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Potential safety effects of a frontal brake light for motor vehicles

Tibor Petzoldt[1] ✉, Katja Schleinitz[2], Rainer Banse[3]
[1]Traffic and Transportation Psychology, TU Dresden, Hettnerstrasse 1, Dresden, Germany
[2]Cognitive and Engineering Psychology, TU Chemnitz, Wilhelm-Raabe-Strasse 43, Chemnitz, Germany
[3]Social and Legal Psychology, University of Bonn, Kaiser-Karl-Ring 9, Bonn, Germany
✉ *E-mail: tibor.petzoldt@tu-dresden.de*

Abstract: The number of pedestrian casualties in crashes with motorised vehicles is still alarming. Misunderstandings about the other road users' intentions are certainly one contributory factor. Especially given recent developments in vehicle automation, informing about 'vehicle behaviour' and 'vehicle intentions' in the absence of any direct interaction between the driver and the outside world is becoming increasingly relevant. A frontal brake light which communicates that a vehicle is decelerating could be a simple approach to support pedestrians and other road users in the interaction with (potentially automated) motorised vehicles. To assess the effect of a frontal brake light on the identification of vehicle deceleration, the authors conducted a video based lab experiment. The brake light facilitated the identification of decelerations considerably. At the same time, the fact that only half of the decelerations were accompanied by the brake light resulted in increased identification times for decelerations in which the frontal brake light was absent compared to a control condition in which none of the decelerations was indicated by such a light. This finding points towards an increasingly conservative approach in the participants' assessment of deceleration, which could be interpreted as an indicator of a potential safety effect of the frontal brake light.

1 Introduction

There is no doubt that pedestrian safety, at least in the western world, has improved considerably over the past four decades. In Germany, the number of pedestrians involved in a crash has been cut in half since 1980, and the number of fatalities has even been reduced to one-seventh. At the same time, this positive development appears to have stagnated in recent years [1]. In 2014, German crash statistics have registered 31,161 pedestrians injured in traffic crashes, among them 523 fatalities. The main responsibility for a pedestrian injury crash was ascribed to the involved pedestrian in only 8907 cases [2]. Analyses conducted by the German Insurers found that motorists' actions, such as violating a pedestrian's right of way or inappropriate behaviour around pedestrian crossings were major causes for such crashes [3]. International data indicate that indeed, violations of a pedestrian's right of way occur rather frequently [4]. It should be pointed out, though, that this does not necessarily imply that in all these cases, the violations are intentional. Simply overlooking the pedestrian because of visual impairments [5, 6] or insufficient ambient illumination [7], as well as misinterpretations of the pedestrian's intentions [8] certainly play a role as well.

As a consequence, it has been attempted to develop vehicle [9] as well as infrastructure based countermeasures [10] that are supposed to help the motorist detect the pedestrian and induce a more appropriate behaviour as a result. This focus is understandable, given that most pedestrian injury crashes are caused by motorised road users. At the same time, it appears just as plausible to support pedestrians in understanding drivers' intentions. While a driver often has a set of cues available to infer whether the pedestrian has perceived the approaching vehicle or to deduct the pedestrian's next actions, such as the pedestrian's posture or direction of gaze, the pedestrian in front of the approaching vehicle has hardly any usable information. Directional indicators are the only explicit technological measure that provides some information to road users ahead. To assure a pedestrian that he has been detected by the motorist, often direct eye contact is required. Deceleration and actual yielding as a result of this detection still can only be identified by continuously observing the vehicle's approach and assessing its speed, distance and/or time to arrival. With the advent of automated vehicles, this problem is about to grow even further. As Lundgren *et al.* [11] have found, pedestrians' willingness to cross in front of an approaching vehicle decreased if the driver was perceived as inattentive. The authors concluded that 'to sustain perceived safety when eye contact is discarded due to vehicle automation, it could be beneficial to provide pedestrians with the corresponding information in some other way (e.g. by means of an external vehicle interface).' (p. 485/486).

