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Potential of auxiliary strobe lights on train locomotives to improve level crossing safety

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ABSTRACT

Inattentiveness of road users on approach to passive railway crossings represents a major threat to level crossing safety. An auxiliary strobe light system installed on trains in addition to existing headlights may help address this issue by providing an ergonomic way of attracting human attention to the level crossing and to the train. The objective of this paper was to investigate the ergonomics and safety potential of auxiliary strobe light systems. A system was implemented on a real railway vehicle and in the virtual environment of a driving simulator. Acceptance of the system, including its usefulness and perceived benefits and drawbacks, as well as its objective effectiveness, were evaluated using questionnaires, behavioural measures, and eye tracking. The safety potential of the system was evaluated with respect to fatal level crossing accidents. The auxiliary strobe lights were preferred over normal lights and were rated as useful, reducing driving speeds, increasing visual scanning at level crossings, and thus aiding detection of a train. The system has the potential to prevent 6–30% of level crossing accidents in Europe. The results suggest that it might be worthwhile to test auxiliary strobe lights in a larger scale real-world experiment. Especially on railway lines with a high number of passive level crossings, this system can be expected to increase safety by supporting timely detection by road users and preventing accidents caused by inattentiveness.

1. Introduction

Level crossings are among the most critical parts of a railway system, their safety depending substantially on the attention and behaviour of road users (European Union Agency for Railways, 2018). At level crossings, road users generally must give way to trains. The behavioural demands imposed on road users by this necessity are especially high at passive level crossings, meaning crossings that are protected by road signs only without the presence of active safety systems, such as barriers, that indicate an approaching train. At a passive crossing, road users bear the responsibility for first detecting the crossing (e.g., based on approach or warning signs), carefully checking to the left and right for an approaching train, then deciding whether to proceed (Dreßler et al., 2020). However, several studies underline that most drivers at passive level crossings tend not to check actively whether a train is approaching (Åberg, 1988; Grippenkoven and Dietsch, 2015; Ngamdung & da Silva, 2013; Wigglesworth, 1978).

Ergonomic design can improve the safety of passive level crossings mainly by ensuring that the crossing driver or vulnerable road user can anticipate an approaching level crossing and will easily detect an approaching train early enough. The former can be addressed by warning the road user at the right time. Early detection can be improved by redesigning either the level crossing, the vehicle, or the train in a way that encourages or enforces slowing down before the level crossing, or by improving the visibility of the train. One possibility is to use in-vehicle warnings of an approaching level crossing (Larue et al., 2015). To be effective, this would require that a large share of vehicles are equipped with this type of system and that it is also used. Stationary peripheral flashing lights in the vicinity of passive level crossings have been proven effective at drawing the visual attention of drivers to the left and right peripheries, enhancing the probability of train detection (Grippenkoven et al., 2016; Grippenkoven, 2020). Additionally, such systems are available to all road users using the level crossing. Comparably, auxiliary strobe lights on approaching locomotives should lead to

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better detection, as strobing or flashing in the periphery of a person's visual field draws their attention directly to the object in a stimulus-driven response (Wickens et al., 2013; Wolfe and Horowitz, 2004; Yantis, 2000). This autonomous attentional response to sudden onsets in the visual periphery is thought to have become hard-wired into the brain's visual processes during evolution because it promoted survival (Yantis, 2000); thus it does not require voluntary effort and is not expected to wear off in repeated level crossing encounters.

Several studies have examined the effect of locomotive-mounted lighting measures on train conspicuity. One of these, by the U.S. Department of Transportation (1995), examined train detectability, arrival time estimation, and accident reduction potential for three experimental auxiliary light installations on a train and compared their safety potential with that of a headlight-only configuration. The systems they installed were (1) strobe lights mounted at the train front on each side, (2) ditch lights illuminating the sides of the track, which regular headlights do not do, and (3) crossing lights, which are essentially a flashing variant of ditch lights (Carroll et al., 1995). Crossing lights produced a statistically significant increase in train detection distance compared to the two other systems and headlight only, and ditch lights produced a significant increase compared to headlight only. The improvement with the strobe light bordered on statistical significance (Carroll et al., 1995), whereas other studies suggest that strobe lights draw attention far more effectively than headlights only (Hopkins and Newfell, 1975; Devoe and Abernethy, 1975). However, some aspects of the methods used by Carroll et al. (1995) may compromise the generalisability of their results. For one thing, the participants in the study knew that a train would be approaching as the target stimulus they had to detect and were therefore actively looking for it, which may have increased their detection rates overall. Furthermore, the participants did not approach the passive level crossing dynamically but were positioned in a stationary chair at a set distance facing the level crossing, which made the task rather artificial.

Cairney et al. (2002) evaluated the effectiveness of headlights and a ditch light, as well as a strobe light combined with crossing lights and headlights. The crossing lights were found to be so bright that they essentially masked the strobe lights and rendered them useless during night-time testing. During daytime testing, none of the lights were found to be effective in bright sunlight. The report concludes that neither of the lighting systems offered a superior alternative to standard headlights, but Cairney (2003) suggests that these results are probably not due as much to the systems themselves as to an unsuitable research design and limited time available for testing.

