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Enhancing Driver Car-Following Performance with a Distance and Acceleration Display

Mehdi Saffarian, Joost C. F. de Winter, and Riender Happee

***Abstract*—A car-following assisting system named the rear window notification display (RWND) was developed, with the aim of improving a driver's manual car-following performance. The RWND presented lead-car acceleration and time headway (THW) (i.e., intervehicle distance divided by the speed of the following car) on the rear window of a lead car, which was driven automatically. A simulator-based experiment with 22 participants showed that the RWND reduced both the mean and standard deviation of THW but did not increase the occurrence of potentially unsafe headways of less than 1 s. The parameter estimation of a common linear car-following model showed that drivers accomplished the performance improvements by adopting higher control gains with respect to intervehicle distance, relative speed, and acceleration. A postexperiment questionnaire revealed that the display was generally not regarded as a distraction nor did participants think that it provided too much information, with means of 4.0 and 2.9, respectively, on a scale from one (completely disagree) to ten (completely agree). The results of this study suggest that the RWND can be used along with Cooperative Adaptive Cruise Control to increase traffic flow without degrading safety.**

***Index Terms*—Adaptive cruise control (ACC), advanced driving assistant systems, car-following model, human–machine interface, visual feedback.**

I. Introduction

BECAUSE of developments in electronics, communication technology, and the processing power of computers, drivers are increasingly aided by advanced driver assistance systems. A growing number of vehicles are now equipped with adaptive cruise control (ACC), a system that has the capacity to adjust both brake and throttle, so as to maintain a constant headway with respect to the vehicle in front [1]–[3]. Marchau *et al.* [4] reviewed intelligent speed adaptation systems, ranging from those that provide information to those that intervene in vehicle operation and noted that, in all the reviewed studies, ACC reduced speeding violations and speed variability.

Several studies have evaluated traffic-flow and human-factor aspects of car following with different ACC systems in various driving conditions [5]–[9]. Evidence suggests that, although ACC potentially enhances safety by helping drivers maintain constant speed and headway [10], drivers must be aware of its limitations and intervene if ACC cannot handle a situation, such as on approaches to sharp curves, when the lead car brakes sharply, or in the event of system failure [11]–[14]. Current experience shows that drivers are less likely to use ACC in heavy traffic [15], which is precisely the situation where the greatest benefits could be achieved in traffic flow (shorter headways, avoiding coming to a full stop), safety (more homogenous traffic patterns), and fuel efficiency (following lead vehicles within their wake region and reducing the frequency and severity of braking and acceleration).

A next generation of ACC systems, known as cooperative ACC (CACC), is addressing the stability limits of conventional ACC systems [16], [17]. CACC systems communicate their kinematic state using high-bandwidth vehicle-to-vehicle communication. With CACC, it is possible to guarantee stability in traffic flow, meaning that intervehicle distance errors decrease as they propagate along the platoon [5], [16]. Simulations have shown that traffic throughput could increase significantly if 60% (or more) of all cars were equipped with CACC technology [7], [18]. However, in the introductory phase of cooperative driving, penetration rates would be low, making it desirable to design a system that can influence the behavior of drivers of cars without such equipment and facilitate cooperation with those vehicles that do have it.

This paper proposes a system that assists drivers of nonequipped cars by displaying combined acceleration information and headway advice on the rear window of cars equipped with CACC. In this simulator study, participants using the rear window notification display (RWND) directly control the vehicle with the gas and brake pedals and the steering wheel. The system design was based on the hypothesis that a display giving visual feedback on lead-car acceleration and time headway (THW) will act as a sensory aid for human drivers and thus enhance their car-following performance.

The paper is organized as follows: Section II presents the concept and design of the RWND. Section III describes the test procedure and experimental setup for evaluating the display

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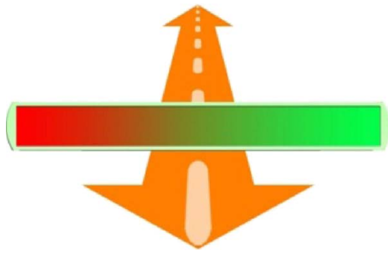

Fig. 1. RWND: Arrows indicate THW deviations (up is too far), and the horizontal bar indicates lead-vehicle acceleration (right is acceleration; left is deceleration).

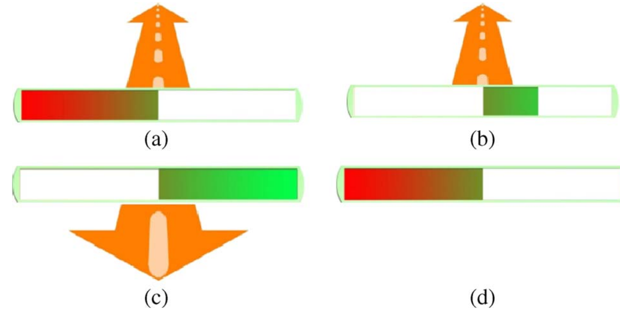

Fig. 2. Four possible states of the RWND: (a) Lead car brakes strongly—THW is greater than 1.5 s (decelerate but close the gap). (b) Lead car is accelerating moderately—THW is greater than 1.5 s (accelerate and close the gap). (c) Lead car is accelerating hard—THW is less than 1.0 s (accelerate but widen the gap). (d) Lead car brakes strongly—THW is between 1.0 and 1.5 s (decelerate and maintain current gap).

in a driving simulator. To examine the effect of the RWND, three types of measures were used: 1) traditional measures, such as mean and standard deviation of THW, to describe observable performance and behavior; 2) parameters of a linear driver model, to clarify how drivers use distance, speed, and acceleration information and how they adapt their control behavior; and 3) a questionnaire surveying drivers' opinions. Section IV discusses our results, while Section V deals with the implications of our research and suggests follow-up research.

II. Method

A. RWND

Previous research shows that, while drivers can detect speed changes, they are not good at estimating the duration and intensity of such changes, particularly regarding approaching objects (e.g., [19] and [20]). Brake lights provide a salient binary cue about deceleration and thus have an alerting function. However, traditional brake lights provide no information about the intensity of braking or about acceleration. This study hypothesized that augmented information on acceleration and deceleration intensity would be essential for improving car-following performance.

