortened y-axis for better visibility is plotted in Figure 16.

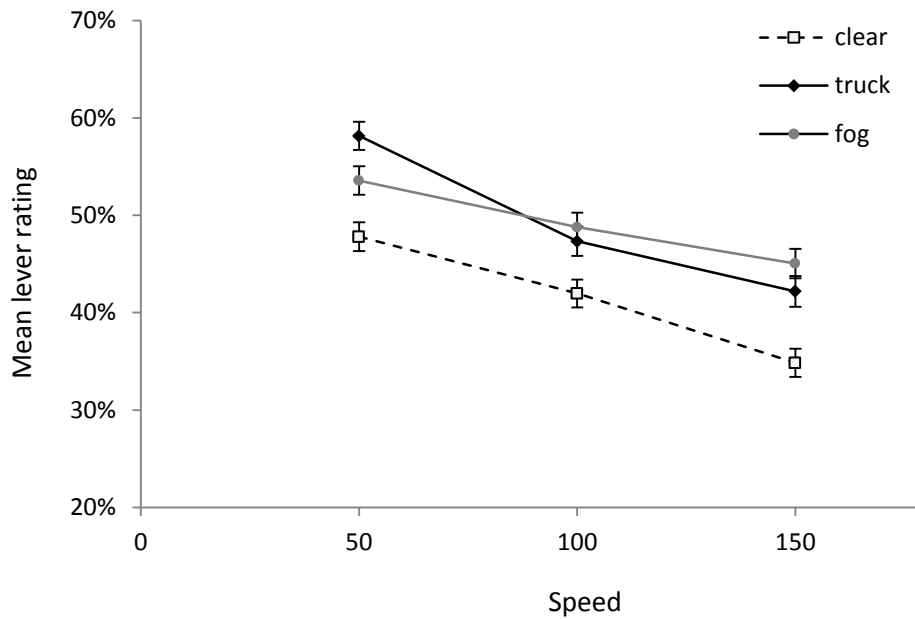


Figure 16. Interaction graph for mean lever ratings for all visibility and speed conditions (please note the shortened y-axis). Error bars show the 95% confidence interval.

In Figure 16 the main effect of speed is visible, lever ratings generally decrease when speed increases. The effect of visibility can also be observed, reduced visibility leads to higher lever ratings, i.e. less comfort, when compared to the clear visibility condition. However, it can be observed that the effect of visibility is influenced by the speed condition. In the 50km/h condition, following a truck is rated as less comfortable than following in a foggy environment. In the 100 and 150km/h condition, visibility does not have the same effect. Here following a truck is rated as more comfortable than following in fog.

#### 4.3.5 Comfortable vs. uncomfortable time headways

The median rating of a given condition indicates if a majority of participants rated a time headway as comfortable or uncomfortable. If the median lever position is lower than 50%, most participants rate a time headway as comfortable, while a median lever position higher than 50% indicates that

most participants rate a time headways as uncomfortable. Hence, comfort ratings can be dichotomized using the median lever position. An analysis of the transition points at which a majority of drivers rate time headway distances as no longer comfortable will be compared for different speed conditions, detailing the results related to our first hypothesis. We assumed there would be no influence of speed on comfort for comparable time headways, so the transition points should not be affected either.

Median ratings of each time headway for all speed and visibility conditions are presented in Table 4. The majority of participants rate time headways of 1.5 seconds and higher as comfortable in the clear visibility condition, i.e. the median lever rating for these time headways is lower than 50% indicating comfortable distances (Table 4). However, it can be observed that there is a difference in median ratings for different speeds. For the 50km/h condition, median ratings of time headway distances switch from comfortable to uncomfortable between 1.5 and 1.25 seconds. The shortest time headway distance that is rated as comfortable by a majority of participants is therefore 1.5 seconds. In the 100km/h condition, median ratings switch from comfortable to uncomfortable, i.e. pass a lever position of 50%, between 1.25 and 1.0 seconds time headway. Therefore the last comfortable time headway for following at 100km/h in clear condition is 1.25 seconds, 0.25 seconds smaller than in the 50km/h condition. This effect of velocity on comfort ratings of time headways is also found in the 150km/h condition, where the median rating changes from comfortable to uncomfortable between 1.0 and 0.5 seconds. Speed therefore appears to influence if a majority of participants rate a time headway as comfortable or uncomfortable in clear visibility conditions.