The idea to support pedestrians and other road users in their understanding of whether an approaching motorised road user has perceived them, and is about to decelerate (and probably yield) is anything but new. Already a patent from 1938 explicitly stated that, while the conventional brake light presented relevant information to the following traffic, there was a 'definite need, experienced by many drivers and by pedestrians, for an indication of the action or intended action of the driver of another motor road vehicle travelling towards or obliquely with respect to the observer' [12] (p. 2). The inventors proposed to put coloured lights on the front of the vehicle. An amber light would be switched on as soon as the driver took of his foot off the accelerator pedal, while a green light would be activated once the driver depressed the brake pedal. Similar patents, praising the potential safety effects of such a frontal brake light, and proposing a variety of different technical solutions, can be found throughout the past decades [13, 14]. Patents from the 1920s, a time when the brake lights as such were still a novel technology, and therefore hardly regulated [15], also show that initial ideas for indicating deceleration actually often included brake lights both in rear and front [16, 17]. The respective arguments for this implementation often explicitly mentioned the need to inform pedestrians about a motor vehicle's behaviour.

Given this long history of the idea of a frontal brake light, one should expect that the potential use and the corresponding effects of such a light have been studied expansively. However, our research uncovered only one single (45-year old) study that explicitly addressed the idea of the frontal brake light [18]. In that study, participants used a frontal brake light on their private vehicle for a month and were then asked about their opinion about the technology as well as their experience in using it. In addition, the second group of participants, which had no previous experience

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with the light, was asked to provide its opinion on the concept. Both groups stated that they considered the technology potentially useful, both for the communication with other drivers and with pedestrians. The possibility to convey information under reduced ambient lighting (e.g. driving at night) was highlighted. The participants that had experienced the brake light on their own vehicles also reported that sometimes, they deliberately depressed the brake pedal to activate the brake light as a means to communicate their intentions to other road users.

Although the potential benefits of the frontal brake light became apparent, a lot of questions remained. Unfortunately, it appears that since then, there have been no further investigations of the frontal brake light regarding, e.g. the effects it could have on road safety and traffic throughput. Potentially undesirable side effects were left unaddressed, too (e.g. potential misunderstandings with regard to driver intentions, confusion due to new/different lighting signals emanating from the vehicle). Only recently, with the advent of vehicle automation, has the issue of communicating vehicle behaviour to other road users gained traction again. For example, Lagström and Lundgren [19] developed an interface that informed other road users about the vehicle's driving mode ('automated') and its intentions ('about to yield', 'resting', 'about to start'). Clamann *et al.* [20] proposed and evaluated a forward facing display that advised pedestrians to cross or not cross the road in front of the vehicle (although it should be noted that the display advised 'walk' only once the vehicle was stopped), or, alternatively, just informed them about the vehicle's speed. While such solutions will certainly, at some point, be implemented, they appear rather sophisticated compared to a simple frontal brake light and are not easily transferable to non-automated vehicles. While a frontal brake light would simply be wired to the brake pedal, information such as 'about to yield' would require additional computations and sensors, or even driver intent detection to be derived. Therefore, for the time being, a frontal brake light seems to be, at least in theory, a reasonable alternative to help other road users infer whether an approaching vehicle is about to let them cross or not (while, of course, lacking the absolute certainty that an 'about to yield' display might provide).

The aim of the experiment reported in this paper was to shed some light onto very basic questions with regard to the potential effects of a frontal brake light. One simple question is how far such a brake light indeed facilitates the detection of deceleration. It might be argued that an earlier detection in itself is probably not an improvement of safety and that it is somewhat trivial to expect that an additional signal would result in earlier responses. At the same time, knowing earlier that an oncoming vehicle is about to stop can certainly impact positively on traffic throughput and general road user satisfaction, as left turn and crossing decisions can be made and subsequent manoeuvres initiated much earlier. Also, an attempt at quantifying this potential improvement in detection is certainly warranted.