THW, defined as intervehicle distance divided by the speed of the following car, is a key indicator of the capacity of any transit system and correlates with a driver's perception of risk as measured with psychophysical methods [21]. It has also been found that drivers' preferred THW in real car-following situations is independent of speed [22]. Thus, THW was selected as the second parameter for the display, combining the safety perception of drivers with network capacity. THW and acceleration have complementary integrator and differentiator characteristics, respectively. Through visualized information of THW and acceleration, the human operator can observe both the long- and short-term effects of their control actions during car following.

The layout of the RWND is shown in Fig. 1. The display employed one horizontal bar and one vertical segment to communicate lead-car acceleration and THW, respectively. In order to facilitate stimulus response compatibility, the horizontal bar was aligned with the gas- and brake-pedal positions. Thus, lead-car acceleration was shown on the right, with the bar filling up according to the magnitude of acceleration. Similarly, deceleration (braking) appeared on the left side. Deceleration and acceleration demands were also distinguished by color, green to the right and red to the left. The right side was full at an acceleration magnitude of 1.6 m/s^2 (and above), while the left side was full at the same deceleration level (and above). The acceleration and deceleration bars were linear up to the saturation level stated earlier.

The second segment of the RWND consisted of one upward arrow and one downward arrow positioned above and below the horizontal bar, respectively. Colored orange, the arrows indicated THW in terms of deviation from the desired margin. An upward arrow meant that the driver should follow closer. If the downward arrow appeared, the following driver was too close and needed to increase THW. When no arrow was visible, the THW was within the desired range, and no action was required. The size of the arrows did not change with respect to the magnitude of the THW deviation. The THW values that triggered the appearance of the arrows were adjustable. In this paper, the setting was as follows. When THW was less than 1 s, the downward arrow appeared, while a THW greater than 1.5 s made the upward arrow visible. This approach is also known as bandwidth augmented feedback; it stimulates satisficing rather than optimizing behavior and prevents the driver from becoming distracted by or dependent on the feedback [23]. Because the augmented feedback is visible only when the information is needed for potential action, this avoids problems that arise with continuous concurrent feedback, such as over corrective control inputs [24].

These thresholds and other aspects of the display were based on a subjective interpretation of safe and comfortable driving during pilot tests in the driving simulator. The threshold of 1 s is the minimum recommended value for maintaining safe headway, according to some authorities, and is associated with comfortable driving [22]. To illustrate functionality, Fig. 2 shows four different states of the display.

In the simulator environment, the RWND was projected onto the rear window of the lead car. The size and position of the display was adjusted based on the relative distance and position of the lead car, so that, for the driver, it seemed as if the display was attached to the lead car. Fig. 3 shows the simulator environment with the RWND. In this snapshot, the lead car was decelerating, and the follower was instructed to increase the gap with respect to the lead car.

Fig. 3. RWND in the fixed-base driving simulator.

B. Driving Simulator

The experiment was conducted using a fixed-base simulator manufactured by Green Dino, with customized data collection. The simulator consisted of a cabin, an Intel Pentium IV 3.0 G computer that ran both the graphics and driving scenario of the simulator software, and a projector screen which provided a 180° horizontal field of view for the driver seated in the cabin. The virtual world was projected by three liquid crystal display (LCD) projectors (front projector NEC VT676, brightness 2100 American National Standards Institute (ANSI) lumens, contrast ratio 400 : 1, resolution 1024 × 768 pixels; side projectors NEC VT470, brightness 2000 ANSI lumens, contrast ratio 400 : 1, resolution 800 × 600 pixels). Integrated visuals of the road and other traffic, along with the car's features such as dashboard and mirrors, were shown on the projector screen. The cabin of the simulator resembled the front portion of a regular passenger car and was equipped with gas, brake, and clutch pedals; steering wheel; and indicators. The simulator software recorded driver actions to control the vehicle and the state of the vehicles in the virtual environment. The car model used in this study had an automatic transmission.

C. Participants

In total, 22 drivers (17 men and 5 women) with an average age of 21.9 $(SD = 1.8$ years) and an average driving experience of 3.1 years $(SD = 1.6$ years) participated in the experiment. All were students at Delft University of Technology, aged from 19 to 26, and were required to have held a driving license for a minimum period of one year. All participants gave informed consent. Participants were not paid for taking part in the experiment.

D. Experimental Design and Procedures

On arrival at the test location, the participants filled in an intake questionnaire, which recorded their personal information (name, age, and contact details), driving experience, and self-rated driving skills. They were also asked if they spent more than one hour playing video games on a weekly basis. Drivers were randomly allocated in two groups. The experimental group ($n = 12$; 4 women; mean age $= 21.5$; mean driving experience $= 2.8$ years) was tested with the RWND, and the control group ($n = 10$; 1 woman, mean age $= 22.3$; mean driving experience $= 3.4$ years) was tested without the RWND.

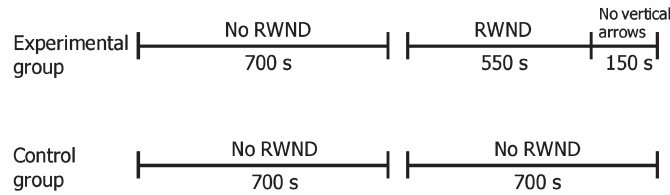

Fig. 4. Experimental design.

Prior to the experiment, the participants were given written instructions. These explained how to use the simulator, including how to adjust the seat position and control the car with the steering wheel and gas and brake pedals. The instructions also included details about the duration of the test and indicated that the task was to drive behind a lead car with a constant THW throughout the whole session, without overtaking. Both groups were informed verbally that the recommended THW was between 1 and 1.5 s. For the participants tested with the RWND, the operation of the display was also explained in writing. They were informed that they drove properly if the THW with respect to the front car was kept within the acceptable range. Before the start of the experiment, they were also given verbal instructions on how to interpret the display. They were free to ask questions or seek further explanation about the system prior to starting the test.

