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Naturalistic driving study on the impact of an aftermarket blind spot monitoring system on the driver's behaviour of heavy goods vehicles and buses on reducing conflicts with pedestrians and cyclists

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ABSTRACT

The risk being severely or fatally injured in crashes with heavy goods vehicle and buses is much higher compared to other vehicles. Especially vulnerable road users such as pedestrian and cyclists are at high risk. In the European Union 4600 pedestrian and more than 2000 cyclists were killed in 2019. 18% of the fatalities were counted in crashes with heavy goods vehicles or buses. Blind spot situations and driver inattention or distraction are causing and contributing crash factors. Driver assistance systems are intended to support drivers and might have a positive effect on the crash avoidance. The objective of the study is the analysis of the change of driver behaviour in heavy goods vehicles and buses due to a aftermarket blind spot monitoring system. In a naturalistic driving study 15 heavy goods vehicles and five buses were equipped with a blind spot monitoring system and data were collected over a period of two years. The results revealed that the system would reduce the number of warnings with vulnerable road users by one third for heavy goods vehicles and 10% for buses. Up to 200 lives annually could potentially be saved with the analysed system, on the assumption that the collision warnings correlate directly with crashes.

1. Introduction

In 2019, 22,772 people in the European Union were killed due to road traffic crashes. Vulnerable road users (VRU – pedestrians and cyclists) accounted for about 30% of those fatalities. Moreover, the number of fatally injured pedestrians and cyclists did not decrease as much as the number of fatally injured occupants of cars. Fatalities of cyclists remained almost stable with approximately 2000 victims claimed each year. The average decrease of pedestrian fatalities was 1.4% between 2014 and 2019. A total of 4600 pedestrians lost their lives on European roads in 2019 (European Commission, 2019).

While the most frequent opponent of fatally injured VRU in the EU are passenger cars (Adminaite et al., 2015), collisions with heavy vehicles (e.g. HGV (Heavy Goods Vehicle) and buses) are often more severe, due to the great vehicle mass and the high likelihood of being run over by the vehicle (Ackery et al., 2012; Bíl et al., 2016; Edwards et al., 2018; Kockum et al., 2017; McCarthy and Gilbert, 1996; Niewoehner and Berg, 2005). Approximately 15% of fatally injured road users in EU countries died in crashes involving HGVs (Evgenikos et al., 2016; Schindler et al., 2022) and 3% in crashes involving buses or coaches (Evgenikos et al., 2016). Evgenikos et al. (Evgenikos et al., 2016) showed that approximately 17% of pedestrian fatalities are in crashes with an HGV and approximately 30% in crashes with a bus or coach. Fatalities among cyclists amounted to approximately 7% in HGV crashes. The share of fatalities is the same for bus or coach crashes and cyclists.

Severe and fatal heavy vehicle crashes involving vulnerable road users (VRUs) frequently involve scenarios with pedestrians crossing in front of the vehicle and cyclists being hit by right-turning HGVs (Kockum et al., 2017). Cyclists most frequently impact the front or right side (in right-handed traffic) of the vehicle (Kockum et al., 2017). One major crash causation factor in these crashes is drivers failing to see pedestrians and cyclists within the vehicles' blind spot (Evgenikos et al., 2016; Kockum et al., 2017; Niewoehner and Berg, 2005; Summerskill and Marshall, 2016). Another important factor is that pedestrians can enter the driveway rather quickly, leaving only little time to react for the driver. Additionally, drivers may not be able to predict the behavior of pedestrians, because of the possibility these have of quickly changing their direction (Kockum et al., 2017). In order to reduce VRU fatalities a variety of different countermeasures can be applied. These include

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raising increased awareness of the danger in both drivers and VRUs, improved visibility due to optimized infrastructure and the use of advanced driver assistance systems (ADAS) (Kockum et al., 2017). A positive effect of ADAS has already been shown in different prospective studies based on real crash simulations (Gruber et al., 2019; Gruber et al., 2018; Ohlin et al., 2019; Páez et al., 2015; Rosen et al., 2010; Saadé et al., 2019). All of them analysed car to pedestrian or cyclist collision. Only very little is being done in terms of effectiveness evaluation of HGV to pedestrian or cyclist collisions (Hoschopf and Tomasch, 2018). Even though, it is expected that ADAS on HGV would even have a huge effect on collision avoidance with vulnerable road users. Thus, the European Commission decided that vulnerable road user detection and warning becomes mandatory in 2022 (European Commission, 2019).

Beside of the before mentioned method of the prospective effectiveness assessment to evaluate the effectiveness of safety systems, naturalistic driving studies (NDS) could be used to evaluate the effectiveness of safety systems. The first NDS, the 100 Car Naturalistic Driving Study (Dingus et al., 2006), observed 100 cars for 12 months. Data from 43,000 h of driving, covering about 3 million kilometers was collected (Dingus et al., 2006). NDS should include at least several months of observation in order to account for seasonal differences (e.g. traffic density, weather conditions, …) and allow for statistically significant conclusions (Barnard et al., 2016; Lietz et al., 2010; van Schagen et al., 2011). One of the major drawbacks of NDS, however, is the lack of experimental control (Barnard et al., 2016). Thus, it may not be possible to identify individual contributing factors in specific conflict situations.

The objective of this research was to evaluate the potential of an aftermarket blind spot monitoring (BSM) system, the Mobileye Shield + for HGV and buses to reduce conflicts with pedestrians and cyclists. A NDS was performed, using warning numbers as surrogate measure for systems' potential to reduce crash numbers.

2. Method

Twenty vehicles (15 HGV and five buses) were equipped with an aftermarket BSM system – the Mobileye (ME) Shield+ (Mobileye Vision Technologies LTD, 2015). The vehicles were based in three different, mostly urban areas in Austria. Naturalistic driving data was collected over a period of two years.

2.1. System configuration

The ME Shield + is an optical, alerting BSM system, featuring three individual cameras (Fig. 1). These are mounted at the windscreen (front), left rear and right rear of the vehicle. An additional camera may be fitted at the drivers' side A-pillar to offer further assistance in (left-) turning scenarios (Mobileye Vision Technologies LTD, 2016b). This camera, however, was not used within the NDS.

Although the main purpose of the systems is to alert (warn) the driver in case of vulnerable road users (VRUs) in close proximity of the vehicle, the ME Shield + offers some additional features such as forward collision warning and lane departure warning (Mobileye Vision Technologies LTD, 2016b). None of these other functions were evaluated within the scope of this study. Fig. 1 shows a schematic of camera locations and observed blind spots.

Each camera has a horizontal FOV (field of view) of 37 degree (Mobileye Vision Technologies LTD, 2016b). The vertical FOV is not specified within the data sheet. The cameras are positioned to detect pedestrians with a height of 1.1 m. The front camera unit (behind the windscreen) includes a gyro-sensor and also the main processing unit. The traffic situation is analyzed by a pattern recognition algorithm at 36 frames per second (Mobileye Vision Technologies LTD, 2016b). The blind spots are thus continuously monitored, which is not possible for a human driver. The system uses three individual displays (one at each a-pillar and one at the center of the windscreen, Fig. 2) to notify the driver in case a VRU is within close proximity of the vehicle. The System known as Eyewatch collects information from all sensors and displays notifications in a central location (Mobileye Vision Technologies LTD, 2016a, 2016b).