Since the effects of additional locomotive lighting devices on road users approaching a level crossing have not been satisfactorily quantified, it seems worthwhile devoting further effort to the scientific examination of this safety measure. Improved headlights could be a cheap and effective solution leading to a significant improvement of safety at passive level crossings. Hence, the objective of this work was to investigate the ergonomics and safety potential of auxiliary strobe lights to improve level crossing safety. Two studies were carried out to this end.

First, a video-based experiment was conducted to obtain the assessments of road safety professionals and non-professionals regarding different configurations of auxiliary strobe lights implemented during the tests. Acceptance of the configurations was assessed in both day and night-time conditions by asking the respondents to rate which of the presented systems they preferred, and which benefits or drawbacks they foresaw with the strobe lights. A potential concern with strobing is that it could be considered annoying or distracting. Specifically, distraction would be a drawback if it influenced the estimation of train arrival. Therefore, the respondents were also asked to provide estimates of the minimum crossing margin they would leave for an approaching train at a level crossing with and without auxiliary strobe lights. If the flashing lights made the estimation of train arrival time harder, we would expect changes in crossing margins. In particular, the perceived difficulty of the task has been linked to an increase of self-reported, subjective estimates of risk (Fuller, 2005). If the flashing lights made the estimation more difficult, it could increase the subjective feeling of risk, which could be compensated for by leaving a longer crossing margin.

The second study was a simulator experiment to investigate whether auxiliary strobe lights facilitate the detection of an approaching train by car drivers at a passive level crossing. Three types of data were collected and analysed to this end: subjective assessments of the usefulness of the system (overall, and for detecting the crossing and/or the train) by questionnaire after the test drive, eye movement data to assess train detection latency as expressed by time-to-first-fixation, and speed profiles ahead of the level crossing to investigate whether potential differences in detection also led to a change in driving behaviour.

2. Method

2.1. Steps in the evaluation

The ergonomics and safety effects of auxiliary strobe lights on user behaviour and experience at level crossings were evaluated based on four steps: i) road users' estimates of the required safety margins for crossing the railway line (based on video data from a real railway environment), ii) driver attention and behaviour (based on eye-tracking data and data on driving speeds collected during the driving simulator study), and iii) acceptance and experienced usefulness of the system for detecting the crossing and/or the train. Finally, iv) the potential safety effects of auxiliary strobe lights were estimated based on the previously presented studies, other earlier literature, and statistics on level crossing safety.

2.2. Concept and prototype of the automatic warning light system

The studied prototype of the automatic warning light system contained three high-intensity LED lights and a control unit. LED lights were high beam accessories approved by the road traffic authorities in Europe. Each unit had a light intensity of 10,000 lumen and a beam range of up to 800 m. The lights could be controlled separately to adjust the blinking pattern. Intensity was not controllable. In the video-based experiment, the lights were installed on a railway vehicle in accordance with prevailing regulations (lights according to 4.2.7.1.2 Marker lights; blinking according to 4.2.7.1.4 Lamp controls, Commission regulation (EU) 2014/1302), in addition to the regular locomotive or railway vehicle headlights (three continuous white headlights, two at the bottom and one at the top). The additional blinking LED lights were installed below each of the headlights (Fig. 1).

The automatic warning light system could be automatically activated at a set distance from the level crossing and deactivated once the train had passed. A level crossing database containing the geolocation of each level crossing and warning trigger-point distances could be used to trigger the auxiliary strobe lights based on the geolocation of the locomotive. The level crossing database would allow settings to be defined for light intensity limits and timing of strobe light patterns at each level crossing, enabling optimal tuning for best performance and minimal disturbance. Additionally, the intensity of the warning light could be adjusted automatically for ambient light conditions at different times of day. The concept for this automatic warning light system was developed as part of the EU project SAFER-LC (Silla et al., 2019).

For the simulator study, a train model featuring a potential future design of a strobe light system was developed using the Vires VTD toolset (Fig. 2). On the front side, strobe elements (a[1]) were positioned around the regular triangular frontal headlight set (b) of a German DB Regio double-decker railcar. The two lower headlight elements stretched around to the side, where an additional upper element (a[2]) was included. The light elements were integrated flush to the body of the railcar.

Fig. 1. Warning light installation on a railway vehicle (left: additional LED lights on; right: additional LED lights off). The control unit was placed inside the cabin.

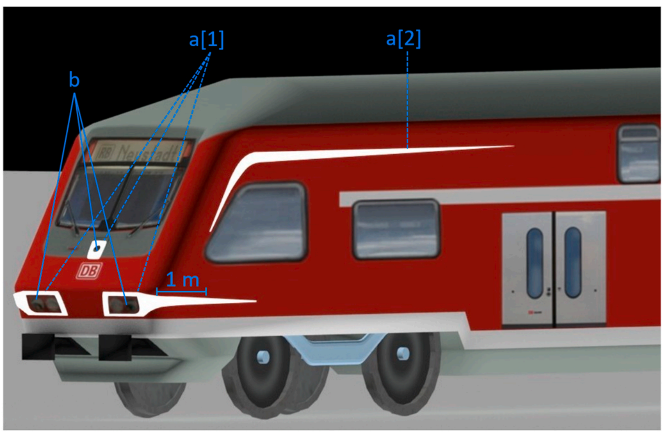

Fig. 2. Train model with integrated strobe light system used in the simulator study.

