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Why do drivers maintain short headways in fog? A driving simulator study evaluating feeling of risk and lateral control during automated and manual car following

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(adapted with minor textual changes)

Abstract

Drivers in fog tend to maintain short headways, but the reasons behind this phenomenon are not well understood. This study evaluated the effect of headway on lateral control and feeling of risk in both foggy and clear conditions. Twenty-seven participants completed four sessions in a driving simulator: clear automated (CA), clear manual (CM), fog automated (FA) and fog manual (FM). In CM and FM, the drivers used the steering wheel, throttle and brake pedals. In CA and FA, a controller regulated the distance to the lead car, and the driver only had to steer. Drivers indicated how much risk they felt on a touchscreen. Consistent with our hypothesis, feeling of risk and steering activity were elevated when the lead car was not visible. These results might explain why drivers adopt short headways in fog.

1. Introduction

Fog is one of the most dangerous conditions a motorist can drive in. Crashes in fog tend to be more severe than crashes in clear weather and are associated with pile-ups involving multiple fatalities (Abdel-Aty, Ekram, Huang, & Choi, 2011; Al-Ghamdi, 2007; Johnson, 1973; Musk, 1991; Sumner, Baguley, & Burton, 1977; Whiffen, Delannoy, & Siok, 2003). Because fog is a rare weather condition, the numbers of fatal road traffic crashes in fog account for only about one to three percent of the total (Organization for Economic Co-operation and Development, 1994). However, on an absolute scale, fog contributes to a considerable number of fatalities. In representative Western countries such as the United States, Canada, and Germany, the annual number of fatal traffic crashes in fog has been estimated at 355, 54 and 33, respectively (Lerner, 2002 cited in Debus et al., 2005; National Highway Traffic Safety Administration Fatality Analysis Reporting System [NHTSA-FARS], 2009; Whiffen et al., 2003).

A peculiar phenomenon of driving in fog is that drivers tend to maintain a shorter headway to the lead vehicle than they do in clear weather. Motorway measurements by White and Jeffery (1980) showed that when visibility dropped below 200 m, drivers reduced their headway, expressed as both inter-vehicle distance and as temporal separation. At a visibility distance of 150 m, about 30% of vehicles maintained headways within 2 s. This percentage was some 2.5 times higher than the percentage observed in normal traffic flow in clear weather. According to White and Jeffery, these findings demonstrate that fog causes platooning and provokes unsafe behavior. Similar findings were reported by Hawkins (1988). A driving-simulator study by Ni, Kang, and Andersen (2010) found that older drivers in particular followed at short headways in fog.

When driving in fog, a driver is deprived of preview and road texture information that may be relevant to lateral control. A simulator study by Uc et al. (2009) found that drivers with Parkinson's disease had poorer lane-keeping accuracy than controls, and that the effect size was larger in mild fog than in clear weather. Brooks et al. (2011) found that the mean percentage of the driving time that the vehicle was entirely within its lane was reduced in fog, but only when the visibility distance dropped below 30 m. A small study in a driving simulator by Malaterre, Hary, & Quéré (1991) showed that driving in fog reduced low frequency steering wheel movements (between 0.1 and 0.3 Hz), indicating reduced use of visual preview information. They hypothesized that a lead vehicle might serve as a guide in lateral control. However, their experiment found no significant differences in steering behavior between driving in fog with versus without the presence of a lead car. As Caro, Cavallo, Marendaz, Boer, and Vienne (2009) pointed out, no experimental data is currently available that proves the influence of the lead car on lateral control in fog.

Caro et al. (2009) showed that maintaining shorter headways in fog led to shorter response times than long headways, due to better contrast and improved visibility of the leading vehicle outline. This suggests that headway reduction is an adaptive mechanism in drivers to achieve faster discrimination of relative motion. The results by Caro et al. (2009) are supported by Kang, Ni, and Andersen (2008), who found that drivers in fog have difficulty detecting rapid speed changes in the lead car.

Another mechanism that may be operating in fog is altered distance perception (Brown, 1970). A fog chamber experiment has shown that in fog people overestimate distance by as much as 60% (Cavallo, Colomb, & Doré, 2001). However, overestimation of distance can only marginally explain the short headways observed in fog, because distance overestimation occurs only in extremely dense fog when just the lead vehicle's lights remain visible and the lead car's outline cannot be perceived (Caro, 2008).

Fog decreases visual stimulation of the peripheral field, reduces global optical flow, and creates a featureless environment. All this may cause drivers to underestimate their speed (Malaterre et al., 1991; Musk, 1991), resulting in headway reduction. Underestimation of speed could be aggravated by the fact that the driver cannot easily check the speedometer while concentrating on the road ahead (Musk, 1991). Snowden, Stimpson, and Ruddle (1998) confirmed that as fog becomes denser, subjects perceived driving scenes to be moving more slowly, and drove at faster speeds in a low-fidelity driving simulator. However, these results are contradicted by a number of studies using more sophisticated driving simulators (e.g., Debus et al., 2005; Owens, Wood, & Carberry, 2010).

In addition to these studies, which use perceptual mechanisms to explain headway reduction, a number of researchers have alluded to emotional variables such as fear, worry, or sense of risk, to explain the headway reduction. There is good reason to believe that emotional variables play a crucial role in car driving. General theories of car driving behavior suggest that psychological mechanisms in car driving can be conceptualized as avoidance of threat (Fuller, 1984) or risk

(Näätänen & Summala, 1974). According to Musk (1991), fog is the weather hazard that drivers fear most. Edwards (1996) pointed out that motorway drivers may be anxious about losing sight of the lead vehicle, being struck by another vehicle from behind, or becoming detached from the road environment. Driving in fog without the presence of a lead vehicle also increases the chance of sudden confrontations with slow-moving vehicles, and drivers may therefore be reluctant to lead a queue (Musk, 1991). A survey of 1,773 drivers found that a psychological push-pull mechanism with respect to other cars contributes to short headways (Schönbach, 1996). In this study, 65% of respondents indicated that it is usually reassuring for them if they see the taillights of the car ahead. A recent driving-simulator study by Broughton, Switzer, and Scott (2007) found that high lead-car speed combined with dense fog prompted two distinctive behaviors in the drivers they tested: one group ceased to follow the lead car within visible limits and dropped back to a longer following distance. The other group maintained visual contact with the lead car, possibly at the expense of safety. These results indicate that the visibility threshold might function as a psychological barrier, separating drivers into laggers (who drive at lower speeds at the expense of unguided driving) and non-laggers (who closely follow a lead car that provides guidance).

Of the reported mechanisms explaining headway reduction, the roles of lateral control and emotional variables such as feeling of risk have hardly been studied experimentally. The present study aimed to understand why drivers maintain short headways in fog by focusing on lateral control and subjective feeling of risk. This paper investigated these two mechanisms using a paradigm involving automated car following at seven preprogrammed following distances, including the condition when the lead car is not visible. Previous driving-simulator research by Lewis-Evans, De Waard, & Brookhuis (2010) showed that the participants' feeling of risk as a function of headway has a horizontal asymptote towards increasing headway: Feeling of risk was low or nil at large headways, but showed an increase around 28 m (i.e., a temporal separation of 2.0 s in that study), and increased further for shorter headways. It was expected that an asymptotic pattern would be replicated in clear weather, but would not be present in foggy conditions. Moreover, it was hypothesized that if the lead car were out of sight in foggy conditions (i.e., large headways), drivers would report higher levels of subjective risk than when the lead car was visible. Furthermore, it was expected that when the lead car is not visible, a more active lateral control behavior would occur, indicating compensatory steering due to lack of preview.

Drivers' feeling of risk and lateral control behavior during manual and automated car-following scenarios were compared for both foggy and clear weather conditions. It was hypothesized that automatic car following would result in lower feelings of risk and reduced lateral control activity than manual car following because of the reduced physical and mental activity required.

2. Method

2.1. Participants

Twenty-seven participants (twenty-two men and five women) who held a driver's license for at least six months were recruited from the university community. All participants provided written informed consent. The experiment was approved by the Human Research Ethics Committee of the Delft University of Technology.

Analysis of an intake questionnaire showed that the mean age of participants was 28.9 years (*SD* = 2.8 years) and they had held a driving license for on average 10.0 years (*SD* = 3.4 years). Fifteen participants reported that they had driven in a simulator before, and five reported playing video games for at least one hour a week. The response to the item "I have good steering skills (for instance in cycling or computer games)" rated 7.4 (*SD* = 1.6) on average, on a scale from one (*completely disagree*) to ten (*completely agree*). Four participants reported driving daily, nine drove weekly, and fourteen monthly or less. Twenty-one participants reported no experience with cruise control systems or indicated that they used cruise control systems less than once a year.

2.2. Apparatus

The fixed-base driving simulator (Figure 1) provided a realistic simulation of a mid-class passenger car with 180° field of view and surround sound. This simulator is used for initial driver training in the Netherlands (Green Dino, 2011). The pedals, steering wheel, ignition key, and seat resembled those of an actual car, and gear changing was automatic. The steering wheel provided force feedback with a passive spring system. The steering sensitivity (i.e., a parameter representing the ratio of lateral acceleration to steering wheel angle) was calibrated to correspond to the steering sensitivity of cars on the road (Katzourakis, De Winter, De Groot, S., & Happee, 2012). The simulation data stream was updated at 50 Hz. The virtual world was depicted by three LCD projectors (one front projector, NEC VT676, brightness 2,100 ANSI lumens, contrast ratio 400:1, resolution 1,024 × 768 pixels; two side projectors, NEC VT470, brightness 2,000 ANSI lumens, contrast ratio 400:1, resolution 800 × 600 pixels). The dashboard, interior, and mirrors were integrated in the projected image. The car model used in this study had an automatic transmission.