When following a vehicle at 50km/h in a foggy environment most participants rate distances smaller than 2.5 seconds as uncomfortable. For 100km/h a time headway of 1.75 is still rated as comfortable, for 150km/h

this distance is even smaller with 1.25 seconds still rated as comfortable by a majority of participants when following in fog. The influence of speed found in the clear visibility condition appears to be similar when visibility is reduced due to fog. The same effect can also be observed when participants follow a truck, the last comfortable time headway distance for a majority of participants is 2.5 seconds for 50km/h, 1.75 seconds for 100km/h, and 1.5 seconds for 150km/h.

Table 4. Median lever ratings for different time headways (TH), speeds, and visibility conditions.

TH	50km/h			100km/h			150km/h		
	clear	fog	truck	clear	fog	truck	clear	fog	truck
0.5	97.2%*	98.1%*	98.4%*	90.8%*	93.9%*	97.6%*	85.2%*	88.0%*	96.5%*
1.0	70.6%*	76.1%*	82.8%*	57.6%*	64.9%*	74.4%*	<b>48.6%</b>	56.2%	61.8%*
1.25	61.2%	65.4%*	75.4%*	<b>48.5%</b>	59.4%	65.3%*	<b>43.8%</b>	<b>48.3%</b>	54.1%
1.5	<b>49.0%</b>	57.5%	64.5%*	<b>48.0%</b>	55.4%	56.3%	<b>41.4%</b>	<b>39.8%</b>	<b>48.5%</b>
1.75	<b>48.5%</b>	55.4%	60.6%*	<b>43.8%</b>	<b>48.6%</b>	<b>48.5%</b>	<b>30.9%</b>	<b>39.6%</b>	<b>47.6%</b>
2.0	<b>47.8%</b>	50.1%	55.4%	<b>42.0%</b>	<b>48.5%</b>	<b>47.6%</b>	<b>33.4%</b>	<b>43.7%</b>	<b>36.6%</b>
2.5	<b>39.7%</b>	<b>47.9%</b>	<b>48.1%</b>	<b>33.9%</b>	<b>43.0%</b>	<b>48.0%</b>	<b>24.3%</b>	<b>40.5%</b>	<b>30.9%</b>
3.0	<b>35.0%</b>	<b>48.4%</b>	<b>42.9%</b>	<b>32.4%</b>	<b>40.6%</b>	<b>37.3%</b>	<b>16.3%</b>	<b>35.5%</b>	<b>25.4%</b>
3.5	<b>33.6%</b>	<b>44.2%</b>	<b>43.1%</b>	<b>24.1%</b>	<b>31.3%</b>	<b>29.1%</b>	<b>11.9%</b>	<b>43.6%</b>	<b>18.6%</b>
4.0	<b>27.5%</b>	<b>38.7%</b>	<b>34.1%</b>	<b>27.2%</b>	<b>31.7%</b>	<b>24.8%</b>	<b>3.0%</b>	<b>37.6%</b>	<b>3.6%</b>

Comfortable ratings with median lever position < 50% in bold.

\* lower bound of 95% confidence interval > 50%.

To find out if the true value for a given time headway rating is higher or lower than 50%, the confidence interval for ratings in each condition was calculated. Conditions in which the lower bound of the confidence interval is higher than 50% are marked with an asterisk in Table 4. In these conditions, the lever rating is expected to be higher than 50% in 95% of all observations. Looking at the data this way, shows a descriptive effect of



more uncomfortable time headways for the reduced visibility conditions, and for lower speeds.

