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Research Article

An investigation of truck drivers' behaviour before and during real-world advanced emergency braking system interventions

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ABSTRACT

Advanced emergency braking systems (AEBS) aim to address rear-end collisions, which are the most common crash type involving heavy good vehicles. Although previous studies have investigated the safety benefits introduced by AEBS, there is a lack of research exploring drivers' behaviour before and after AEBS interventions. In this paper, we analyzed 6-s long event-triggered naturalistic driving data, collected from heavy goods vehicles every time an AEBS braking intervention occurred, either as preliminary mitigation braking (pMB) or full mitigation braking (MB). The analyses focused on rear-end critical situations in which the drivers did not brake before a collision warning (CW) or a mitigation braking was triggered by the system. The rear-end critical situations encompassed scenarios where the lead vehicle was the same for the whole duration of the event.

The results show that full mitigation braking are rare events, occurring in approximately 5 % of the complete dataset. Besides, drivers of heavy goods vehicles are in 75 % of the cases already braking before the intervention of CW. Analyzing in detail a restricted number of interventions from CW and MB, it was found that drivers are keeping headway shorter than 1 s in 44.4 % and 53.6 % of the cases respectively. The annotations performed on the restricted dataset indicate that the drivers were "out of the loop" in 57.3 % of CW interventions and 65 % of MB interventions. However, this finding should be taken with caution, due to the lack of video recordings: in fact, the lack of a fast drivers' response could also be an indication of overtrust in the system or a sign of the drivers assessing the situation as not enough critical to require a braking. Further naturalistic driving studies with increased data frequency and availability of video data are recommended to investigate deeper on this matter.

1. Introduction

The negative contribution of heavy goods vehicles (HGV) to the traffic safety problem has been a concern for years, due to their over-representation in crashes and especially in collisions with severe outcomes. On a Europe-wide level, HGVs contributed during 2019 to 12.0 % of road fatalities, despite being implicated in only 4.4 % of all road collisions [1]. Rear-end crashes where an HGV strikes another vehicle are one of the most common crash scenarios for HGVs in Sweden and Europe, accounting for about 7–10 % of all crashes [1,2]. Studies investigating these crashes, using various datasets from different countries, have found distraction, close following, and fatigue as the main contributing factors [3–5].

The recent introduction of advanced driver assistance systems in the form of frontal collision warning (FCW) systems and advanced emergency braking systems (AEBS) aims at preventing or mitigating rear-end crashes. These systems act by warning the driver or directly intervening and became mandatory equipment on newly registered HGVs from 2015 in Europe [6]. Studies assessing the effectiveness of FCW and AEBS installed in HGVs have so far shown promising results in preventing or mitigating the consequences of rear-end collisions. Jermakian [7] predicted a 37 % reduction in rear-end collisions involving medium and heavy large trucks, when using forward collision warning systems: this study based its analyses on records retrieved from the databases NASS GES and FARS in the U.S. Later, Woodrooffe et al. [8] performed the first research to estimate the benefits introduced by both FCW and Collision Mitigation Braking (CMB) technology to heavy trucks. The authors created a simulated reference dataset based on real crashes extracted from U.S. nationally representative crash databases. Their results indicated that FCW alone could provide a 22–24 %

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decrease in fatal crashes, while CMB alone could bring a 3–4 % reduction in fatal crashes. All the studies cited so far used data acquired through crash databases or naturalistic studies to estimate the benefits based on simulations or assessment. On the other hand, the study by Teoh [9] calculated for the first time the effectiveness of the systems, by investigating crashes in trucks equipped with FCW and AEBS. The authors computed crash rate ratios for vehicles equipped with and without these technologies and concluded that FCW and AEBS could respectively reduce by 41 % and 44 % the number of rear-end crashes.

