Informal document No. GRE-53-2
(53rd GRE, 4-8 October 2004,
agenda item 2.6.)

(transmitted by the expert from
the Netherlands)

TNO Human Factors

TNO Human Factors
Kampweg 5
P.O. Box 23
3769 ZG SOESTERBERG
The Netherlands

www.tno.nl

T +31 346 356 211
F +31 346 353 977

TNO-report

TM-04-C020

Evaluation of Emergency Brake Light Display (EBLD) systems

Date	25 May 2004
Author(s)	J.W.A.M. Alferdinck

Copy no.	
Number of copies	12
Number of pages	24
Number of appendices	5
Contractor	Vehicle Standards Development, Zoetermeer, The Netherlands
Project number	013.74104

All rights reserved.
No part of this publication may be reproduced and/or published by print, photoprint, microfilm or any other means without the previous written consent of TNO.

In case this report was drafted on instructions, the rights and obligations of contracting parties are subject to either the Standard Conditions for research instructions given to TNO, or the relevant agreement concluded between the contracting parties.
Submitting the report for inspection to parties who have a direct interest is permitted.

© 2004 TNO

CONTENTS Page

Rep.No. TM-04-C020 TNO Human Factors
Soesterberg, The Netherlands

Evaluation of Emergency Brake Light Display (EBLD) systems

J.W.A.M. Alferdinck

SUMMARY

Purpose: An international discussion on the improvement of the rear stop signals of cars is focussing on a signal for emergency braking, called *Emergency Brake Light Display* (EBLD). EBLD will be additional to the current rear stop lamps and should lead to a more adequate reaction of the road user when the car in front is braking hard. The EBLD systems currently being considered as candidates for regulations are based on switching on (additional) flashing rear lighting signals. By order of the RDW (Vehicle Standards Development) in the Netherlands we have conducted a comparative study.
Methods: We conducted a reaction time experiment with real car lamps in the laboratory. The subject’s reaction of the normal braking light signal was compared to four EBLD types, all equipped with filament bulbs. One EBLD consisted of the normal stop lamps flashing at 5 Hz. The other three EBLDs were a combination of the normal stop lamps and additional flashing lamps, i.e., a rear fog lamp flashing at 1.5 Hz or 5 Hz and direction indicator lamps flashing at 1.5 Hz. The signals were presented during a simulated driving task. During half of the presentations there was an additional distraction task that simulated the effect of a short inspection of in-car equipment.
Results: In terms of reaction time, relatively to the normal braking lights, there was no benefit of any of the emergency braking light signals, both in conditions with and without distraction task. On the contrary, in the condition with distraction task, the braking light signal with the stop lamps flashing at 5 Hz was worse than the normal braking light signal; the reaction time being 80 ms longer than the average reaction time in any of the other braking light conditions. In the conditions without distraction task no reaction time difference was found. On average, the distraction task increased the reaction time with 240 ms.
In terms of missed signals, there was a favourable effect of the EBLD with the rear fog lamp flashing at 1.5 Hz. During the distraction task, the percentage of missed signals of this EBLD was 5%, while the percentage missed signals for the normal braking light signal was 15%. There was no significant difference in missed signals between the normal braking light signal and the other EBLDs. In the condition without distraction task no difference in missed signals was found. On average, the percentage of missed braking signals increased from 0.6% to 11% by adding the distraction task.
The poor performance of the 5 Hz signals may be explained by the limited dynamic behaviour of lamps with filament bulbs. Only 80 % of the maximum light output is reached and in the first part of the signal it is even lower. The increment intensity, corrected for this adverse high frequency behaviour, is a good predictor of the performance ranking.
Conclusions: EBLD equipped with incandescent lamps are not effective when they are flashing at 5 Hz. Lower frequencies (1.5 Hz) are only effective in combination with high intensities. Since LED light sources do not suffer from slow rise times it is recommended to include LEDs in further experiments.

Evaluatie van noodstop remlicht signalen

J.W.A.M. Alferdinck

SAMENVATTING

Vraagstelling: Er is een internationale discussie gaande over the verbeteren van the remlicht van auto's. Deze wordt nu toegespitst op het verbeteren van het remlichtsignaal voor een noodstop, dat *Emergency Brake Light Display* (EBLD) genoemd wordt. Het EBLD zal toegevoegd moeten worden aan het huidige remlichtsignaal en zal moeten leiden tot een meer adequate reactie van de weggebruiker wanneer de voorligger hard op de rem trapt. De EBLD systemen die op dit moment als kandidaten worden beschouwd voor reglementering zijn gebaseerd op het aanschakelen van (extra) knipperende lampen van bestaande verlichtingssignalen. In opdracht van de RDW (Ontwikkeling Voertuigreglementering) hebben we een vergelijkende studie uitgevoerd.
Werkwijze: We hebben een reactietijd experiment uitgevoerd in het laboratorium met echte autolampen. De reacties van de proefpersonen op het normale remlichtsignaal is vergeleken met vier EBLD typen, allemaal voorzien van gloeilampen. Één EBLD bestond uit het normale remlicht dat knipperde met een frequentie van 5 Hz. De andere drie EBLD typen waren combinaties van een normaal remlicht en extra knipperende lampen, namelijk, een mistlamp knipperend met 1.5 Hz of 5 Hz en waarschuwinglichten knipperend met 1.5 Hz. De signalen werden gepresenteerd gedurende een rijtaak. Gedurende de helft van de presentaties was er een extra afleidende taak die het effect simuleerde van het kort raadplegen van apparatuur in de auto.
Resultaten: In termen van reactietijd, voor de condities met en zonder afleidende taak, bleek geen van de EBLD signalen beter te zijn dan het normale remlichtsignaal. In tegendeel, in de conditie met afleidende taak was het EBLD signaal met de knipperende remlichten op 5 Hz slechter dan het normale remlicht; de reactietijd was 80 ms langer dan het gemiddelde van alle andere remsignaal-condities. In de condities zonder afleidende taak werd geen reactietijdverschillen gevonden. Gemiddeld zorgde de afleidende taak voor een verhoging van de reactietijd met 240 ms.
In termen van gemiste remsignalen was er een gunstig effect van het EBLD met de mistlamp met een knipperfrequentie van 1,5 Hz. Gedurende de afleidende taak was het percentage gemiste remsignalen voor dit EBLD signaal 5%, terwijl het percentage gemiste signalen voor het normale remlichtsignaal 15% was. In de conditie zonder afleidende taak zijn er geen verschillen gemeten in gemiste remsignalen. De afleidende taak verhoogde het percentage gemiste remsignalen gemiddeld van 0,5% naar 11%.
De slechte prestaties van de 5 Hz signalen kunnen waarschijnlijk verklaard worden door het beperkte dynamische gedrag van de lampen die zijn uitgerust met gloeilampen. De lichtopbrengst bereikt maar 80% van het maximum en in het eerste deel van het signaal zelf minder. De intensiteittoename, gecorrigeerd voor het nadelige effect van de hoge frequentie, is een goede voorspeller van de prestatierangorde.
Conclusies: EBLDs uitgevoerd met gloeilampen zijn niet effectief bij knipperfrequentie van 5 Hz. Lagere frequenties (1,5 Hz) zijn alleen effectief in combinatie met hoge lichtintensiteiten. Omdat LEDs geen last hebben van ongunstig dynamisch gedrag wordt aanbevolen deze te betrekken in verder onderzoek.