#### 4.4 Discussion

In this study we examined the influence of different time headways on subjective comfort when following another vehicle with different speeds under different visibility conditions in an autonomous vehicle. In our first hypothesis we postulated that speed would not influence the subjective comfort for a given time headway. This hypothesis cannot be confirmed by the data, since in this study speed influences how comfortable a time headway is perceived. Further analysis also showed that time headways are rated as uncomfortable at lower speeds while the same time headways are perceived as comfortable at higher speeds. Speed did therefore not only influence the rating of time headways, but changed the perception of time headway following distances in this study. This result stands in contrast to the assumptions made on the basis of results of self- and assisted-driving, where a given comfortable time headway of one speed will also be experienced as comfortable at a different speed. These assumptions can therefore not be extended to fully autonomous driving. It is important to keep in mind that this study differs from earlier studies on time headway and subjective experience, in that the simulated car in this study was completely autonomous. Participants therefore did not have any control over the car. This could have a general effect on perceived comfort levels for time headways. If there was a simple effect of control, i.e. that less control (as in autonomous driving) leads to less comfort for a given time headway, this effect would be constant for different speeds. This simple effect would therefore not lead to the results found in this study. The nature of the effect of speed on comfort ratings of time headways therefore needs to be researched in more detail.

In our second hypothesis we postulated that reduced visibility leads to a decrease in comfortable ratings when compared to the same distances in the clear visibility condition. In this study, participants rated time headways as significantly more uncomfortable when visibility was reduced by a truck or due to fog, supporting our hypothesis. As discussed earlier, research on self-driving has not found a consistent effect of reduced visibility on car following behavior. The results of this study appear to support findings of increased headway following in reduced visibility conditions, and expand these findings to autonomous driving. Our results suggest that contrasting effects of a perception bias regarding the overestimation of the vehicle to vehicle distance and the underestimation of vehicle speed are not as large as the opposing behavioral effects of change in driver behavior.

In light of the conflicting results of earlier studies and their theoretical derivations, three arguments can be made about the experimental conditions that influenced our findings. First, participants were not motivated to drive fast or seek small time headways in our study, which could have influenced how time headways are rated by participants. Second, if the theory by Van der Hulst et al. (1998) is correct, and drivers increase their alertness in reduced visibility conditions to be able to follow close to other vehicles, this is an effect that cannot be transferred to autonomous cars. It can be assumed that drivers of autonomous cars expect the sensors of the car to always work on the highest alertness possible, i.e. that there is no extra alertness level for driving in reduced visibility conditions, allowing for close car following. This also holds true for the theory put forward by Sayer et al. (2000) and Brackstone et al. (2009) of easier following behind large vehicle due to possibly freed up mental resources stemming from reduced monitoring needs. Third, if drivers follow closer to large vehicles because they want to overtake them as fast as possible, as postulated by Harb et al. (2007), this effect would not materialize in our study, because there was no overtaking

by the autonomous car and participants could not initiate an overtaking maneuver.

In our third hypothesis we postulated that participants would rate time headways as more uncomfortable when following a truck, compared with following in a foggy traffic environment. Our results do not support this hypothesis, as an ANOVA showed no significant difference between comfort ratings of time headways of the fog and the truck condition. However, there was a significant interaction of visibility and speed. In the 50km/h condition, following a truck was indeed rated as more uncomfortable than following in fog. This effect was not present in the 100 and 150km/h conditions. Following a truck was therefore only rated as more uncomfortable than following in fog for the lowest speed presented in this study. A possible explanation for this effect could be the number of lanes in each traffic environment. In the 50km/h condition, participants drove on a two lane road, with one lane of traffic in each direction. In the 100 and 150km/h condition, there were two and three lanes of traffic in the same direction. Since the truck blocks the view of the lane ahead, the loss of additional lanes for possible evasive manoeuvres might contribute to the effect.

Effects of visibility on comfort ratings can also be observed descriptively in Figure 14 and Figure 15, small time headways are more often rated as uncomfortable in the truck condition than in the fog condition. A descriptive effect of fog on comfort ratings of time headways can be observed for larger time headways. While comfort increases with time headways in the truck condition, ratings stay more constant in the fog condition. This effect is most pronounced in the 150km/h condition. A possible explanation for this effect is the range of 200 meters set for the fog condition in this study. Although even in the largest time headway conditions of four seconds the lead vehicle is always visible (as the largest

distance of the 150km/h condition is 166.66 meters), visibility of the lead vehicle is highly reduced in these conditions. Furthermore, the lead vehicle is close to the edge of the visible driving environment, making emergency breaking manoeuvres more likely. This might be the onset of the effect of close following to keep eye-contact to the lead vehicle, found by Caro et al. (2009) and Broughton et al. (2007). The influence of the visibility range of driving in fog needs to be researched further to be able to interpret the influence of this effect.