The ME Shield + continuously monitors if VRU (pedestrians and cyclists) are situated within the blind spots of the vehicle. There are two different types of VRU-related warnings, depending on the criticality of the situation (Englander et al., 2017; Mobileye Vision Technologies LTD, 2016b):

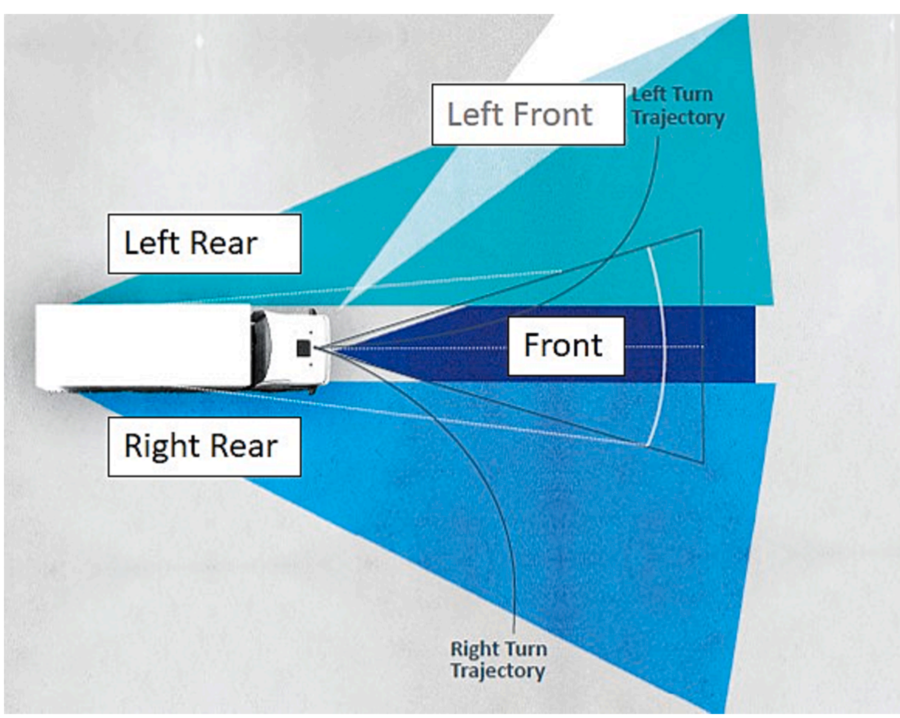

Fig. 1. Camera locations and monitored blind spots (Mobileye Vision Technologies LTD, 2016b).

Fig. 2. Displays of the ME Shield+ (Mobileye Vision Technologies LTD, 2016b).

- PDZ (pedestrian danger zone): A VRU is within close proximity of the vehicle, but there is no imminent danger of a collision. An optical warning appears at the corresponding display and the Eyewatch. This can also be understood as a normal interaction of vehicles with pedestrians and cyclists. However, the visual warning of the vehicle driver generates increased attention.
- PCW (pedestrian collision warning): A VRU is within close proximity of the vehicle. There is imminent danger of a collision. An optical warning appears at the corresponding display and the Eyewatch. Additionally, the driver is alerted via acoustic signal.

The blind spots observed by the rear cameras are subdivided into what are described as a safe zone and danger zone for the VRU. Depending on the intended path of the vehicle the individual cameras are operated in either low- or high-sensitivity mode. In low-sensitivity mode (i.e. when going straight), the narrow danger zone, extending from 4 m in front of the rear camera to the front of the vehicle and 0.8 m in lateral direction. In high-sensitivity mode (i.e. when turning), the width of the danger zone is increased to 3.5 m for the inner camera (Fig. 3) while the longitudinal extent is not modified (Mobileye Vision Technologies LTD, 2016b).

In case the time to collision (TTC, (Winner et al., 2015)) falls below a critical limit, a PCW is triggered because there is imminent risk of a collision (Englander et al., 2017; Mobileye Vision Technologies LTD, 2016b). The TTC is calculated based on the speed and vector of the moving pedestrian. The TTC for the PCW was 1.7 s and for the PDZ 2.5 s (Wolf, 2019).

The purpose of these warnings is to increase the driver's attention and to allow for a correct and in-time reaction (e.g. braking). Pedestrians are detected at vehicle speeds of 1–70 km/h, cyclists at 0–70 km/h. The threshold of 1 km/h for pedestrians is to avoid false warnings when people are getting on and off the vehicle (bus) (Mobileye Vision Technologies LTD, 2016b).

Although the system is capable of distinguishing between pedestrians and cyclists, there is no specific warning for one or the other. Hence, all evaluations presented hereafter include warnings with pedestrians and cyclists.

2.2. Vehicle fleet

Fifteen HGVs and five buses were equipped with the ME Shield+. Vehicles were not chosen systematically. Instead this research relied on the readiness of companies to participate and install the system in their vehicles. Driving routes were not selected systematically, because the companies that participated chose the routes based on their specific demands. Thus, the routes might not be representative for the entire HGV and bus fleet in Austria. Vehicles were located in three, mostly urban Austrian areas. The proportion of HGV and buses was not consistent across the three regions. Therefore, no conclusions based on geographical areas were possible and all evaluations were performed with respect to the entire HGV- or bus-fleet.

2.3. Data collection and evaluation

The ME Shield + was connected to a telemetry system, collecting and storing the collected data for further analysis. In addition to the status type (PDZ or PCW), vehicle data (e.g. vehicle type, mileage, etc.) were collected. Therefore, each warning contains additional information:

- Date and time
- Vehicle type (HGV/bus) and vehicle name
- Mileage (odometer reading)
- Travel speed
- Camera location
- GPS position (latidute and longitude)

Each alert is labeled using status type (PDZ/PCW) and camera location (L: left, F: front, R: right). Thus, a collision warning detected by the right camera will be labeled as PCW-R.

Since one of the main objectives of this research was to evaluate if BSM are able to reduce driver warnings, it was a crucial task to collect warning data from driving without BSM. Therefore, the system was operated in silent (baseline) mode immediately after installation, meaning that data was collected, but the drivers were not notified. Since a technician had to access the vehicle to activate warnings for the drivers (active mode - treatment), not all vehicles were driving in silent mode for the same period of time. Therefore, it was not possible to collect data for driving without BSM systems for all vehicles. For almost halve of the vehicles the BSM was used in active mode immediately after installation. For the comparison of warnings in silent and active mode, data from the five HGV (out of 15) and four buses (out of five) could be used (Table 1).

3. Results

During the NDS 1.05 million warnings in 1.13 million kilometres travelled were collected, resulting in about 1 warning per kilometre. The HGVs together covered a total distance of approximately 0.71 million km, resulting in an average of 2,827 km per vehicle per month. These