1 INTRODUCTION

In the GRE[1], a group of light experts dealing with the preparation of international standards (ECE regulations), there is a discussion on the improvement of the rear stop signals of cars. This discussion is focussing now on a signal for emergency braking, which is called the *Emergency Brake Light Display* (EBLD). The EBLD is additional to the current rear stop lamps and should lead to a more adequate reaction of the road user when the car in front is braking hard. A number of countries recognise the importance of the implementation of requirements for EBLD but there is no consensus on the specifications of the system (GRE, 2003c; GRE, 2003b; GRE, 2003a). Three EBLD systems are currently being considered as candidates for a comparative study, all three based on switching on *additional* (flashing) lamps of current rear lighting signals (see Table 1 for lamp details):

- Stop lamps flashing with a frequency between 3 and 7 Hz.
- Hazard warning signal flashing with a frequency between 1 and 2 Hz.
- Flashing rear fog lamp. Flashing frequency to be specified. Two frequencies are proposed for testing.

In the literature it is suggested that flashing lights have more attention attraction properties than continuous lights, especially when they appear in the periphery of the visual field (Gail et al., 2001). A road user who is temporarily not looking at the road, for instance when inspecting in-car equipment, will notice a flashing (brake) light better than a steady one. This argues in favour of a *flashing* EBLD.

Table 1 Luminous intensities of rear lamps as required by the ECE, the target intensities (bold printed), and the actual realised intensities in the experiment.

Lamp type	Luminous intensity (cd)						
	Requirements according ECE regulations		Actual				
	Minimum	Maximum (Single lamp)	Mean	Number	Standard deviation	Minimum	Maximum
Rear position	4	**12**	7.33	8	4.9	1.8	12.5
Stop (S1)	**60**	185	59.4	8	5.2	53.3	67.3
Centre stop (S3)	**25**	80	23.6	4	8.5	11.7	31.4
Rear fog	**150**	300	170	4	9	161	179
Direction indicator (2a), hazard warning signal[1]	**50**	350	53.6	8	4.6	48.6	62.4

[1] Regulation ECE: Flashing frequency between 1 and 2 Hz.

In the following we describe an experiment in which we compared the performance of four EBLD systems with the normal stopping signal in a laboratory experiment, using real lamps in a driving context. The performance of the stop signal was determined by measuring reaction time and number of missed stop signals. When we designed the experiment we did not expect very large differences between the normal braking lights and the flashing braking lights in case the driver is looking straight ahead. In that situation the driver reacts on the onset of the light. Since the timing of the onset is not different for a continuous light and a flashing light no differences were expected in reaction time. However, the largest effect on reaction time and the number of missed signals was expected when the driver looks down or aside, for example to check in-car

[1] GRE = Groupe de Rapporteurs sur l'Éclairage (Meeting of the Experts on Lighting and Light Signalling).

equipment. We therefore added a distraction task at the position at which typically in-car equipment is located.

2 METHOD

2.1 Apparatus

We performed a laboratory experiment similar to a previous experiment done at TNO Human Factors (Theeuwes & Alferdinck, 1995)[2]. We used two rigs, made of plywood, which represent the rear side of a car. Figure 1 gives an impression of a "experimental car". Various lamps are installed at the rigs. The lamps can show the various signals at realistic luminous intensities and colours.

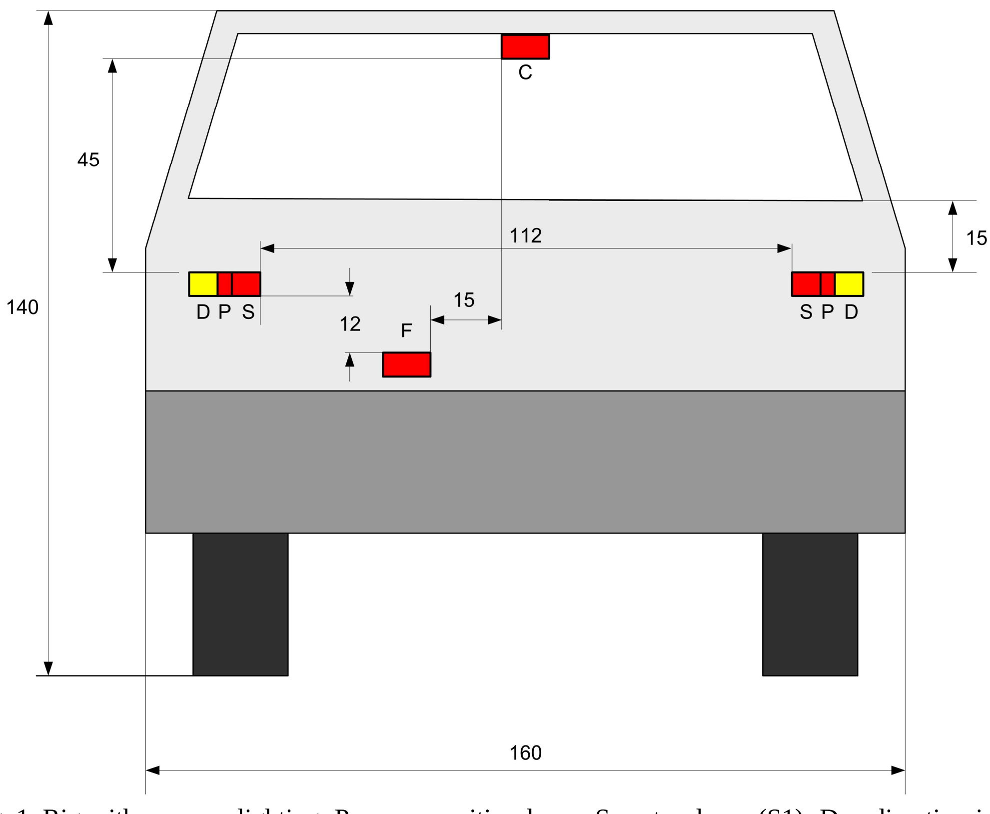

Fig. 1 Rig with rear car lighting. P = rear position lamp, S = stop lamp (S1), D = direction indicator and hazard warning signal, F = rear fog lamp, C = central high mounted stop lamp (S3). All dimensions are in cm.

The positions of the lamps on the rig are according ECE regulations 48 (ECE, 2004), i.e., the lamps are mounted within the height limits, according the minimum required distances from the edge of the vehicle and minimum separations between lamps. The fog lamp was positioned left from the centre and somewhat lower than the stop lamps.

---

[2] This study was also published as TNO report in English (Theeuwes & Alferdinck, 1993) and an article in Dutch (Theeuwes & Alferdinck, 1994).

The luminous intensities of the lamps obey the relevant ECE regulations 6, 7, and 38 (ECE, 2002a; ECE, 2002b; ECE, 2002c). Table I list the minimum and maximum luminous intensities, the target intensities and the actual realised intensities at the rigs. The target intensity of the rear position lamps was the maximum required intensity. The target intensity of the lamps, which are part of the EBLD system (stop lamps, direction indicators, fog lamps) was the minimum intensity according the ECE regulations. Hence, this is a worst case scenario for the visibility of the EBLD system. The position lamps were equipped with 12V/10W filament bulbs as light sources. All other lamps were provided with 12V/21W filament bulbs. The voltage at the lamps varied between 13 and 14 Volts. The target intensities were adjusted to the proper values by applying the appropriate neutral density filters at the front lenses. The actual realised luminous intensities are fairly close to the target values. One exception is the luminous intensity of the rear position lamp. The luminous intensity of these lamps decreased during the experiment but on average stayed within the required intensities.