2.3. Pilot design and apparatus

The concept of the strobe light system was piloted via a web questionnaire, using videos of the prototype from a real railway environment, and in a driving simulator experiment using the train model with integrated strobe lights.

Filming for the web questionnaire was done on 14 March 2019 in Sääksjärvi, Finland, where the system prototype was being tested on the main railway network, on one of three tracks reserved for the tests. No official level crossing existed at the site, but a road user camera could easily be installed 2 m from the track at a height of around 1.25 m. A rented railway vehicle equipped with the auxiliary strobe lights was driven through the imaginary level crossing several times, both in daytime conditions (12 p.m.–1:30 p.m.) and during darkness (11 p.m.–1:30 a.m.) at a speed of 20 km/h. On each approach, the system was set to produce a specific strobe light pattern according to one of three test configurations and one reference setup (cf. Table 1). The duration of each blink was 100 ms, and in the case of several blinks there was a 100 ms pause between blinks. There was also a 2 s break between each sequence of blink(s). The reference setup had the standard train configuration of three continuous white headlights, two at the bottom and one at the top. In the alternative configurations, additional blinking LED lights were installed below each of the headlights. The approach of the railway vehicle to the imaginary level crossing was filmed from the roadside, recreating the perspective of a pedestrian looking right, down the track, from the level crossing. Footage was shot for all light configurations both in daytime and at night.

The simulator study took place in one of the MoSAIC fixed-base driving simulators at the DLR in Braunschweig, Germany (cf. DLR, 2021). The driving environment was presented to the participants via three full-HD 50-inch monitors spanning a visual angle of 140°, using the Vires VTD (Virtual Test Drive) toolset, Version 1.4 (Fig. 3). The three monitors were arranged around an interactive car dashboard including a speedometer display, a steering wheel, accelerator and braking pedal with force feedback, and a separate left exterior mirror display. The visual simulation ran on three synchronised computers (60 Hz synchronisation, standard PC including Nvidia GeForce GTX 580 graphic card), with one computer controlling the sensors and actors of the driver interface (CAN) and the recording of driving data (sampling rate 20 Hz). During the drive on a rural road, each participant encountered multiple level crossings with different safety measures. One of the measures tested was the auxiliary strobe light system for trains. Its effects were assessed in a between-subjects comparison: In a train encounter at one of the level crossings, one half of the participants experienced a train with active strobe lights, the other half encountered a standard train. The train speed when approaching the level crossing was 80 km/h. Unlike in the web questionnaire, the focus of the study was not to compare different configurations but to test the principle of the strobe light against other safety measures, using one configuration example. In the strobe light condition, the blinking (160 ms on and 160 ms off, alternating) started as soon as the train appeared in the periphery and continued until the leading railcar had reached the level crossing, which took approximately 15 s. The route altered between villages and open terrain in which the level crossings were situated. The intermediate sections between the level crossings were long enough to guarantee a driving duration of at least 7 min between any two crossings. The virtual environment was crossed in daylight conditions. The passive level crossings were always approached on a straight road section of 500 m with a clear view of the railway tracks. The speed limit on these road sections was set to 50 km/h. A Smart Eye Pro four-camera contact-free remote eye tracker was used to record eye movements with a sampling rate of 125 Hz using Smart Eye Pro software version 9.0.

Table 1
Four light configurations tested in the video-based questionnaire.

Configuration/Number of blinks	Description
C0	Reference system without strobe light
C1	Single blink every 2 s (blink 100 ms + break 2 s)
C2	Double blink every 2 s (blink 100 ms + break 100 ms + blink 100 ms + break 2 s)
C3	Triple blink every 2 s (blink 100 ms + break 100 ms + blink 100 ms + break 100 ms + blink 100 ms + break 2 s)

2.4. Procedure, participants, and analyses

2.4.1. Video-based evaluation

Evaluation of the videos was done with a web-based questionnaire. One sample of respondents consisted of rail and road transport experts connected to the SAFER-LC project. For comparison, the questionnaire was also completed by a second sample of non-expert students from the local university. Three alternative light configurations were compared with the standard reference configuration both in day- and night-time conditions.

Eight videos were rated as part of the questionnaire: four in daytime

Fig. 3. Simulated driving environment. The train with the strobe light system is approaching from the left.

conditions demonstrating the reference system and three alternative configurations, and similarly four in night-time conditions. The duration of the videos was 66–68 s for daytime and 111–130 s for night-time footage, the latter being longer because the train becomes visible sooner in the dark. The questionnaire started with the presentation and evaluation of all four daytime videos, followed by the four night-time ones. Fig. 4 shows still pictures from the videos included in the web-based questionnaire.

The reference configuration without blinks (C0) was always presented first, followed by the configurations with two blinks (C2), one blink (C1), and finally three blinks (C3). For each configuration, participants were asked to watch the video and report at what point they would no longer start crossing the railway line. This was done to investigate whether the configurations with flashing lights might elicit an illusion of faster movement or make the train appear more threatening. For these three alternative configurations, the participants were further asked whether they perceived any benefits or drawbacks compared to the reference configuration and, if so, to describe them. After watching all four day/night-time videos, the participants reported which one they preferred and why.

Answering was voluntary and anonymous. For the expert sample, the link to the questionnaire was sent via a project email list, and for the non-experts to various email lists of the local university. In total, 18 expert and 16 non-expert responses were received and analysed.