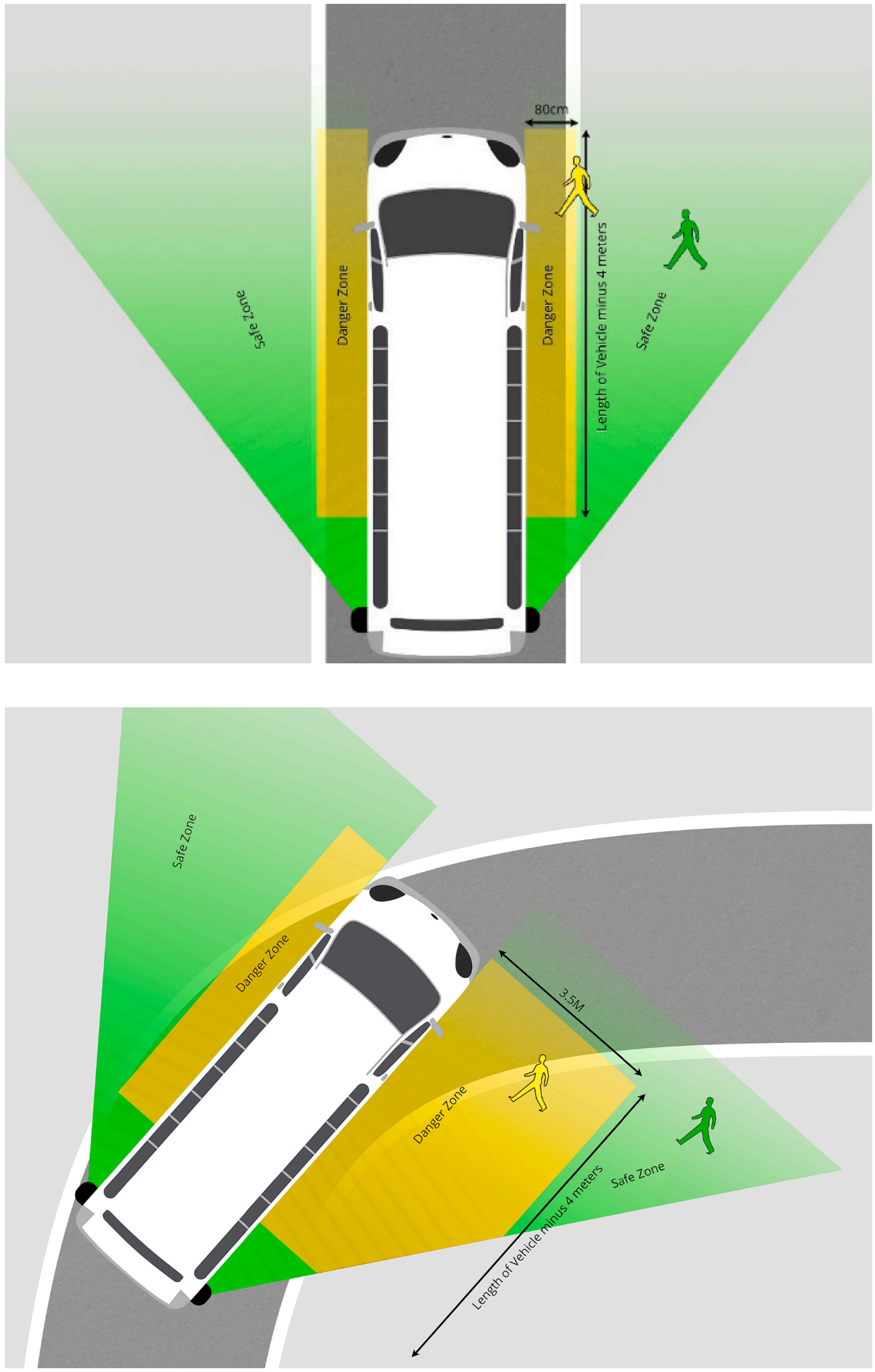

Fig. 3. Narrow and wide danger zone monitored by the ME shield+ (Mobileye Vision Technologies LTD, 2016b).

vehicles accounted for a total of 186,000 warnings (0.26 warnings per km). In total, buses covered 0.42 million km (3,886 km per vehicle per month). About 870,000 warnings between buses and VRU were obtained, resulting in 2.06 warnings per km (Table 2).

In about 95% of all warnings (approx. 1 million), no imminent risk of collision was detected, i.e. the VRU was detected within the danger zone. In comparison, imminent risk of collision was present in about 5% of warnings (56,582), i.e. the VRU was detected within the danger zone. Nevertheless, no vehicle was involved in a collision with a VRU during the study. The share of PCW was 7.6% for HGV, compared to 4.9% for buses.

3.1. *Warnings through the course of day, week and year*

Fig. 4 and Fig. 5 show the share of PDZ and PCW over the course of a day for HGV and buses normalized by the distance covered by the vehicle within this hour. Each bar shows the number of warnings per kilometer.

The number of warnings starts around 5 am in the morning and peaks around midday (11 am). During lunch time between 1 and 2 pm, only a small number of warnings can be observed. After lunch time the number of warnings increases again until the evening (peak at 5 pm). Obviously the warning density is significantly lower in the early morning and late

Table 1
Data collection period for each vehicle (white boxes: no data collection; grey boxes: data collection).

	Silent mode								Active mode																		
	-8	-7	-6	-5	-4	-3	-2	-1	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	..
Bus1					■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Bus2	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Bus3	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Bus4									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Bus5	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV1									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV2									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV3									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV4									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV5									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV6						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV7						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV8									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV9						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV10						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV11									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV12						■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV13									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV14									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■
HGV15									■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■

Table 2
Number of warnings per kilometer driven.

	HGV	Bus
PDZ	0.24	1.96
PCW	0.02	0.10
	0.26	2.06

evening. Although very few warnings were counted during the night hours, these are issued as collision warnings (PCW).

For buses, the warnings also start in the morning around 5 am and increase until around 10 am Between 10 am and 6 pm they remain at a constant level until they drop again. Between 11 pm and 4 am the buses were not active.

On working days the number of warnings is almost constant for HGVs (Fig. 6), while decreasing significantly during weekends. This pattern applied for PDZ and PCW. For buses the number of warnings is much higher compared to HGV (Fig. 7). On weekends the number of warnings is slightly reduced.

Fig. 8 and Fig. 9 show the share of PDZ and PCW over the course of a year for HGV and buses. The number of warnings increases between March and June and drops during the holiday season (July and August), before slightly increasing again when school and university terms start (September, October). This pattern is similar for PDZ and PCW and for both vehicle types.

3.2. Warnings with respect to camera location

In the following section the occurrence of PDZ and PCW w.r.t. camera locations is presented. The distribution of PDZ w.r.t. camera location is similar for HGV and buses. The majority of warnings is

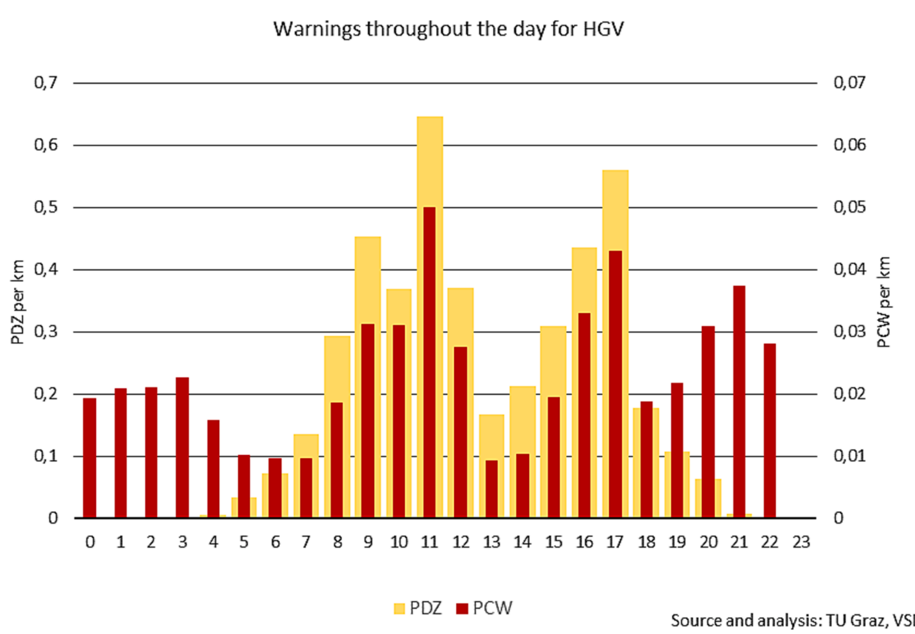

Fig. 4. Warnings per km throughout the day for HGV.

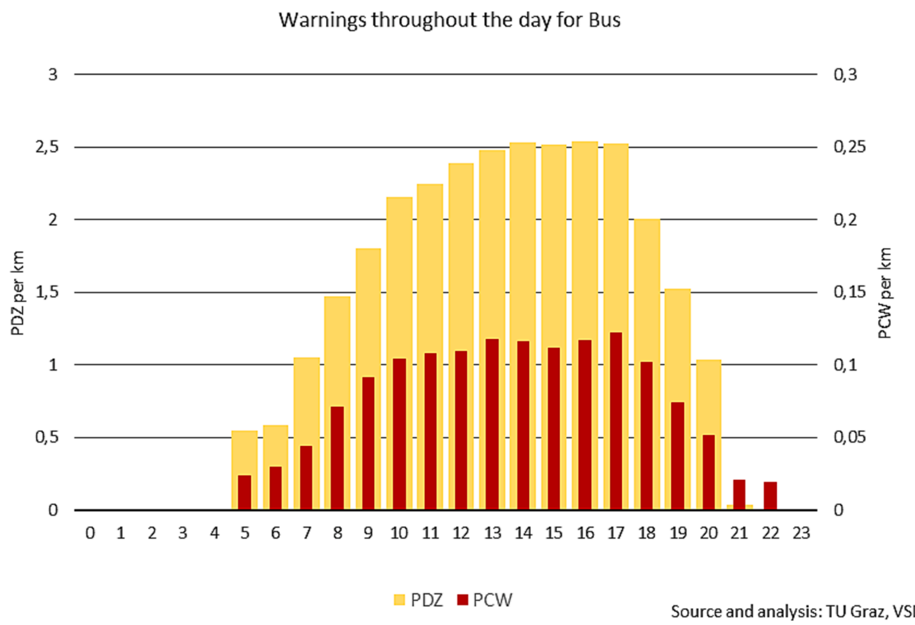

Fig. 5. Warnings per km throughout the day for bus.