This study has multiple limitations. The simulation of driving in a fixed based simulator, and especially the simulation of fog are different from real life driving and reduced visibility in the real-life driving environment. The results therefore have to be confirmed in real life driving conditions. The autonomous car simulated in this study was highly simplified. The car always drove with the exact speed of 50, 100, or 150km/h, kept the lane perfectly, and never overtook another vehicle. Future studies need to simulate autonomous cars that are closer to their real life counterparts in their behavior. The exposure to autonomous driving was very limited for most participants, it can be assumed that none of them had used an autonomous car in the past. It seems advisable to give participants more time to familiarize themselves with the behavior of the simulated car as drivers need time to develop a mental model of a car's automation (Beggiato, Pereira, Petzoldt, Krems, 2015). While the choice of using the truck model for the 150km/h condition was made with the intention to not change the model within the visibility condition, future studies should use vehicle models that can easily achieve the speeds that are simulated, such as large vans. Participants in this study were relatively young and inexperienced, as discussed before, experience has an influence on following behavior and should be investigated in future studies on this topic.

In summary, the results of this study add to the existing literature on car following and are a first step in expanding earlier findings for self-driving to autonomous driving. Speed influenced the comfort ratings of time headways, a finding that contrasts with results found in self and assisted driving. Reduced visibility led to a decrease in comfort. There was an interaction effect for the reduced visibility condition, i.e. following a truck at 50km/h was more uncomfortable than following in fog. This effect was not present in the 100 and 150km/h condition. Future studies need to investigate these effects in real life driving.

#### 4.5 References

Al-Ghamdi, A. S. (2007). Experimental evaluation of fog warning system. *Accident Analysis & Prevention*, 39(6), 1065-1072.

Aronsson, G., & Rissler, A. (1998). Psychophysiological stress reactions in female and male urban bus drivers. *Journal of occupational health psychology*, 3(2), 122.

Ayres, T. J., Li, L., Schleuning, D., & Young, D. (2001). Preferred time-headway of highway drivers. In *Intelligent Transportation Systems, 2001. Proceedings. 2001 IEEE* (pp. 826-829). IEEE.

Beggiato, M., Pereira, M., Petzoldt, T., & Krems, J. (2015). Learning and development of trust, acceptance and the mental model of ACC. A longitudinal on-road study. *Transportation research part F: traffic psychology and behaviour*, 35, 75-84.

Brackstone, M., Waterson, B., & McDonald, M. (2009). Determinants of following headway in congested traffic. *Transportation Research Part F: Traffic Psychology and Behaviour*, 12(2), 131-142.

Broughton, K. L., Switzer, F., & Scott, D. (2007). Car following decisions under three visibility conditions and two speeds tested with a driving simulator. *Accident Analysis & Prevention*, 39(1), 106-116.

Buchner, A., Brandt, M., Bell, R., & Weise, J. (2006). Car backlight position and fog density bias observer-car distance estimates and time-to-collision judgments. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 48(2), 300-317.

Caro, S., Cavallo, V., Marendaz, C., Boer, E. R., & Vienne, F. (2009). Can headway reduction in fog be explained by impaired perception of relative motion?. *Human factors*, 51(3), 378-392.

Cavallo, V., Colomb, M., & Doré, J. (2001). Distance perception of vehicle rear lights in fog. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 43(3), 442-451.

Charlton, S. G., Starkey, N. J., Perrone, J. A., & Isler, R. B. (2014). What's the risk? A comparison of actual and perceived driving risk. *Transportation research part F: traffic psychology and behaviour*, 25, 50-64.

Distler, H., & Bühlhoff, H. H. (1996). Velocity perception in 3-D environments. *Perception*, 25(1 suppl), 37-37.

Duan, J., Li, Z., & Salvendy, G. (2013). Risk illusions in car following: Is a smaller headway always perceived as more dangerous?. *Safety science*, 53, 25-33.

Evans, G. W. (1994). Working on the hot seat: Urban bus operators. *Accident Analysis & Prevention*, 26(2), 181-193.

Evans, L., & Rothery, R. (1976). The influence of forward vision and target size on apparent inter-vehicular spacing. *Transportation Science*, 10(1), 85-101.

Green, P., & Yoo, H. (1999). *Driver behavior while following cars, trucks, and buses* (No. UMTRI-99-14).