2.4.2. Driving simulator study

Participants were recruited from the Braunschweig area via notices in local stores and Internet ads, and randomly assigned to one of two groups based on the train light design (auxiliary strobe lights vs. standard). Upon arrival at the test site, the participants were welcomed, given written instructions, and asked about any remaining questions before giving their consent to participate. After calibration of the eye-tracking system, participants completed a training drive of about 5 min that did not involve any level crossings. In the following test drive, each participant encountered several level crossings, two of which were relevant to the assessment of the strobe light system. The first one, encountered at around 7 min of driving, served as the baseline and involved a standard passive level crossing safety layout with no train approaching. At the second one, which was structurally identical and crossed after approximately 35 min, a train approached the crossing at the same time as the driver. The trigger point and velocity of the train were set such that drivers had to give way if they were travelling at the permitted speed. When the train first became visible in the periphery, the participants were on average 250 m ahead of the level crossing. The train's light design varied between participants: one half encountered a train with active strobe lights, the other half a standard configuration that included the additional light elements in a non-lit, non-strobing fashion.

To avoid unwanted behavioural bias, a cover story was used to distract participants from the level crossing focus of the study. Participants were informed that the study was about coping with challenging situations when driving. They completed a secondary task on a mobile phone once while driving through each of the villages between the road sections with level crossings. The real purpose of the study was revealed immediately after the study.

The eye-tracking data was analysed for the latency with which the approaching train received the first fixation by each participant after it appeared in the periphery, as a surrogate measure of how early the train was detected by the participants. To be most illustrative, this latency was expressed in terms of the distance travelled (m) between the onset of the train and the first fixation on it.

To assess the effect of the auxiliary strobe light on participants' driving behaviour, speed choice on approach to the level crossing was compared between the two train conditions (auxiliary strobe light vs. regular headlight). To control for potential individual differences, the speed difference between the baseline (level crossing without a train) and the segment involving a train was used for this analysis instead of the absolute speed during the train encounter.

Immediately after the virtual test drive participants completed a questionnaire, giving their subjective evaluation of the effectiveness of the train light measure on a six-point Likert scale. In the questionnaire, the auxiliary strobe light system was explained to all participants with a short text and a large image of a train equipped with the system (Fig. 2). The assessment could therefore be made both by the participants who encountered the locomotive with auxiliary strobe lights and by those who only saw a regular locomotive.

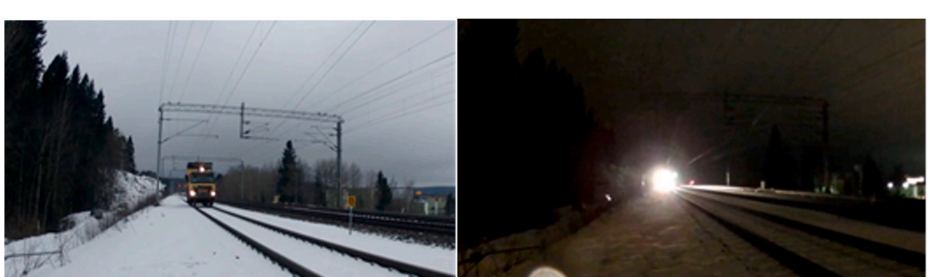

Fig. 4. Still pictures from videos included in the web-based questionnaire. (Left: daytime with reference configuration; right: night-time with reference configuration).

A total of 52 participants (24 male, 28 female) took part in the study. The conduct of the study and the assessment of driving, gaze and subjective data were somewhat restricted because several participants had to abort the test due to motion sickness caused by the simulator, and technical problems were encountered with gaze detection or calibration quality for eye-tracking. Participants who stopped due to motion sickness still completed the questionnaire (in which all the tested measures were explained once more with text and images) if they felt comfortable doing so. Subjective assessments were collected from 49 participants (24 male, 25 female, age 18–65 yrs, M = 35.3, SD = 13.1). A complete set of driving data could be obtained from 46 participants (22 male, 24 female, age 18–65 yrs, M = 34.4, SD = 12.5), and a complete set of gaze data was obtained from 39 participants (18 male, 21 female, age 18–65 yrs, M = 34.4, SD = 12.7).

3. Results

3.1. Road user estimates on required safety margins

The participants were asked to report the moment at which they would no longer cross the track. The effects of configuration, ambient light and respondent group were analysed using a mixed ANOVA. Sphericity was tested with Mauchly's test, and Greenhouse-Geisser correction was applied for the configuration (epsilon = 0.69) and group x configuration interaction analysis (epsilon = 0.69). Generalised Eta squared (η^2G) was used to assess effect sizes.

The crossing margins were shorter in all daytime videos compared with night-time videos, $F(1,32) = 299.24$, $p < .001$, $\eta^2G = 0.541$ (Fig. 5). The mean crossing margin in daytime videos was M = 28 s, (SD = 17 s, Mdn = 22 s) and in night-time videos M = 77 s (SD = 30 s, Mdn = 84 s). The large difference could be attributed partly to night-time videos being longer than those shot in daytime (roughly 120 s vs. 60 s) due to the earlier visibility of the train in darkness. On the other hand, Fig. 5 shows that some participants chose short margins even at night. A significant group and ambient light interaction indicated that among non-experts, the difference between night and day videos was greater than among experts, $F(1, 32) = 5.43$, $p = .026$, $\eta^2G = 0.021$ (non-experts' difference M = 56.42, SE = 4.19; experts' difference M = 43.02, SE = 3.94).