The colours of the lamps were measured and the CIE chromaticity co-ordinates (x, y) are within the required limitations (ECE, 2002b; ECE, 2002a). See Appendix B for more detailed information. Two flashing frequencies were used: 1.5 Hz and 5 Hz. The real frequencies deviated a few percent from these target values and were 1.52 Hz and 4.88 Hz (Fig. 6).

2.2 Braking light signals

The rigs were able to show various rear light signals. Besides the position lights and the braking light signal, with a continuous light from the two stop lamps (S1) and the central high mounted stop lamp (S3), four different emergency braking light signals could be shown. Table 2 lists this braking light signals with the flashing frequencies and the lamps used. The short designation is further used in this report.

Table 2 Braking light signals used in the experiment, one normal brake light signal and four emergency braking light signals.

Short designation	**Braking light signal**
Normal	Normal stop lamps (S1 + S3)
Fog 1.5 Hz	Normal stop lamps (S1 + S3) + rear fog lamp flashing at a frequency of 1,5 Hz.
Fog 5 Hz	Normal stop lamps (S1 + S3) + rear fog lamp flashing at a frequency of 5 Hz.
Stop 5 Hz	Stop lamps (S1 + S3) flashing at frequency of 5 Hz
Hazard 1.5 Hz	Normal stop lamps (S1 + S3) + Hazard warning signal flashing at a frequency 1.5 Hz

Figure 2 gives a visual overview of braking light configurations. The first configuration is a car with only position lights on during normal driving (*No braking*). The four EBLD systems were compared to a control condition with the standard stop lights (*Normal*). The frequency of the flashing stop lamp (*Stop 5 Hz*) was 5 Hz, which is the middle of the range from 3 to 7 Hz, in line with a proposal in the GRE. The flashing frequency of the hazard warning signal (*Hazard 1.5 Hz*) was 1.5 Hz. This frequency is in the middle of the allowed range from 1 to 2 Hz for the hazard warning signal. These two frequencies were also chosen for the EBLD systems with the flashing rear fog lamp (*Fog 1.5 Hz* and *Fog 5 Hz*).

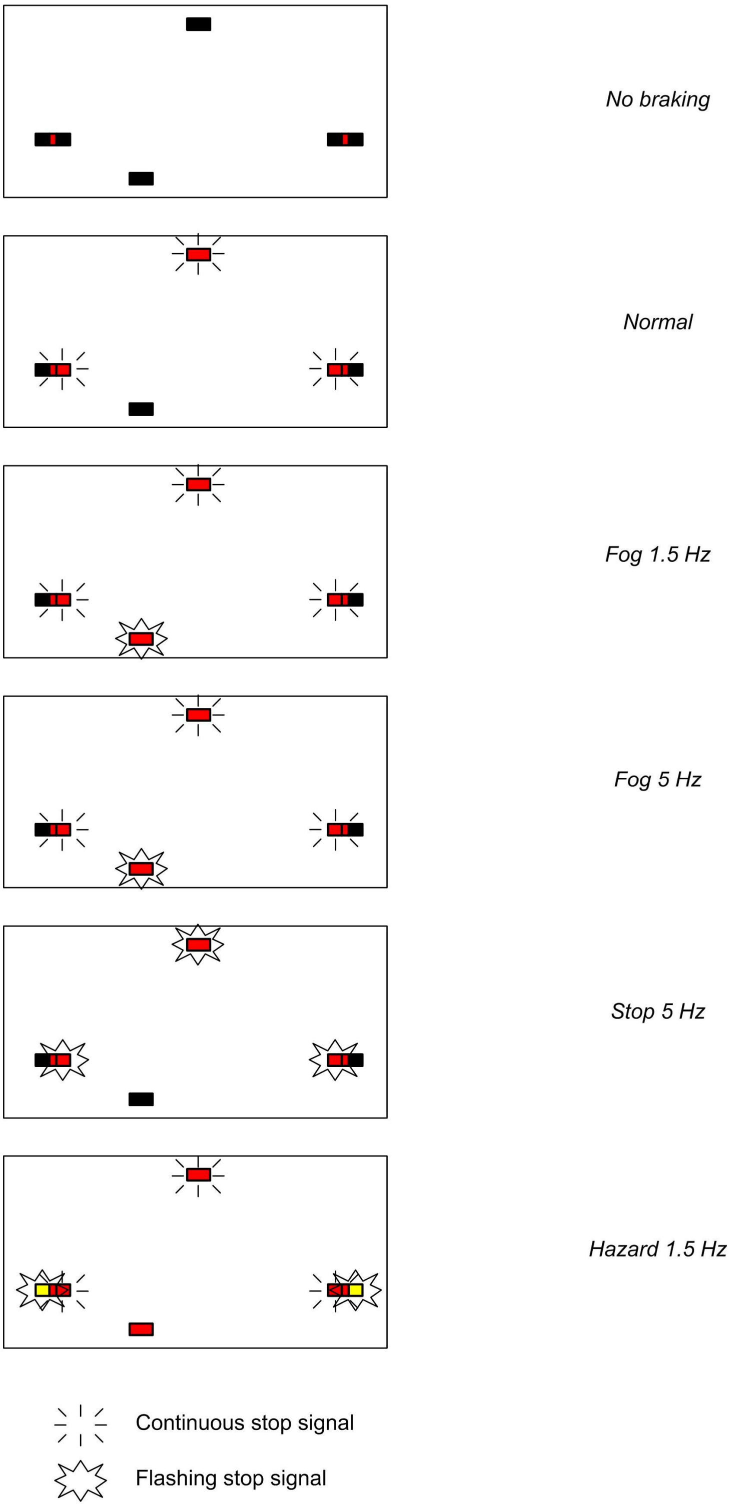

Fig. 2 Stop lamp configurations. See also Figure 1 and Table 2.

Two identical rigs were placed next to each other, simulating a situation on a motorway with one car in the left lane and one car in the right lane. The subject is seated at about 30 m from the rigs (Fig. 3), a distance that is comparable to typical following distances in normal traffic (e.g., a headway of 1.5 seconds with a speed of about 72 km/h).

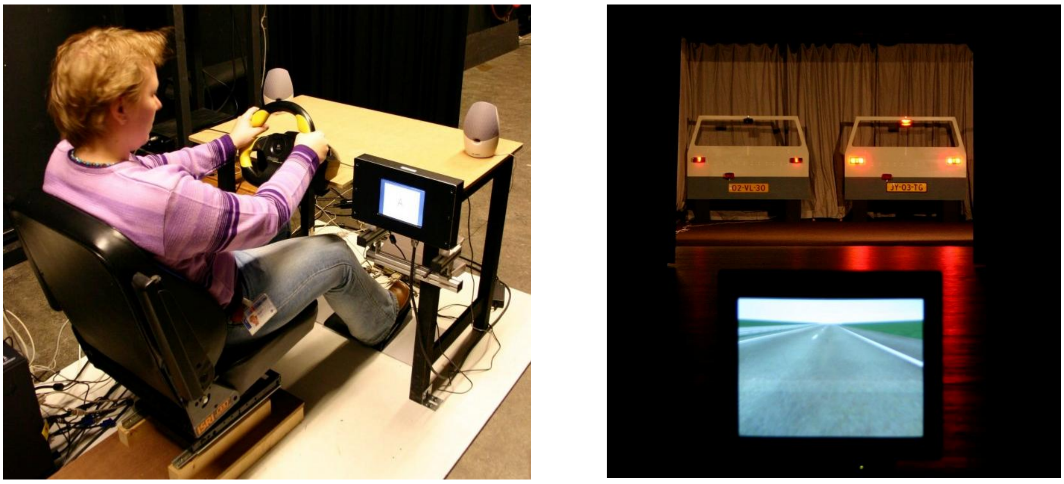

Fig. 3 Subject in the experimental set-up with the distraction display (left) and the view of the subject with the rigs and the simulated road display (right).