In addition to the previous studies estimating the benefits of FCW and AEBS, research has been conducted to examine truck drivers' behaviour in response to a FCW. Bao et al. [10] performed a naturalistic driving study with 18 commercial drivers using vehicles equipped with a prototypical version of FCW. The authors found that mean time headway during driving with activated FCW increased in dense traffic circumstances and with adverse weather situations, compared to the baseline condition without FCW. Overall, drivers kept a mean time headway greater than 2.5 s both in baseline and FCW condition, but a minimum time headway less than 1 s was found in 15.9 % and 16.3 % of the observed following events during driving with FCW and in the baseline respectively. A later article [11] analyzed critical events collected from 20 truck drivers during a field operational test conducted with vehicles equipped with FCW: drivers braked almost simultaneously to the issue of the FCW warning, which led the authors to assume that the drivers were aware of the threat before the warning was provided. Shao et al. [12] investigated 7057 warnings issued by FCW, in a field study conducted in China with 39 trucks and 50 drivers. The authors clustered drivers' responses to FCW in low-risk, mid-risk, and high-risk levels, based on measures of average velocity change, reaction time, and minimum TTC. The clustering of drivers was used to find the best suitable warning time for FCW.

While studies exist on truck drivers' behaviour as a response to FCW, research is lacking on how drivers react to the AEBS braking. To the knowledge of the authors, only one study investigated drivers' behaviour before, during and after the braking of AEBS [13]. In their research, Flannagan et al. analyzed the interventions of FCW and AEBS—named respectively as Intelligent Brake Assist (IBA) and Front Automatic Braking (FAB)—with longer duration than 0.08 s and occurring at speeds higher than 10 mph, in a fleet of 2000 passenger vehicles. Alongside other purposes, the authors also aimed to determine the speeds before the systems' interventions, the scenarios leading to the intervention, and the driver's braking behaviour. The results showed that the driver was already slowing down in 32.7 % of the selected events, before the systems intervened. On the other hand, the data also indicated that, in 48 % of the events, the drivers did not brake at all. Despite the valuable findings provided, the study by Flannagan et al. focused on passenger cars' drivers and no research has been conducted to date on truck drivers' behaviour before, during and after AEBS braking. These types of studies are required for developing models of drivers' behaviour used in safety benefit assessment of active safety systems (see for example [14]) and for improving the design of these systems [15].

Given the research gap, the purpose of the paper is to assess truck drivers' behaviour before, during and after the activation of FCW and AEBS. The detailed research questions for the study are:

- RQ1: How do truck drivers behave before the triggering of FCW and AEBS, with respect to braking patterns and maintained time headway to the vehicle in front?
- RQ2; What is the drivers' response to FCW and AEBS triggering, measured as response time to system's activation?

To achieve the aim of this paper, we analyzed AEBS interventions obtained from naturalistic data collected via a large fleet of HGVs.

2. Material and methods

2.1. Data source

For the analyses in this paper, we used data concerning AEBS interventions from Volvo and Renault HGVs registered in France and Germany. In a first step, we extracted all logged data for the years 2019, 2020 and 2021. The size of the dataset is counted in ten-thousands of interventions, but the exact number of cases cannot be reported for confidentiality reasons. Hereafter, the term "case" will be used to describe a single logged AEBS intervention event.

Each case is logged when an AEBS braking (C or D in Fig. 1) is triggered, providing data 3 s before and after the intervention for a 6 s log with a 5 Hz sampling frequency. The logged data consists of a sub-set of signals which show:

- The speed, acceleration and location of the ego vehicle (EV), as well as the driver interventions (use of steering wheel, brake pedal and accelerator pedal).
- The speed, acceleration, and location of the AEBS target vehicle (referred to as lead vehicle, LV).
- AEBS intervention type (preliminary collision warning (pCW – A), collision warning (CW - B), preliminary mitigation braking (pMB - C), and mitigation braking (MB - D).

The first intervention (pCW, A) presents a solid red warning light in the windscreen (Fig. 2 left) or instrument cluster (Fig. 2 right). In the second step (CW, B), the red light starts flashing and an audible warning is issued to the driver. This flashing and audible warning is active throughout the pMB (optional brake intervention with lower brake demand depending on the criticality of the situation) and MB (emergency braking with more than 5 m/s^2 deceleration).

2.2. Data selected for analysis

The full dataset was filtered for cases where the lead vehicle did not change throughout the maneuver. Thus, the final dataset used for the analysis only included rear-end scenarios where the lead vehicle was stopped or decelerating and excluded cut-in and cut-out maneuvers. After this initial filtering, a second filtering was applied to create two sub-samples based on the intervention type.