Harb, R., Radwan, E., Yan, X., & Abdel-Aty, M. (2007). Light truck vehicles (LTVs) contribution to rear-end collisions. *Accident Analysis & Prevention*, 39(5), 1026-1036.

Horswill, M. S., & Plooy, A. M. (2008). Reducing contrast makes speeds in a video-based driving simulator harder to discriminate as well as making them appear slower. *Perception*, 37(8), 1269-1275.

Kang, J., Ni, R., & Andersen, G. (2008). Effects of reduced visibility from fog on car-following performance. *Transportation Research Record: Journal of the Transportation Research Board*, (2069), 9-15.

Lewis-Evans, B., De Waard, D., & Brookhuis, K. A. (2010). That's close enough—A threshold effect of time headway on the experience of risk, task difficulty, effort, and comfort. *Accident Analysis & Prevention*, 42(6), 1926-1933.

Mueller, A. S., & Trick, L. M. (2012). Driving in fog: The effects of driving experience and visibility on speed compensation and hazard avoidance. *Accident Analysis & Prevention*, 48, 472-479.

O'Shea, R. P., Blackburn, S. G., & Ono, H. (1994). Contrast as a depth cue. *Vision research*, 34(12), 1595-1604.

Pekkanen, J., Lappi, O., Itkonen, T. H., & Summala, H. (2017). Task-difficulty homeostasis in car following models: experimental validation using self-paced visual occlusion. *PLoS one*, 12(1), e0169704.

Ross, H. E. (1967). Water, fog and the size—distance invariance hypothesis. *British Journal of Psychology*, 58(3-4), 301-313.

Sayer, J. R., Mefford, M. L., & Huang, R. (2000). The effect of lead-vehicle size on driver following behavior. *Ann Arbor*, 1001, 48109-2150.

Siebert, F. W., Oehl, M., Bersch, F., & Pfister, H. R. (2017). The exact determination of subjective risk and comfort thresholds in car following. *Transportation research part F: traffic psychology and behaviour*, 46, 1-13.

Siebert, F. W., Oehl, M., & Pfister, H. R. (2014). The influence of time headway on subjective driver states in adaptive cruise control. *Transportation research part F: traffic psychology and behaviour*, 25, 65-73.



Snowden, R. J., Stimpson, N., & Ruddle, R. A. (1998). Speed perception fogs up as visibility drops. *Nature*, *392*, 450.

Sotiropoulos, G., Seitz, A. R., & Seriès, P. (2014). Contrast dependency and prior expectations in human speed perception. *Vision research*, *97*, 16-23.

Sumner, R., Baguley, C., & Burton, J. (1977). Driving in fog on the M4. Transport and Road Research Laboratory Supplementary Report 281. Crowthorne, UK.

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.

Trick, L. M., Toxopeus, R., & Wilson, D. (2010). The effects of visibility conditions, traffic density, and navigational challenge on speed compensation and driving performance in older adults. *Accident Analysis & Prevention*, *42*(6), 1661-1671.

Van der Hulst, M., Rothengatter, T., & Meijman, T. (1998). Strategic adaptations to lack of preview in driving. *Transportation research part F: traffic psychology and behaviour*, *1*(1), 59-75.

Vehrs, W., & Hogrefe, C. J. (1986). Nicht-verbale Erlebnisbeschreibung. *Göttingen: Hogrefe*.

Vivoli, G., Bergomi, M., Rovesti, S., Carrozzi, G., & Vezzosi, A. (1993). Biochemical and haemodynamic indicators of stress in truck drivers. *Ergonomics*, *36*(9), 1089-1097.

Wasielewski, P. (1981). The effect of car size on headways in freely flowing freeway traffic. *Transportation Science*, *15*(4), 364-378.

Winsum, W. V., & Heino, A. (1996). Choice of time-headway in car-following and the role of time-to-collision information in braking. *Ergonomics*, 39(4), 579-592.

Winsum, W. V. (1999). The human element in car following models. *Transportation research part F: traffic psychology and behaviour*, 2(4), 207-211.