Both the main effect of the configuration ($F(2.07, 66.08) = 7.33$, $\eta^2G = 0.011$, $p = .001$) and its interaction with ambient light were significant ($F2.63, 84.07) = 7.30$, $\eta^2G = 0.011$, $p < .001$). Post-hoc contrasts were run to compare the crossing margins in each of the three auxiliary strobe light configurations (C1 to C3) with those in the standard configuration C0. In the daytime videos, none of the strobe light conditions were statistically significantly different from C0. In the night videos, C1 and C2, but not C3, had statistically significantly longer margins than C0 ($p < .001$). P-values were adjusted for three tests with Dunnett's method. The statistically significant differences in the night-time videos were small (C0 vs. C1: Cohen's d = 0.29, C0 vs. C1: Cohen's d = 0.35).

3.2. Driver attention and behaviour

All but one participant in the simulator study were able to detect the train and let it pass before they crossed the level crossing. The one participant who did not look at the train and crossed right in front of it did so with the standard train design. The latency of train detection, as measured by the distance travelled between train onset and the first fixation on it, was significantly smaller for the strobe light (M = 8.2 m, SD = 9.3) than for the standard train design (M = 30.5 m, SD = 27.6 m). Moreover, train detection was more reliable with the strobe light setup, as shown by a much narrower distribution of values compared to the standard setup (cf. Fig. 6) and illustrated by the maxima: The participant who was slowest to fixate on the standard train after its onset travelled a further 110 m, compared to only 37 m for the slowest participant to note the train with auxiliary strobe lights (an outlier already).

The mean values of the velocity difference profiles on level crossing approach (baseline minus respective train condition, i.e., how much slower did participants drive when a train was present, compared to the baseline without a train) are depicted in Fig. 7.

In both curves there is a point at which the speed starts to drop compared to the condition without a train (circles in Fig. 7), indicating the average moment when participants started to slow down after noticing the train. The data indicates that drivers not only noticed the train earlier when it was equipped with auxiliary strobe lights, but also used this information to adapt their speed sooner.

Four independent samples t-tests were calculated for distances of 300 m, 200 m, 100 m, and 0 m ahead of the level crossing, to compare the mean values of speed reduction between the regular headlight condition and the auxiliary strobe light condition. Welch's *t*-test was used due to unequal variances. Due to the four pairwise tests the level of significance was reduced to $\alpha = .013$ using a Bonferroni correction. The results are presented in Table 2. Only the *t*-test comparing the amount of speed reduction between the train lighting conditions at a distance of 200 m reached statistical significance, $t(37.737) = -3.18$, $p = .003$. While the participants in the regular headlight condition had barely

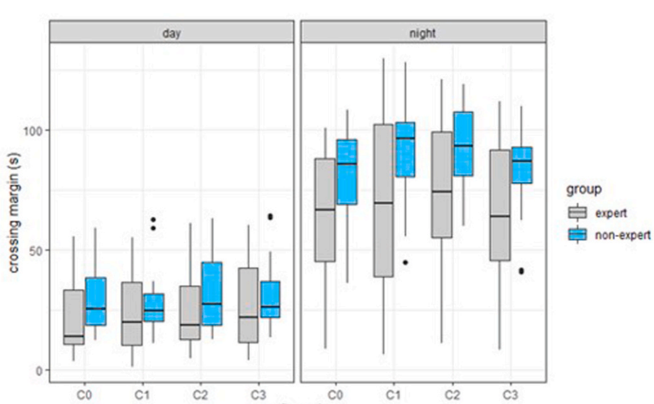

Fig. 5. Crossing margins (s) of experts and non-experts with different configurations in daytime (left) and night-time (right) conditions. Boxplots showing the 25th, 50th and 75th percentiles and hinges extending 1.5 times the interquartile range.

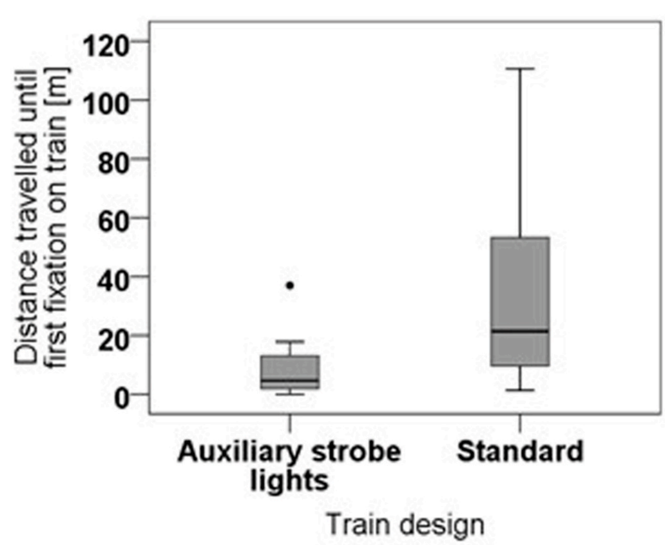

Fig. 6. Distribution of distance travelled between train onset and first fixation on the train in the two train light conditions (boxplot).