The first sub-sample focused on the Collision Warning, and we were interested in cases where the drivers did not brake before the system was triggered, as we assumed that a lack of braking would imply that the drivers were not aware of the critical situation arising ahead. In addition, the data were filtered to include only long-haul type heavy goods vehicles and maneuvers with initial speed higher than 70 km/h, to obtain a reasonable size for the dataset to be analyzed.

The second sub-sample focused on the Mitigation Braking, and the interest was again for cases where the drivers did not brake before the system intervention was triggered. Since these are rare cases, no further

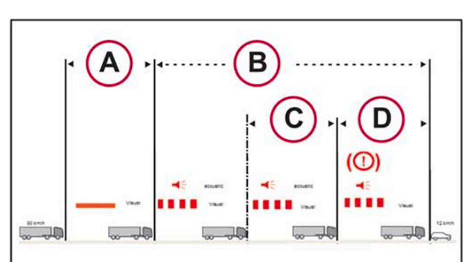

Fig. 1. Intervention cascade (A: preliminary Collision Warning (pCW), B: Collision Warning (CW), C: preliminary Mitigation Braking (pMB), D: Mitigation Braking (MB)).

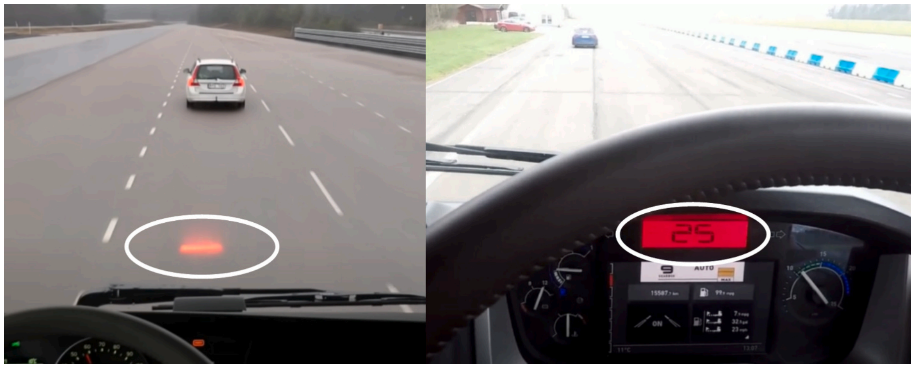

Fig. 2. Placement of visual collision warning (highlighted by white oval, left: Volvo, right: Renault) from [19].

sample size reduction was necessary.

2.3. Data enrichment and annotation

The two final sub-samples were manually reviewed by the authors of this paper, which annotated information about initial speed, use of the pedals and steering.

Time headway was calculated with an approximation using the distance between the ego vehicle and the lead vehicle, divided by the speed of the ego vehicle. The metric was measured before the lead vehicle started to slow down when the decrease in speed was visible in the log. When the decrease in speed occurred earlier than the start of the log, the time headway was assessed at the beginning of the event. The annotator recorded events where drivers kept a minimum time headway lower than 1.5 s in the timespan leading up to the triggering of the intervention. Although previous literature defined close followings when time headway is below 1 s for passenger cars [16,17], the threshold of 1.5 s was chosen in this paper since the analyzed cases involved heavy vehicles and high speeds. The assessment of time headway focused on truck drivers' behaviour before the triggering of FCW and AEBS and, therefore, aimed to answer RQ1.

Based on the timeseries signals characterizing the kinematics of ego and lead vehicles, as well as the pedal use by the driver of the ego vehicle, the annotator judged whether the driver was in the loop. In this paper, we adopted the definitions of being in the loop provided by [18], i.e. if the driver was in physical control of the vehicle and aware of the driving situation. The annotator identified the point in time when the situation turned critical—that is when the lead vehicle started to decelerate—and assessed how long it took for the drivers of the ego vehicle to release the accelerator pedal and/or start braking. When the time was equal to or larger than 1 s, the driver was coded as out of the loop because it was assumed that the driver was not aware of the potential critical situation arising ahead. This threshold was chosen based on the results from [19], showing that the initiation of braking takes maximum one second from the point in time when drivers look back to the road, for events with high kinematic urgency.