Each participant completed one training session and two test sessions. The training session was a short introduction of 300 s in an urban environment that allowed drivers to become acquainted with driving in the simulator. The training session exposed drivers to common maneuvers, including negotiating busy or slow traffic, slowing down, speeding up, changing lane, and steering without the RWND. After training, drivers from both groups completed two 700-s driving sessions. The control group completed these sessions without the RWND. Participants from the experimental group drove the first session without the RWND and the second session with this display. During the experimental group's second session (driving with the RWND), the vertical arrows switched off after 550 s without prior notice. The acceleration information from the horizontal bar remained unchanged. After each session, the participants stepped out of the simulator for a break of approximately 3 min. The design of the experiment is shown in Fig. 4.

The lead car in both 700-s sessions had a predefined but subjectively unpredictable speed profile with speeds ranging from 15 to 110 km/h representing a highway with busy traffic (see Fig. 5). The speed profile of the lead car was set to be identical for every test. However, small random variations existed between individual sessions, induced by the modeled dynamics of other traffic.

E. Dependent Measures

Traditional Performance Measures: The traditional car-following performance measures calculated for each session and each participant were as follows.

1) *Minimum distance (in meters)*: the minimum distance between the front bumper of the participant's car and the rear bumper of the lead car;

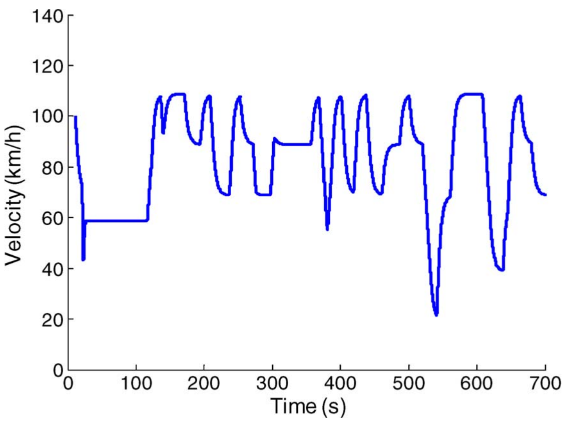

Fig. 5. Speed profile of the lead car.

2) *Maximum distance (in meters)*: the maximum distance between the front bumper of the participant's car and the rear bumper of the lead car;
3) *Mean distance (in meters)*: the average distance between the front bumper of the participant's car and the rear bumper of the lead car;
4) *Mean relative speed* (Δv) (in meters per second): the average of the absolute difference between the speed of the participant's car and the speed of the lead car;
5) *Mean acceleration (in meters per second squared)*: the average of the absolute acceleration of the participant's car;
6) *Mean jerk (in meters per cubic second)*: the average of the absolute jerk of the participant's car;
7) $THW < 1$ s (*percent of time*): the percentage of time that the THW was less than 1 s, indicating that the following vehicle was too close;
8) 1 s $\leq THW < 1.5$ s (*percent of time*): the percentage of time that the THW was between 1 and 1.5 s.
9) $THW < 1$ s (percent of time): the percentage of time that the THW was greater than 1.5 s.

Driver Model Parameters: Parameters of a generic driver model were estimated for each session and each participant, aiming to quantify the effect of the RWND on the driving behavior in terms of feedback delays and gains. This study used a common linear car-following model [25]–[27]. The acceleration a_i of the participant's car (i) was expressed as

$$a_i(t) = K_v \Delta v_i(t-\tau) + K_d \left\{\Delta x_i(t-\tau) - h_i(t)\right\} + K_a a_{i-1}(t-\tau) \quad (1)$$

$$h_i(t) = h_0 + h_v v_i(t) \quad (2)$$

with τ being the driver's visuomotor delay, Δv_i being the speed difference between the lead and the participant's car, Δx_i being the following distance, and a_{i-1} being the acceleration of the lead car. Variable $h_i(t)$ describes the desired following distance with h_0 representing the desired distance at standstill and h_v representing an additional THW describing the dependence of the desired distance on the speed v_i of the participant's car. K_v, K_d, and K_a represent speed, distance, and acceleration gains, respectively. K_v and K_d are corrective feedback gains controlling relative speed and distance, respectively. The acceleration gain K_a represents feedforward control; when $K_a = 1$, the participant's car would follow the lead car perfectly. Such an acceleration gain is not commonly included in car-following driver models but has been added here to describe the expected use of the acceleration display of the RWND.

A nonlinear Levenberg–Marquardt optimization algorithm was used to estimate the individual-driver parameters for each session. The model parameters were estimated by minimizing the squared deviation of predicted and measured vehicle motion. Realistic feedback delays were estimated when using an acceleration-based error criterion, while delays were often estimated to be zero when using a distance-based criterion. The parameter h_0 could only be estimated when distance was included in the criterion. In order to select the most appropriate error criterion and to quantify the estimation accuracy, a sensitivity analysis was performed using a model simulation with known parameters and reestimating the parameters for ten sets of randomly selected initial parameters with ten added noise realizations. Optimal accuracy was obtained with a criterion using the weighted sum of the errors in following distance and acceleration such that both constitute about 50% of the criterion. It was not possible to accurately estimate both parameters h_0 and h_v for this scenario due to their interacting role, and hence, a fixed value $h_v = 1$ as in [26] was adopted for all tests. With these choices, all parameters except for the position feedback gain K_d showed estimation errors below 10%.

Subjective Evaluation: After the second session, the participants were asked to step out of the simulator and complete a questionnaire. The responses were scaled from one (completely disagree) to ten (completely agree) and focused on the drivers' subjective analysis of the simulated car-following task. Participants from the experimental group were also asked to rate the RWND's usefulness, readability, visibility, clarity, and distracting effect, as well as the amount of information it provided. A set of relevant questions was selected for describing the subjective rating on specific aspects of the tests and the display (Table I).

F. *Statistical Analysis*

The effect of the RWND was evaluated by the following: 1) comparing the two sessions of the experimental group and 2) comparing the experimental group's second session with the control group's second session. Two comparisons served as negative control: 1) The two sessions of the control group were compared to determine whether performance in the simulator was stable and not distorted by learning effects, and 2) the experimental group's first session and the control group's first session were compared to verify whether group behavior was comparable, indicating adequate randomization.