Figure 1. Driving simulator in the experimental setup. The lead car is driving 31 m ahead of the participant's car. The driver is indicating the level of risk he is feeling on the touchscreen mounted on the steering wheel. Note that the eye-tracking equipment was not used in this experiment.

2.3. Experimental conditions

The experiment contained four sessions, each featuring a weather/driving condition applied in a within-subject design: clear automated (CA), clear manual (CM), fog automated (FA), and fog manual (FM). The order of sessions was counterbalanced using a Latin square. In the CM and FM sessions, the drivers operated the steering wheel, throttle, and brake pedals. In the CA and FA sessions, an automatic controller regulated the throttle and brake, and the driver had only to steer the car. In all CA and FA sessions, headway as a function of time was identical throughout the session.

The fog was created by blending a light grey color with each rasterized pixel fragment's post-texturing color. The blending factor was a linear function of the distance in eye coordinates to the fragment being fogged and was 100% for 40 m. The subjective visibility threshold of the lead car corresponded to a bumper-to-bumper distance of approximately 35 m, representing dense fog (Musk, 1991).

Table 1. Summary of the behavior of the lead car and participant's car (i.e., following car) during the experiment.

	Lead car in all sessions	**Participants' car in clear automated (CA) and fog automated (FA) sessions**	**Participants' car in clear manual (CM) and fog manual (FM) sessions**
Constant-speed phase (40–300 s)	Constant speed of 80 km/h	Seven 10-s intervals with constant distance (26, 81, 16, 31, 6, 21, and 161 m). In between these intervals, the automatic controller adjusted the distance.	Manual longitudinal control using brake and throttle pedals
Variable-speed phase (330–420 s)	Multisine speed profile with mean speed = 99 km/h and *SD* of speed = 10 km/h	Multisine speed profile; follows lead car at virtually constant distance of 30 m (*SD* = 0.5 m). Mean speed = 99 km/h and *SD* of speed = 10 km/h.	Manual longitudinal control using brake and throttle pedals

Note. In all sessions, drivers had to steer themselves while gear changing was automatic.

All sessions took place on a straight motorway with three 5-m wide lanes. There was no other traffic besides the participants' car and the lead car driving along the right-hand lane. The speed profile of the lead car was the same in all sessions (see Section 3.2). Each session contained two main phases: a 260-s constant-speed phase during which the lead car kept a constant-speed (i.e., from 40 s to 300 s) and a 90-s variable-speed phase during which the lead car's speed was a multisine with different phase shifts (from 330 s to 420 s). The multisine was designed such that lead car speed was not predictable for the participant (cf. Jagacinski & Flach, 2003). The automatic controller used the start-up phase (0–40 s) and transition phase (300–330 s) to acquire the desired initial following distance and velocity. At the start of the experiment, the participant's car stood still, 35 m behind the lead car. The automatic controller resembled a real adaptive cruise control (ACC) system and used a string-stable sliding mode controller to ensure constant spacing with respect to the lead car (Rajamani et al., 2000). In the constant-speed phase, the automatic controller successively maintained the following seven bumper-to-bumper distances (with corresponding time interval of the session in parentheses): 26 m (50–60 s), 81 m (80–90 s), 16 m (120–130 s), 31 m (150–160 s), 6 m (180–190 s), 21 m (210–220 s), and 161 m (260–270 s). Thus, the lead car was not visible for two of the seven distances. The inter-vehicle distance of 31 m is shown in Figure 1. In the variable-speed phase, the automatic controller kept the following distance close to 30 m (*SD* = 0.5 m). The behavior of both lead car and participant's car is summarized in Table 1.

2.4. Information provided to participants

Participants were informed in writing that the goal of the experiment was to investigate how visibility (i.e., presence or absence of fog) and adaptive cruise control (ACC i.e., a system that automatically keeps a constant following distance to the car in front) influence driving performance and behavior. They were also informed about the four experimental conditions, the simulator controls, the questionnaire, and risk measurement (see below). The instructions stated that their task was to 1) follow the car in front, 2) drive swiftly but safely, and 3) always keep the car accurately centered in the right-hand lane and not overtake or change lanes. Finally, the documentation informed drivers about the possible occurrence of simulator sickness, and stated that they could leave the experiment any time they wished.

2.5. Procedures

On arriving at the driving-simulator laboratory, participants read the information sheet, signed the informed consent form, and completed a short intake questionnaire. They then sat in the simulator and performed two practice sessions of four minutes each, the first with clear vision, the second with the fog. In the first two minutes of each practice session, participants drove manually and in the last two minutes, they drove with the automatic controller activated.

Next, the participants completed the four 420 s experimental sessions. After each session, participants got out of the simulator for a short break (about four minutes) and to fill in a questionnaire containing the six-item NASA Task Load Index (Hart & Staveland, 1988; a widely used questionnaire in driving research, see e.g., De Groot, Centeno Ricote, & De Winter, 2012; Dey & Mann, 2010; Hart, 2006; Stinchcombe & Gagnon, 2010) as well as four items on the participant's feeling of risk and self-confidence. The extra items were: 1) "I had a feeling of risk during driving”, “I think I drove more safely than the average participant in this experimental condition”, “This car-following task was easy”, “I felt confident in my own capability to act appropriately”, all on a 21-tick scale from 0% (strongly disagree) to 100% (strongly agree).

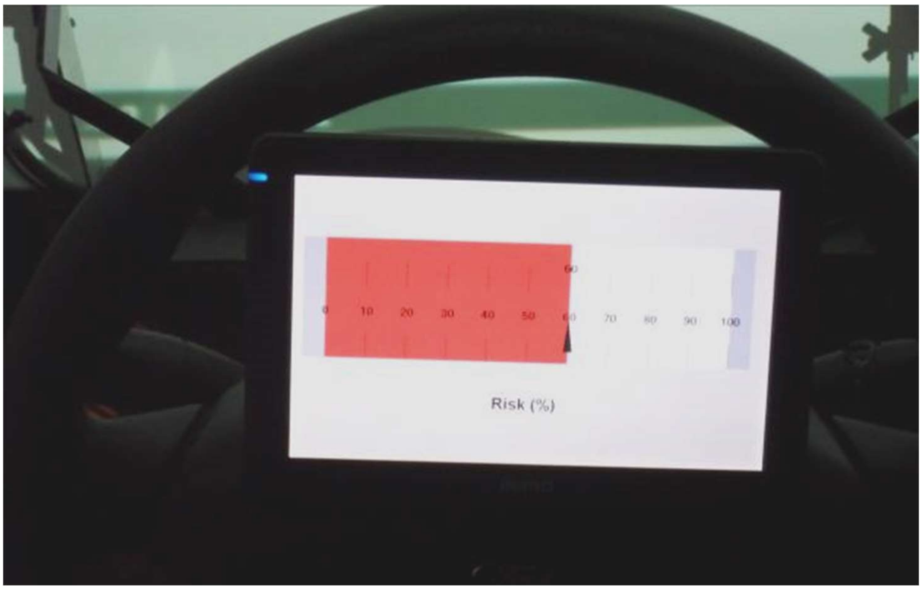

Figure 2. The touch screen interface used by the participants to indicate their feeling of risk at several prescribed moments.

During all sessions, participants had the secondary task of indicating their feeling of risk using a touchscreen mounted on the steering wheel. At the sound of a beep, the participants had to rate how much risk they felt on a scale from 0% (no risk at all) to 100% (extremely risky), on a horizontal bar with 10% increments (Figure 2). The beep was produced at the following moments of each session, t = 50, 80, 120, 150, 180, 210, 260, 310, 330, 350, 370, 390, and 410 s. The first seven beeps corresponded to the seven following distances in the constant-speed phase with the automatic controller, and the remaining six beeps were displayed every 20 s in the variable-speed phase.

2.6. Dependent variables

First, the steering angle data was filtered using a second-order Butterworth forward-reverse digital filter with a cutoff frequency at 1 Hz, using MATLAB’s *filtfilt* function, in order to remove sensor noise. Next, steering activity was calculated by applying a finite impulse response (FIR) forward-reverse digital filter on the absolute steering angular speed, also using MATLAB’s *filtfilt* function.

The filter assigned equal weight to samples and used a 10 s interval (i.e., 10 s before and 10 s after). By applying such a low pass filter, a reliable indication about the participants' temporal fluctuations of steering activity within the session was obtained.

Descriptive statistics (means and standard deviations of participants) of the following measures were calculated for the constant-speed phase and variable-speed phase.

2.6.1. Vehicle control activity

- *Mean steering activity (deg/s)*: Steering activity is a measure of lateral control. A low steering activity indicates smooth steering, whereas a high value describes compensatory and corrective steering.

- *Standard deviation of the throttle position (%)*: This measure represents the participant's activity with the throttle pedal.

- Standard deviation of the brake position (%): This measure represents the participant's activity with the brake pedal.