Finally, the time between the start of the intervention and the drivers' action on the accelerator/brake pedal was used as a metric to code if the driver was acting as a response to the system: we assumed that the driver was not responding to the intervention if the response time was lower than 0.5 s. This threshold was defined based on previous research [20] that assessed 0.52 s as the minimum response time to a warning. For further analysis, we used time to start of braking (TTsb); this metric describes the time span between the triggering of the intervention and when the driver depresses the brake pedal. The use of brake and accelerator pedal targeted truck drivers' behaviour before, during and after the triggering of FCW and AEBS, hence addressing both RQ1 and RQ2.

For the analyses carried out in this paper, the logged cases were grouped based on the presence of the different intervention types (see Table 1). Groupings that are missing (i.e. pure interventions of pCW, CW, pMB and MB) were not in the dataset due to how the logging worked and hence are not shown in the table. The driver's action in relation to each intervention type can generally be categorized as shown in Table 2, and this grouping was performed for each of the four different intervention types.

Table 1
Grouping of cases based on intervention type.

Intervention grouping	Explanation
1: pCW-CW-pMB-MB	A preliminary Collision Warning (pCW), Collision Warning (CW), preliminary Mitigation Braking (pMB) and Mitigation Braking (MB) interventions are present in this case
2: CW-pMB-MB	A CW, pMB and MB intervention are present in this case
3: pCW-CW-pMB	A pCW, CW and pMB intervention are present in this case
4: CW-pMB	A CW and pMB intervention are present in this case
5: pCW-CW-MB	A pCW, CW and MB intervention are present in this case
6: pCW-MB	A pCW and MB intervention are present in this case
7: CW-MB	A CW and MB intervention are present in this case

Table 2
Grouping of driver's braking in relation to intervention (please note that this grouping was performed for each intervention type).

Braking grouping	Explanation
A: nothing	The driver does not brake and there is no activity from any intervention type (e.g. no pCW present in this case and the driver does not brake either).
B: sys	Only the intervention type in question triggers and the driver does not brake (e.g. pCW triggers and the driver does not brake).
C: driver	Only the driver brakes and the intervention type in question does not trigger (e.g. no pCW present in this case but the driver brakes as a response to the critical situation).
D: sys - driver	The intervention type in question triggers, and, while it is still active, the driver starts braking as well
E: sys – pause - driver	The intervention type in question triggers, and the driver starts braking after the intervention has ended
F: driver - sys	The driver starts braking, and the system intervention is triggered while the driver is still braking
G: driver – pause - sys	The driver starts braking, and the system intervention is triggered after the driver stopped braking
H: driver – pause - sys - driver	The driver starts braking, and, after the driver stopped braking, the system intervention is triggered and the driver starts braking again after that
K: driver – pause - driver - sys	The driver starts braking, and, after the driver stopped braking, the driver starts braking again, and during the second braking the system intervention is triggered
L: other	All remaining cases that do not fit any of the previous groupings

3. Results

3.1. General overview

This section gives a short overview of the full dataset extracted for the analysis, while the following two sections will focus on the two datasets obtained by the filtering process explained earlier.

Table 3 shows an overview of how many cases were classified in each intervention grouping described in the previous Table 1. MB intervened in only 4.8 % of the cases, while almost the totality of cases included either the combination of CW and pMB (66.5 %) or the combination of pCW, CW and pMB (28.7 %).

Table 4 shows an overview of how many cases were included in each braking grouping for the CW and MB interventions. For the CW, the drivers were already braking when the CW intervention was triggered in 76.6 % of cases (groups F, G, H and K). In 22.5 % of cases, the drivers applied the brakes after the CW intervention was triggered (groups D and E), and there are only a few cases where the drivers did not use the brake at all (group B, 0.3 %).

In almost all cases where the MB triggered, the drivers were already braking when the MB intervention was activated (groups F, G, H and K, corresponding to 98.35 % of the number of cases where MB triggered). However, there is a minority of cases where a MB intervention is triggered without driver braking (group B, corresponding to 0.41 % of the number of cases where MB triggered).