In the former study we did not find differences between reaction times measured in day and night conditions (Theeuwes & Alferdinck, 1995). Therefore we have measured only one light condition, i.e., the twilight condition, with the position lamps switched on and an average illuminance at the rig of about 130 lx. The rigs were illuminated with two halogen lamps (800 W/240 V).

2.3 Driving task

The main task of the subject was a driving task, which is similar to a driving task in a real car with a steering wheel, accelerator, and a brake pedal. The subject was asked to imagine that he or she was driving a car in the right lane of a motorway with 2 × 2 lanes. The tracking task was displayed at a computer monitor (29 cm × 39 cm) at a distance at 5 meters in front of the subject. The luminance of the screen was between 30 cd/m² (road) and 100 cd/m² (sky). The centre of the monitor was 42 cm above the ground. The subject’s eyes were, depending on the subject’s size, between 111 cm and 119 cm above the ground.

We used driving simulator software to model the tracking task. A straight motorway was modelled with 2 × 2 lanes. The lane width was 3.5 m. When the subject pressed the accelerator pedal the car came at a constant speed in a few seconds (*cruise control*). The steering wheel was used to keep the car between the lines of the right driving lane. Side wind was simulated so that the subject had to correct the course of the car continuously. The combination of a speed of 50 km/h and a side wind corresponding to a disturbance of the steering signal with maximal 10 degrees appeared to be a driving task with a reasonable difficulty (see Appendix C). When one of the sides car was more than 50 cm outside the lane limits an auditive signal warned the subject that he or she had to correct the course of the car.

At random chosen moments during the driving task a stop signal (normal stop signal or EBLD) was switched on at one of the two rigs for 1.7 seconds. In order to comprise three complete on-periods of a 1.5 Hz flashing signal, the presentation time was somewhat longer than the 1.5 seconds as used in the former study (Theeuwes & Alferdinck, 1995). The task of the subject was to brake as fast as possible when the *right* car "brakes". The reaction time and the number of missed stop signals were recorded. Reaction time was measured at the moment the accelerator pedal was released. Between presentations of the stop signals there was a random time between 7 and 23 seconds. One third of the presentations occurred at the left car. In those cases subjects were required not to brake (*catch trials*). These catch trails were added to ensure that subjects would not simply respond to any light switched on. Similar to real-life driving, subjects had to determine whether the light onset was relevant to them, that is, whether the onset came from the right or left car. When the subject reacted too late (i.e. 2 seconds later than the offset of the brake signal, or 3.7 seconds after the on-set of the brake signal) the response was labelled as a missed signal. Responses to the catch trials (left car) were not analysed.

2.4 Distraction task

In the "distraction conditions" the subject was instructed to perform a secondary task in addition to the driving task, forcing him or her to look away from the road scene in front to the display on the side (distraction task) (Broadbent & Broadbent, 1987). This task consists of the rapid presentation of a series of letters at the centre of the screen. In order to execute this task appropriately one has to pay focused attention to the stream of letters presented at the centre of the screen. In addition, previous studies have demonstrated that paying attention to a stream of letter reduces the attention resources available in the periphery (Joseph et al., 1996). In order to simulate a practical situation as checking and operating in-car equipment (phone, navigation system, radio, etc.) we used a so-called RSVP (Rapid Serial Visual Presentation) task. The task was presented on a small monitor screen (10 cm × 13 cm) that was positioned 34 cm right from the steering wheel (Fig. 3, left). The centre of the screen was 70 cm above the ground. For an average subject this corresponds to a downward angle of 41 degrees and a sideward angle of 33 degrees. After a sound a series of ten large black capital letters (height 2.5 cm) were presented in the middle of the white screen. The length of one presentation was 2.5 seconds. So, each letter was only visible for 250 ms. The letters were randomly chosen from the set A, B, C, D, E, and F. Successive letters were unequal. The task of the subject was to count how many times the letter A appeared. When this letter appeared two times in a presentation the subject has to push a little button at the steering wheel.

When a brake signal was presented during the distraction task, the distraction task started between 0.5 and 1.5 seconds after the onset of the brake signal.

2.5 Subjects

Twenty-one paid subjects participated in the experiment (11 male and 10 female) with ages between 21 and 53 (average 36.8, standard deviation = 10.9). All subjects had a normal colour vision, tested with the Ishihara colour blindness test and the Farnsworth Tritan plate (Fletcher & Voke, 1985). They had also a normal visual acuity. The TNO Landolt-C visual acuity varied between 1 and 2.5 (average = 1.55, standard deviation = 0.37). All subjects had a driving license. See Appendix E for further details.

2.6 Procedure

Before the experiment the subject's data were noted and the vision was tested. The subjects were informed by written instructions (Appendix A). They were told to perform the driving task as accurately as possible and to respond as fast as possible with their right foot to the onset of the brake lights presented on the lighting rig located at the right side. Subject had to refrain from responding when the lighting rig on the left side was switched on.

Each subject drove five runs. Each run lasted about 11 minutes. Before the start of the experiment the subject drove one practice run in order to become familiar with the driving task, responding to the stop signals and the distraction task. Between the runs the subjects had a rests of about 5 minutes. The whole procedure lasted for about two hours per subject.

2.7 Experimental design

The experimental design was as follows.

Independent variables:

- Braking light signal (*Normal*, *Fog 1.5 Hz*, *Fog 5 Hz*, *Stop 5 Hz*, *Hazard 1.5 Hz*)
- Distraction task (no, yes);

Dependent variables:

- Reaction time (ms)
- Percentage missed braking light signals.

The braking light signals varied between runs. Every subject drove five runs, one for each braking light signals. In order to avoid order effects, the runs were balanced by means of 5 × 5 Latin squares, i.e., for every subject the order of the runs was different. The detailed description is given in Appendix D.

In each run the braking light signal was presented 36 times, 24 presentation on the right rig and 12 presentation on the left rig. Half of the braking light signal presentations (18) were during a presentation of the distraction task. Nine presentations of the distraction task without a simultaneously presented braking light signal were added (Table 3). The total number of presentations was 45 presentations per run × 5 runs × 21 subjects = 4725. Since only the responses to the right rig were valid the total number of analysed presentations was 24×5×21 = 2520.

Table 3 Number of braking light signal presentations and distraction tasks in one run.