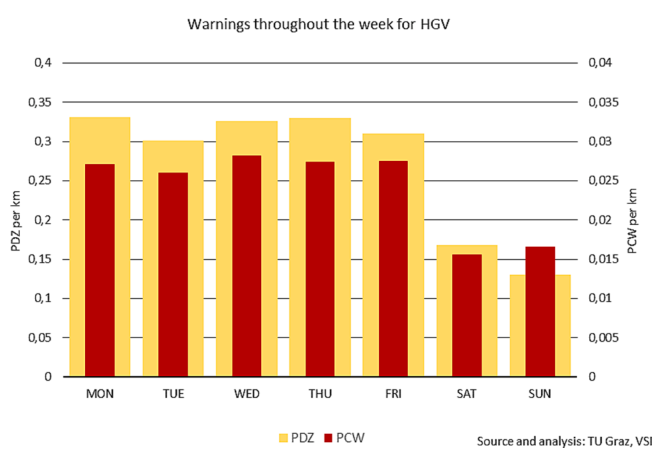

Fig. 6. Warnings per km throughout the week for HGV.

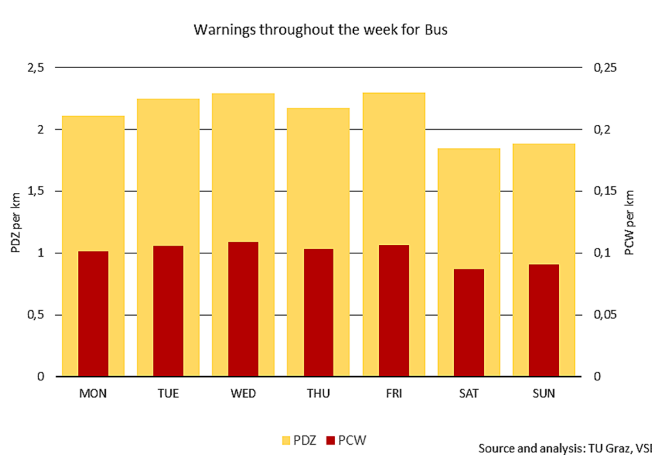

Fig. 7. Warnings per km throughout the week for bus.

detected from the front camera (64% vs. 58% respectively). For HGV, right and left cameras detect an almost equal share of PDZ (17% vs. 20%; Fig. 10 left). For buses the right camera detects a higher share of PDZ (35%), than the left (7%). When analyzing PCW, the situation is quite different for HGV and buses. For HGV, PCW-R account for almost two thirds (68%) of all PCW (front 11%, left 21%) (Fig. 10 right). For buses the share of PCW-F is almost the same as for PDZ-F (58%), while an increased share of PCW-L is detected (15%), compared to PDZ. Accordingly, the share of PCW-R is slightly reduced to 27%.

3.3. System activation

When comparing driving in silent and active mode, data from the five HGV (out of 15) and four buses (out of five) could be used. In order to make data comparable, warning numbers were normalized by the distance covered by the specific vehicle type.

The number of PDZ/km decreased from 0.46 (silent mode) to 0.28 (active mode) for HGV (-41%; Fig. 11) and from 2.4 to 2.0 for buses (-20%; Fig. 12). PCW were reduced by 33% for HGV (from 0.036 to 0.024; Fig. 11) and 10% for buses (from 0.11 to 0.10; Fig. 12). This means that, prior to activation, HGV travelled about 28 km between two PCW, while travelling 41 km between two PCW when the system is active. Buses covered an average distance of approximately 10 km between two PCW after activation, compared to 9 km prior to activation.

In addition to these overall reduction rates, an investigation on the time dependent behavior of warning rates was carried out. A third order centered simple moving average filter was used to smooth the data (Hedderich and Sachs, 2016).

Data from three months prior to 21 months after activation were available for HGV (Fig. 13). After a first drop immediately following on from activation (months 1–4), the warning frequency decreased even further (months 5–8) before increasing again (months 9–14). Although there is some increase, the level remains lower than prior to activation.

Data from 8 months prior to 16 months after activation were available for buses (Fig. 14). Periodical fluctuations appear depending on VRU density. One can see that there is an immediate drop of PDZ warnings as soon as the system is activated. For PCW this immediate drop is not as remarkable as for PDZ. Although the warning frequency (PDZ and PCW) increases again, the level remains lower than it was prior to activation.

Since a right-turning of HGV is a potentially dangerous situation for

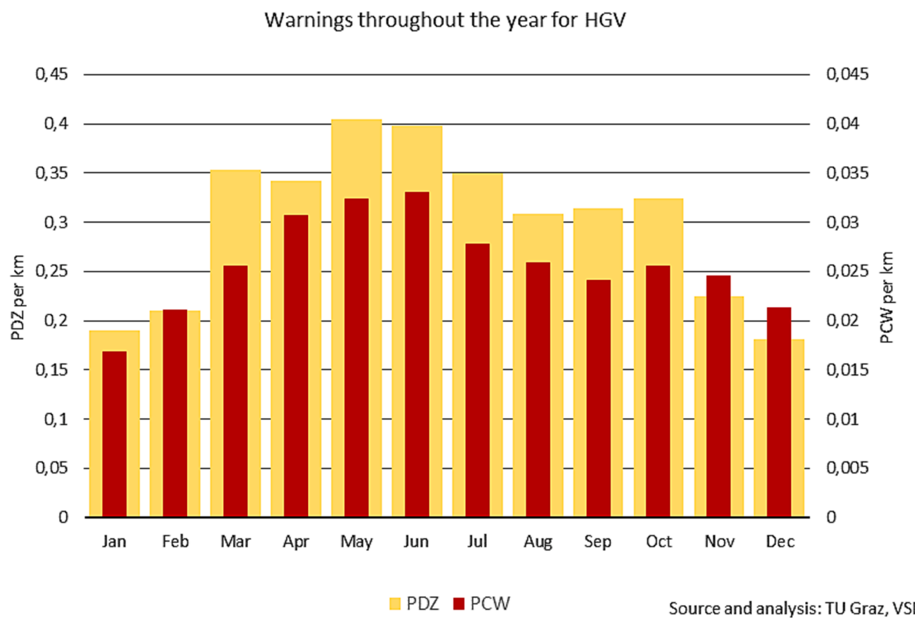

Fig. 8. Warnings per km throughout the year for HGV.

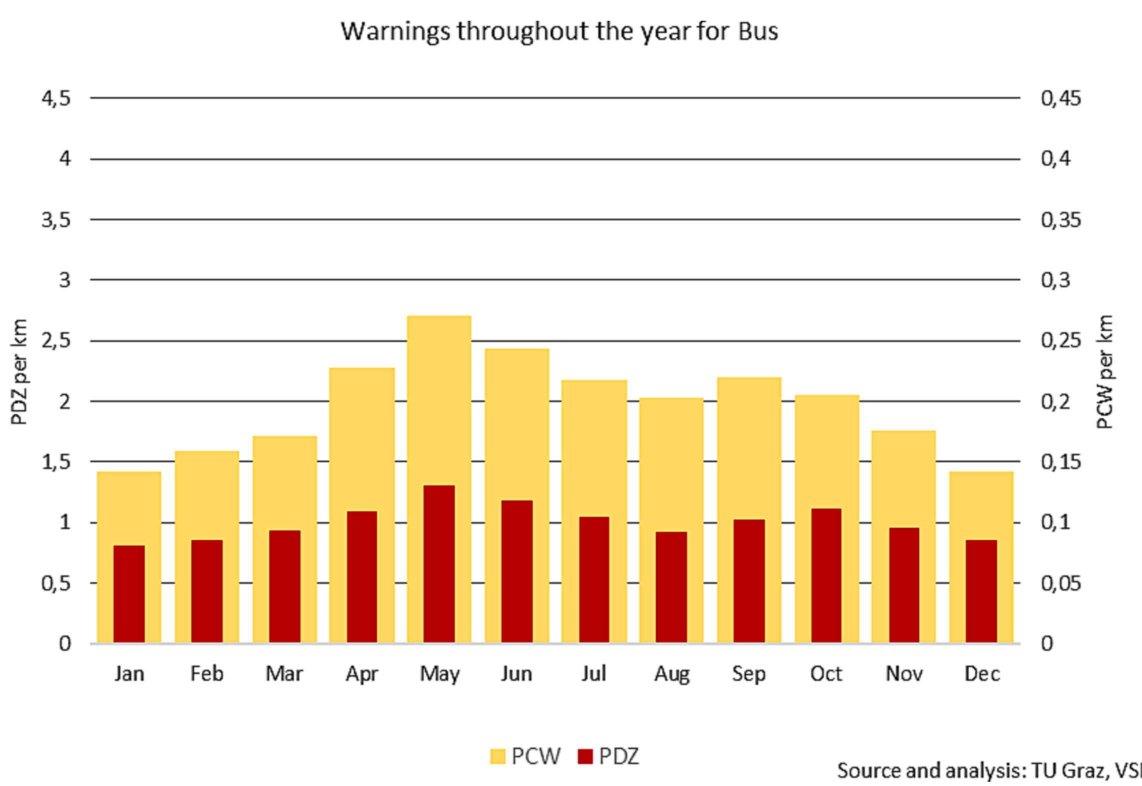

Fig. 9. Warnings per km throughout the year for bus.

pedestrians and cyclists, the reduction of PCW was analyzed w.r.t. camera location for HGV (Fig. 15). The PCW-frequency decreased the most at the left side of the vehicle (−61%), followed by the front (−25%) and the right side (−20%).