3.2. Collision warning

The filtering described earlier led to 368 cases. After closely looking at the data, we only retained cases on highway-type roads that were not in proximity to a curve and on- or off-ramp. This filtering—motivated by the will to extract cases in which the speeds of the ego and lead vehicles were not affected by the road infrastructure—provided a reasonably sized dataset of 117 cases. Table 5 summarizes the intervention grouping for the resulting dataset; it is worth noting that the percentage share between groups 3 and 4 have flipped in this filtered sub-sample compared to the full dataset: in cases where the drivers start braking after the CW has been triggered, a pCW has been present in 65.8 % of cases, whereas this accounts only for 28.7 % in the full dataset.

For the brake grouping, the CW provides the warning before the driver starts braking in 95.7 % of the cases (see category D in Table 6). There are a handful cases where the driver does not brake at all (category B) or the driver brakes after CW has ended (category E). Like for the intervention grouping, also the brake grouping shows a remarkable difference compared to the results obtained for the full dataset: in the full dataset, the drivers intervened before the system in about 75 % of the cases.

Fig. 3 shows that drivers kept on average a time headway of 1.23 s to the lead vehicle. The metric was shorter than 1.5 s in 80 cases (68.4 %), and shorter than 1 s in 52 cases (44.4 %). From the manual annotations, it was judged that the drivers were not in the loop in 67 cases (57.3 %). In 69 cases (59.0 %), the driver's braking cannot be considered a response to the CW, since the driver's response occurred within 0.5 s from the warning activation.

Table 3
Share of cases in each intervention groupings for the whole dataset.

Intervention grouping	Whole dataset
1: pCW-CW-pMB-MB	1.8 %
2: CW-pMB-MB	2.3 %
3: pCW-CW-pMB	28.7 %
4: CW-pMB	66.5 %
5: pCW-CW-MB	0.2 %
6: pCW-MB	0.1 %
7: CW-MB	0.4 %

Table 4
Share of cases in the braking groupings for the full CW and MB datasets (groupings A and L excluded in this table, so the sum for each column does not add up to 100 %).

Brake grouping	CW dataset	MB dataset
B: sys	0.29 %	0.02 %
C: driver	0.29 %	95.14 %
D: sys – driver	22.06 %	0.06 %
E: sys - pause – driver	0.42 %	0.00 %
F: driver – sys	66.78 %	4.30 %
G: driver - pause – sys	0.18 %	0.01 %
H: driver – pause - sys – driver	3.64 %	0.01 %
K: driver – pause - driver – sys	5.99 %	0.46 %

Table 5
Intervention groupings for the selected CW cases.

Intervention Grouping	Cases	Percentage
1: pCW-CW-pMB-MB	3	2.6 %
2: CW-pMB-MB	4	3.4 %
3: pCW-CW-pMB	77	65.8 %
4: CW-pMB	33	28.2 %
5: pCW-CW-MB	0	0.0 %
7: CW-MB	0	0.0 %

Table 6
Braking groupings for the selected CW cases.

Brake grouping	Cases	Percentage
B: sys	2	1.7 %
D: sys - driver	112	95.7 %
E: sys – pause - driver	3	2.6 %

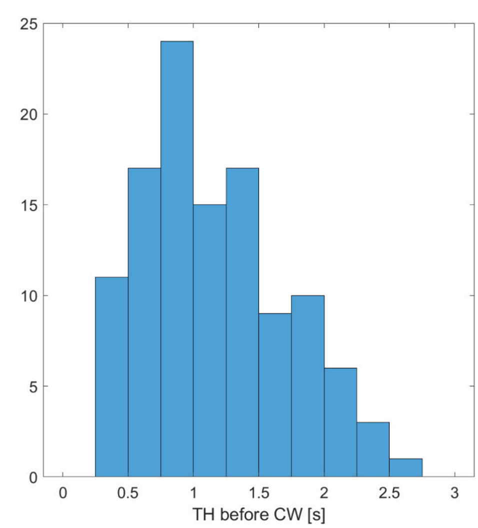

Fig. 3. Time Headway distribution for the selected CW cases, before the AEBS intervention.