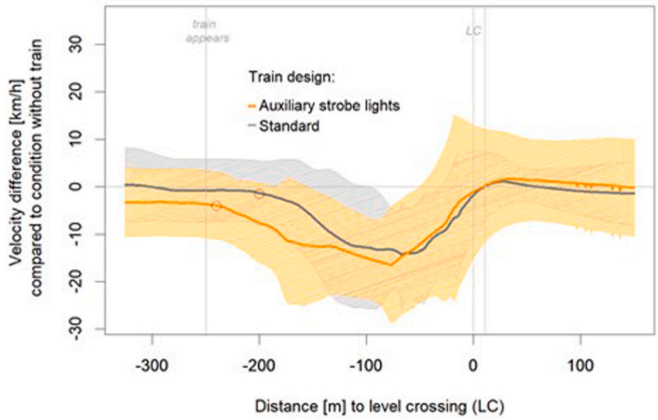

Fig. 7. Speed profiles on level crossing approach in two train design conditions. Thick lines: mean velocity difference to baseline condition, error bands: mean ± 1SD.

Table 2
Results of independent samples t-tests for four distances ahead of level crossing.

Mean speed difference (km/h) between train and no-train condition (SD)						
		Train with regular headlight	Train with auxiliary strobe light	t	df	p
Distance ahead of the level crossing	300 m	+0.16 (*6.95*)	- 3.47 (*8.25*)	−15.129	37.96	.14
	200 m	- 0.64 (*6.78*)	- 8.61 (*9.07*)	−31.779	37.74	.003*
	100 m	- 9.77 (*11.88*)	- 14.86 (*9.98*)	−14.464	33.30	.16
	0 m	- 1.27 (*11.50*)	- 1.94 (*13.81*)	- 0.1662	37.98	.87

reduced their speed at this distance (M = −0.64 km/h), the participants who encountered the train with the auxiliary strobe lights had already reduced their speed by 8.61 km/h on average compared to the baseline. This suggests that the train with the auxiliary strobe lights was perceived earlier by participants, resulting in an earlier adaptation of driving behaviour.

3.3. Acceptance and experienced usefulness of the system

Overall, in the web-based questionnaire, in daytime all the alternative configurations were considered better than the reference configuration. At night, the responses followed the same pattern but were slightly less favourable towards the alternative configurations than by day.

Most of the respondents shown the three alternative configurations saw benefits with the auxiliary strobe light, both in daytime and at night. Fewer than one fifth of the experts and 31–44% of the non-experts saw drawbacks with the alternative configurations in daytime, and around one third of all respondents at night compared to the regular headlights (Table 3). Most comments on the benefits concerned better visibility and detectability. Some responses mentioned that it was easier to judge the approach speed, or that the train seemed faster with flashing lights. Drawbacks mentioned were potential disturbance and misinterpretations caused by flashing lights.

With the daytime videos, most of the experts preferred the alternative configuration C3 with three blinks (Fig. 8). With the night-time videos, experts did not clearly prefer one configuration over another. Among non-experts, configuration C3 with three blinks was most preferred both in the daytime and at night. C2 with two blinks was almost as popular.

Table 3
Proportion of participants who saw benefits and drawbacks (compared to reference system C0) for the alternative configurations.

Group	Timing	Configuration	Benefits (%)	Drawbacks (%)
Experts	Day	C1	67	17
		C2	78	17
		C3	72	17
	Night	C1	56	33
		C2	72	28
		C3	56	33
Non-experts	Day	C1	69	31
		C2	81	44
		C3	69	38
	Night	C1	62	38
		C2	88	38
		C3	94	31

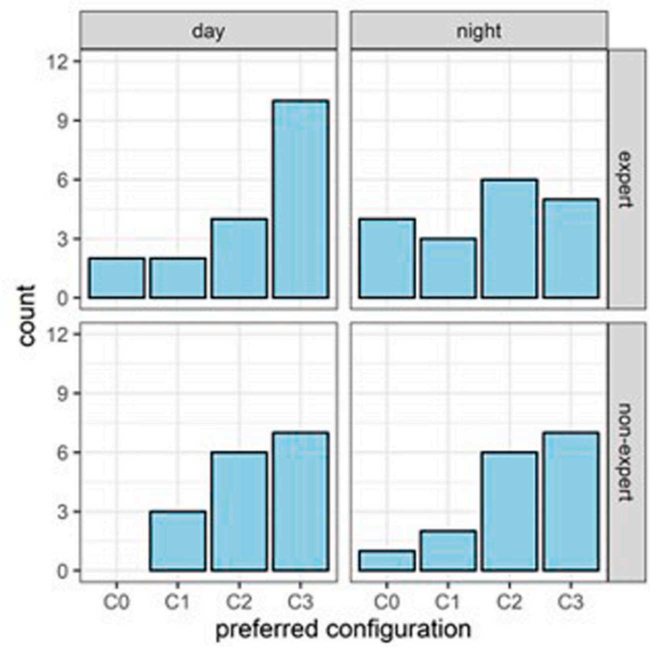

Fig. 8. Preferred configuration in daytime (left) and night-time (right) conditions. Experts' responses at the top and non-experts' at the bottom.