## 5 Conclusion

While each article in Chapter 2, 3, and 4 contains a discussion in which the results of individual experiments are discussed, the broad context of all three studies and the four research questions, formulated at the start of this dissertation, will be discussed in this chapter to present a comprehensive overview of the dissertation. Additionally, implications of the results of this dissertation for driver behavior modelling, as well as new opportunities for further research will be presented.

The first research question addressed the yet unexamined issue whether there is a threshold effect for time headways at different velocities. In this dissertation a threshold effect for time headway was defined as a constant level of subjectively experienced variables, e.g. risk and comfort, for a number of time headways. After a critical time headway was passed, these previously constant ratings were hypothesized to change rapidly. In the first experiment, this effect was descriptively observed for a velocity of 50km/h, 100km/h, and 150km/h (Figure 2). A regression analysis supported this descriptive conclusion: time headways larger than the hypothesized threshold were not significantly influenced by changing time headways, while time headways smaller than the threshold have a significant influence on subjective ratings. This threshold effect for the subjective experience of time headways was found for different velocities of 50km/h, 100km/h, and 150km/h. It is important to remember that while all experiments in this dissertation focused on the position of time headway thresholds, only the first study directly investigated the existence of a threshold effect. For the second and third experiment the existence of a threshold for the subjective experience of time headways was assumed. The method of limits used in the second experiment is a method used specifically for independent variables that elicit a threshold response, and the lever used in the third study for rating time headways is mechanically designed to have a noticeable haptic

effect when a threshold is passed. However, since a threshold effect was found for 50km/h by Lewis-Evans et al. (2010) and these results were replicated in the first experiment, these pieces of evidence were considered to be sufficient to assume the existence of a threshold effect for the second and third experiment.

The question about the existence of a threshold effect also has implication for the validity of zero- or target-theories (Fuller, 2005; Näätänen, & Summala, 1994; Summala, 1988, Wilde, 1982) as described in Chapters 1, 2.1, and 3.1. In the first experiment of this dissertation, a majority of participants did not report the experience of e.g. risk for large time headways (see Chapter 2.3 and 2.4). While the absence of subjective risk for large time headways is an indication for the validity of the zero-models, it is important to remember that there is no objective risk when driving in a simulator. Even with these limitations in mind, the results of this dissertation support zero-risk theories.

The second research question addressed the possible influence of velocity on the position of time headways thresholds. The results of the present research are inconclusive with regard to this question, since in the three experiments, the threshold position was influenced by velocity depending on the level of control a driver had over the vehicle. Due to the differing results for different levels of control, the results need to be looked at in more detail. In the first experiment, the conclusion that speed does not influence threshold positions stems from two observations. First, the descriptive findings of subjective Likert-scale ratings presented in Figure 2 and second, the subsequent regression analysis presented in Table 1. It has to be acknowledged that the regression analysis cannot be used to exactly pinpoint the location of the threshold. Due to the specified time headway ranges (derived from the assumed threshold position in Figure 2), the regression analysis only shows that time headways between 2.5 seconds and

4.0 seconds do not significantly influence subjective ratings and that subjective ratings are significantly influenced by time headways between 0.5 and 2.0 seconds. These findings do not by themselves allow the conclusion that the threshold is located between 2.0 and 2.5 seconds time headway. In this respect, the results for the subjective ratings of criticality (Figure 3), where time headways at 50km/h were generally rated as more critical than time headways at 100km/h and 150km/h, appear in a new light. While this difference in criticality was initially attributed to the road environment in the simulation (see Chapter 2.4) it could have been an indication of a possible influence of speed on time headway ratings.

To meet the challenges of threshold identification, the method of limits was used in the second experiment. While the author would argue that the method was applied successfully, the limitations of the two stage utilization of the method of limits, i.e., the static starting points of time headway sequences could have allowed participants to count the number of time headway steps at different speeds. This would result in equal time headway thresholds for different velocities. Hence, the author would advise researchers to vary starting points of the method of limits in the future.

After having found no significant influence of speed on time headway thresholds in experiment 1 and experiment 2, the results of the third study were not expected. A possible reason for the decrease in uncomfortable ratings at higher speeds might be the absence of the need to steer the vehicle. In the first and second experiment participants had to keep the lane by using the steering wheel in both the self- and assisted-driving conditions. This opens the possibility of steering errors that result in accidents. Since small steering errors are more dangerous at high speeds, the lack of steering input due to fully automated driving in the third experiment could have made high speed driving appear more comfortable. Generally, there was no influence of velocity on the position of time headway thresholds for self-

and assisted-driving. In automated driving, velocity influenced time headway thresholds, in that the time headway distances of thresholds decreased with increasing velocity.