In around 66 % of cases, the drivers did not use the accelerator during the 6-s logged event, but there are about 31 % of the cases where the drivers had the accelerator pedal pressed before the warning activation and they kept it pressed after the CW was triggered. In 2.6 % of cases, the drivers accelerated again towards the end of the CW, possibly to override the intervention.

The average speed of the EV at the start of the event was 82 km/h and mostly remained constant until the LV started braking. The corresponding distance of the EV to the LV was 30 m on average and kept relatively constant until the LV started decelerating and until the CW triggered. Due to the low TH maintained by the drivers, minimal changes in speed or distance of the LV resulted in CW activation. In our dataset, we did not have cases where the LV was stationary, and the minimum speed of the LV when it started decelerating was above 50 km/h.

Fig. 4 shows the time to start of braking (TTsb) of the ego vehicle drivers in comparison to when the CW was triggered. In more than half of the cases, TTsb is smaller than 0.5 s.

3.3. Mitigation braking

For the MB analysis, 61 cases were extracted from the dataset, but 5 cases were removed after manual review (e.g. cases recorded at a test track), leaving 56 cases for the analysis. Table 7 shows that almost 40 % of these cases went through the full intervention cascade, followed by the grouping where only the pCW was not present. However, in 19.6 % of the cases, the situation turned critical quickly and there was no time to trigger a pCW or pMB. Compared to the results in the full dataset, cases with the full cascade of intervention, cases with CW-pMB-MB intervention, and cases with pCW, CW and MB intervention became prevalent.

Regarding the braking groups, the driver is braking after the MB intervention in most cases, although with 80.4 % the share is 15 % lower than for CW (see Table 8). The second largest category are cases where only the MB is intervening, and the driver is not braking. The relative split between the three categories is analogous to the one shown for the full dataset in Table 4, once the irrelevant brake groupings (i.e. C, F, G, H and K) are removed.

The annotated time headway was most of the time below the criticality threshold of 1.5 s (83.9 %, see Fig. 5) and was below 1.0 s in 53.6 % of the cases. The average time headway—equal to 0.92 s—is low considering that the ego vehicle is travelling at speeds higher than 70 km/h, and this result is expected given that the MB activated to avoid a potential crash. In 65 % of the cases, it was judged that the drivers were out of the loop.

The speed trends are very similar to those observed for the selected CW cases: the ego vehicle speeds only reduce slightly between the maximum speed at the beginning of the event (75 km/h on average) and the point when the lead vehicle slows down. On the other hand, the lead vehicle speeds show bigger differences between these points, compared to the CW cases. When the EV is following the LV, the average distance is approximately 17 m, which is remarkably short considering that the ego vehicle is travelling at speeds around 75 km/h. The distance only changes marginally before a MB is triggered.

Fig. 6 shows the TTsb of the ego vehicle drivers in comparison to

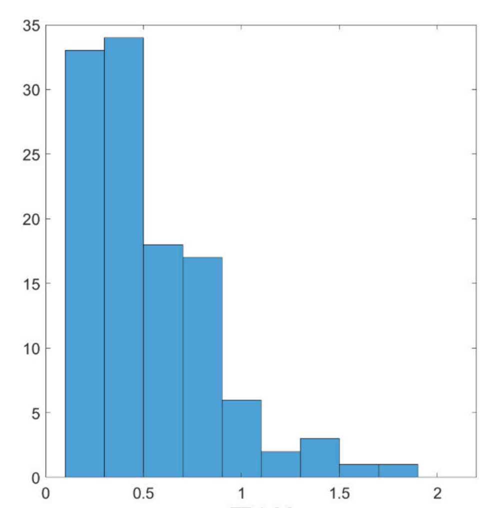

Fig. 4. Time to start of braking (TTsb) after CW intervention, for the selected CW cases (this figure is only based on the cases where the driver brakes, which are 115).

Table 7
Intervention groupings for the selected MB cases.

Intervention Grouping	Cases	Percentage
1: pCW-CW-pMB-MB	21	37.5 %
2: CW-pMB-MB	15	26.8 %
5: pCW-CW-MB	6	10.7 %
6: pCW-MB	3	5.4 %
7: CW-MB	11	19.6 %

Table 8
Braking groupings for the selected MB cases.