Whilst there is no huge difference of the velocity for PCW-L and PCW-F between silent and active mode, the mean velocity for PCW-R increases from 42.25 km/h in silent mode to 47.28 km/h in active mode for HGV. This increasing tendency was not found in bus data. The velocity remained almost unchanged between silent and active mode.

4. Discussion

During the NDS, the data for 1.05 million warnings were collected, with the vehicles concerned having travelled 1.13 million kilometres. An immediate risk of collision (PCW) has been identified for trucks every 50 km (0.02 warnings per kilometer). For buses, however, an immediate risk of collision was significantly more frequent (0.1 warnings per kilometer). Especially for the buses, a very high number of warnings occurred without an immediate danger to the pedestrian. This is found for both the front and the right camera. A major reason for this are the

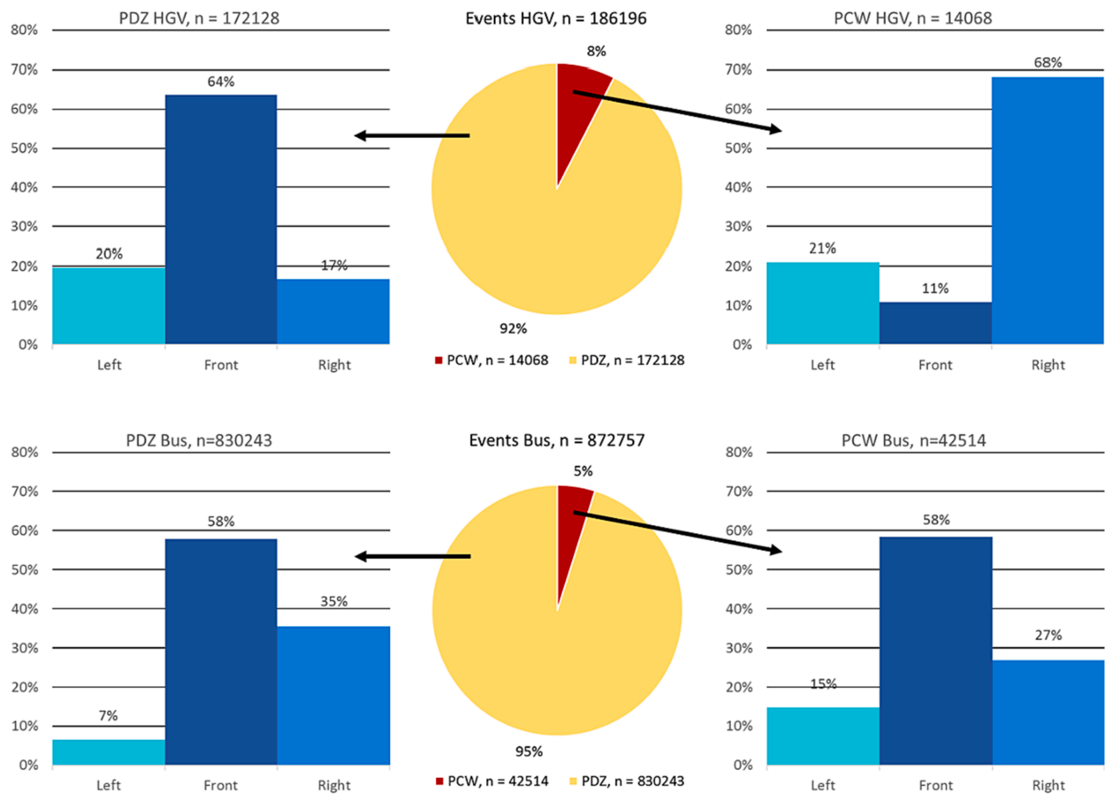

Fig. 10. PDZ and PCW share (center), PDZ (left) and PCW (right) distribution w.r.t. camera location for HGV and bus.

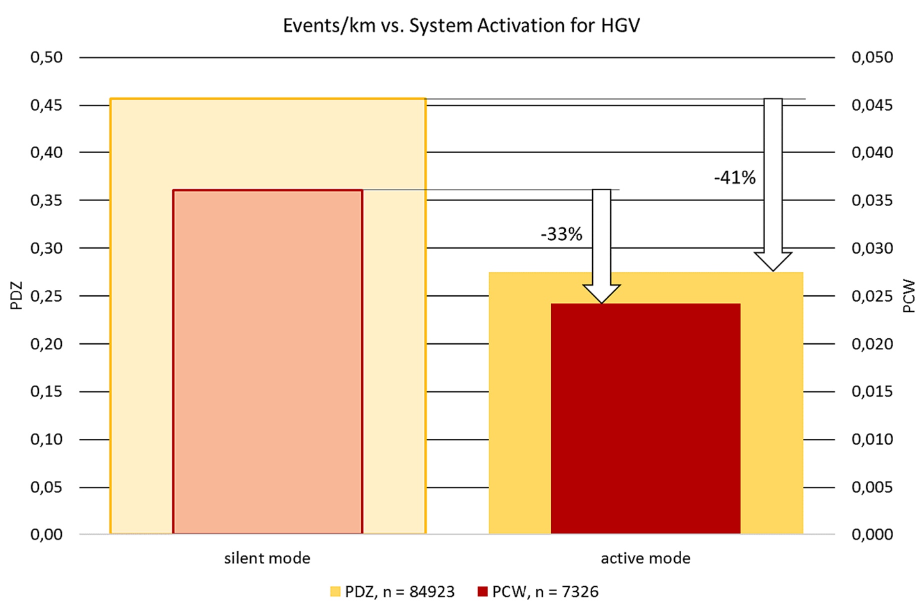

Fig. 11. PDZ and PCW per km in silent and active mode for HGV.

system specifications. On the right side, pedestrians are detected as soon as they are within a distance of less than 80 cm from the vehicle. At bus stops the pedestrians are waiting close to the road and are very often within this distance when the bus is entering the bus stop (Englander et al., 2017; Kaltenbrunner, 2018). Furthermore, it was found out that in larger bus stations, pedestrians also cross the bus lane significantly more often, which explains the frequent warnings of the front camera (Kaltenbrunner, 2018). Thus, this high number of warnings is more likely associated to regular interactions between buses and VRUs rather than conflicts with immediate danger of a collision.