This partly answers the third research question: “Is there a difference in the position of time headway thresholds between different levels of control over the vehicle?”. One effect of control was observed and discussed in research question number two, speed influenced time headway thresholds only in fully automated driving, but not in self- or assisted-driving. For a more general comparison of the location of time headway thresholds in self-, assisted- and automated driving, the time headway thresholds found in the second and the third experiment are plotted in Figure 17. Due to the different methodologies, threshold data in the figure is adapted in the following way: for the second experiment only the comfort group thresholds are plotted, to allow comparison to the third experiment in which comfort was the dependent variable. For the third experiment only data from the clear visibility condition was used to calculate thresholds, to allow comparison with the second experiment’s results where visibility was clear. Thresholds in the third experiment were calculated as the mean of two time headways: the time headway distance where the lower bound of the confidence interval for lever ratings was lower than 50% (i.e. still within the comfortable rating range), and the time headway distance where the lower bound of the confidence interval for lever ratings was higher than 50% (i.e. within the uncomfortable rating range). The thresholds can be identified in Table 4, they are calculated as the average of the last time headway marked with an asterisk and the first time headway without an asterisk. For this data no standard deviation could be calculated.

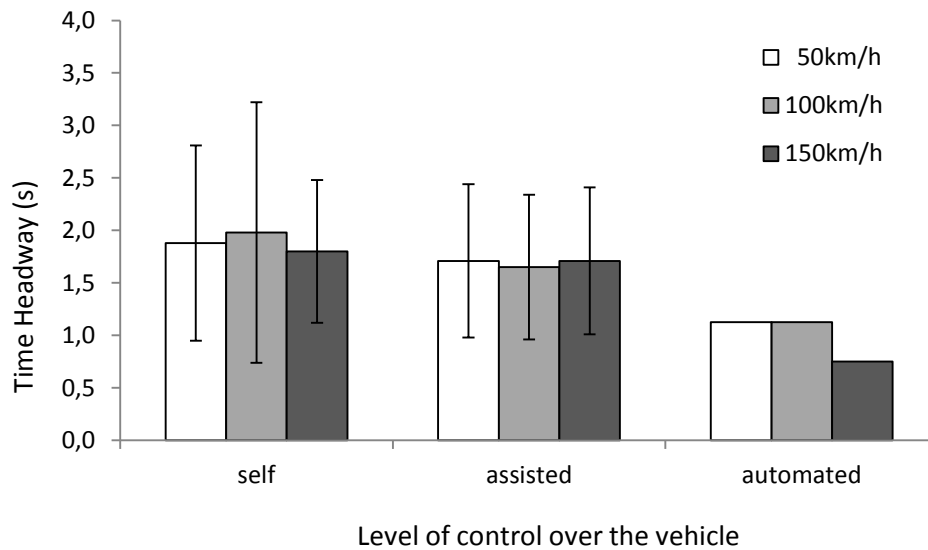


Figure 17. Time headway thresholds and standard deviation for different speeds and levels of control over the simulated vehicle.

When analyzing this data, it is important to recall how it was calculated. While thresholds for self- and assisted-driving (experiment two) are calculated as the average of individual thresholds of the comfort group, the thresholds for automated driving (experiment 3) are calculated as the average of the two time headways before and after the lower bound of the confidence interval of all ratings surpassed 50% (i.e. where the 95% confidence interval did not include the comfortable rating area anymore). Due to the difference in calculation, the thresholds are only compared descriptively. As described in Chapter 3, there is no significant difference in the location of time headway thresholds between self-and assisted driving. Time headway thresholds found for self-driving in experiment 2 were 1.88 seconds for 50km/h, 1.98 seconds for 100km/h, and 1.8 seconds for 150km/h. Time headway thresholds found for assisted driving in experiment 2 were 1.71 seconds for 50km/h, 1.65 seconds for 100km/h, and 1.71 seconds for 150km/h. The time headway thresholds found in experiment 3 for automated driving are markedly lower than thresholds for self- and assisted-driving. The time headway thresholds found for automated driving

were 1.13 seconds for 50km/h, 1.13 seconds for 100km/h, and 0.75 seconds for 150km/h. In this dissertation, there was a difference in the position of time headway thresholds between different levels of control over the vehicle. Thresholds for automated driving were lower than thresholds for self- and assisted-driving. Future research needs to investigate if individual thresholds still show a correlation over the three levels of control over the car, as they do for self- and assisted-driving (Figure 9).