Braking light signal	Distraction task	No distraction task	Total
Right rig	12	12	24
Left rig (catch trails)	6	6	12
No	9	–	9
Total	27	18	45

2.8 Analysis

In order to reveal the effect of the independent variables on the dependent variables results were statistically tested with an analysis of variance (ANOVA) and a post-hoc Tukey test. An effect was considered to be significant when the probability (p) that the effect is due to change is lower than 5% ($p<0.05$). All individually measured reaction times and missed signals were submitted to the ANOVA with braking light signal (*Normal*, *Fog 1.5 Hz*, *Fog 5 Hz*, *Stop 5 Hz*, *Hazard 5 Hz*) and distraction task (yes, no) as main factors. The variable subject was considered as a random factor. Only reaction times less than 3.7 s were used for the analysis. Responses with longer reaction times were considered as missed signals.

3 RESULTS

3.1 Reaction time

Figure 4 shows the average reaction time for the various brake light signals in the condition with and without distraction task.

The distraction task has the most striking effect on the reaction time. The ANOVA showed that this effect is highly significant [$F(1, 20.1)=82.7$; $p<0.001$]. The task increases the average reaction time with 240 ms. Thus, when the subjects were looking at the monitor of the distraction task it took them about a quarter of a second more before they had judged the rigs and responded by releasing the accelerator pedal. This finding implies that the secondary task used in this experiment was quite effective in pulling attention away from the main task, conditions that mimic real driving conditions in which drivers interact with on-board equipment.

The ANOVA showed also a significant main effect on reaction time for the factor braking light signal [$F(4, 82.7)=6.57$; $p=0.00012$]. The post-hoc analysis showed that the reaction time for *Stop 5 Hz* is about 80 ms longer than any of the other braking light signals configurations. No difference was found between the other braking light signals.

The interaction between these two factors, i.e., that the brake light signals behave differently in the condition with and without distraction task, was marginally significant [$F(4, 83.1)=2.22$; $p=0.074$]. A post-hoc analysis showed only differences between the braking light signals in case of the distraction task ($p<0.001$), i.e., the *Stop 5 Hz* condition had the highest reaction times and the other braking light signals did not differ.

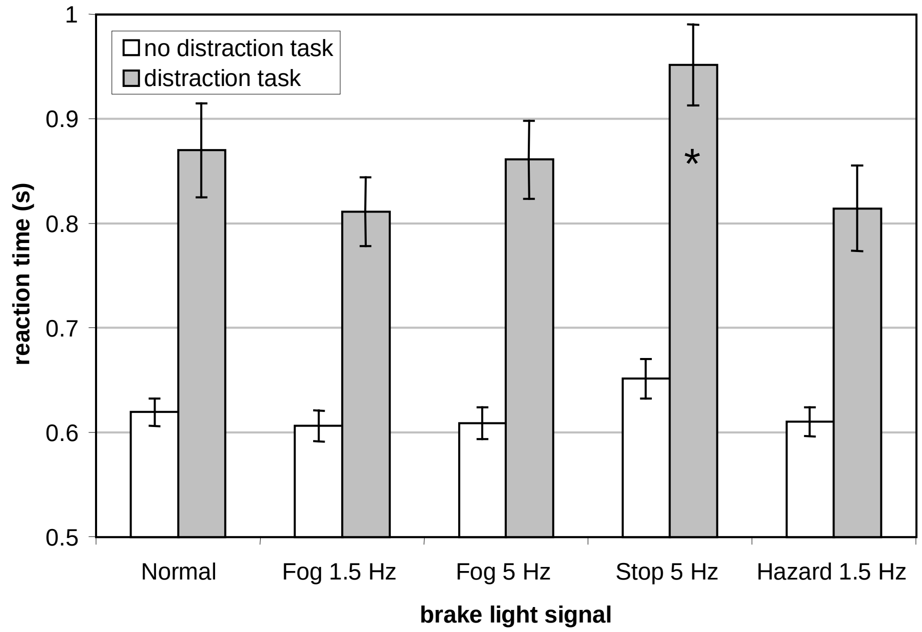

Fig. 4 Average reaction times for the various brake light signals in the conditions with and without distraction task. The error bars indicate the standard error of the mean (SEM). * = Significantly different from all other brake light signals, with distraction task.

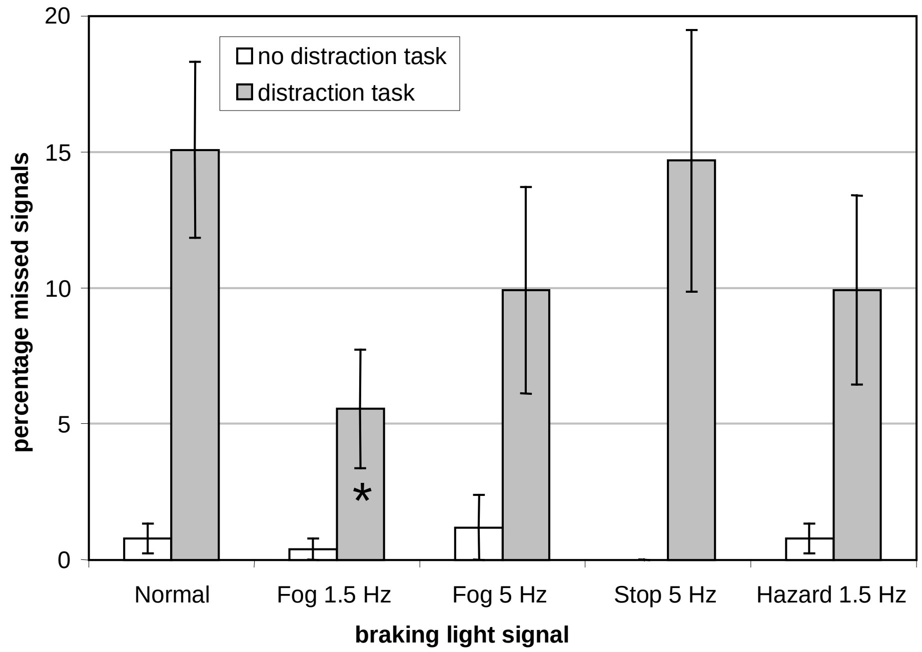

Fig. 5 Average percentage missed braking light signals for the various types of braking light signals in the conditions with and without distraction task. The error bars indicate the standard error of the mean (SEM). * = Significantly different from *Normal* and *Stop 5 Hz*, with distraction task.

3.2 Missed signals

The percentages missed braking light signals for the various types of braking light signals in the conditions with and without distraction task are plotted in Figure 5.

The distraction task has a large effect on the percentage missed signals, just like it has on the reaction time. The ANOVA showed that this effect is highly significant [$F(1, 20)=18.3$; $p=0.00037$]. The average percentage missed signals without distraction task is 0.6% and increases to 11% in case of a distraction task. Thus about one tenth of the braking light signals were not noticed at all when the subjects were looking at the monitor of the distraction task.

The ANOVA showed no significant main effect on missed braking light signals for the factor braking light signal [$F(4, 80)=1.55$; $p=0.20$]. So, when all data is averaged there is no difference between the braking light signals.

The interaction between the factors distraction task and braking light signal was, just like for reaction time, marginally significant [$F(4, 80)=2.11$; $p=0.087$). Also here one could say that there is a trend that the differences between the braking light signals are larger in case of a distraction task. The post-hoc analysis showed that the percentage of missed signals for the braking light signal *Fog 1.5 Hz* is lower than for the *Normal* and *Stop 5 Hz* conditions in case of a distraction task ($p<0.000034$). Thus, when the subject was looking at the distraction task monitor the *Fog 1.5 Hz* was the most conspicuous signal. Only 5.6% of these signals were missed. The *Normal* and *Stop 1.5 Hz* signals were missed in 15% of the presentations. The other two braking light signals were missed in about 10% of the cases.