Although no questionnaires were provided to drivers to evaluate the acceptance of the system in this study, feedback was collected or strange behavior was observed. Most of the complaints were about the high and frequent number of warnings. This was possibly the reason why some individual drivers taped off the camera so that no more warnings were recorded. The trucks and buses were operated by several drivers. Thus, it is not possible to identify individual vehicles that temporarily had the camera taped off from the recorded data. Lau and Burns (Lau and Burns, 2020) reported similar findings. They also used the Mobileye Shield + in their study. Although positive performance were observed, the

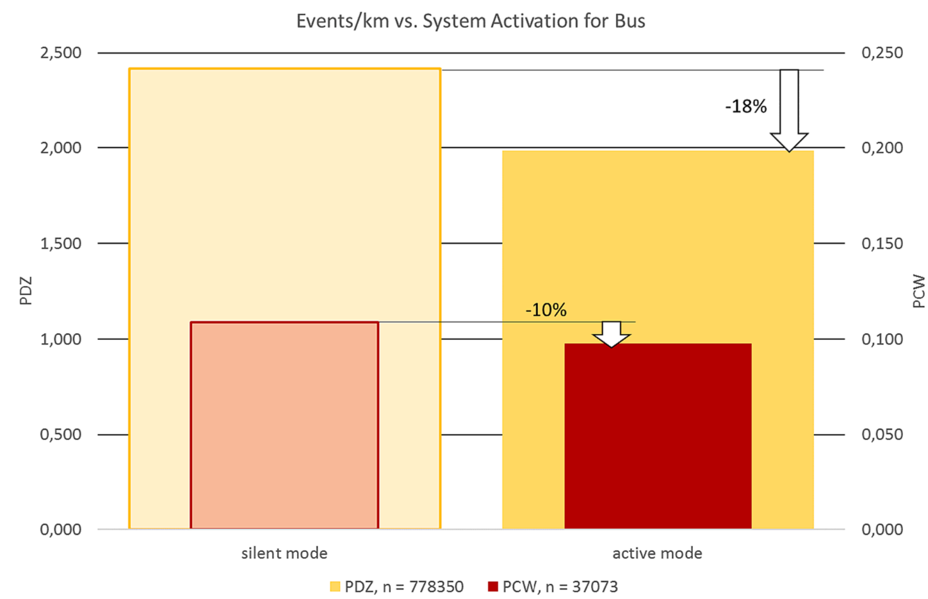

Fig. 12. PDZ and PCW per km in silent and active mode for Bus.

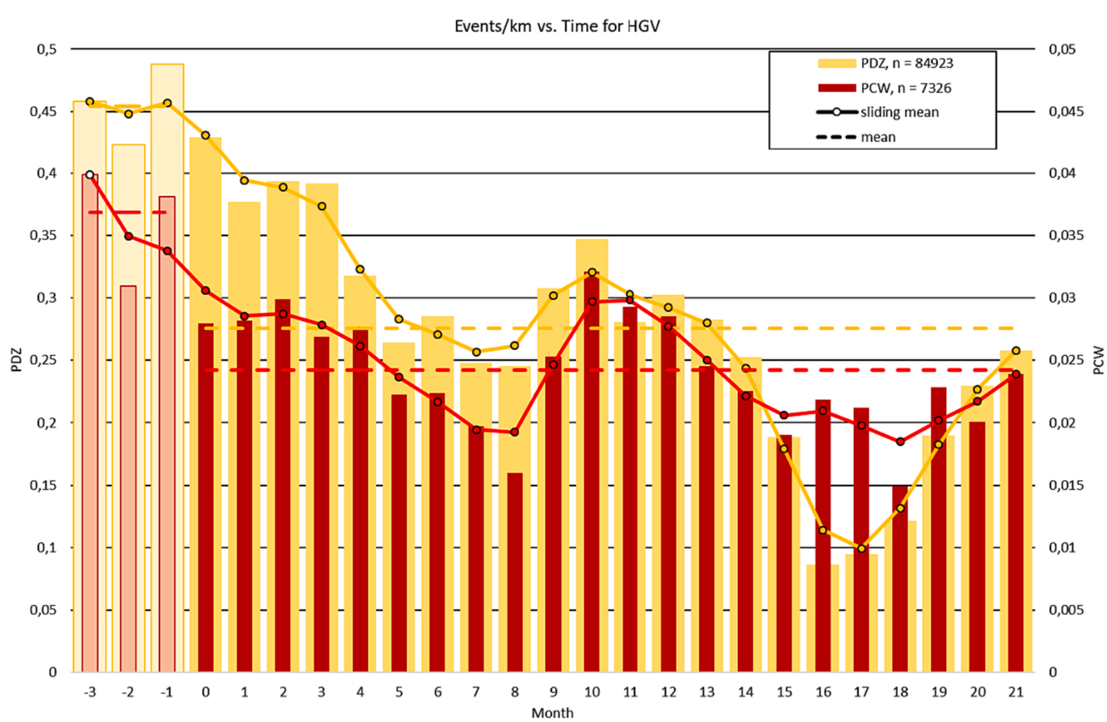

Fig. 13. Time series of PDZ and PCW per km in silent and active mode for HGV.

participants reported very negative impressions, e.g. distraction and system unreliability which decreases the user acceptance.

For verification purposes NDS data was compared against data of the Austrian National Accident Statistics. The appropriate crash figures are given in the appendix.

4.1. Course of day, weekdays and calendar month

Crash and warning numbers for HGVs show a good correlation throughout the course of a year. Within the first half of the year the correlation is slightly better than for the second. Nevertheless, general trends seen in the national statistics data are also present in NDS data. In case of increasing crash numbers, warning numbers also increase and vice versa. For buses the correlation is even better than for HGV, with June and October being the exception.

When comparing data w.r.t. day of week, a good correlation for HGVs and for buses was found. The only slight mismatch was found on weekends. The number of warnings in the NDS data ramains the same at Saturday and Sunday, whereas the crash data is significantly lower on Sunday.

Warning in the NDS and crash data from national statistics showed good correlation regarding time of day. In the HGV data the morning crash peak (9–11 am) is not present in the NDS data. In the NDS data a peak was found at 11 am and a second one in the afternoon at 5 pm. The crash data did not show a peak in the afternoon. NDS and national statistics data show better correlation for buses than for HGVs, except

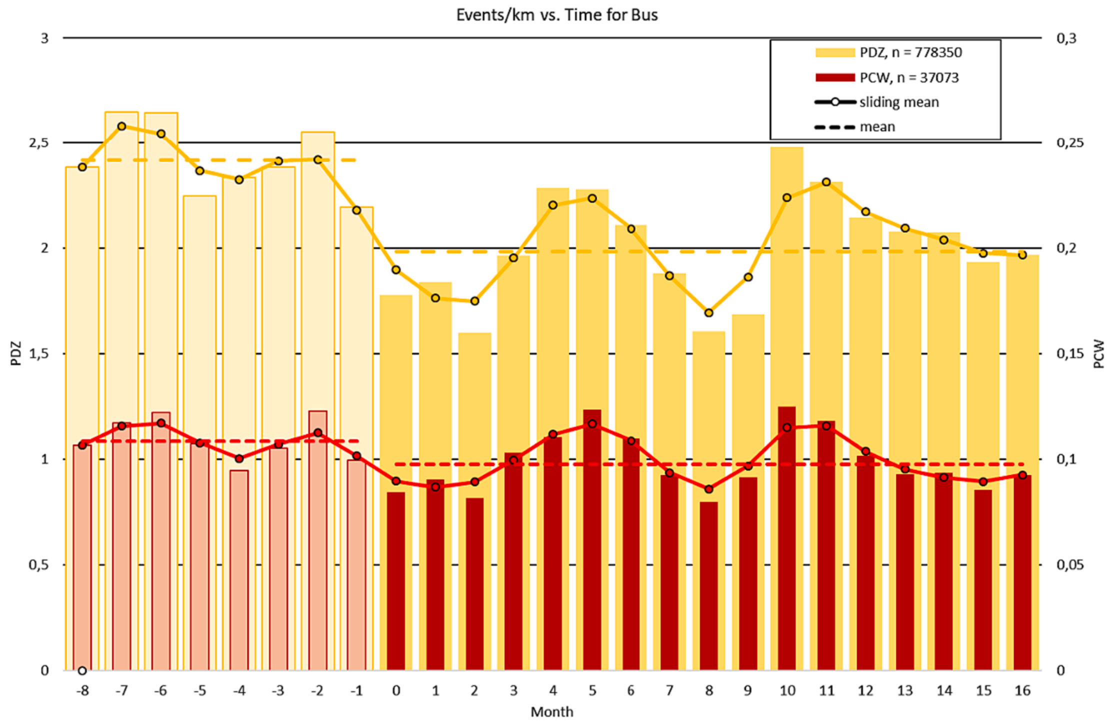

Fig. 14. Time series of PDZ and PCW per km in silent and active mode for bus.