The two groups were compared with an independent-sample t test, whereas the two sessions of the same group were compared using a paired t test. The Type I error rate (alpha) was set at .05. The analyses were all based on the data recorded between 60 and 550 s per session. The first 60 s was excluded because the car started from standstill resulting in initially large THWs and because the driver variability occurring in the speedup phase of the car was not of interest.

TABLE I
LIST OF SELECTED QUESTIONS IN THE QUESTIONNAIRE AND THEIR SUBJECTIVE RATING (MEANS WITH STANDARD DEVIATIONS IN PARENTHESES) ON A SCALE FROM ONE (COMPLETELY DISAGREE) TO TEN (COMPLETELY AGREE). Q1–Q11 WERE COMMON FOR BOTH GROUPS. Q12–Q20 WERE SPECIFIC TO THE EXPERIMENTAL GROUP TESTED WITH THE RWND ($n = 12$ FOR THE EXPERIMENTAL GROUP; $n = 10$ FOR THE CONTROL GROUP)

#	Question item	Experimental group *M* (*SD*)	Control group *M* (*SD*)	*p*
5	I had problems concentrating on the driving task.	4.0 (2.1)	4.0 (1.9)	1.000
7	The simulator is realistic.	5.6 (2.1)	4.3 (1.3)	.107
8	The simulator visual scene is realistic.	6.2 (2.1)	5.5 (2.1)	.443
9	The simulator controls are realistic.	4.8 (1.7)	4.7 (1.9)	.949
10	I was able to judge distances accurately.	5.3 (1.9)	5.8 (2.3)	.579
11	I was able to judge speed accurately.	4.3 (2.1)	5.2 (2.2)	.358
12	I was able to read the information given by the RWND at the advised distance.	7.2 (1.5)	-	-
13	The RWND was distracting me.	4.0 (2.4)	-	-
14	The RWND was giving me enough information.	6.8 (1.5)	-	-
15	The RWND was giving me too much information.	2.9 (1.9)	-	-
16	The RWND helped me to improve keeping the right distance to the preceding car.	6.3 (2.5)	-	-
17	I could understand the information given on the RWND.	8.3 (1.1)	-	-
18	I prefer driving with RWND over a car which is not equipped with a RWND.	4.7 (2.6)	-	-
19	In real traffic I would follow the advice of the RWND to help to increase the road capacity.	6.2 (2.4)	-	-
20	The RWND had great potential to help to solve traffic jam problems.	6.7 (2.7)	-	-

TABLE II
TRADITIONAL PERFORMANCE MEASURES (MEANS OF PARTICIPANTS WITH STANDARD DEVIATIONS IN PARENTHESES AND p VALUES FOR GROUP COMPARISONS, $n = 12$ FOR THE EXPERIMENTAL GROUP AND $n = 10$ FOR THE CONTROL GROUP; ALL RESULTS BASED ON THE DATA RECORDED BETWEEN 60 AND 550 S OF THE SESSIONS)

Group and session – mean (*SD*)	Min distance (m)	Max distance (m)	Mean distance (m)	Mean Δv (m/s)	Mean acc (m/s^2)	Mean jerk (m/s^3)	THW <1s % of time	1≤ THW <1.5s % of time	THW ≥1.5s % of time
Session 1. Experimental group (RWND OFF)	13.9 (6.1)	134.3 (67.3)	57.2 (29.7)	2.11 (0.80)	0.57 (0.13)	0.45 (0.17)	17 (26)	20 (18)	61 (35)
Session 1. Control group (RWND OFF)	10.9 (5.4)	139.3 (64.6)	55.4 (25.4)	2.17 (0.59)	0.54 (0.10)	0.40 (0.11)	9 (10)	23 (18)	66 (24)
Session 2. Experimental group (RWND ON)	14.1 (4.4)	65.8 (18.9)	33.6 (6.8)	1.27 (0.31)	0.64 (0.09)	0.55 (0.17)	10 (10)	69 (12)	21 (12)
Session 2. Control group (RWND OFF)	11.9 (6.5)	99.0 (17.0)	45.7 (11.5)	2.04 (0.52)	0.59 (0.05)	0.43 (0.09)	12 (11)	34 (15)	54 (21)
Comparison - *p* values									
Experimental vs. Control (session 1)	.248	.861	.879	.846	.568	.400	.376	.711	.712
Experimental vs. Control (session 2)	.358	**<.001**	**.006**	**<.001**	.113	.065	.579	**<.001**	**<.001**
Session 1 vs. Session 2 (experimental group)	.945	**.004**	**.022**	**.003**	**.026**	**.019**	.240	**<.001**	**<.001**
Session 1 vs. Session 2 (control group)	.681	.079	.315	.589	.196	.435	.274	**.050**	**.048**

Two analyses assessed the effect of two phases in the second session. 1) For the experimental group, the data between 60 and 550 s were compared with the final 150 s (i.e., between 550 and 700 s), and 2) the final 150 s of the experimental group was compared with the final 150 s of the control group.

With regard to the post-test questionnaire, descriptive statistics (means and standard deviations) were reported, and comparisons between experimental and control group were carried out using an independent-sample t test.

III. RESULTS

A. Subjective Evaluation

As shown in Table I, drivers rated the simulator as moderately realistic and gave a low score to their ability to judge speed accurately (Q11). The RWND was rated positively on readability (Q12), amount of information (Q14), perceived effectiveness (Q16), and understandability (Q17) (6.3–8.3 on the scale from $1 =$ completely disagree to $10 =$ completely agree). Questions Q13 and Q15 resulted in low scores, indicating that the display was generally regarded as not being distracting nor did it provide too much information. The relatively high standard deviation on Q13 was associated with two participants who reported that they found the RWND to be distracting (eight and nine on the scale from one to ten). The preferences for driving a car with the RWND (Q18), following RWND advice (Q19), and the potential to solve traffic jams (Q20) were rated as moderate to positive (4.7–6.7 on the scale from one to ten) with a high standard deviation, partly because one participant gave a rating of one in response to Q18, Q19, and Q20.