2.6.2. Driving performance

- *Standard deviation of lateral position (SDLP; m)*: SDLP is a commonly used measure describing a driver's swerving on the road (e.g., Brookhuis, De Waard, & Fairclough, 2003; Dijksterhuis, Brookhuis, & De Waard, 2011; Van der Zwaag et al., 2012).

- *Mean following distance (m)*.

- *Standard deviation of following distance (m)*: This measure describes how well the participant nullified distance differences with respect to the lead car (cf. Brookhuis, De Waard, & Mulder, 1994, showing that this is a valid measure that can be used in an on-the-road test battery)

2.6.3. Subjective evaluation

- *Mean feeling of risk (%)*: This measure represents the average risk level as indicated on the touchscreen.

- *Responses to the questionnaire (%)*.

In order to test our hypotheses regarding feeling of risk and lateral control as a function of following distance, steering activity levels and following distances were extracted from the constant-speed phase at t = 55, 85, 125, 155, 185, 215, and 265 s, in the middle of each of the 10-s constant-distance intervals. The feeling-of-risk levels were extracted at the end of each 10-s interval, that is, at t = 60, 90, 130, 160, 190, 220, and 270 s.

2.7. Statistical analyses

Comparisons between experimental sessions and following distances were all conducted with paired t tests. Because of the heterogeneity of variances between groups, and the expected nonlinear relationships between feeling of risk and steering activity versus distance, simple t tests were preferred over complex bivariate or multivariate tests. The steering activities and feeling-of-risk levels corresponding to the seven following distances in the constant-speed phase were rank transformed (Conover & Iman, 1981) prior to submitting to the t test, for higher robustness and to cope with possible outliers.

3. Results

3.1. Excluded sessions

One participant driving in the FM session did not keep the lead car in sight, maintaining a speed of about 40 km/h throughout the session and gradually increasing the following distance to about 4.5 km. Later on, this participant said that he had chosen to drive at this speed because he wanted to maintain a safe stopping distance in case an obstacle appeared on the road. Due to the long following distance, this session and corresponding questionnaire were withdrawn from the analysis. The first participant in the experiment braked repeatedly in the FA session, thereby inadvertently interfering with the automatic controller. This session and corresponding questionnaire were also withdrawn from the analysis. After this session, the written task instructions was clarified by including a statement that told drivers not to press the brake pedal during the automated sessions. Analysis of the results showed that in all later CA and FA sessions, participants obeyed the instructions and did not use the brakes.

Two participants driving in the FM session lost contact with the lead car in the variable-speed phase, resulting in long following distances (> 200 m). The CM session was stopped accidently at

400 s instead of 420 s for one participant. The variable-speed phase for these three sessions was withdrawn, but their constant-speed phase and questionnaire results were kept in the analysis. In summary, all twenty-seven participants were included in the analysis, but two sessions were excluded completely, and for three other sessions, the variable-speed phase was excluded.

3.2. Descriptive statistics

Table 2 shows descriptive statistics for all four sessions. FM resulted in closer following (lower *M* Distance) and more consistent car following (lower *SD* Distance) than CM. Driving in fog evoked more active steering and higher feeling of risk than driving in clear visibility (FM > CM and FA > CA). The SDLP was lowest in the FM session compared to the other sessions, indicating that manual driving in fog resulted in superior lane-keeping performance. The questionnaire results showed that fog resulted in a higher level of risk and mental and physical demands, compared to clear visibility (FM > CM and FA > CA).

Figures 3 to 6 illustrate the following distance, speed, feeling of risk, and steering activity, respectively, as a function of time for each of the four sessions. Figure 3 shows that for FM, drivers adopted a closer headway throughout the session compared to CM. Figure 4 shows that in the FM session, participants followed the lead car by closely matching the lead-car speed profile (high control gain) in the variable-speed phase, whereas in CM, drivers were able to 'absorb' the speed variations of the lead car with limited speed adaptations, because of the larger following distance. The high control gain, indicating higher longitudinal control activity for FM compared to CM, is also demonstrated by *SD* Throttle and *SD* Brake in Table 2.

The feeling of risk presented in Figure 5 shows a wider range of risk feeling with automated car following (CA and FA) than with manual car following (CM and FM). Fog resulted in overall higher feelings of risk than clear conditions (FA > CA, FM > CM). Figure 6 shows that steering activity was highest with the lead car out of sight (distance > 35 m) in the fog sessions, that is t = 80–90 s and t = 260–270 s in FA, as well as around t = 315 s in FA and FM.

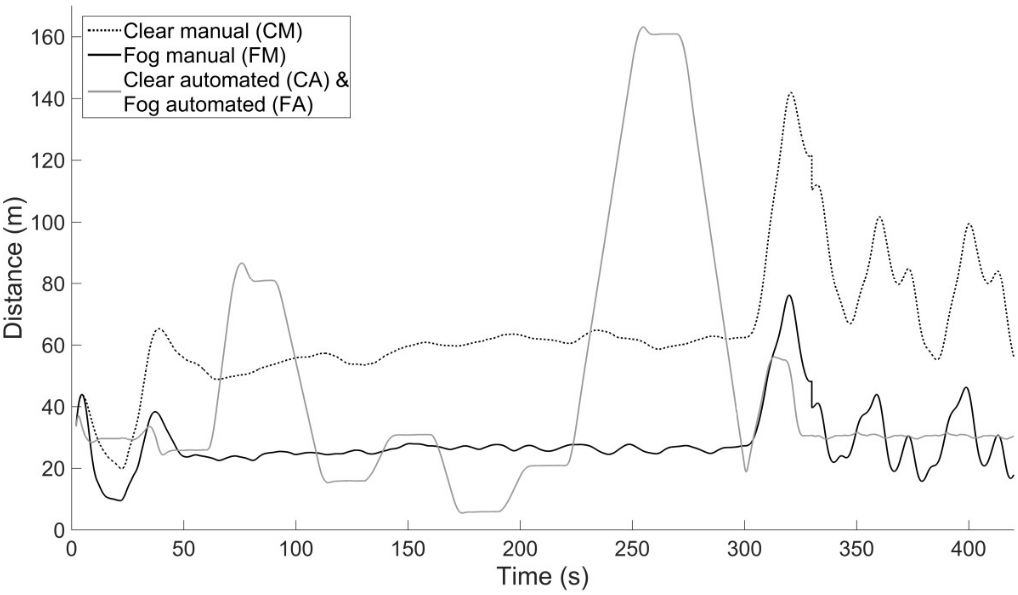

Figure 3. Following distance during the experiment for all four experimental conditions. The lines represent the participants' average per time point. Note that distance as a function of time is identical for each driver in clear automated and fog automated.

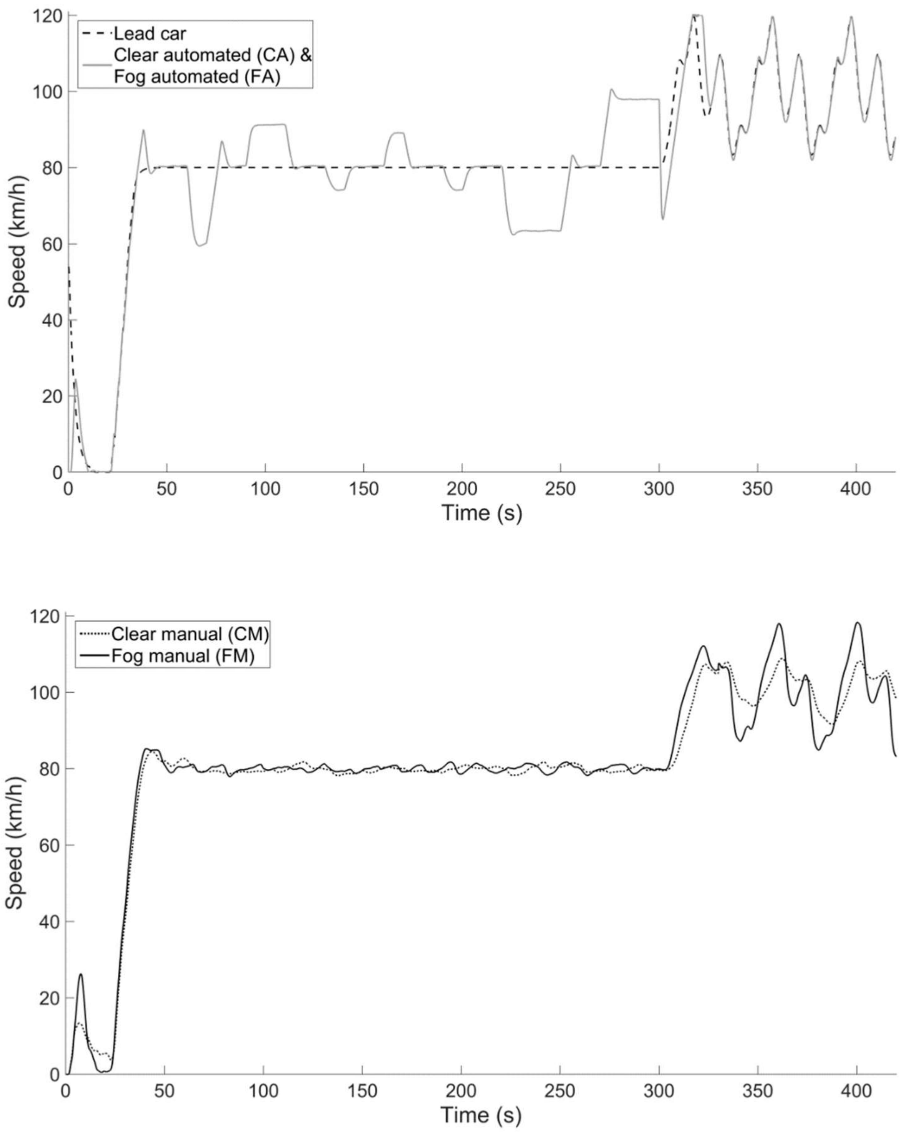

Figure 4. Speed of the driver's car and the lead car during the experiment, for all four experimental conditions (top: lead car in all conditions, clear automated, and fog automated; bottom: clear manual and fog manual). The lines represent the participants' average per time point. Note that speed is identical for each driver in clear automated and fog automated. The automatic controller required some time to catch up with the lead car in the transition between constant-speed and variable-speed phase (300–330 s).