The participants in the driving simulator study were asked to rate the general usefulness of this system in preventing collisions between cars and trains, on a scale of 1 ("totally useless") to 6 ("extremely useful"). The auxiliary strobe lights received an average rating of 4.63 (SD = 1.51). Participants were also invited to judge the extent to which auxiliary strobe lights help detect the level crossing ahead, from 1 ("not at all") to 6 ("extremely"). The mean assessment on this scale was 3.53 (SD = 1.62). Third, participants used the same scale to rate to what extent the auxiliary lights support detection of an approaching train. In this assessment, the strobe light received the highest average rating of 5.05 with the smallest standard deviation (SD = 1.24).

3.4. Estimation of safety potential

The safety potential of the auxiliary strobe lights was estimated based on findings from earlier studies, other earlier literature, and statistics on level crossing safety.

Mok and Savage (2005) analysed US level crossing accident data (1975–2001) using negative binomial regression analysis. Their results show that the use of ditch lights (additional lights on locomotives) reduced level crossing accidents by 29% and fatalities by 44%. In addition to the gradual improvement of level crossing safety over this period, the data showed a substantial 30% decrease in accidents from 1994 to 1998, following a Federal Railroad Administration mandate to install ditch lights on all trains. These reduction estimates were not directly applied to our estimate since the modelling exploited almost 20-year-old accident data. European railway safety has improved since then; thus the obtained effectiveness estimates cannot be applied as such to the current situation. In addition, Mok and Savage (2005) mentioned that the calculated reduction could also be influenced by general improvements in road safety and improvements in level crossing environments that could not be considered by the model.

Grippenkoven et al. (2016) piloted a measure using flashing lights positioned in the peripheral vicinity of a level crossing. The peripheral lights were located near the tracks to the left and right of the road and were activated whenever a road user was approaching the level crossing, to support the visual sampling for potentially approaching trains. Grippenkoven et al. (2016) found a reduction in the fraction of drivers who did not look for a train of 47% on the left and 23% on the right in daytime, and 59% on the left and 53% on the right at night, compared to a passive level crossing without the measure. The findings were also considered relevant for the measure of additional flashing lights on trains. However, they were not directly applied to the effectiveness estimate (i.e., the share of level crossing accidents that could be prevented with this system). This was because: i) the reduction estimates of Grippenkoven et al. (2016) (23–59%) are limited to level crossing accidents due to observation error instead of all level crossing accidents; ii) it is not possible to assume that all road users who look at an approaching train will also act appropriately to avoid an accident; and iii) greater emphasis should be put on the results obtained in daytime, since, based on Silla et al. (2017), most level crossing accidents occur during daytime.

The estimate on the potential effectiveness of the system was made based on the information that 63% of LC accidents are due to observation error (Laapotti, 2016), and of those LC accidents 23–47% could be prevented during daytime (Grippenkoven et al., 2016). Based on Grippenkoven et al. (2016), the effectiveness could be higher during darkness, but on the other hand we cannot be sure that all road users who look at an approaching train will also act appropriately to avoid an accident, which was considered to reduce the estimate. Therefore, it was estimated that auxiliary strobe lights would have the potential to prevent 15–30% of relevant level crossing accidents and target a rather large share of level crossing accidents—between 39.8% (passive level crossings only) and 100% (all level crossings) depending on the approach (Silla et al., 2019). By multiplying the previous estimates, the safety measure is estimated to have the potential to prevent 6–30% of level crossing accidents in Europe. Based on Silla et al. (2017), it is expected that the effectiveness of this measure is higher at passive than at active level crossings due to a high share (34.9%) of accidents at the latter, which are due to other human risk factors (i.e., deliberate risk taking) which (most probably) cannot be prevented with this measure (the corresponding share at passive level crossings is 2.8% only).

4. Discussion and conclusions

The objective of this work was to investigate the potential of auxiliary strobe lights on train locomotives to improve level crossing safety by providing an ergonomic way of attracting human attention to the crossing and to the train. The evaluation of the ergonomics and the safety potential of auxiliary strobe lights on user behaviour and experience at level crossings covered four aspects: i) road users' estimates of the required safety margins for crossing the railway line, ii) driver attention and behaviour, iii) acceptance and experienced usefulness of the system, and iv) estimates based on previous studies, other earlier literature, and statistics on level crossing safety. The respective results are discussed below.

4.1. Road user estimates on required safety margins

The results do not show a large difference between flashing lights and standard non-flashing lights with respect to self-reported crossing margins. Only in night-time videos did two of the configurations (one blink and two blinks) have significantly greater crossing margins than with the non-flashing light, but the effect was still small. Hence, the results do not suggest that flashing lights would make it more difficult (or easier) to judge the arrival time of a train.

The crossing margins were larger in night-time videos than in daytime footage. This is consistent with the task-difficulty model, given that in the night-time videos the lack of visual elements other than lights must have made it harder to judge the distance to the train. However, the comparison is not entirely fair, as the night-time videos were longer than day-time footage and at night the higher visual contrast makes it easier to detect the presence of a train.

4.2. Driver attention and behaviour

In the simulator study, the train equipped with auxiliary strobe lights was detected sooner by participants than the train with regular headlights. Thus, the approach speed of the participant's vehicle dropped earlier as well. Generally, earlier detection of a train is positive since it leaves more time for road users to adapt their driving behaviour and cross safely. Moreover, it increases the overall probability of detecting a train in time.