While the activation of a frontal brake light in a certain situation might facilitate the detection of deceleration, a non-activation in such a situation carries important information, too. Different from the rear brake light, where activation is indicative of a potential hazard (a vehicle about to stop) for the following traffic, for the frontal brake light, the non-activation would be the indicator for a potentially dangerous situation (a vehicle not stopping). In an environment in which the frontal brake light would be compulsory, this, again, would be a trivial matter – is the brake light activated, the vehicle decelerates, is it not activated, the vehicle does not decelerate. In the short and medium terms, however, a much more realistic scenario would be an environment in which only a portion of all vehicles is equipped with the technology. Other road users could not rely solely on the activation of the light to decide on their turning/crossing manoeuvres. They still would have to identify deceleration from the movement of approaching vehicles. In such a scenario, the question is how the fact that a subset of all vehicles on the road is equipped with a frontal brake light affects other road users' behaviour when confronted with a decelerating vehicle that is not equipped with the frontal brake light.

In the reported experiment, we tried to quantify the potential benefit of an activated frontal brake light with regard to the identification of deceleration. We hypothesised that decelerations accompanied by the activation of the frontal brake light would be perceived much earlier than decelerations without the brake light. In addition, we also wanted to explore the brake light's effect in a mixed traffic environment. More specifically, we wanted to assess whether the fact that a deceleration might potentially be accompanied by a brake light impacts on the identification of decelerations for which this is not the case.

2 Method

2.1 Design

To answer the research questions, we conducted a video based lab experiment. In the first of two experimental blocks, the participants' task was to identify a braking manoeuvre without the help of a frontal brake light. In the second block, the frontal brake light was active in half of all braking manoeuvres. This design allowed us, by comparing trials with and without frontal brake light activation, to assess the potential effect the frontal brake light might have on the identification of braking manoeuvres (block I/II without versus block II with). At the same time, it enabled us to investigate in how far the possibility of a frontal brake light activation impacts on the identification of braking manoeuvres that are not accompanied by the light (block I without versus block II without). In addition, we varied approach speed and deceleration on two levels each. For our analysis, this resulted in a $3 \times 2 \times 2$ repeated measures design with the factors 'condition' (block I without, block II without, block II with), speed (30 km/h, 50 km/h) and deceleration (3.5 m/s^2, 5 m/s^2).

2.2 Participants

Thirty-one students of Technische Universität Chemnitz took part in this experiment. Twenty-seven of them were holding a driving licence. Eighteen participants were female and 13 were male, with a mean age of 24.2 years ($SD = 4.9$). They received course credits or monetary compensation (€5) for their participation.

2.3 Material

In our experiment, we used video clips (30 fps, 1920×1080 px) of a vehicle approaching (Fig. 1, top) with an initial speed of either 30 km/h or 50 km/h, as well as decelerations of either 3.5 m/s^2 or 5 m/s^2 (until the vehicle came to a standstill). In addition, the initiation of the deceleration was varied with regard to its physical distance from the camera position (30 m or 20 m from the camera) and its time distance from the start of the video (3 s or 4 s), in order to prevent participants from using strategies that would be based on such aspects. The use of video material from two different sites was supposed to further impede the development of such strategies. To reduce the predictability of the scenarios, we also created video clips in which the vehicle did not decelerate, but rather passed the observer's position at unreduced speed (30 km/h or 50 km/h). From each site, an equal number of clips was used, with equal distribution of all relevant factors between the clips from the two sites. Overall, the video clips were between ca. 6 and 9 s in length, dependent on the defined onset of the braking manoeuvre, the initial speed and the deceleration.

In some of the experimental trials, the brake manoeuvre was indicated by a frontal brake light. This brake light was physically mounted above the vehicle's license plate (see Fig. 1, middle/bottom), and lit up as soon as deceleration set in. As the brake light on the front, other than the ones on the rear, has no warning function, but rather indicates that a safe crossing in front of the vehicle might be possible, we decided for a green (instead of a red) light. We did not consider industrial guidelines or official regulations with regard to the colouring of the light at this stage. Our only requirement was that the light would be clearly visible in the video material.