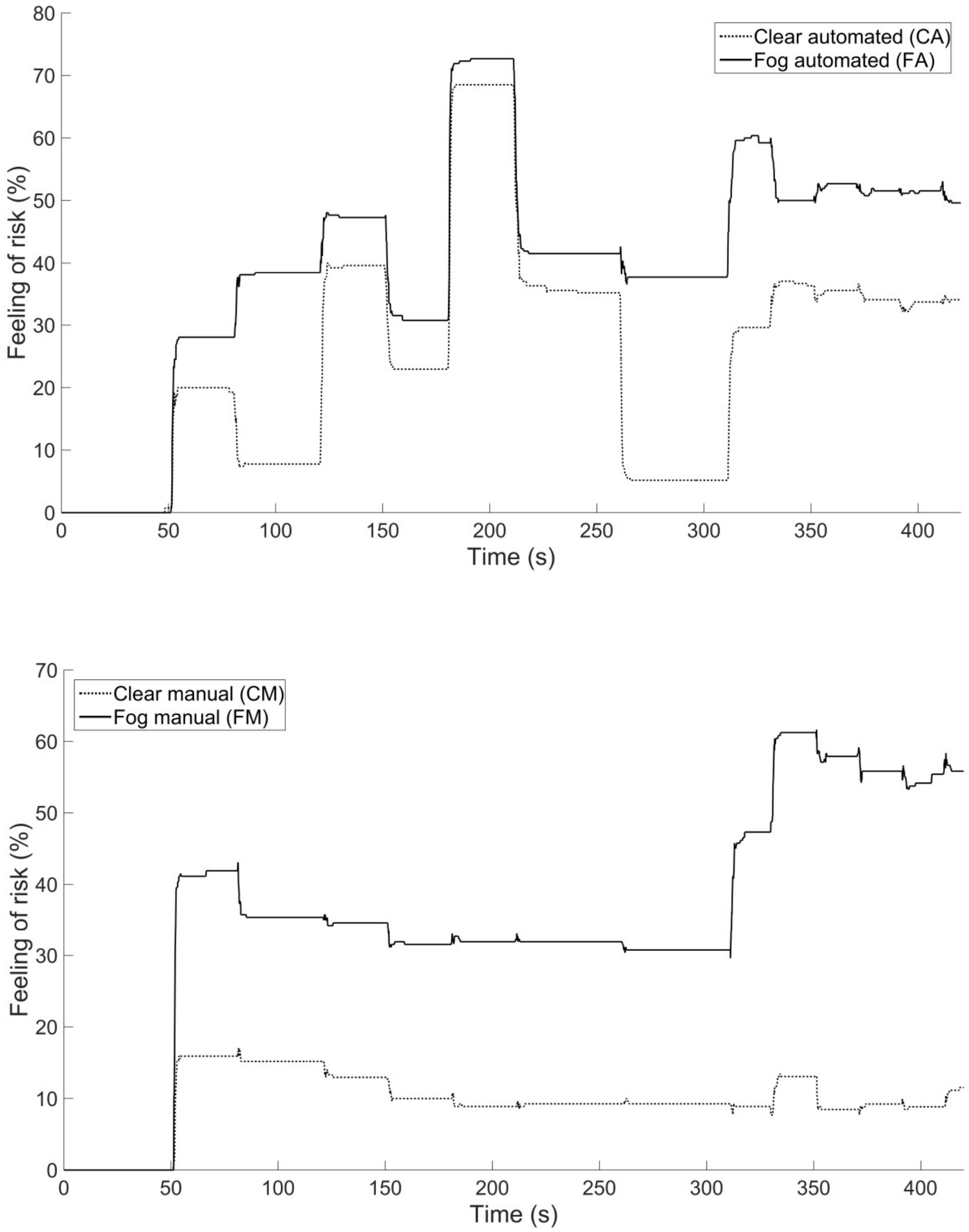

Figure 5. Feeling of risk as indicated by drivers during the experiment for all four experimental conditions (top: clear automated and fog automated; bottom: clear manual and fog manual). The lines represent the participants' average per time point. Note that risk levels changed at distinct moments, when drivers responded to the sound of the beep.

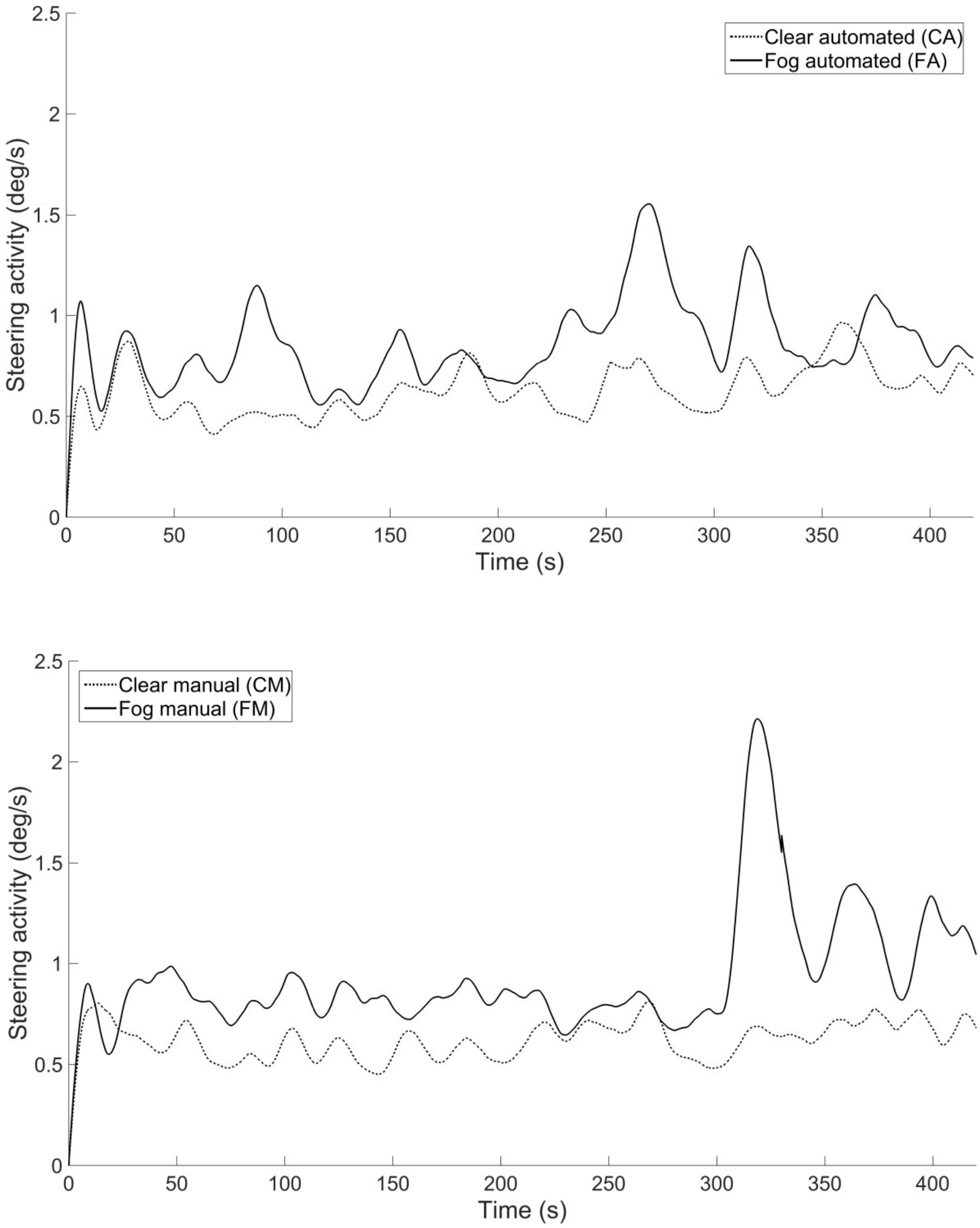

Figure 6. Steering activity during the experiment for all four experimental conditions (top: clear automated and fog automated; bottom: clear manual and fog manual). The lines represent the participants' average per time point.

Table 2. Descriptive statistics, showing the means across participants (standard deviations in parentheses), and the *p*-values for comparisons between sessions.