4 DISCUSSION

4.1 Distraction task

This study showed that a distraction during a driving task, simulating the inspection of in-car equipment for a few seconds, has a large adverse effect on the perceiving of braking light signals of cars in front. On average, the reaction time increases with 240 ms. The reason for this large increase in reaction time is that the secondary task requires attention that cannot be used to detect signals presented at the roadway. This situation occurs quite frequently during actual driving, and only will increase in the future as more and more equipment comes to the car. Note that it is these situations that cause traffic accidents and especially in those situations an adequate design of the brake light signalling system can be beneficial.

4.2 Dynamic behaviour

In terms of reaction time, the performance of none of the emergency braking light signals is significantly better than the normal braking light signal. On the contrary, the braking light signal with the stop lamps flashing at 5 Hz is worse than the normal braking light signal; the reaction time is 80 ms longer. However, in terms of missed signals, one of the emergency braking light signals is better than the normal braking light signal. With the distraction task the braking light signal consisting of the normal braking light signal in combination with the flashing fog lamp at

1.5 Hz (*Fog 1.5 Hz*) is missed in only 5% of the cases while the normal braking light signal is missed in 15% of the cases.

How can these results be explained? In order to find a proper explanation we measured the dynamic behaviour of the lamps used in this experiment. Figure 6 shows the normalised light output of lamps with continuous light and flashing light at 1.5 Hz and 5 Hz, for a 1.7 seconds presentation time. At time = 0 s the lamps are switched on. It needs a certain time before the filaments of these incandescent lamps are at a sufficient temperature and to emit enough light to be visible. After about 300 ms the lamps are at 100% light output. The 50% level is reached after 100 ms. These rise times are similar for all lamps that were used for the braking light signals, because all lamps had the same bulbs with the same voltage and wattage (12V/21W).

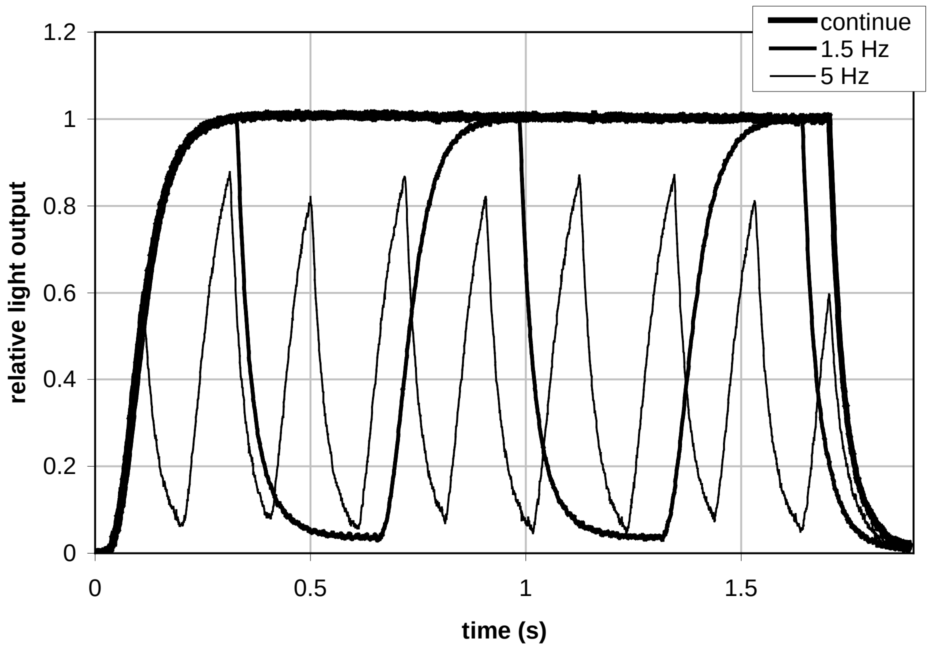

Fig. 6 Dynamic behaviour for a continuous lamp and flashing lamps at 1.5 Hz and 5 Hz for a presentation time of 1.7 seconds.

The 1.5 Hz signal reached the maximum light output before the light is switched off after a half period (333 ms). Between the on periods the lamp is not completely switched off and has still a light level of 4%. The filament has not enough time to cool down completely. The 5 Hz signal does not reach the maximum light output at all. Only a light level of 80% is reached at the peaks. The first peak is only 60% of the maximum level. The minimum light level in the off periods is about 10%. The lower maximum levels and the extra low level of the first peak of the 5 Hz signals is probably responsible for the longer reaction times for these signals in comparison a continuous signal with the same maximum light output. This adverse effect of the high frequency can be noticed for two cases. First, the reaction time for the *Stop 5 Hz* reaction time is longer than the reaction time for the *Normal* braking light signal. Second, the *Fog 5 Hz* signal seems to perform worse than the *Fog 1.5 Hz* signal (Fig. 4).

Also note that the *Stop 5 Hz* braking light signal is the only EBLD signal that is constructed with only one light signal, the normal stop lamps. All other EBLD signals are combinations of two signals, the normal stop lamps and an additional flashing rear fog lamp or hazard warning signal (Table 2). This gives a stronger signal that in principle should have a better performance. Therefore the total amount of luminous intensity that is switched on when stop signal is presented can give more insight in the ranking of the measured reaction times and percentage missed signals. In Table 4 the total luminous intensities that is switched on (increment) when a braking light signal is presented. The values are based on the target intensities in Table 1 for continuous signals. The 5 Hz signals are multiplied by a factor 0.8 accounting for the estimated effect the dynamic behaviour of these signals. It is expected that the largest increment will correspond to the shortest reaction times and lowest percentage missed signals. The table shows that the best performance is expected for the *Fog 1.5 Hz* signal and the worst for the *Stop 5 Hz*. This is indeed the case, as we saw before. The performance ranking corresponds rather well with the results shown in Figures 4 and 5. The higher the increment intensity (corrected for high frequency behaviour) the better the performance.

Table 4 Total luminous intensity that is switched on (increment) when a braking light signal is presented.

Braking light signal	Total intensity (cd)	Performance ranking
Normal	145 (2×60+25)	4
Fog 1.5 Hz	295 (2×60+25 + 150)	1
Fog 5 Hz	265 (2×60+25 + 0.8×150)	2
Stop 5 Hz	116 (0.8×(2×60+25))	5
Hazard 1.5 Hz	245 (2×60+25 + 2×50)	3

4.3 Further research

In this experiment we did not find a benefit of the signals flashing at 5 Hz. It is known that flashing lights with a frequency of 5 Hz are more conspicuous in the periphery than lights with lower frequencies (Boff & Lincoln, 1988). The advantages of the higher frequency apparently were undone by the adverse dynamic behaviour of the filament bulbs. Since more and more cars are equipped with LED lamps, which do not suffer from a poor dynamic behaviour, it is recommended to do further research on the performance of ELBD with LED lamps. In a first additional experiment we could start with replacing only the filament bulb of the S3 lamp by a LED lamp. In a next experiment all the stop lamps can be equipped with LEDs. For LED lamps with equal maximum light output, we expect that the reaction times for signals flashing at 5 Hz will be at least as short as the reaction times of the normal (continuous) braking light signal. In a recent study on flashing LED lamps it was found that LED lamps flashing at a higher frequency, perceived in the periphery of the visual field, have a higher conspicuity (Toet & Varkevisser, 2003). Therefore we also expect that, during a distraction task, the percentage of missed signal flashing at 5 Hz will be lower than for continuous signals.