The actual basis for the final videos used in the experiment were recordings of a vehicle approaching and passing the position of the camera at a slow, constant speed (20 km/h) that were then processed to create the deceleration artificially. This was done in

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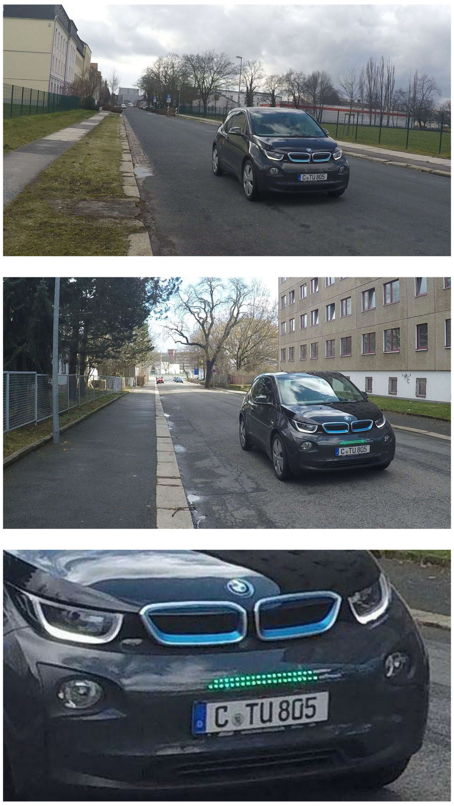

Fig. 1 *Screenshots out of the video material. (Top) recording site one, no frontal brake light activated, (middle) recording site two, frontal brake light activated, (bottom) close-up of frontal brake light*

order to have complete control over the depicted deceleration, both with regard to the onset and the magnitude, which could hardly be achieved through manual braking. Per the site, three video clips were recorded – one without frontal brake light, one with frontal brake light activation in a distance of 30 m from the camera, and one with frontal brake light activation in a distance of 20 m from the camera. The light was activated by pressing a button inside the vehicle. The videos were recorded with a comparatively high frame rate (120 fps) so that further processing (e.g. artificial acceleration or deceleration of the video) would be possible while still preserving the fluency of the vehicle's approach. The collected videos were cut into single frames, and a selection of these single frames (based on the research design, i.e. the required onset of deceleration and its magnitude) was pasted together to create realistic depictions of the different speed and deceleration levels (as a side effect, this resulted in the removal of auditory information). It was taken care that the videos did not contain any visibly moving elements (apart from the vehicle) that could have served as indicators that the speed of the video was manipulated.

2.4 Procedure

The experiment was conducted in the labs of TU Chemnitz. Participants were seated about 50 cm from a 23″ screen, on which the video material was presented in full screen mode. The complete experiment was implemented within OpenSesame [21].

First, participants were presented with general information about the experiment. This included examples of the video material that was to follow, as well as an introduction to the participants' task, which was to judge if/when the approaching vehicle is decelerating. As soon as such a deceleration was identified, participants had to press the space bar (or not press it if there was no deceleration). Participants were instructed to try to avoid false alarms, i.e. they were supposed to only press the space bar once they were relatively certain that a deceleration had occurred. In the instructions, the situation was likened to a pedestrian waiting to cross, a scenario in which the identification of deceleration would be an important factor when trying to find out if the approaching vehicle is yielding (and a situation in which, obviously, a false alarm could have devastating consequences). However, it was also made clear to them that their task was not to actually indicate crossing intent (or include aspects of crossing in their assessment). Participants completed three practice trials, in which they were presented one trial without deceleration and two trials that covered both speed and deceleration levels, to become familiar with the task.

After that, participants were confronted with the first experimental block, which included 36 trials, among them 8 without deceleration, in randomised order. In this first block, none of the decelerations were indicated by the frontal brake light. Also, the instructions up to this point had not mentioned the possibility of a frontal brake light, so participants were essentially assessing the potential deceleration of approaching vehicles as they would do currently in real traffic.

Once the first block was concluded, participants received instructions with regard to the frontal brake light, including an example video. It was clarified that each activation of the brake light was an indicator for an actual deceleration. At the same time, it was explained that not every deceleration went with the activation of the brake light, which was allegedly caused by a malfunction of the light. The participants' task remained unchanged. They were again presented with 36 randomised experimental trials, 8 of them without deceleration. Half of the presented decelerations were indicated by the frontal brake light.