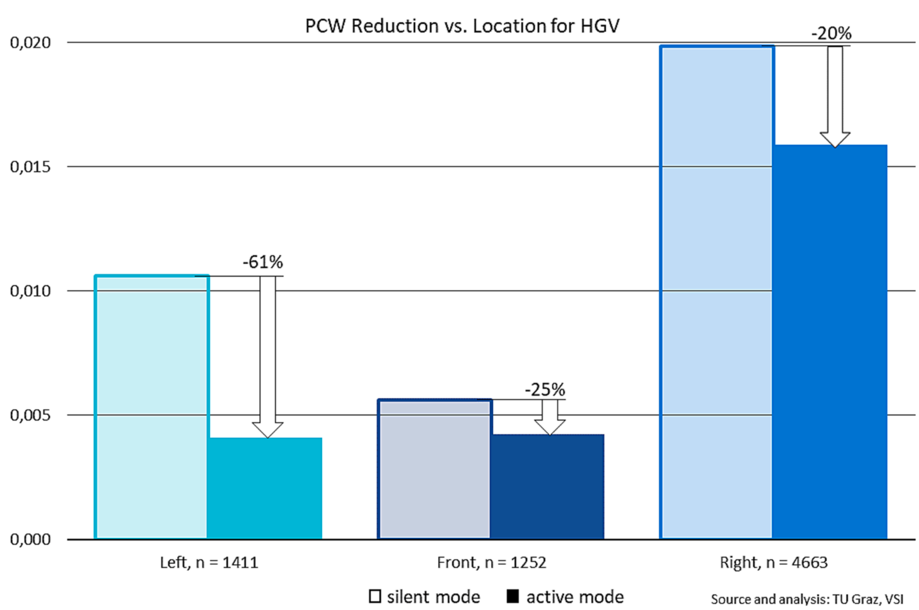

Fig. 15. Reduction of PCW per km for HGV w.r.t. camera location.

that the crash peak at 7 am is not present in NDS data. The correlation between NDS and crash data is weaker regarding time of day, compared to year and day of week. This can probably be explained by the fact that the selection of the vehicle fleet did not take place on a systematic basis.

In general, good correlation between warning and crash data was found. This implies that a reduction of warnings would result in a decrease of crash numbers.

4.2. System activation

NDS data showed an immediate decrease of warning frequency after activating the BSM system. For HGV PDZ decreased by 41% and PCW by 33%. For buses the effect was not as significant, with reduction rates of 18% for PDZ and 10% for PCW, respectively. This is probably related to the fact that buses face a higher exposure in the first place (e.g. pedestrian interaction at bus stops) and their drivers are more aware of VRU within close proximity of the vehicle. Additionally it is not possible for bus drivers to avoid areas with a high VRU density (e.g. bus stops). Hence, a reduction as seen for HGVs might not be possible for buses.

The full potential of the BSM system was available immediately after activation, expressed by an instant reduction of warning frequency. After this initial drop, warning numbers show good correlation with VRU density (comparison of national accident statistics and NDS data). At any time within the study the warning frequency was lower with activated BSM compared to driving without BSM (silent mode). When analyzing time-series data, no reduction of the systems' effect was found. Hence, there is no habituation of drivers to the BSM system. Nevertheless, extrapolation of time-series data is not possible in order to estimate the long term effects of the BSM system.

The very low number of PDZ warnings for HGVs in month 16 to 18 according to the PDZ events per kilometre cannot be explained by the data collected in the NDS. The PCW events per kilometre did not show such a drastic reduction in the data during the same time period. This artefact, however, was not present in the bus data.

One fundamental hypothesis of crash research is that the number of traffic conflicts correlates with the number of crashes (Hydén, 1987). Combining the findings of this study with the theory of Hydén, BSM systems have the potential to reduce the number of crashes between HGV/buses and pedestrians/cyclists. In correlation with the decrease in PCW events by one third, approximately four fatal crashes with pedestrians and HGVs could potentially be reduced on average each year in Austria (crash data provided in the Appendix). Two crashes with cyclists might be avoidable. Nine crashes with severely injured pedestrians and 12 crashes with minor injuries might by reduced (nine severely injured cyclist crashes and 16 crashes with minor injuries). In the case of bus crashes, fatal crashes with pedestrians and cyclists are very rare in Austria. Thus, the impact on fatally injured pedestrians and cyclists on bus crashes are neglectable. Three severely injured pedestrian victims and ten with minor injuries might be avoided annually. One severely injured cyclist and four with minor injuries from crashes might be prevented each year. Based on the latest figures for the European Union (European Commission, 2022, August) the lives of approximately 115 pedestrians and 65 cyclists could be saved annually that might otherwise have been lost as a result of crashes with HGVs. Furthermore, the lives of nine pedestrians and three cyclists could also be saved that might have been lost as a result of crashes with a bus.

4.3. Right camera events

No definite conclusion is possible from the analysis of the right camera events in HGVs. Although the number of PCW-R dropped by 20%, the velocity increases from about 42 km/h to 47 km/h. However, these phenomena were not present in bus data. One possible explanation is the lack of discrimination between pedestrians and cyclists in NDS data. Thus, overtaking cyclists with insufficient lateral clearance (cyclist in danger zone, lateral distance less than 0.8 m) results in PCW-R. Kovaceva et al. (Kovaceva et al., 2019) found that the mean lateral clearance of motorized vehicles overtaking cyclists is 1.29 m (SD = 0.5 m). Assuming a normal distribution for lateral clearance in combination with the danger zone width of the ME Shield+, about 16% of all cycling overtaking maneuvers would result in PCWs. This is in line with the findings of (Chuang et al., 2013; Love et al., 2012), who found that the lateral clearance is less than 1 m in about 16% to 20% of maneuvers where motorists overtake cyclists. Furthermore, (Walker, 2007) found that buses and HGVs - usually driven by professional drivers - keep a significantly lower lateral clearance when overtaking cyclists. A survey amongst cyclists in Norway (Pokorny et al., 2018) showed that trucks overtaking cyclists is frequently experienced manoeuvres by cyclists as critical events. It can be concluded that the reduction of PCW-R refers to reducing warnings with pedestrians (low velocity), while overtaking cyclists remains within the data set (high velocity), resulting in a higher mean velocity at PCW-R with activated BSM. Nevertheless, it was not possible to determine the share of cyclists overtaking maneuvers and therefore to draw a definite conclusion using NDS data collected within this research.

The analysed system in the NDS detected pedestrians at vehicle speeds of 1–70 km/h. Even though the reason is to avoid false warnings when people get on and off a bus, in situations in which the pedestrian crosses directly in front of an HGV this person will be in the driver's blind spot. In the study by Schindler et al. 10 out of 16 HGVs were initially standing and the pedestrian crossed directly in front of the truck when the truck started to accelerate (Schindler et al., 2022). If the driver received the collision warning signal at the vehicle speed of 1 km/h a collision might not have been prevented, because the reaction time of the driver given this warning must also be considered. With different acceleration levels (Fuerbeth et al., 1993) and the reaction time of the driver (Burckhardt, 1985; Fitch et al., 2010; Green, 2000; Zhang et al., 2006) several meters might be needed to stop the truck again and this will result in the pedestrian being run over.

5. Limitations

Although the presented findings are promising in terms of reducing pedestrian/cyclist crashes involving HGVs and buses, the limitations should not be omitted:

The composition of the vehicle fleets and their corresponding regions and routes were not chosen systematic processes. Hence, NDS data might not be representative for the whole of Austria.

The vehicle fleet (share of HGVs/buses) within the individual regions was not homogeneous. Even though the average distance travelled by each bus was 1.77 times higher compared to HGVs, only five busses were included in the study.

The system detected pedestrians at speeds of from 1 km/h to 70 km/h.

Although capable, the Mobileye Shield+, does not give different warnings for pedestrians and cyclists.

After some time in silent mode, the system was operated in active mode until the end of the study. The time in silent mode was not consistent for all vehicles. The reason for this is found in the coordination of the installation of the system at the vehicles of the individual companies.

Since no video data was captured, more detailed evaluations were not possible.

For further studies the use of a BSM system that produces different warnings for different VRU (pedestrians/cyclists) is recommended, since this would enable the drawing of advanced conclusions. Additional valuable data could be gathered if it were possible to put the system back to silent mode following on from a period in active mode, to see if adaption of driver behavior persists even without active BSM.

6. Conclusions

1. The number of warnings between HGVs/buses and VRU is reduced by BSM systems.

2. A 41% reduction of PDZ and a 33% reduction of PCW per km was found for HGVs. Buses had less significant reductions than HGVs (18% for PDZ, 10% for PCW).