In our study, the conditions for participants to detect a train on approach to the level crossing were extraordinarily good: during the last 500 m the road was straight and flat and led to the level crossing at a 90° angle with a sight triangle free of obstacles. This may be seen as a shortcoming of the study, since the layout of most passive level crossings is less ideal. However, the auxiliary strobe lights were found to be of benefit even under these conditions. Therefore, we argue that the effect of the strobe lights would likely be even stronger under real, less ideal conditions (e.g., larger crossing angle, bad weather, occluding vegetation, etc.), as the detection of standard railway vehicles is poorer in such environments. Strobe lights automatically draw visual attention and will remain active for as long as they are within the maximum field of vision, which normally extends up to 110° on either side of the centre axis.

In the simulator study, each participant was able to cross safely. However, this might be due to the somewhat artificial conditions of the road approach described above.

4.3. Acceptance and experienced usefulness of the system

Based on the judgements on video data, flashing lights were evaluated as better than regular headlights. Specifically, auxiliary strobe lights were estimated to improve visibility and detectability of the train as well as the safety of level crossings. Potential drawbacks mentioned were that flashing lights may be disturbing or could cause glare. Concerns about misinterpreting the flashing lights were also raised.

In daytime conditions, the experts clearly preferred warning lights with three consecutive blinks followed by a 3-s break (instead of a single or double blink every 3 s). In night-time conditions, none of the configurations were clearly preferred. The non-experts had the same preference for warning lights with three consecutive blinks followed by a 3-s break both in daytime and at night. However, the warning lights with a double blink every 3 s was almost as popular. The results suggest that flashing lights caused more glare or were more disturbing during darkness. Also, at night the train may be easily detectable even without flashing lights. Among the non-experts, configuration three (triple blink every 3 s) was most preferred both in daytime and at night, but configuration two (double blink every 3 s) was also popular. The visual quality of the night-time videos was not as good as daytime footage, which may have influenced the ratings.

Based on the questionnaire results, auxiliary strobe lights appear to be a promising way to increase the detectability of approaching trains, especially in daytime conditions. There were concerns that flashing lights might be disturbing or misleading during darkness. However, although during darkness trains might be more noticeable than in daytime, auxiliary strobe lights could still support early detection. Potential drawbacks of flashing lights and ways to address them, e.g., by focusing the lights and adapting them to lighting conditions, should be investigated further.

The subjective ratings of the participants in the driving simulator study were consistent with the subjective ratings of the video survey. Participants in the driving simulator study also recognised the safety potential of auxiliary strobe lights mounted on the locomotive and estimated that this system supports early detection of approaching trains. This qualitative judgement is supported by the quantitative data assessed in the experiment.

It should be noted that the auxiliary strobe light systems assessed in the video-based study and in the driving simulator study were slightly different (frontal headlights only with 100 ms break between flashes vs. frontal and lateral headlights with alternating blinking: 160 ms on and 160 ms off until the level crossing was reached). However, the focus of these studies was also somewhat different. Specifically, the video-based experiment focused on assessments of different configurations of auxiliary strobe lights implemented during the tests, and on the acceptance of this system, whereas the focus of the simulator study was not to compare configurations but to test the principle of a strobe light vs. other safety measures, using one example configuration.

The two implementations tested represent two different ways in which the concept of strobe lights can be specified with different combinations of features. Both implementations proved effective on the criteria measured. This suggests that there is a range of specific feature combinations that work. Both pilot studies provided valuable input to the discussion on the evaluation of ergonomics and the safety potential of auxiliary strobe lights on user behaviour. Further research could address the investigation of optimum values and how their combination may differ depending on factors such as environmental conditions.

4.4. Estimation of safety potential

In the safety potential estimation, it was assessed that this safety measure has the potential to prevent 6–30% of level crossing accidents in Europe if all relevant level crossings, trains and/or road users were equipped with the system. One-hundred-percent coverage of implementation is not a realistic assumption, but it shows the potential that this measure has to improve the safety of level crossings. Silla et al. (2019) estimated the safety effects of 13 innovative and low-cost level crossing measures, and better train visibility using lights was estimated to have the highest safety potential. The safety potential of other measures varied between 0% and 15%.

4.5. Conclusions

This study produces additional insights on the effects of additional locomotive lighting devices on road user behaviour while approaching a level crossing. Both railway-safety expert and non-expert respondents viewed the auxiliary strobe lights positively, indicating that the proposed design could be acceptable. The promising positive changes in road user behaviour and visual scanning from the simulator study and the positive safety potential estimation indicate that safety benefits could be obtained when using auxiliary strobe lights in addition to regular headlights. Therefore, we suggest testing auxiliary strobe lights in a larger scale real-world experiment. Especially on railway lines with a high number of passive level crossings, this system can be expected to increase safety by supporting the timely detection of trains by road users, and thus to reduce the noteworthy number of severe accidents caused by inattentiveness. However, it should be noted that this study addressed only a small number of potential strobe light configurations and light positioning possibilities. Therefore, further research could be done on these topics and on how these different options can be affected e.g., by different weather conditions or speed and/or distance of the approaching train.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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