After the second block, participants provided demographic information. In addition, they were asked to indicate their level of (dis)agreement (5 point scale) with six statements regarding the potential usefulness and safety effects of a frontal brake light. Overall, the experiment took between 20 and 30 min to complete.

3 Results

First, we reviewed the dataset for false alarms. In a total of 496 trials without deceleration (across all participants), there were only 14 cases (9 in block I, 5 in block II) in which participants erroneously indicated to have perceived deceleration, which is a rate of 2.8%. We also found 20 cases (16 in block I, 4 in block II) in 1736 trials (a rate of 1.1%) in which participants indicated to have perceived a deceleration before its actual onset. These cases were removed from further analysis.

Fig. 2 shows the participants' mean identification times (from the onset of deceleration until pressing the space bar). It is obvious that the activation of the brake light made the perception of the deceleration much easier, with clear reductions in identification time compared to the other two conditions. At the same time, however, it is clearly visible that participants showed increases in identification time for the deceleration without brake light in block II in comparison to block I. Also apparent are the effects of approach speed and deceleration, which exclusively impacted on the perception of decelerations when no brake light was activated. A three-factor ANOVA for repeated measures confirmed these impressions, with significant main effects for all three factors, as well as significant interactions (for all test statistics, see Table 1). Post-hoc comparisons (Bonferroni correction for multiple comparisons) also showed significant differences between block I and block II without brake light activation ($p = 0.002$, $d = 0.70$), as well as between these two conditions and the condition with brake light activation (both $p < 0.001$, $d = 3.25$ and 4.31, respectively). Table 2 shows the participants' assessment of the frontal brake light as measured with the help of a few general statements. Participants painted a rather positive picture of the frontal brake light, both with regard to its general potential and its specific effect on road safety. Only a few participants selected neutral or negative response alternatives.

4 Discussion and conclusions

The results of our investigation indicate that the use of a frontal brake light can lead to considerable improvements in the identification of a vehicle decelerating. This, in itself, is not surprising. The extent of these improvements, however, is remarkable. For example, without a frontal brake light, the

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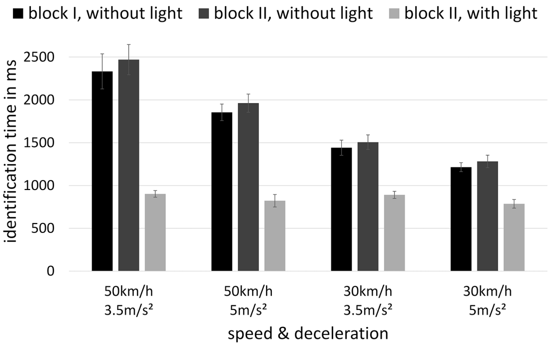

Fig. 2 *Participants' identification times as a function of experimental condition, vehicle approach speed and vehicle deceleration. Error bars indicate the standard error*

identification of a rather average deceleration (3.5 m/s^2) that started at a typical approach speed (50 km/h) took a full 1.5 s longer than with the light. This technology, therefore, has obviously the potential to speed up decision processes with regard to pedestrian crossing decisions. In general, any road user ahead, e.g. another car about to make a left turn across our vehicle's lane, might benefit from the information. It has to be acknowledged, however, that the chosen laboratory setup and the video material that was used reflect only parts of a natural crossing situation. The depiction of a vehicle decelerating on a computer screen (especially without activated frontal brake light) certainly complicates the identification of such a manoeuvre. Relevant cues that are usually helpful in identifying deceleration are missing. As a consequence, it has to be assumed that the time actually saved under the depicted circumstances as a result of the frontal brake light activation might be somewhat less. At the same time, it is reasonable to expect that under specific environmental conditions which were not tested in the reported experiment, such as insufficient ambient illumination, the effects of a frontal brake light would be even more pronounced.