3. Pedestrians and cyclists would benefit far more from this technology if it were installed on trucks. In addition, the number of pedestrian and cyclist fatalities in collisions with trucks is significantly higher than in collisions with buses. Up to 200 lives (180 pedestrrians and 12 cyclists) a year could be saved in the European Union as a result of this.

4. The system potential is available immediately after installation. No habituation effect was found.

5. Contradictory results were shown for right-turning of HGVs, because the ME Shield + does not give separate warnings for pedestrians and cyclists.

6. A good correlation was shown between warning and crash data. Reducing warning numbers will thus also reduce the number of crashes.

CRediT authorship contribution statement

Ernst Tomasch: Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Stefan Smit:** Formal analysis, Investigation, Writing – original draft, Visualization.

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.

Data availability

The authors do not have permission to share data.

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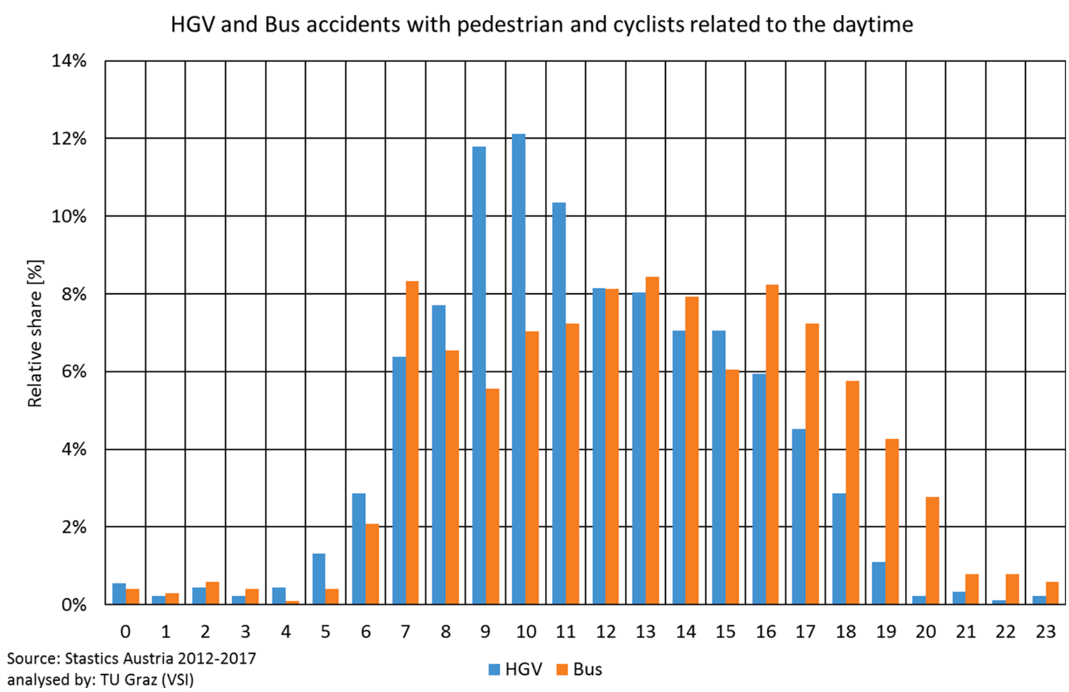
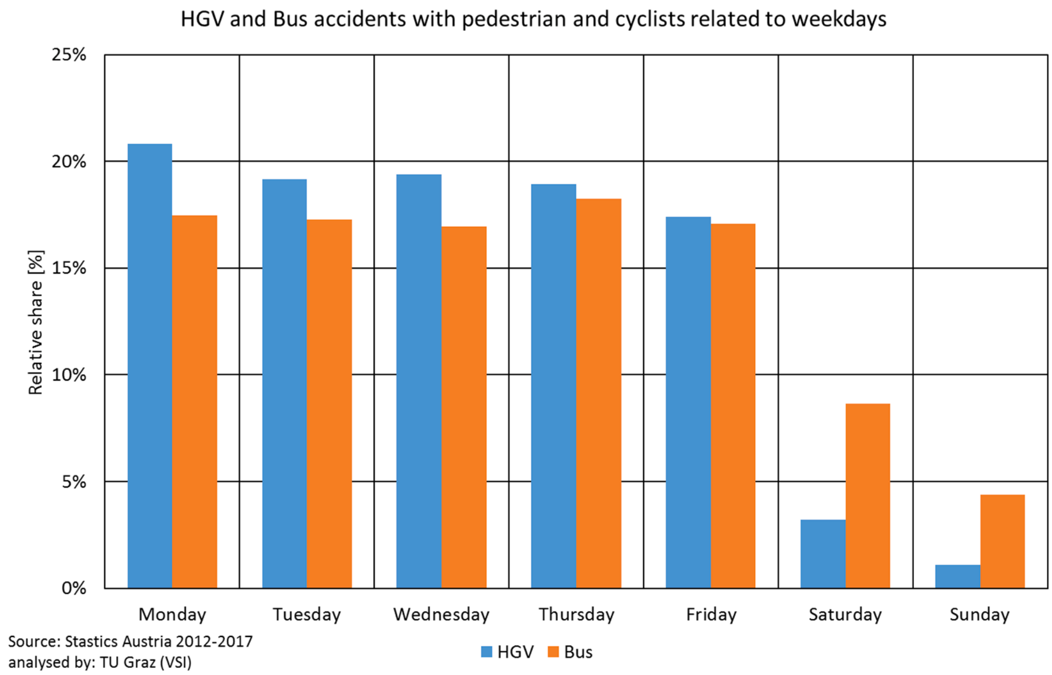
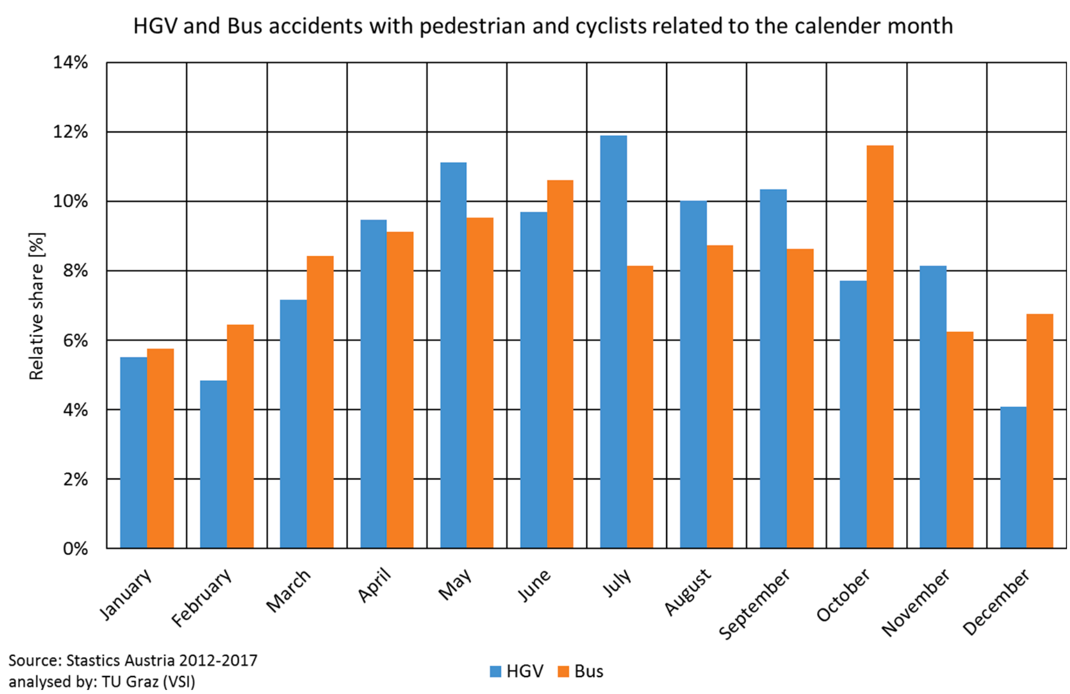
Appendix

Crashes of HGV vs. pedestrian and cyclist and buses vs. pedestrian and cyclists between 2012 and 2017 (Statistik Austria, 2023).

		Minor	Severe	Fatal	Total
HGV	Pedestrian	214	156	70	440
	Cyclist	281	155	32	468
Bus	Pedestrian	558	153	11	722
	Cyclist	220	59	7	286







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