5 CONCLUSIONS

A reaction time experiment was conducted in the laboratory in order to compare the performance of the normal braking light signal with four types of emergency braking light displays (EBLD), equipped with filament bulbs. One EBLD is the stop lamps flashing at 5 Hz (*Stop 5 Hz*), the other three are a combination of the normal stop signal and a flashing lamps, a fog lamp flashing at 1.5 Hz or 5 Hz (*Fog 1.5 Hz*, *Fog 5 Hz*) and a the hazard warning signal flashing at 1.5 Hz (*Hazard 1.5 Hz*). The performance was measured during a driving task, with and without a distraction task. This distraction task simulated a short inspection of in-car equipment.

- The distraction task increases the reaction time with 240 ms and the percentage missed braking light signals from 0.6% to 11%.
- In terms of reaction time, the performance of none of the emergency braking light signals was better than the normal braking light signal. On the contrary, the braking light signal with the stop lamps flashing at 5 Hz is even worse than the normal braking light signal; the reaction time is 80 ms longer.
- During the distraction task the percentage of missed signals is lower for the emergency braking light signals with the fog lamps flashing at 1,5 Hz (5%) than for the normal braking light signal (15%). There was no difference between normal stop lamps and the other EBLDs.
- The poor performance of the 5 Hz signals may be explained by the dynamic behaviour of these signals for filament bulbs. Only 80% of the maximum light output is reached and in the first part of the signal it is even lower. The increment intensity, corrected for adverse high frequency behaviour, is a good predictor for the performance ranking.
- It is recommended to perform further experiments with stop lamps replaced by LED lamps. These light sources do not suffer from adverse dynamic behaviour.

ACKNOWLEDGMENT

I thank Prof. Dr. Jan Theeuwes, Department of Cognitive Psychology, Vrije Universiteit, Amsterdam, for his advice on the experimental method.

REFERENCES

Boff, K.R. & Lincoln, J.E. (1988). *Engineering data compendium. Human Perception and Performance* (Vol. I). New York: Wiley & Sons.

Broadbent, D.E. & Broadbent, M.H.P. (1987). From detection to identification: Response to multiple targets in rapid serial visual presentation. *Perception & Psychophysics, 42,* 105-113.

Brouwer, W.H., Waterink, W., Wolffelaar, P.C. van & Rothengatter, T. (1991). Divided attention in experienced young and older driver: Lane tracking and visual analysis in a dynamic driving simulator. *Human Factors, 33 (5),* 573-582.

Daanen, H.A.M., Vliert, E. van de & Huang, X. (2003). Driving performance in cold, warm, and thermoneutral environments. *Applied Ergonomics, 34,* 597-602.

ECE (2002a). *Uniform provisions concerning the approval of direction indicators for motor vehicles and their trailers* (Regulation No. 6). Geneva: United Nations, Economic Commission for Europe.

ECE (2002b). *Uniform provisions concerning the approval of front and rear position (side) lamps, stop-lamps and end-outline marker lamps for motor vehicles (except motor cycles) and their trailers* (Regulation No. 7). Geneva: United Nations, Economic Commission for Europe.

ECE (2002c). *Uniform provisions concerning the approval of rear fog lamps for power-driven vehicles and their trailers* (Regulation No. 38). Geneva: United Nations, Economic Commission for Europe.

ECE (2004). *Uniform provisions concerning the approval of vehicles with regard to the installation of lighting and lighting-signalling devices* (Regulation No. 48). Geneva: United Nations, Economic Commission for Europe.

Fletcher, R. & Voke, J. (1985). *Defective colour vision*. Bristol, UK: Adam Hilger Ltd.

Gail, J., Lorig, M., Gelau, C., Heuzeroth, D. & Sievert, W. (2001). *Optimierung des rückwärtigen Signalbildes zur Reduziering von Auffahrunfällen bei Gefahrenbremsung* [Optimization of rear signal pattern for reduction of rear-end accidents during emergency braking manoeuvres] (Berichte der BAST, Fahrzeugtechnik, Heft F39). Bergisch Gladbach, Germany: Bundesanstalt für Strassenwesen (BAST).

GRE (2003a). *Proposal for amendments to regulation No. 48, Presented by France* (Informal document No. 1, 51st GRE, 15-19 September 2003, agenda item 1.1.2.9). Geneva: Economic Commission for Europe.

GRE (2003b). *Proposal for draft amendments to Regulation no. 48 (Installation of lighting and light-signalling devices)* (Working document TRANS/WP.29/GRE/2003/21 (France)). Geneva: Economic Commission for Europe.

GRE (2003c). *Proposal for draft amendments to regulation No. 48, 02 Series of amendments, transmitted by the Experts from Germany* (Informal document No. 6, 51st GRE, 15-19 September 2003, agenda item 1.1.2.9). Geneva: Economic Commission for Europe.

Joseph, J.S., Chun, M.M. & Nakayama, K. (1996). Attentional requirements in a “preattentive” feature search task. *Nature, 379,* 805-807.

Theeuwes, J. & Alferdinck, J.W.A.M. (1993). *Rear light arrangements for cars equipped with a center stop lamp* (Report IZF 1993 C-29). Soesterberg, The Netherlands: TNO Institute for Perception[3].

Theeuwes, J. & Alferdinck, J.W.A.M. (1994). *Achterlicht-configuraties van personenauto’s uitgerust met een derde hooggeplaatst remlicht*. In F.J.J.M.Steyvers & A.R.A. van der Horst (Eds.), *Verkeersgedrag in onderzoek* (pp. 3-9). Haren: Verkeerskundig Studiecentrum, Rijksuniversiteit Groningen.

Theeuwes, J. & Alferdinck, J.W.A.M. (1995). Rear light arrangements for cars equipped with a center high-mounted stop lamp. *Human Factors, 37,* 371-380.

[3] Former name of TNO Human Factors, changed in 1994.

Toet, A. & Varkevisser, J. (2003). *Expertoordeel over de invloed van knipperfrequentie en gebruik van LED flitslampen op opvallendheid van waarschuwingslichten bij AHOB spoorwegovergangen* [Expert opinion on the influence of flash frequency and use of LED flashlights on conspicuity of warning lights on AHOB railway crossings] (Report TM-03-C043, in Dutch). Soesterberg, The Netherlands: TNO Human Factors.

Soesterberg, 25 May 2004

J.W.A.M. Alferdinck, B.Sc.
(Author, Project leader)

APPENDIX A Subject instructions

You are going to participate in the EBLD experiment (EBLD = *Emergency Brake Light Display*). The purpose of this experiment is to measure the ability of road users to detect the stop lamps of cars in front them.

You have to perform a steering task that is very similar to a real driving task. Imagine that you are driving a car at the right lane of a motorway with 2 x 2 lanes. The image of the road will be presented in front of you on a computer monitor. You can use the steering wheel, accelerator pedal and the brake pedal. When you press the accelerator pedal the car will come in a few seconds at a constant speed (*cruise control*). The steering wheel must be used in order to keep the car between the lines of the right driving lane. When the car is outside this line, an auditive warning signal will sound.