It also should be noted that the identification of deceleration is neither identical nor necessarily perfectly correlated with the actual initiation of a crossing or turning manoeuvre by the observer. For example, as a result of the much earlier identification of the deceleration, the vehicle's approach speed when the identification occurs is still rather high (compared to a later identification, as it is found without the brake light). Therefore, it is possible that despite the earlier identification, road users would not necessarily initiate a turning/crossing manoeuvre immediately, since the potential consequences of a misjudgement would, as a result of the comparatively high speed, be quite severe. In fact, it would be rather problematic if road users initiated crossing or turning manoeuvres right away, without verifying that it is indeed safe to cross. To address this issue, additional investigations that not only look into the perception of deceleration but also actual crossing decisions, are required. Especially the question of when the vehicle starts to brake, both in terms of physical and time distance, necessitates a more systematic approach in the variation of these factors.

Clearly, much more important than improvements in detection, which might or might not increase traffic throughput, are the potential safety effects generated by a frontal brake light. In that regard, the fact that the identification of a deceleration without activated brake light in block II took longer than the identification of such a deceleration in block I is most informative. This finding should not be interpreted as an actual decrement in detection performance. Instead, this delayed identification of the deceleration can be ascribed to a change in the observers' decision criterion. It seems as if the participants, when confronted with a context in which a portion of the deceleration events would be indicated by a frontal brake light, wanted to be 'really sure' that there was a deceleration in cases in which no brake light was activated. Participants appeared to 'wait' (for a very short period of time) for the brake light to occur, which would have provided a much higher level of confidence that, indeed, the vehicle was decelerating. As a result, participants became more conservative when required to indicate that they had perceived the deceleration. On a descriptive level, the reduction of false alarms and early responses in block II is an additional indicator for this increased conservatism.

However, while we were able to verify the general potential of a frontal brake light, a lot of questions remain. It is unclear how road users who have not been exposed to the frontal brake light previously would respond to its sudden appearance on the road. Likewise, the brake light's potential to contribute to dangerous misunderstandings in situations in which a driver does not intend to stop, despite depressing the brake pedal, needs to be addressed. Corresponding campaigns that inform the public about the technology and its limitations could certainly be helpful to reduce possible negative effects.

In addition, design issues, such as the colour of the brake light, its luminance, its form or its position on the vehicle front need to be investigated further to maximise the frontal brake light's conspicuity and intelligibility. Most of these aspects, however, cannot be addressed in a video-based setup. Studies in light tunnels, in which ambient lighting conditions can be manipulated along a variety of factors, and as a consequence allow for the investigation of a wide range of use cases, are necessary to clarify such details. Among these details is also the question of whether any effect that can be found in the clean experimental environment indeed carries over to an environment that contains an abundance of other light sources, such as inner city traffic. In such a scenario, in which not only the lights (front, rear, brake) of many different road users but also illuminated adverts, shop windows and so on, compete for attention, it is certainly debatable whether an additional (coloured) frontal brake light is really helpful, rather a distraction or even confusing. Still, given the still considerable numbers of killed and injured pedestrians, the rise of automated

Table 1 Test statistics for three-factor ANOVA

	df	*F*	*p*	η_p^2
condition	2, 60	363.07	<0.001	0.92
speed	1, 30	305.32	<0.001	0.91
deceleration	1, 30	123.04	<0.001	0.80
condition × speed	2, 60	164.37	<0.001	0.84
condition × deceleration	2, 60	22.45	<0.001	0.43
speed × deceleration	1, 30	13.50	<0.001	0.31
condition × speed × deceleration	2, 60	10.70	<0.001	0.26

Table 2 Participants' general assessment of the frontal brake light through agreement to a set of statements, relative frequencies in %

	completely disagree	disagree somewhat	neither nor	agree somewhat	completely agree
I1	0	0	0	35.5	64.5
I2	74.2	25.8	0	0	0
I3	0	0	9.7	54.8	35.5
I4	0	0	12.9	51.6	35.5
I5	0	3.2	9.7	51.6	35.5
I6	0	9.7	41.9	29.0	19.4

(Items: 'The frontal brake light…' I1 – '…is a good idea.', I2 – '…does have no advantages.', I3 – '…can make traffic safer.', I4 – '…can prevent crashes.', I5 – '…increases pedestrian safety.', I6 – '…can facilitate getting ahead in traffic.')

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vehicles, and the general potential of the frontal brake light, a further assessment of this technology might prove valuable.

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