	CA	CM	FA	FM	*p* CA vs. FA	*p* CM vs. FM	*p* CA vs. CM	*p* FA vs. FM
Constant-speed phase (40–300 s)								
M Steering activity (deg/s)	0.58 (0.30)	0.59 (0.21)	0.85 (0.41)	0.81 (0.33)	**.000**	**.000**	.712	.587
SD Throttle (%)	-	9 (4)	-	12 (6)	-	**.001**	-	-
SD Brake (%)	-	0.7 (2.0)	-	1.2 (2.8)	-	**.025**	-	-
SDLP (m)	0.37 (0.14)	0.30 (0.10)	0.34 (0.09)	0.26 (0.08)	**.043**	**.009**	**.003**	**.000**
M Distance (m)	55 (0)	59 (47)	55 (0)	26 (5)	-	**.000**	.665	**.000**
SD Distance (m)	48 (0)	16 (14)	48 (0)	5 (2)	-	**.000**	**.000**	**.000**
M Feeling of risk (%)	26 (15)	11 (11)	40 (15)	32 (18)	**.000**	**.000**	**.000**	**.004**
Variable-speed phase (330–420 s)								
M Steering activity (deg/s)	0.74 (0.51)	0.69 (0.28)	0.86 (0.46)	1.15 (0.48)	.197	**.000**	.489	**.000**
SD Throttle (%)	-	18 (7)	-	30 (6)	-	**.000**	-	-
SD Brake (%)	-	2.0 (3.1)	-	9.4 (3.7)	-	**.000**	-	-
SDLP (m)	0.36 (0.12)	0.34 (0.10)	0.34 (0.12)	0.27 (0.08)	.531	**.000**	.360	**.036**
M Distance (m)	30 (0)	81 (45)	30 (0)	29 (8)	-	**.000**	**.000**	.500
SD Distance (m)	0 (0)	21 (8)	0 (0)	12 (5)	-	**.000**	**.000**	**.000**
M Feeling of risk (%)	35 (23)	10 (10)	51 (24)	57 (23)	**.000**	**.000**	**.000**	.109
Questionnaires								
TLX Mental demand (%)	25 (22)	27 (24)	42 (23)	51 (21)	**.000**	**.000**	.622	.062
TLX Physical demand (%)	17 (15)	23 (21)	25 (18)	35 (22)	**.005**	**.016**	.063	.075
I had a feeling of risk during driving (%)	44 (23)	20 (19)	63 (23)	59 (25)	**.002**	**.000**	**.000**	.323
This car-following task was easy (%)	77 (21)	75 (20)	68 (22)	51 (23)	.103	**.000**	.726	**.001**

Note 1. CA = Clear automated, CM = Clear manual, FA = Fog automated, FM = Fog manual, TLX = Task Load Index

Note 2. Table includes only four selected questionnaire items that reveal large effects. p values < .05 are in boldface.

3.3. Feeling of risk as a function of following distance

Figure 7 illustrates the feeling of risk in the constant-speed phase as a function of following distance. Corresponding means and standard deviations are provided in Table 3. The differences in feeling of risk between CA and FA were relatively small at 6, 16, 21, 26, and 31 m (t = 1.89, 2.72, 1.67, 3.46, 2.44; p = .070, .012, .107, .002, .022) compared to the CA-FA differences in feeling of risk at 81 and 161 m (t = 7.57, 11.7, both $p < .001$).

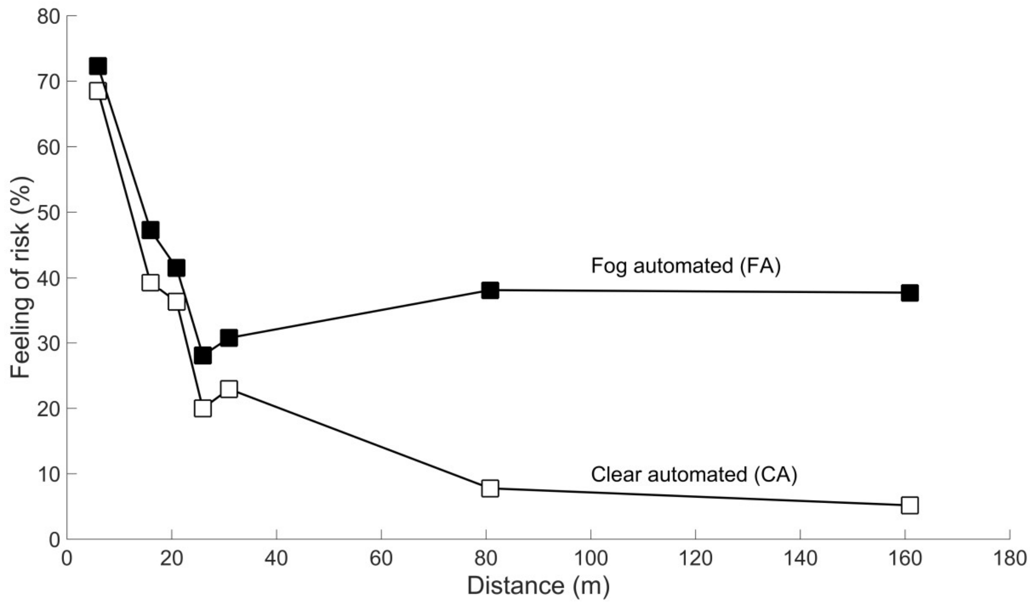

Figure 7. Mean of feeling of risk versus mean of following distance, derived from various moments in the constant-speed phase (*t* = 60, 90, 130, 160, 190, 220, and 270 s). Mean distances are sorted in ascending order with a line connecting the points.

Table 3. Means (standard deviations in parentheses) of participants' following distance, feeling of risk, and steering activity during the constant-speed phase.

	Distance (m)			Feeling of risk (%)				Steering activity (deg/s)			
t **(s)**	**CA and FA**	**CM**	**FM**	**CA**	**CM**	**FA**	**FM**	**CA**	**CM**	**FA**	**FM**
55	26 (0)	54 (53)	24 (12)	20 (17)	16 (18)	28 (18)	41 (22)	0.57 (0.25)	0.72 (0.63)	0.76 (0.41)	0.87 (0.47)
85	81 (0)	53 (65)	24 (8)	8 (13)	15 (16)	38 (22)	35 (19)	0.52 (0.28)	0.55 (0.19)	1.09 (0.84)	0.82 (0.27)
125	16 (0)	54 (56)	26 (7)	39 (26)	13 (16)	47 (22)	35 (20)	0.58 (0.41)	0.63 (0.35)	0.63 (0.44)	0.89 (0.39)
155	31 (0)	61 (58)	28 (7)	23 (21)	10 (14)	31 (18)	32 (21)	0.67 (0.43)	0.65 (0.26)	0.93 (0.77)	0.73 (0.35)
185	6 (0)	62 (54)	27 (6)	69 (22)	9 (13)	72 (25)	32 (19)	0.80 (0.78)	0.63 (0.34)	0.82 (0.65)	0.92 (0.68)
215	21 (0)	62 (38)	26 (6)	36 (21)	9 (11)	42 (21)	32 (19)	0.66 (0.35)	0.67 (0.36)	0.73 (0.45)	0.86 (0.50)
265	161 (0)	59 (40)	26 (6)	5 (11)	9 (10)	38 (21)	31 (19)	0.79 (0.87)	0.77 (0.63)	1.49 (1.07)	0.86 (0.44)

Note 1. CA = Clear automated, CM = Clear manual, FA = Fog automated, FM = Fog manual. Distance and steering activity were extracted at the middle of each 10-s interval (time denoted as t), whereas feeling of risk were extracted at the end of each 10-s interval (t + 5 s).

Figure 7 further shows that in FA, the feeling of risk follows a distinct pattern, with risk being high for the shortest following distance (6 m), decreasing up to about the visibility threshold, and then rising with increasing distance. A paired t test showed that the feeling of risk in FA was significantly *higher* for a following distance of 81 m ($t = 2.08$, $p = .048$) and 161 m ($t = 2.03$, $p = .053$), as compared to a following distance of 26 m. In contrast, for CA, the feeling of risk was *lower* for 81 m ($t = -5.18$, $p < .001$) and 161 m ($t = -6.57$, $p < .001$) compared to the feeling of risk at 26 m. In other words, consistent with our hypothesis, the reported feeling of risk in FA was elevated when the lead car was not visible (i.e., distance > 35 m).

3.4. Lateral control as a function of following distance

Figure 8 shows the influence of following distance on steering activity, with corresponding means and standard deviations shown in Table 3. It can be seen that steering activity was higher for FA than CA. The differences between FA and CA were relatively small at 6, 16, and 21 m (t = 0.12, 0.90, 0.68; p = .906, .375, .503).

They were somewhat larger at 26 and 31 m (t = 1.58, 2.40; p = .126, .024), and were very large at 81 and 161 m (t = 5.63, 4.73, both $p < .001$). Mean steering activity when following at a distance of 161 m in FA was 1.49 deg/s, which is considerably higher than mean steering activity at 21 m (0.73 deg/s, $t = -4.71$, $p < .001$). For CA, these means were 0.79 and 0.66 deg/s, respectively, an insignificant effect ($t = -0.27$, $p = .788$). These results support our hypothesis that steering activity is high when the lead car is out of sight (distance > 35 m in fog).