The fourth research question addressed the influence of reduced forward visibility on the position of time headway thresholds. This research question can only be answered for automated driving, as visibility was not varied in the first and second experiment. In automated driving, visibility did influence comfort ratings of time headways. Under reduced visibility, time headways were rated as less comfortable, resulting in a higher time headway threshold, compared to clear visibility. An additional effect was found for the type of visibility reduction: following a truck was rated as less comfortable than following a normal sized car in fog for 50km/h. This effect was not observed 100km/h and 150km/h. These results of differing influences of visibility reduction on comfort ratings of time headways need to be researched further. Possible reasons for this finding are discussed in Chapter 4.4.

In summary, this dissertation represents further evidence for the existence of a threshold effect of time headway and the subjective experience of drivers. This time headway threshold is not influenced by the velocity of the vehicle in self-driving and assisted-driving. However, in automated driving, the time headway threshold position for the experience of comfort is influenced by velocity, in that the threshold shifts to smaller time headways for higher velocities. Irrespective of velocity, time headway thresholds are markedly lower for automated driving when compared to self- and assisted-driving. Forward visibility influences the position of time



headway thresholds in automated driving: results suggest that reduced visibility leads to a shift in time headway thresholds towards larger time headways.

The results of this dissertation lead to new questions that need to be addressed in future research. While evidence for the existence of a threshold for the subjective experience of time headway was found, this dissertation did not explore the influence of drivers' individual characteristics, such as long-term personality traits or short-term driver states, on the position of individual time headway thresholds. This relation represents a promising research direction, since individual time headways thresholds (visualized for assisted-driving in Figure 9) show a high variance between individual drivers. The influence of the level of vehicle control on time headway threshold positions was an unexpected result that needs to be investigated further. Automated cars depend on different levels of driver monitoring (NHTSA, 2013), and different levels of driver involvement in the monitoring task may influence time headway thresholds. Results on the influence of forward visibility show distinctive influences on the experience of time headway depending on the reason for the forward visibility reduction. When driving in fog, different densities and visibility ranges could influence the size of the effect of shifted time headway thresholds. Since all experiments presented in this dissertation were conducted in a driving simulator, studies in real-life traffic will need to reproduce all findings before their validity for real-life driving can be assumed.

Advanced driver assistant systems and automated driving will play an important part in the world's future mobility concepts. While the technical aspects of assisted and automated driving are currently focused on by the industry, the presented research investigated some of the psychological aspects of assisted and automated driving which are as important as the technical aspects.

## 5.1 References

Fuller, R. (2005). Towards a general theory of driver behaviour. *Accident Analysis & Prevention*, 37(3), 461-472.

Lewis-Evans, B., De Waard, D., & Brookhuis, K. A. (2010). That's close enough—A threshold effect of time headway on the experience of risk, task difficulty, effort, and comfort. *Accident Analysis & Prevention*, 42(6), 1926-1933.

Näätänen, R., & Summala, H. (1974). A model for the role of motivational factors in drivers' decision-making. *Accident Analysis & Prevention*, 6(3), 243-261.

NHTSA, National Highway Traffic Safety Administration (2013). *Preliminary Statement of Policy Concerning Automated Vehicles*. Retrieved from: [http://www.nhtsa.gov/staticfiles/rulemaking/pdf/Automated\\_Vehicles\\_Policy.pdf](http://www.nhtsa.gov/staticfiles/rulemaking/pdf/Automated_Vehicles_Policy.pdf)

Summala, H. (1988). Risk control is not risk adjustment: The zero-risk theory of driver behaviour and its implications. *Ergonomics*, 31(4), 491-506.

Wilde, G. J. S. (1982). The theory of risk homeostasis: implications for safety and health. *Risk analysis*, 2(4), 209-225.