B. Traditional Performance Measures and Driver-Model Parameters

For the experimental group using the RWND in session 2, several significant effects in both traditional measures (Table II) and estimated model parameters (Table III) were found, as compared to the control group in session 2 and the experimental

TABLE III

DRIVER-MODEL PARAMETERS (MEANS OF PARTICIPANTS WITH STANDARD DEVIATIONS IN PARENTHESES AND p VALUES FOR GROUP COMPARISONS, $n = 12$ FOR THE EXPERIMENTAL GROUP AND $n = 10$ FOR THE CONTROL GROUP; ALL RESULTS BASED ON THE DATA RECORDED BETWEEN 60 AND 550 S OF THE SESSIONS). VAF = VARIANCE ACCOUNTED FOR

Group and session – mean (*SD*)	**VAF Δx**	**VAF acceleration**	K_v **(1/s)**	K_d **(1/s²)**	K_a **(-)**	**τ (s)**	h_0 **(m)**
Session 1. Experimental group (RWND OFF)	0.57 (0.16)	0.43 (0.15)	0.27 (0.12)	0.016 (.013)	0.076 (0.078)	0.72 (0.45)	30.4 (28.7)
Session 1. Control group (RWND OFF)	0.65 (0.10)	0.45 (0.09)	0.24 (0.06)	0.018 (.020)	0.079 (0.115)	0.80 (0.37)	25.9 (13.7)
Session 2. Experimental group (RWND ON)	0.59 (0.14)	0.45 (0.13)	0.58 (0.33)	0.097 (.171)	0.124 (0.115)	0.69 (0.19)	8.4 (4.3)
Session 2. Control group (RWND OFF)	0.63 (0.11)	0.44 (0.10)	0.24 (0.06)	0.026 (.020)	0.084 (0.124)	0.67 (0.35)	18.7 (8.7)
Comparison - *p* values							
Experimental group vs. control group (session 1)	.214	.735	.422	.789	.954	.643	.651
Experimental group vs. control group (session 2)	.465	.843	**.005**	.210	.444	.855	**.002**
Session 1 vs. session 2 (experimental group)	.768	.628	**.010**	.139	.257	.873	**.019**
Session 1 vs. session 2 (control group)	.469	.543	.558	.376	.921	.497	.137

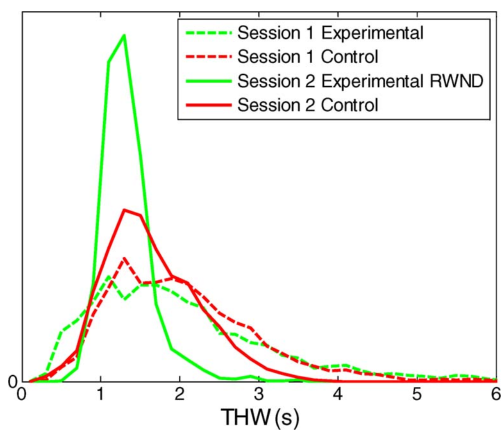

Fig. 6. THW distribution for all four conditions.

group in session 1. With the RWND, the average and maximum following distance, average speed difference (Δv), and time that THW exceeded 1.5 s were significantly reduced. However, the percentage of time that THW was below 1 s remained at the same level, suggesting that safety was not compromised. Fig. 6 also shows improved adherence to instructions, in terms of the indicated THW value (1–1.5 s), with the RWND. At the same time, acceleration and jerk increased significantly, indicating more and/or stronger control actions.

Tables II and III reveal no significant differences between the experimental and control groups in session 1, confirming their similarity. For the control group, who drove both sessions without the RWND, THW exceeded a value of 1.5 less and was more frequently in the desired range of 1–1.5 s in session 2 than in session 1, whereas no significant effects were found for the other measures, suggesting very limited learning effects between sessions.

Fig. 7 shows a typical model result for one driver in one session. The distance is well predicted up to 160 s, but the driver allows a large gap at 175 s where the model maintains a shorter following distance. The model parameters indicated increased control gains when using the RWND, with distance, speed, and acceleration gains roughly doubled. These effects are highly significant for the speed gain K_v but not significant

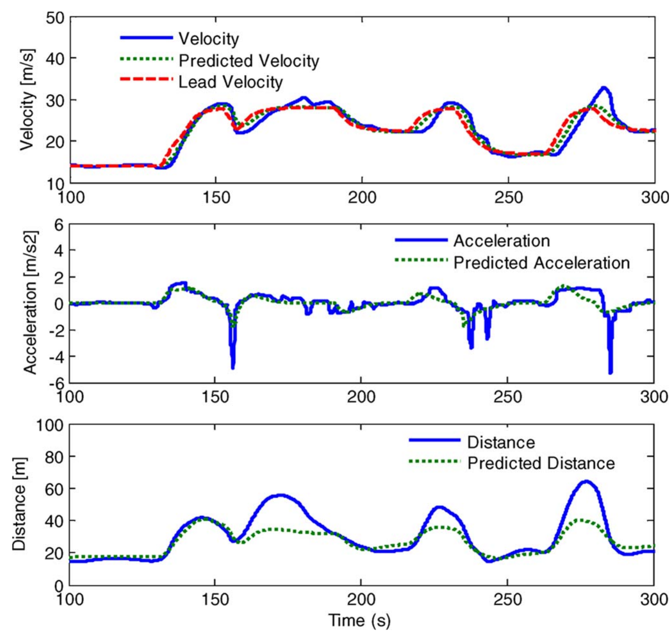

Fig. 7. Test data and model fit for a typical participant; session 2; control group.

for the distance gain K_d and the acceleration gain K_a. The acceleration gain K_a is estimated to be negligible ($< .02$) in six out of ten cases without the RWND and in 3 out of 11 cases with RWND (in the optimization, K_a was constrained to a minimum of zero). If drivers adopted an acceleration gain $K_a = 1$, they would follow the lead car perfectly, and the feedback terms K_v and K_d would only be needed for additional correction of imprecise feedforward control. The estimated K_a values around 0.12 suggest that such behavior was not achieved, even with the RWND. When using the RWND, the estimated desired following distance at zero speed h_0 is reduced in agreement with the reduced mean and maximum distance, as shown in Table II.