Brake grouping	Cases	Percentage
B - sys	9	16.1 %
D – sys - driver	45	80.4 %
E – sys - pause - driver	2	3.5 %

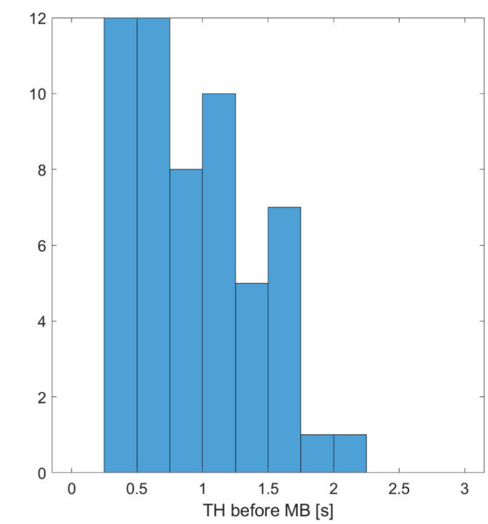

Fig. 5. Time Headway distribution for the selected MB cases, before the AEBS intervention.

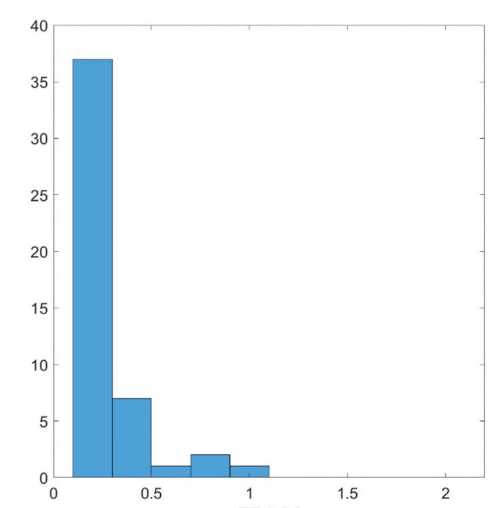

Fig. 6. Time to start of braking (TTsb) for MB (this figure is only based on the cases where the driver brakes, which are 47).

when the MB was triggered. There are only three cases (5 %) where the TTsb is greater than 0.5 s.

4. Discussion

This paper analyzed naturalistic event-triggered data recorded when AEBS intervened— either as preliminary mitigation braking (pMB) or mitigation braking (MB)—and included data during the 3 s before and after the intervention.

The results based on the full dataset—which can be counted in ten-thousands of cases—show that only approximately a quarter of the events include an intervention of a preliminary collision warning (pCW). This finding implies that rear-end critical situations arise suddenly, probably due to cut-in and cut-out maneuvers. However, the interventions of the full mitigation braking in the dataset are rare events, indicating that the drivers are fast in reacting to the threats. Looking more specifically at the motorists' braking during the events, we observed that HGV drivers were already braking before the CW intervention in approximately 75 % of the cases, in the full dataset. These findings could be motivated by two possible behaviours of the drivers. The first one is that drivers might be aware of the forward threat before the CW is issued, as reported by [11], either because their gaze is directed towards the road ahead or because the drivers can perceive the forward threat with their peripheral vision. The second assumption is that drivers might redirect their gaze towards the forward road, due to the deceleration initiated by the Adaptive Cruise Control after the lead vehicle braking, as found by [20]. Based on the results of this study, we cannot come to a definitive conclusion on why drivers braked before the activation of the CW, due to the lack of video data and information about the activation of Adaptive Cruise Control. Similar trends were found for the intervention of MB: drivers braked before the system in almost all the events which required the system activation. Apart from the prompt drivers' response, these results also show that the earlier interventions of pCW, CW and pMB are effective in triggering the drivers' braking, and that while drivers are reacting to the threat, the full MB braking can still support them to avoid a collision.