Two backsides of cars are positioned in front of you. They represent two cars “driving” in front of you, one at the left driving lane and one at the right driving lane. When the right car (the car that is driving in the same lane as you) brakes, and the stop lamps goes on, you have to *brake as fast as possible*. When the left cars brakes you are not allowed to brake. The stop lamps can consist of normal stop lamps, flashing stop lamps or a combination of normal stop lamps and flashing direction indicators or a flashing fog lamp. The experiment resumes when press the accelerator pedal again. It should be noted that the car in front and you self do not move really.

In addition to the driving task you have to perform another task which is presented at a small monitor at the right after a beep. During a few seconds a number of letters will be presented. The series of letters can contain 0, 1, or 2 times the letter “A”. When you see two times an “A” you must push one of a buttons at the steering wheel. When you saw no or only one “A” you must *not* push a button.

You can practice this procedure in a test run.

Previously, your visual acuity and colour vision will be tested.

The total length of the test is about 2.5 hours, including instruction, eye tests and breaks.

If you have any questions you can ask the test leader.

Success

APPENDIX B Colour measurements

The CIE colour co-ordinates were measured as follows. A white standard was placed in front of the lamp in the middle of the light bundle at a distance of about 70 cm. The colour of the reflecting light was measured with a spectroradiometer (Photo Research, PR 650). The colour co-ordinates, averaged over the two rigs, are plotted in Figure B.1. The colour boxes for amber and red are according the ECE requirements (ECE, 2002b; ECE, 2002a).

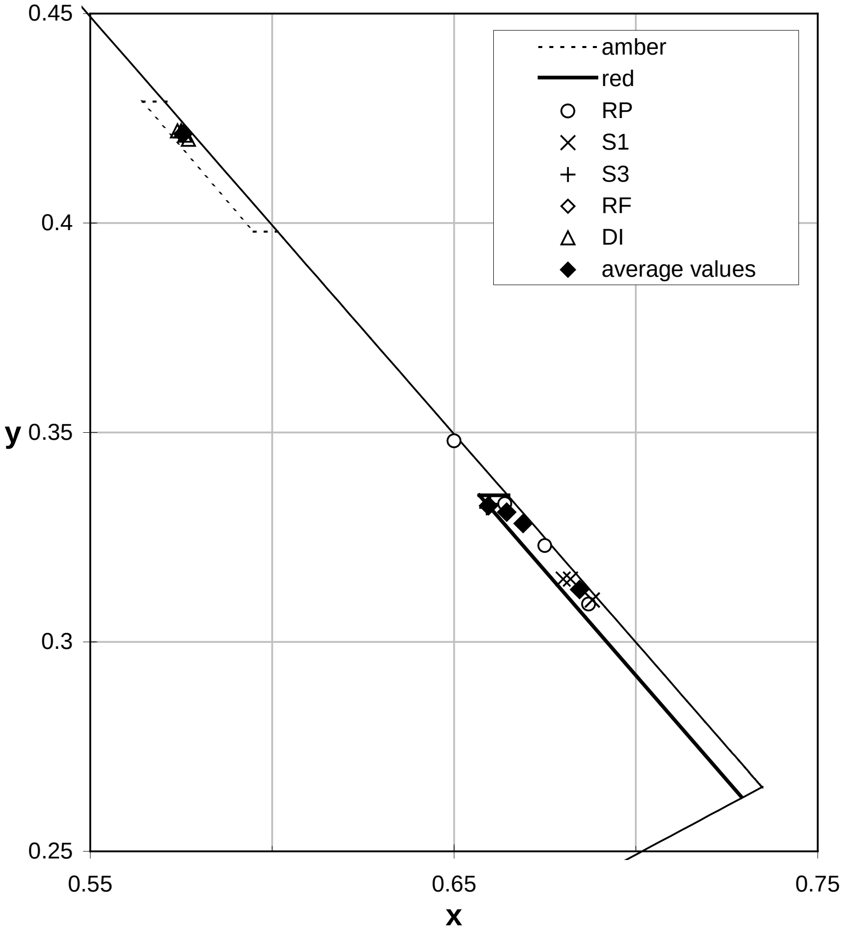

Fig. B.1 Colour co-ordinates of the amber and red lamps of the rig. RP = rear position lamp, S1 = normal stop lamp, S3 = central high mounted stop lamp, DI = direction indicator and hazard warning signal, RF = rear fog lamp.

APPENDIX C Driving task

The error signal was added to the steering signal and can be considered as a random side wind (Brouwer et al., 1991; Daanen et al., 2003). The error signal is a summation of three sinus signals and was calculated according the next equation.

$$S = K.[A_1.R_1.\sin(2\pi.F_1.t)+A_2.R_2.\sin(2\pi.F_2.t)+A_3.R_3.\sin(2\pi.F_3.t)]$$

Where,

S	= Error signal in radians
A_1, A_2, A_3	= Maximum amplitudes, which were set at values of 1, 0.5 and 0.25.
R_1, R_2, R_3	= Random figures between –1 and +1.
F_1, F_2, F_3	= Frequencies, which were set at values of 1/15 Hz, 1/7.5 Hz, and 1/3.75 Hz.
t	= the time in seconds.
K	= Gain factor for setting the difficulty of the driving task. This factor was set to 0.1 radians. This appeared to be a reasonable driving task difficulty in combination with a constant speed of 50 km/h. The maximum amplitude for this gain factor setting can be 0.1 x (1+0.5+0.25) = 0.175 radians or 10 degrees.

APPENDIX D Order of presentations

Table D.1 Order of the runs per subject.

Subject identification number	Order of the runs				
2	2	3	4	5	1
3	3	4	5	1	2
4	4	5	1	2	3
5	5	1	2	3	4
6	1	3	2	5	4
7	2	4	3	1	5
8	3	5	4	2	1
9	4	1	5	3	2
10	5	2	1	4	3
11	1	4	3	5	2
12	2	5	4	1	3
13	3	1	5	2	4
14	4	2	1	3	5
15	5	3	2	4	1
16	1	5	3	2	4
17	2	1	4	3	5
18	3	2	5	4	1
19	4	3	1	5	2
20	5	4	2	1	3
21	1	2	3	4	5
22	2	3	4	5	1

Notes

- The subject number 1 was skipped due to technical problems.
- The run numbers correspond to the braking light signals as follows.

Run number	Braking light signal (short designation)
1	*Normal*
2	*Fog 1.5 Hz*
3	*Fog 5 Hz*
4	*Stop 5 Hz*
5	*Hazard 1.5 Hz*

APPENDIX E Subject data

Table E.1 Subject data.

Subject identification number	Gender (F=female M=male)	Visual acuity	Age (years)
2	M	2	45
3	F	1	47
4	M	1.5	28
5	M	1.5	51
6	M	1.25	31
7	M	1.25	46
8	M	1.5	23
9	M	1.5	34
10	M	1.5	53
11	F	1.5	35
12	F	1.5	22
13	F	1.5	47
14	F	1.5	50
15	F	1.5	38
16	M	1.25	31
17	F	1.5	44
18	F	1.25	21
19	M	1.5	46
20	F	2.5	30
21	F	1.5	21
22	M	2.5	26
	Average =	1.55	36.6
	Standard deviation =	0.37	10.9
	Minimum =	1	21
	Maximum =	2.5	53

Notes

- The subject number 1 was dropped due to technical problems.
- The TNO visual acuity is defined as the reciprocal of the Landolt-C gap size in arcminutes that can be resolved.
- All subjects had a normal colour vision.