Of the 32 relationships probed in Tables II and III (experimental group session 2 versus control group session 2 and experimental group session 1 versus experimental group session 2), 16 were significant at the .05 level, and 6 were

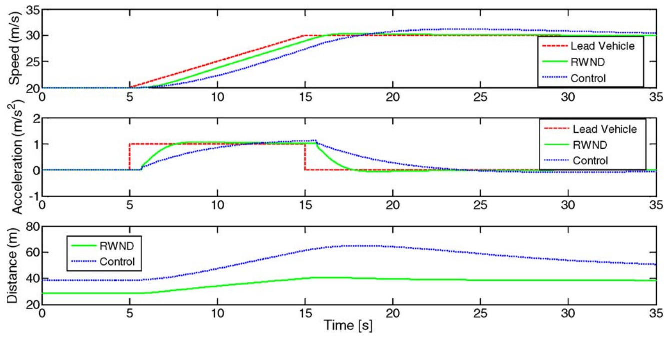

Fig. 8. Effect of RWND predicted, simulating the average model parameters in session 2 for experimental and control groups for a ramp increase of the lead-car speed.

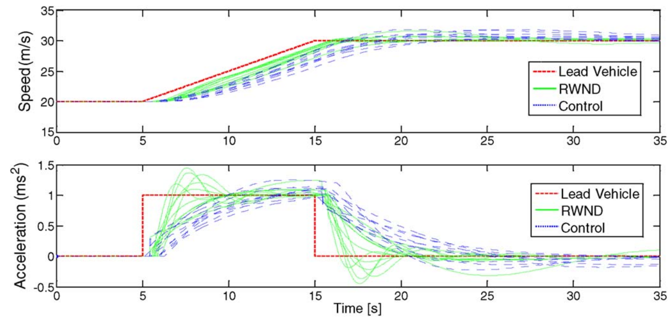

Fig. 9. Effect of RWND predicted, simulating individual model parameters in session 2 for experimental and control groups for a ramp increase of the lead-car speed.

significant at the .001 level. The p value for the session 1 versus session 2 comparison of the experimental group regarding $1 <$ THW < 1.5 equaled 4.9^*10^{-8}, with all 12 participants improving their performance. This indicates that, even after applying a Bonferroni correction for multiple testing, by multiplying the p value by 32, the p value would still be extremely small, and the risk of Type I errors would be negligible.

Finally, the results for the first and second phases of the RWND session were compared. The arrows indicating THW were switched off after 550 s without notifying the drivers. The acceleration display remained active during the entire session. With the RWND in phase 2, the time that THW was in the recommended range of 1–1.5 s was reduced from 69% to 40% ($p < .001$), while such a trend was not observed in the control group in session 2 (from 34% to 39%, $p = .172$). This suggests that the THW arrows effectively assisted the driver. No further significant differences between phase 1 and phase 2 with the RWND were found, possibly as a result of the short time frame involved (150 s with vertical indicators disengaged). In phase 2 of session 2, the mean Δv with the RWND (1.21 m/s) was significantly ($p = .026$) lower than in the control group (1.72 m/s), indicating benefits of the RWND even when only the acceleration is displayed.

To illustrate the effects of the RWND on car-following behavior, the driver-model response for a simple scenario consisting of a ramped increase of lead-car speed was simulated. These simulations show the nominal driver behavior as captured by the model and thus exclude unpredictable and/or time-variant behavior as present in the original data. Fig. 8 shows the predicted effect of the RWND simulating the average model parameters in session 2. Apparently, tighter nominal control is achieved with the RWND. The conventional measures (see Table II) and the model parameters (see Table III) of the experimental group indicated substantial variations between subjects. Fig. 9 shows these between-subject variations by plotting simulated responses using the estimated parameters of individual participants.

IV. Discussion

This study presented a novel advisory display to improve drivers' car-following performance. The display projected acceleration and THW information onto the rear window of the lead car. The most important finding is that drivers with the RWND outperformed the control group by achieving a smaller headway and reduced speed differences with respect to the lead car. Drivers with the RWND maintained more homogenous headways during car following, with a significantly reduced occurrence of large gaps between vehicles. The occurrence of short THW (< 1 s) did not increase because of the RWND, suggesting that safety was not compromised. This performance gain was achieved with a significantly larger acceleration and jerk in the RWND condition, indicating enlarged control effort. Note that this study was performed in a fixed-base simulator, where the lack of haptic and vestibular acceleration cues may have induced abrupt gas- and brake-pedal actions.

The driver-model parameters provided complementary information with respect to the traditional performance measures and gave information about how drivers use distance, speed, and acceleration information with and without the RWND. The time delay identified from the model was roughly similar to the values reported by Brackstone and McDonald [25] and Brackstone *et al.* [28]. The driver-model parameters showed that drivers with the RWND achieved enhanced car-following performance by adopting higher control gains. This result confirms earlier findings that drivers are capable of using augmented information on a lead car's acceleration during car following [29]. The driver-model parameters indicate that the acceleration gain K_a is relatively low and varies between participants even when an acceleration cue is displayed. It may be that the acceleration cue merely helps drivers to detect speed changes more effectively. Figs. 8 and 9 show nominal driver behavior as captured by the driver model. While Fig. 8 shows "average" behavior, Fig. 9 shows substantial between-driver variations. To investigate the advantages of using the RWND in complex traffic flows, the driver model (with parameter sets representing between-driver variations) can be applied to simulate RWND benefits in microscopic traffic-flow models.

The questionnaire revealed that the display was generally regarded as not distracting, suggesting that the RWND may have potential in real vehicles. Participants rated the driving simulator as moderately realistic and indicated that they had some difficulty judging speed accurately. These results correspond to previous research using the same driving simulator [30] and may be explained by the lack of vestibular motion cues, the limited resolution provided by the LCD projectors, and the lack of binocular depth cues. However, driver-simulator validity is an ongoing field of investigation, and simulators have proven to be valuable tools as far as relative comparisons between experimental conditions are concerned [31], [32].