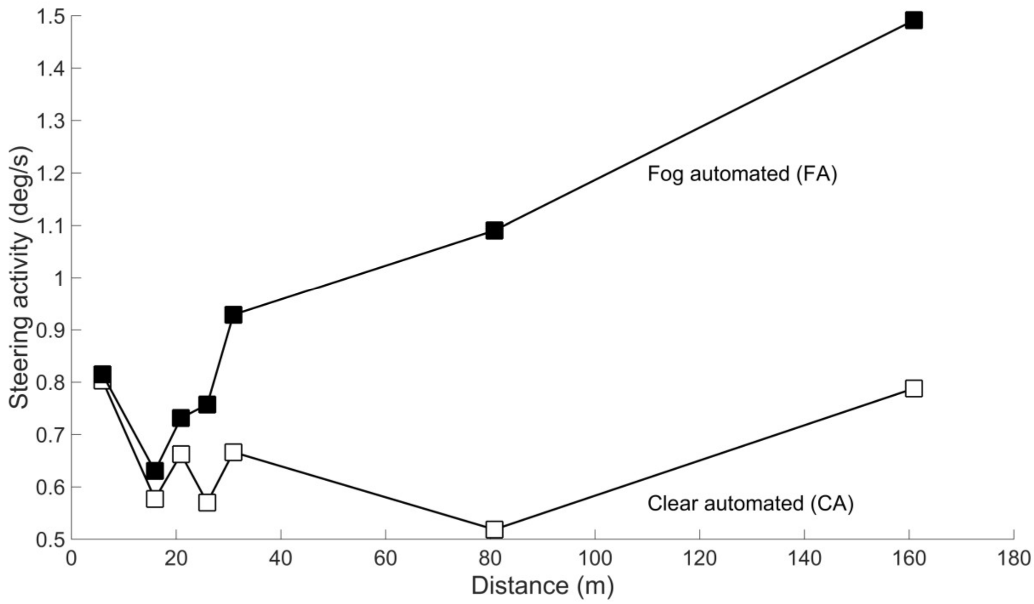

Figure 8. Mean steering activity versus mean of following distance, derived from various moments in the constant-speed phase (*t* = 55, 85, 125, 155, 185, 215, and 265 s). Mean distances are sorted in ascending order with a line connecting the points.

3.5. Differences between automated and manual car following

Additionally, it was investigated whether feeling of risk and steering activity differed between manual and automated car following. Table 2 shows that for the constant-speed phase, feeling of risk was significantly higher during automated compared to manual following (CA > CM and FA > FM). Steering activity, on the other hand, revealed no significant differences between the automatic and manual sessions. Note that the mean following distances also differed during the sessions (cf. Figure 3) and could have acted as a confound. Therefore, this study investigated whether feeling of risk and steering activity were different between automated and manual following when following distance was taken into consideration.

In FM, the mean following distance was 26 m and mean feeling of risk was 34% (averages of the seven values shown in Table 3). This feeling of risk in FM was not significantly different from the feeling of risk in FA at 26 m (28%, $t = 1.71$, $p = .100$). The mean following distance for CM was 51 m, and mean feeling of risk was 12% (averages again taken from Table 3). The feeling-of-risk value does not deviate significantly from the corresponding value in CA (15%, $t = -1.09$, $p = .286$;

the average feeling of risk for the 31 m and 81 m distances in CA was used). In other words, there were no significant differences during the constant-speed phase between automated and manual car following in the indicated feeling of risk, when equivalent following distances are compared.

Mean steering activity for the seven distances in FM was 0.85 deg/s (average of the seven values shown in Table 3), significantly higher than mean steering activity in FA at 26 m (0.76 deg/s, t = 2.65, p = .014). The mean steering activity for CM was 0.66 deg/s, which was significantly higher than the steering activity in CA, averaged for the 31 m and 81 m distances (0.59 deg/s, t = 2.27, p = .032). Summarizing, when equivalent following distances are compared, steering activity was slightly higher in FM compared to FA, as well as for CM compared to CA.

4. Discussion

The aim of this study was to understand the mechanisms behind the observation that drivers maintain short headways in fog by focusing on the effects of headway and fog on lateral control (i.e., steering activity) and subjective feeling of risk during driving. During manual car following in fog, participants maintained headways that were just within the visibility threshold. Even though drivers were instructed to follow the car in front, three drivers lost contact with the lead car in fog. Broughton et al. (2007) similarly found that fog separates drivers into so-called non-lagging and lagging drivers.

For clear automated (CA), an asymptotic pattern for feeling of risk versus following distance was found, supporting a previous driving-simulator study by Lewis-Evans et al. (2010). Consistent with our hypotheses, for automated car following in fog (FA), steering activity and feeling of risk were elevated when the lead car was out of sight as compared to when the car was in sight. The lowest feeling of risk was observed when the lead car was *just* within the visibility threshold. These results suggest that the lead vehicle provides a guide, resulting in reduced lateral control activity. The standard deviation of lateral position (SDLP, a measure of lateral swerving performance) was lowest when manually driving in fog, indicating that drivers used the increased steering activity to improve their lateral performance (see also De Groot, De Winter, Garcia, Mulder & Wieringa, 2011; He & McCarley, 2011; Macdonald & Hoffmann, 1980).

When distance was taken into account, feeling of risk showed no difference between manual and automatic car following. The lack of difference between automated and manual driving is remarkable, given that the ACC relieved the driver of two important tasks: controlling the pedals and remaining vigilant with respect to the lead car's behavior. Note that the baseline levels of mental or physical demand (i.e., in the CM and FM sessions) were already low to begin with (Table 2) suggesting that floor effects may have occurred. A pilot experiment with other participants found lower subjective risk (as reported in a questionnaire) for automatic than for manual car following in fog. In this other experiment, the lead car had large fluctuations in speed, creating a more demanding driving task (Happee, Saffarian, Terken, Shahab, & Uyttendaele, 2011).

Our research provides the first experimental evidence to explain the role of feeling of risk and lateral control in headway reduction. Of course, this does not rule out that other mechanisms might play a role as well. For example, there is also support for the influence of fog on relative speed perception (Boer, Caro, Cavallo, & Arcueil, 2007; Boer, Caro, & Cavallo, 2008; Caro et al., 2009).

Despite its substantive findings, our study is not free of limitations. First, the lead car always drove perfectly down the center of the lane. A more realistic condition could have been achieved by implementing natural lane-keeping behavior for the lead car.

Second, a lane width of 5 m was used in this experiment which is relatively wide. On Dutch or North American motorways, for example, lane widths of 3.5 or 3.7 m are standard. It is known that reduction of lane width reduces SDLP, increases lane-boundary crossings, lowers speed, and increases subjective ratings of risk and mental effort (e.g., Dijksterhuis et al., 2011; Godley, Triggs, & Fildes, 2004; Lewis-Evans & Charlton, 2006; Yagar & Van Aerde, 1983). Lane width is likely to interact with lateral control behavior in fog, because drivers may use the lane markers as visual guidance. The interactive effect of lane width on lane maintenance in fog is an interesting topic for further research.

Third, this study did not involve traffic other than the car in front, which limits the external validity of the results. In real traffic, it has been observed that fog reduces the frequency of overtaking (White & Jeffery, 1980). Drivers who would normally overtake a lead car in clear visibility will be inclined to remain in their own lane in fog, potentially contributing to reduced headways. Furthermore, in real traffic, fog muffles sound, which might also contribute to the tendency to close following, and the ability to anticipate collisions (Musk, 1991).

Fourth, our fixed-base driving simulator used in this research offered medium fidelity in terms of visual cues and auditory cues and did not stimulate the vestibular organ. Drivers tend to behave differently in a simulator than they would do in a real car, demonstrating comparatively higher driving speeds, jerkier acceleration and braking behavior, altered lateral control behavior, and reduced perception of risk (e.g., Blana & Golias, 2002; Boer, Girshik, Yamamura, & Kuge, 2000; De Groot, De Winter, Mulder & Wieringa, 2011; De Groot & De Winter, 2011; Green, 2005; Hurwitz, Knodler, & Dulaski, 2005; Lew et al., 2005). Although driver behavior in the simulator is possibly biased in the absolute sense, simulators have proven value for establishing *relative* comparisons between different groups of drivers or experimental conditions, including drivers' risk-taking behavior (e.g., Bédard, Parkkari, Weaver, Riendeau, & Dahlquist, 2010; Deery & Fildes, 1999; De Winter et al., 2009; Godley, Triggs, & Fildes, 2002; Green, 2005; Lee, Lee, Cameron, & Li-Tsang, 2003; Reimer & Mehler, 2011; Wang et al., 2010).

Fifth, in order to acquire identical headways as a function of time in the CA and FA sessions, it was chosen to present the headways in the same order (26, 81, 16, 31, 6, 21, and 161 m) for each participant. There is some concern in the traffic-psychology literature that lack of randomization can distort self-reported feeling of risk (see Lewis-Evans & Rothengatter, 2009 for a comprehensive study). However, these concerns apply particularly to research that presents the independent variable in a monotonically ascending order, which was clearly not the case in this study which applied a semi-random order, and applied the sessions (i.e., CA, CM, FA, and FM) in fully randomized order.