More detailed analyses were conducted on a restricted number of cases where the drivers started braking after either a CW or a MB was triggered, and where the lead vehicle did not change throughout the maneuver. In the filtered dataset including both CW and MB cases, HGV drivers maintain average distances smaller than 30 m, despite the high travelling speeds over 70 km/h. The resulting time headways are on average 1.23 s and 0.9 s, before the activation of collision warning and mitigation braking respectively. These values are surprisingly lower than the threshold of 2.25 s required by law for heavy goods vehicles in countries like Germany [22]. Besides, the values of time headways are shorter than 1.0 s in 44.4 % and 53.6 % of the cases respectively for CW and MB. These findings substantially differ from the ones discovered by [10], who found values of time headways lower than 1 s in only 15.9 % of the observed following events during driving with FCW. The difference in the outcomes might be due to the higher criticality of the events presented in this paper, in comparison with the ones extracted by [10]. On the other hand, the short headways noticed in this study might also be the consequence of negative behavioral adaptation to the system: drivers might rely on AEBS to resolve the critical situations based on previous positive experiences and therefore accept short margins. Previous research conducted with passenger car drivers [23–25] showed that systems providing feedback about time headway or following distances succeeded in increasing the time headway kept by the drivers. Similar research has not been conducted yet with HGV drivers and further research is therefore advised on this matter.

Based on manual annotations of the events, we labelled that the drivers were "out of the loop" if they required more than 1 s to release the accelerator pedal and/or start braking, once the situation turned critical. Our results indicate that drivers were not in the loop in 57.3 % and 65.0 % of the cases, respectively for the datasets with CW and MB braking interventions. However, it could also be that drivers felt in control of the situation and did not consider the situation critical enough to decelerate the vehicle; instead, they possibly considered the collision warning a nuisance and tried to override it. This interpretation of the data seems realistic for at least 2.6 % of the cases, where the drivers depress the accelerator pedal after the intervention of the collision warning, and for an additional 31 % of the cases where the drivers press the accelerator pedal before the CW and keep it pressed after the CW is triggered. The use of the accelerator pedal during and after the activation of CW was unexpected, and no previous research could be found to confirm or reject these results. Further studies, in real-world conditions and using cameras recording the drivers' cabin, are therefore recommended.

With respect to the filtered MB dataset, we found that the drivers did not use the brake pedal at all during and after the intervention, in 16.1 % of the cases. This result is similar to the findings by [26], who reported that drivers did not react within 5 s from the system onset in 17 % of MB interventions. This outcome could be the consequence of long-lasting visual distracting tasks already pinpointed by previous research [1,3] or fatigued and drowsy driving. In these cases where there is no driver's response, the most valid conclusion is that a crash would have happened without the intervention of the advanced emergency braking system. Nevertheless, another hypothesis could be that drivers relied on the system to brake and avoid the crash. Future research should investigate the matter and the availability of video recordings inside the cabin would support this type of studies.

For the analysis of drivers' braking response times (TTsb), the activation of either collision warning or mitigation braking has been considered as the initiation event, for CW and MB cases respectively. The resulting TTsb was within 0.5 s for collision warning in approximately 57 % of the cases and for mitigation braking in about 95 % of the cases; previous research [20] assessed 0.52 s as the minimum response time to a warning, so it can be argued that the drivers in the above specified cases are not braking as a response to the system intervention, but might already be prompted by earlier steps in the intervention cascade (e.g. by pCW). Other cues, most probably optical such as looming [27], kinematics like deceleration [21] or the pre-collision or collision warning in the MB cases are triggering drivers' responses. Previous analyses of mean driver response times to forward collisions warning [10] showed higher values (1.62 s), compared to our study (0.52 s), possibly attributable to the lower criticality of the rear-end events.

While this real-world naturalistic data provides a unique analysis opportunity, this research is not without shortcomings. The main limitations of this study derive from the method used for the data acquisition. The 5 Hz frequency used for data logging did not allow for a detailed assessment of the driver response, due to the considerable time gaps between two consecutive datapoints. Besides, the lack of video recordings showing the cabin view limited the analysis on driver behaviour, especially the assessment of the attentional status of the driver. Finally, the 6-s duration of the events limited the consistent calculation of the time headway in all analyzed cases, at the beginning of the event. Therefore, we recommend that future data acquisitions use a higher sampling frequency, video recordings of the cabin view and a longer duration of the data stored to allow for more detailed analyses.

CRediT authorship contribution statement

Ron Schindler: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Giulio Bianchi Piccinini:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **Laurent Decoster:** Writing – review & editing, Validation, Resources, Methodology, Investigation, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest.

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