Van der Hulst [33] argued that the late detection of lead-car deceleration is the primary human error in distance keeping. A study of Brackstone *et al.* [28] showed that the behavior of the car in front has the largest influence on the chosen headway, as compared to other factors such as road type and traffic-flow condition. Muhrer and Vollrath [34] examined the role of expectation in car following, for instance, when a lead car suddenly brakes. Their findings suggest developing assisting systems that generate anticipation in drivers, particularly in a car-following driving situation where the lead car is driving at a constant speed and drivers cannot foresee the need for action. Knowing that a primary source of information during the car-following task is available through the brake lights of the leading car, different brake-light arrangements have been tested to improve the accuracy and speed of drivers' reaction time and their situation awareness [35], [36]. A dynamic brake-light concept has been studied as well in a driving simulator, showing that subjects braked sooner when brake lights were artificially expanding as a function of the hazard. This concept was most effective for poor visibility conditions: at night without headlights, such that the lead-vehicle brake lights were most salient [37], [38]. The RWND effect is comparable to the effect of brake lights, as both result in driver awareness and action. The distinguishing factor is that, unlike traditional brake lights, the RWND communicates the magnitude of acceleration and deceleration to the driver, helping him to better implement the start, duration, and level of their control action in response to lead-car behavior. Given that human understanding and interaction with ACC are two of the barriers for achieving ACC benefits in different working regimes [15], a display similar to the RWND could support drivers in their understanding of ACC and next-generation technology, such as CACC. Some examples of this include visualizing the performance and limits of ACC systems, indicating proper conditions for initiating transitional maneuvers such as gap creation, joining or separation, and authority exchanges between car and driver.

The RWND could be placed on the inside of a rear window, possibly integrated with an extra brake light, such that the rear view is not compromised, or it could be placed externally, taking into account legal requirements for brake lights and regular illumination. The height and dimensions of the display should follow regulations in place for the Center High Mounted Stop Lamps in passenger cars [39], whereas variables such as color and intensity would have to follow the limits drafted in relevant standards [40]. Finally, it should be noted that the current RWND is designed to be displayed on a rear window, in order to assist following cars that are not equipped with CACC. Similar results are expected if the information is shown on a head-up display in the following car itself.

V. Conclusion and Recommendations

This paper has reported on an RWND developed to help drivers follow cars precisely and accurately. Displayed on the rear window of the lead car, the RWND has shown the THW and acceleration of the lead car in an intuitive way for the human driver. The simulator-based study has shown that the RWND is capable of enhancing driver car-following behavior, reducing mean THW and speed and distance variance at the expense of more control effort. Drivers did not consider the RWND to be a distraction, possibly because the arrows did not appear when THW was within the desired range of 1–1.5 s. In conclusion, the results of this study suggest that the RWND can be used along with CACC to increase network capacity without degrading safety. Mental workload and distraction effects should be evaluated in further experiments, including on-road testing in a naturalistic environment and a more diverse population.

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References

[1] E. Adell, A. Várhelyi, and M. D. Fontana, "The effects of a driver assistance system for safe speed and safe distance—A real-life field study," *Transp. Res. Part C: Emerging Technol.*, vol. 19, no. 1, pp. 145–155, Feb. 2011.

[2] A. Kesting, M. Treiber, M. Schönhof, and D. Helbing, "Adaptive cruise control design for active congestion avoidance," *Transp. Res. Part C: Emerging Technol.*, vol. 16, no. 6, pp. 668–683, Dec. 2008.

[3] N. van Nes, M. Houtenbos, and I. van Schagen, "Improving speed behaviour: The potential of in-car speed assistance and speed limit credibility," *IET Intell. Transp. Syst.*, vol. 2, no. 4, pp. 323–330, Dec. 2008.

[4] V. Marchau, N. van Nes, L. Walta, and P. Morsink, "Enhancing speed management by in-car speed assistance systems," *IET Intell. Transp. Syst.*, vol. 4, no. 1, pp. 3–11, Mar. 2010.

[5] O. Gietelink, J. Ploeg, B. de Schutter, and M. Verhaegen, "Development of advanced driver assistance systems with vehicle hardware-in-the-loop simulations," *Veh. Syst. Dyn., Int. J. Veh.*, vol. 44, no. 7, pp. 569–590, Jul. 2006.

[6] S. H. Hamdar, M. Treiber, H. S. Mahmassani, and A. Kesting, "Modeling driver behavior as sequential risk-taking task," *Transp. Res. Rec., J. Transp. Res. Board*, vol. 2088, pp. 208–217, 2008.

[7] B. van Arem, C. J. G. van Driel, and R. Visser, "The impact of cooperative adaptive cruise control on traffic-flow characteristics," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 429–436, Dec. 2006.

[8] M. Mulder, J. J. A. Pauwelussen, M. M. van Paassen, M. Mulder, and D. A. Abbink, "Active deceleration support in car following," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 40, no. 6, pp. 1271–1284, Nov. 2010.

[9] H. H. Chiang, S. J. Wu, J. W. Perng, B. F. Wu, and T. T. Lee, "The human-in-the-loop design approach to the longitudinal automation system for an intelligent vehicle," *IEEE Trans. Syst., Man, Cybern. A, Syst., Humans*, vol. 40, no. 4, pp. 708–720, Jul. 2010.

[10] L. C. Davis, "Effect of adaptive cruise control systems on traffic flow," *Phys. Rev. E—Statist., Nonlin., Soft Matter Phys.*, vol. 69, no. 6, pp. 066 110-1–066 110-8, Jun. 2004.

[11] M. S. Young and N. A. Stanton, "Back to the future: Brake reaction times for manual and automated vehicles," *Ergonomics*, vol. 50, no. 1, pp. 46–58, Jan. 2007.

[12] C. M. Rubin-Brown and H. A. Parker, "Behavioural adaptation to adaptive cruise control (ACC): Implications for preventive strategies," *Transp. Res. Part F, Traffic Psychol. Behav.*, vol. 7, no. 2, pp. 59–76, Mar. 2004.