Sixth, the results may depend on the type of simulated fog. It seems that researchers use vastly different methods for simulating fog of various densities (e.g., Allen, Rosenthal, Aponso, & Park, 2003; Broughton et al., 2007; Hoogendoorn, Hoogendoorn, Brookhuis, & Daamen , 2010, 2011; Kolisetty, Iryo, Asakura, & Kuroda, 2006; Pretto & Chatziastros, 2006; Rimini-Doering, Manstetten, Altmueller, Ladstaetter, & Mahler, 2001; Stanton & Pinto, 2000; Takayama & Nass, 2008; Van der Hulst, Rothengatter, & Meijman, 1998). Snowden et al. (1998) used a uniform contrast reduction whereas Dumont, Paulmier, Lecocq, and Kemeny (2004) proposed rendering sophisticated fog for both daytime and nighttime conditions, including light from headlamps scattered back by minute water droplets. In our experiment a thick fog was simulated using color blending as a function of distance without simulating fog lights which may remain visible when the outline of the car is no longer in sight (cf. Caro, 2008). Subjectively the simulated fog was realistic and none of the participants reported anything unusual regarding its appearance.

How can the present results be used to improve road safety? Our results suggest that headway reduction in fog does not constitute irrational or irresponsible driver behavior as has been suggested by several authors (e.g., Hawkins, 1988). Instead, headway reduction provides advantages such as smoother lateral control behavior, reduced feeling of risk (and, arguably, reduced objective risk), as well as improved perception of speed differences (demonstrated by Caro et al., 2009). Therefore, drivers should not be advised to maintain larger headways. Instead, drivers should be encouraged to reduce speed in order to shorten stopping distance.

Several studies have found beneficial effects of fog signaling and speed advisory systems (e.g., Hogema & Van der Horst, 1997; see also Hassan & Abdel-Aty, 2011 for a questionnaire study), whereas computerized traffic detection and warning systems on motorways are commonplace internationally. Another option is to give drivers proper advice about the impending situation. For example, Charissis & Papanastasiou (2010) used a simulator to test a head-up display (HUD) system in foggy conditions. Their HUD provided minimalist visual representations of real objects, such as lead vehicle symbols, lane symbols, and traffic symbols indicating congestion in close proximity. They found that the HUD dramatically reduced the number of collisions and improved subjects' maintenance of following distance, when compared to unaided driving. A third option is to use ACC using radar measurements of inter-vehicle spacing, or cooperative adaptive cruise control (CACC) using vehicle-to-vehicle communication (Naus, Vugts, Ploeg, Van de Molengraft, & Steinbuch, 2010). ACC and CACC automate the driving task and allow precise control of shorter headways between following vehicles. As illustrated in Figure 7, shorter headways can induce an elevated feeling of risk, even with automation. Thus also with automation a driver information system may be needed to inform drivers of the actions taken by the automated system and to provide sufficient reassurance about proper functioning of the system.

In conclusion, the present results suggest that there are two advantages to maintaining a close headway in fog: reduced feeling of risk and improved lateral control. These results are valuable for devising effective driver assistance and support systems.

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6. References

Abdel-Aty, M., Ekram, A.-A., Huang, H., & Choi, K. (2011). A study on crashes related to visibility obstruction due to fog and smoke. *Accident Analysis & Prevention, 43*, 1730–1737.

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

Allen, R. W., Rosenthal, T. J., Aponso, B. L., & Park, G. (2003). Scenarios produced by procedural methods for driving research, assessment and training applications. In *Proceedings of the Driving Simulation Conference North America*, Dearborn, MI.

Bédard, M., Parkkari, M., Weaver, B., Riendeau, J., & Dahlquist, M. (2010). Assessment of driving performance using a simulator protocol: Validity and reproducibility. *American Journal of Occupational Therapy, 64*, 336–340.

Blana, E., & Golias, J. (2002). Differences between vehicle lateral displacement on the road and in a fixed-base simulator. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 44*, 303–313.

Boer, E.R., Caro, S., & Cavallo, V. (2008). A perceptually grounded driver model for car following in fog. In *Proceedings of the Driving Simulation Conference Europe* (pp. 247–249), Monte Carlo, Monaco.

Boer, E. R., Caro, S., Cavallo, V., & Arcueil, F. (2007). A cybernetic perspective on car following in fog. In *Proceedings of the fourth international driving symposium on human factors in driver assessment, training and vehicle design* (pp. 9–12).

Boer, E. R., Girshik, A. R., Yamamura, T., & Kuge, N. (2000). Experiencing the same road twice: a driver-centred comparison between simulation and reality. In *Driving Simulation Conference* (pp. 33–55). Paris, France.

Brookhuis, K. A., De Waard, D., & Fairclough, S. H. (2003). Criteria for driver impairment. *Ergonomics, 46*(5), 433–445.

Brookhuis, K., De Waard, D. D., & Mulder, B. (1994). Measuring driving performance by car-following in traffic. *Ergonomics, 37*, 427–434.

Brooks, J. O., Crisler, M. C., Klein, N., Goodenough, R., Beeco, R. W., Guirl, C., … Beck, C. (2011). Speed choice and driving performance in simulated foggy conditions. *Accident Analysis & Prevention, 43*, 698–705.

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

Brown, I. (1970). Motorway crashes in fog-who's to blame? *New Scientist*, 544–545.

Caro, S. (2008). *Perception et contrôle de la distance intervéhiculaire en condition de brouillard: Etude sur simulateur*. Université Grenoble. Retrieved from https://hal.inria.fr/file/index/docid/544889/filename/TheseStephaneCaro.pdf

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: The Journal of the Human Factors and Ergonomics Society, 51*, 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* 442–451.

Charissis, V., & Papanastasiou, S. (2010). Human–machine collaboration through vehicle head up display interface. *Cognition, Technology & Work, 12*(1), 41–50.

Conover, W. J., & Iman, R. L. (1981). Rank transformations as a bridge between parametric and nonparametric statistics. *The American Statistician, 35*(3), 124–129.

Debus, G., Heller, D., Wille, M., Dütschke, E., Normann, M., Placke, L., … , Benmimoun, A. (2005). *Risikoanalyse von Massenunfällen bei Nebel* [*Risk analysis for multiple car collisions in fog*] (Report No. M 169). Bergisch-Gladbach, Germany: Bundesanstalt für Strassenwesen.

Deery, H. A., & Fildes, B. N. (1999). Young novice driver subtypes: Relationship to high-risk behavior, traffic accident record, and simulator driving performance. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 41*(4), 628–643.

De Groot, S., Centeno Ricote, F., & De Winter, J. C. F. (2012). The effect of tire grip on learning driving skill and driving style: A driving simulator study. *Transportation Research Part F: Traffic Psychology and Behaviour, 15*, 413–426.

De Groot, S., & De Winter, J. C. F. (2011). On the way to pole position: The effect of tire grip on learning to drive a racecar. In *Proceedings of IEEE International Conference on Systems, Man, and Cybernetics* (pp. 133–138). Anchorage, AK.

De Groot, S., De Winter, J. C. F., Garcia, J. M. L., Mulder, M., & Wieringa, P. A. (2011). The effect of concurrent bandwidth feedback on learning the lane-keeping task in a driving simulator. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 53*, 50–62.

De Groot, S., De Winter, J. C. F., Mulder, M., & Wieringa, P. A. (2011). Nonvestibular motion cueing in a fixed-base driving simulator: Effects on driver braking and cornering performance. *Presence: Teleoperators and Virtual Environments, 20*, 117–142.

De Winter, J. C. F., De Groot, S., Mulder, M., Wieringa, P. A., Dankelman, J., & Mulder, J. A. (2009). Relationships between driving simulator performance and driving test results. *Ergonomics, 52*, 137–153.

Dey, A., & Mann, D. D. (2010). Sensitivity and diagnosticity of NASA-TLX and simplified SWAT to assess the mental workload associated with operating an agricultural sprayer. *Ergonomics, 53*, 848–857.

Dijksterhuis, C., Brookhuis, K. A., & De Waard, D. (2011). Effects of steering demand on lane keeping behaviour, self-reports, and physiology. A simulator study. *Accident Analysis & Prevention, 43*, 1074–1081.

Dumont, E., Paulmier, G., Lecocq, P., & Kemeny, A. (2004). Computational and experimental assessment of real-time front-lighting simulation in night-time fog. In *Driving Simulation Conference* (pp. 197–208). Paris, France.

Edwards, J. B. (1996). Weather-related road accidents in England and Wales: a spatial analysis. *Journal of Transport Geography, 4*, 201–212.

Fuller, R. (1984). A conceptualization of driving behaviour as threat avoidance. *Ergonomics*, *27,* 1139–1155.

Godley, S. T., Triggs, T. J., & Fildes, B. N. (2002). Driving simulator validation for speed research. *Accident Analysis & Prevention, 34*, 589–600.

Godley, S. T., Triggs, T. J., & Fildes, B. N. (2004). Perceptual lane width, wide perceptual road centre markings and driving speeds. *Ergonomics, 47*, 237–256.

Green, P. (2005). How driving simulator data quality can be improved. In *Proceedings of the Driving Simulator Conference North America*, Orlando, FL. Retrieved from http://umich.edu/~driving/publications/How_Driving_Simulator_Data_Quality_Can%20Be_Improved_Final_Paper.pdf

Green Dino. (2011). *Driving Simulators*. Retrieved from http://www.greendino.nl/driving-simulators.html

Happee, R., Saffarian, M., Terken, J., Shahab, Q., & Uyttendaele, A. (2011, May). Human factors in the Connect & Drive project. Paper presented at the 8th International Automotive Congress. Eindhoven, The Netherlands.

Hart, S. G. (2006). NASA-task load index (NASA-TLX); 20 years later. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 50*, 904–908.

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. In P. Hancock and N. Meshkati (Eds.), *Human mental workload* (Vol. 2, pp. 139–183). Amsterdam, North Holland.