[13] B. Seppelt and J. Lee, “Making adaptive cruise control (ACC) limits visible,” *Int. J. Human-Comput. Stud.*, vol. 65, no. 3, pp. 192–205, Mar. 2007.
[14] N. Stanton and P. Marsden, “Drive-by-wire systems: Some reflections on the trend to automate the driver role,” *Proc. Inst. Mech. Eng., Part D: J. Automobile Eng.*, vol. 211, no. 4, pp. 267–276, 1997.
[15] G. R. Marsden, M. McDonald, and M. A. Brackstone, “Towards an understanding of adaptive cruise control,” *Transp. Res. Part C: Emerging Technol.*, vol. 9, no. 1, pp. 33–51, Feb. 2001.
[16] G. J. L. Naus, R. P. A. Vugts, J. Ploeg, M. J. G. van de Molengraft, and M. Steinbuch, “String-stable CACC design and experimental validation: A frequency-domain approach,” *IEEE Trans. Veh. Technol.*, vol. 59, no. 9, pp. 4268–4279, Nov. 2010.
[17] R. Rajamani, S. B. Choi, B. K. Law, J. K. Hedrick, R. Prohaska, and P. Kretz, “Design and experimental implementation of longitudinal control for a platoon of automated vehicles,” *J. Dyn. Sys., Meas. Control, Trans. ASME*, vol. 122, no. 3, pp. 470–476, Sep. 2000.
[18] V. Milanés, J. Alonso, L. Bouraoui, and J. Ploeg, “Cooperative maneuvering in close environments among cybercars and dual-mode cars,” *IEEE Trans. Intell. Transp. Syst.*, vol. 12, no. 1, pp. 15–24, Mar. 2011.
[19] V. E. Cavallo and A. S. Cohen, “Perception,” in *Traffic Psychology Today*, P. E. Barjonet, Ed. Boston, MA: Kluwer, 2001, pp. 63–89.
[20] J. C. F. de Winter, A. C. E. Spek, S. de Groot, and P. A. Wieringa, “Left-turn gap acceptance in a simulator: Driving skill or driving style?” in *Proc. Driving Simul. Conf.*, Monte Carlo, Monaco, 2009.
[21] T. Kondoh, T. Yamamura, S. Kitazaki, N. Kuge, and E. R. Boer, “Back to the future: Brake reaction times for manual and automated vehicles,” *J. Mech. Syst. Trans. Logist.*, vol. 1, no. 2, pp. 170–180, 2007.
[22] M. Taieb-Maimon and D. Shinar, “Minimum and comfortable driving headways: Reality versus perception,” *Hum. Factors*, vol. 43, no. 1, pp. 159–172, Mar. 2001.
[23] S. de Groot, J. C. F. de Winter, J. M. López-Garcia, M. Mulder, and P. A. Wieringa, “The effect of concurrent bandwidth feedback on learning the lane keeping task in a driving simulator,” *Hum. Factors*, vol. 53, no. 1, pp. 50–62, Feb. 2011.
[24] P. M. van Leeuwen, S. de Groot, R. Happee, and J. C. F. de Winter, “Effects of concurrent continuous visual feedback on learning the lane keeping task,” in *Proc. 6th Int. Driving Symp. Hum. Factors Driver Assessment, Training Veh. Des.*, Lake Tahoe, CA, 2011, pp. 482–488.
[25] M. Brackstone and M. McDonald, “Car-following: A historical review,” *Transp. Res. F*, vol. 2, no. 4, pp. 181–196, 1999.
[26] W. Helly, “Simulation of bottlenecks in single lane traffic flow,” in *Proc. Symp. Theory Traffic Flow, Res. Lab.*, Detroit, MI, 1959, pp. 207–238.
[27] D. A. Abbink, “Neuromuscular analysis of haptic gas pedal feedback during car following,” Ph.D. dissertation, Delft Univ. Technol., Delft, The Netherlands, 2006.
[28] M. Brackstone, B. Waterson, and M. McDonald, “Determinants of following headway in congested traffic,” *Transp. Res. Part F, Traffic Psychol. Behav.*, vol. 12, no. 2, pp. 131–142, Mar. 2009.
[29] B. Sultan, M. Brackstone, and M. McDonald, “Driver’s use of deceleration and acceleration information in car-following process,” *Transp. Res. Rec.*, vol. 1883, pp. 31–39, Jan. 2004.
[30] S. de Groot, J. C. F. de Winter, M. Mulder, and P. A. Wieringa, “Non-vestibular motion cueing in a fixed-base driving simulator: Effects on driver braking and cornering performance,” *Presence: Teleoper. Virtual Environ.*, vol. 20, no. 2, pp. 117–142, Apr. 2011.
[31] A. Kemeny and F. Panerai, “Evaluating perception in driving simulation experiments,” *Trends Cognitive Sci.*, vol. 7, no. 1, pp. 31–37, Jan. 2003.
[32] G. Reymond and A. Kemeny, “Motion cueing in the Renault driving simulator,” *Veh. Syst. Dyn.*, vol. 34, no. 4, pp. 249–259, 2000.
[33] M. van der Hulst, “Anticipation and the adaptive control of safety margins in driving,” *Ergonomics*, vol. 42, no. 2, pp. 336–345, Feb. 1999.
[34] E. Muhrer and M. Vollrath, “Expectations while car following—The consequences for driving behaviour in a simulated driving task,” *Accident Anal. Prevention*, vol. 42, no. 6, pp. 2158–2164, Nov. 2010.
[35] J. Theeuwes and J. W. A. M. Alferdinck, “Rear light arrangement for cars equipped with a centre high-mounted stop lamp,” *Hum. Factors*, vol. 37, no. 2, pp. 371–380, Jun. 1995.
[36] J. W. A. M. Alferdinck, “Evaluation of Emergency Brake Light Display (EBLD) systems,” TNO Hum. Factors, Soesterberg, The Netherlands, Rep. TM-04-C020, 2004.
[37] Z. Li, “An empirical investigation of the effect of manipulating optical looming cues on braking behavior in a simulated automobile driving task,” Ph.D. dissertation, Univ. Toronto, Toronto, ON, Canada, 2006.
[38] Z. Li and P. Milgram, “An empirical investigation of a dynamic brake light concept for reduction of rear-end collisions through manipulation of optical looming,” *Int. J. Hum.-Comput. Stud.*, vol. 66, no. 3, pp. 158–172, Mar. 2008.
[39] C. J. Kahane and E. Hertz, “The long-term effectiveness of Center High Mounted Stop Lamps in passenger cars and light trucks,” NHTSA, Washington, D.C., Tech. Rep. DOT HS 808 696, 1998.
[40] UNECE Regulation No. 87. [Online]. Available: http://www.unece.org/fileadmin/DAM/trans/main/wp29/wp29regs/r087r2e.pdf

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