Hassan, H. M., & Abdel-Aty, M. A. (2011). Analysis of drivers' behavior under reduced visibility conditions using a Structural Equation Modeling approach. *Transportation Research Part F: Traffic Psychology and Behaviour, 14*(6), 614–625.

Hawkins, R. K. (1988). Motorway traffic behaviour in reduced visibility conditions. In A.G. Gale et al. (Eds.), *Vision in vehicles II* (pp. 9–21). Amsterdam: Elsevier Science.

He, J., & McCarley, J. S. (2011). Effects of cognitive distraction on lane-keeping: performance loss or improvement? *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 55*, 1894–1898.

Hogema, J., & van der Horst, R. (1997). Evaluation of A16 motorway fog-signaling system with respect to driving behavior. *Transportation Research Record: Journal of the Transportation Research Board, 1573*, 63–67.

Hoogendoorn, R. G., Hoogendoorn, S. P., Brookhuis, K. A., & Daamen, W. (2010). Simple and multi-anticipative car-following models: performance and parameter value effects in case of fog. In *Proceedings of the Transportation Research Board (TRB) Traffic Flow Theory and Characteristics Committee (AHB45) Summer Meeting* (pp. 2–16).

Hoogendoorn, R. G., Hoogendoorn, S. P., Brookhuis, K. A., & Daamen, W. (2011). Longitudinal driving behavior under adverse conditions: A close look at psycho-spacing models. *Procedia - Social and Behavioral Sciences, 20*, 536–546.

Hurwitz, D. S., Knodler, M. A., & Dulaski, D. M. (2005). Speed perception fidelity in a driving simulator environment. In *Proceedings of the Driving Simulator Conference North America* (pp. 343–352). Orlando, FL.

Jagacinski, R. J., & Flach, J. (2003). *Control theory for humans: quantitative approaches to modeling performance*. Mahwah, N. J.: L. Erlbaum Associates.

Johnson, H. D. (1973). *Motorway accidents in fog and darkness* (Report No. LR573). Crowthorne, UK: Transport and Road Research Laboratory.

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.

Katzourakis, D., De Winter, J. C. F., De Groot, S., & Happee, R. (2012). Driving simulator parameterization using double-lane change steering metrics as recorded on five modern cars. *Simulation Modelling Practice and Theory, 26*, 96–112.

Kolisetty, V. G. B., Iryo, T., Asakura, Y., & Kuroda, K. (2006). Effect of variable message signs on driver speed behavior on a section of expressway under adverse fog conditions - A driving simulator approach. *Journal of Advanced Transportation, 40*, 47–74.

Lee, H. C., Lee, A. H., Cameron, D., & Li-Tsang, C. (2003). Using a driving simulator to identify older drivers at inflated risk of motor vehicle crashes. *Journal of Safety Research, 34*, 453–459.

Lerner, M. (2002). Nebelunfälle in Deutschland in den Jahren 1995–1999. *Zeitschrift Für Verkehrssicherheit, 48*, 27–29.

Lew, H. L., Poole, J. H., Lee, E. H., Jaffe, D. L., Huang, H.-C., & Brodd, E. (2005). Predictive validity of driving-simulator assessments following traumatic brain injury: a preliminary study. *Brain Injury, 19*, 177–188.

Lewis-Evans, B., & Charlton, S. G. (2006). Explicit and implicit processes in behavioural adaptation to road width. *Accident Analysis & Prevention, 38*, 610–617.

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*, 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*, 1053–1063.

Macdonald, W. A., & Hoffmann, E. R. (1980). Review of relationships between steering wheel reversal rate and driving task demand. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 22*, 733–739.

Malaterre, G., Hary, A., & Quéré, F. (1991). Analyse spectral des mouvements de volant par temps de brouillard sur simulateur de conduite [Spectral analysis of steering wheel movements in fog in a driving simulator]. *Recherche Transports Sécurité, 30*, 52–56.

Musk, L. F. (1991). The fog hazard. In: A.H. Perry & L.J. Symons (Eds). *Highway meteorology* (pp. 91–130). London: E & FN Spon.

Näätänen, R., & Summala, H. (1974). A model for the role of motivational factors in drivers' decision-making. *Accident Analysis and Prevention*, *6*(3-4), 243–261.

National Highway Traffic Safety Administration Fatality Analysis Reporting System (NHTSA-FARS). (2009). Retrieved from http://www-fars.nhtsa.dot.gov

Naus, G. J. L., Vugts, R. P. A., Ploeg, J., Van de Molengraft, M. J. G., & Steinbuch, M. (2010). String-stable CACC design and experimental validation: A frequency-domain approach. *IEEE Transactions on Vehicular Technology, 59*, 4268–4279

Ni, R., Kang, J. J., & Andersen, G. J. (2010). Age-related declines in car following performance under simulated fog conditions. *Accident Analysis & Prevention*, *42*, 818–826.

Organization for Economic Co-operation and Development (OECD). (1994). Resolution no. 94/1 on driving in weather conditions of poor visibility. European Conference of Ministers of Transport (ECMT). Retrieved from http://www.internationaltransportforum.org/Pub/pdf/09CDsr/PDF_EN/15Res94_1_EN.pdf

Owens, D. A., Wood, J., & Carberry, T. (2010). Effects of reduced contrast on the perception and control of speed when driving. *Perception, 39*, 1199–1215.

Pretto, P., & Chatziastros, A. (2006). Changes in optic flow and scene contrast affect the driving speed. In *Driving Simulation Conference Europe* (pp. 263–272). Paris, France. Retrieved from http://www.safedriver.gr/data/141/DSC_2000-Pretto,Chatziastros_4076[0].pdf

Rajamani, R., Choi, S. B., Law, B. K., Hedrick, J. K., Prohaska, R., & Kretz, P. (2000). Design and experimental implementation of longitudinal control for a platoon of automated vehicles. *Journal of Dynamic Systems, Measurement, and Control, 122*, 470–476.

Reimer, B., & Mehler, B. (2011). The impact of cognitive workload on physiological arousal in young adult drivers: a field study and simulation validation. *Ergonomics, 54*, 932–942.

Rimini-Doering, M., Manstetten, D., Altmueller, T., Ladstaetter, U., & Mahler, M. (2001). Monitoring driver drowsiness and stress in a driving simulator. In *First International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design* (pp. 58–63). Retrieved from http://drivingassessment.uiowa.edu/DA2001/10_Rimini_Doering_Maria.pdf

Schönbach, P. (1996). Massenunfälle bei Nebel [Multiple car collisions in fog]. *Zeitschrift Für Sozialpsychologie*, 109–125.

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

Stanton, N., & Pinto, M. (2000). Behavioural compensation by drivers of a simulator when using a vision enhancement system. *Ergonomics, 43*, 1359–1370.

Stinchcombe, A., & Gagnon, S. (2010). Driving in dangerous territory: Complexity and road-characteristics influence attentional demand. *Transportation Research Part F: Traffic Psychology and Behaviour, 13*, 388–396.

Sumner, R., Baguley, C., & Burton, J. (1977). *Driving in fog on the M4* (Supplementary Report No. 281). Crowthorne, UK: Transport and Road Research Laboratory.

Takayama, L., & Nass, C. (2008). Driver safety and information from afar: An experimental driving simulator study of wireless vs. in-car information services. *International Journal of Human-Computer Studies, 66*, 173–184.

Uc, E. Y., Rizzo, M., Anderson, S. W., Dastrup, E., Sparks, J. D., & Dawson, J. D. (2009). Driving under low-contrast visibility conditions in Parkinson disease. *Neurology*, *73*, 1103–1110.

Van der Hulst, M. V. D., Rothengatter, T., & Meijman, T. (1998). Strategic adaptations to lack of preview in driving. *Transportation Research Part F: Traffic Psychology and Behaviour*, *1*, 59–75.

Van der Zwaag, M. D., Dijksterhuis, C., De Waard, D., Mulder, B. L. J. M., Westerink, J. H. D. M., & Brookhuis, K. A. (2012). The influence of music on mood and performance while driving. *Ergonomics, 55*, 12–22.

Wang, Y., Mehler, B., Reimer, B., Lammers, V., D'Ambrosio, L. A., & Coughlin, J. F. (2010). The validity of driving simulation for assessing differences between in-vehicle informational interfaces: A comparison with field testing. *Ergonomics*, *53*, 404–420.

Whiffen, B., Delannoy, P., & Siok, S. (2003). Fog: Impact on road transportation and mitigation options. In *10th World Congress and Exhibition on Intelligent Transportation Systems and Services*. Madrid, Spain. Retrieved from http://www.chebucto.ns.ca/Science/AIMET/archive/whiffen_et_al_2003.pdf

White, M. E., & Jeffery, D. J. (1980). *Some aspects of motorway traffic behaviour in fog* (Report No. 958). Crowthorne, UK: Transport and Road Research Laboratory.

Yagar, S., & Van Aerde, M. (1983). Geometric and environmental effects on speeds of 2-lane highways. *Transportation Research Part A, 17*, 315–325.

Appendix. Photos made for different bumper-to-bumper following distances between the participant's car and the lead car in the fog condition.

Following Distance = 6 m

Following Distance = 16 m

Following Distance = 21 m

Following Distance = 26 m

Following Distance = 31 m

Following Distance = 81 m

Following Distance = 161 m

Appendix. Photo of the car following scenario in the clear weather condition