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I want to brake free: The effect of connected vehicle features on driver behaviour, usability and acceptance.

William Payre & Cyriel Diels
Institute for Future Transport and Cities,
National Transport Design Centre,
Coventry University, Swift Road, Coventry, UK, CV1 2TT

Abstract: This study evaluated the effectiveness and acceptance of four connected vehicle features, i.e. Emergency Electronic Brake Lights (EEBL), Emergency Vehicle Warning (EVW), Roadworks warning (RWW) and Traffic Condition Warning (TCW) which were presented via a mobile phone mounted near the line of sight. A driving simulator study was conducted in which 36 drivers were exposed to different levels of urgent and critical situations. They involved the approach of an emergency vehicle, an emergency braking of a lead vehicle, a roadworks area and a congested section of a road. All these events took place in a simulated motorway scenario. In the EEBL event, the vehicle braking ahead with the brake lights on was either visible or not (between-subjects). Whereas no effect of RWW and TCW were observed on driving behaviour, results showed that drivers who were shown the EEBL warnings had shorter braking and decelerating response times, and a slower mean speed during the events, and this was independent of brake lights visibility. The EVW resulted in participants giving way to the emergency vehicle (i.e. staying on the slow lane instead of overtaking slower vehicles) more frequently than those who did not receive the warning. The mobile phone app was accepted and considered usable. Locating the mobile phone in different locations within the drivers' line of sight (i.e. dashboard, instrument cluster) did not impact significantly neither drivers' attitudes nor behaviour. Additional in-vehicle information systems could enhance safety and allow emergency vehicles to get faster to their destination.

Keywords: connected vehicle; human machine interface; mobile phone app; road safety; behaviour; usability; acceptance; driving; Emergency Electronic Brake Lights; Emergency Vehicle Warning; V2V; V2I

1. Introduction

1.1 Background

In-vehicle information systems (IVIS) transmitted via vehicle to vehicle (V2V) or vehicle to infrastructure (V2I) technologies have the potential to enhance road safety by enhancing drivers' situation awareness and behaviour. Situation awareness is the knowledge of what is happening around an individual (Endsley, 1995; Salmon, Stanton, Walker, Jenkins, Ladva, Rafferty & Young, 2009), and it encompasses three levels: perception, comprehension and projection. Individuals' level of situation awareness is deemed crucial in system design (Endsley, Bolte & Jones, 2003) and is even more critical in transport safety as drivers are exposed to various hazards sometimes requiring to perform urgent manoeuvres such as braking. For instance, a driving simulator study on a rear-end collision avoidance system showed that an early in-vehicle warning decreased the number of collisions by 80.7% (Lee, McGhee, Brown & Reyes, 2002). Such a feature is a potential asset in terms of safety if properly designed. A combination of various in-vehicle warnings with different applications may also be beneficial if they are properly integrated within the vehicle environment. For example, multimodality displays pairing visual and acoustic signals positively impacted road hazard perception, especially amongst older drivers (Liu, 2001). The combination of either haptic or auditory with visual warnings decreased time-to-collision in a driving simulator study (Lee, Hoffman & Hayes, 2004). The use of only one modality to convey warnings has been investigated and results are mitigated. Auditory icons, such as a car horn or skidding tyres, can decrease drivers' response time but also lead to inappropriate responses to hazardous situations (Graham, 1999). A vibrotactile warning signal indicating a sudden deceleration of the lead car reduced individuals' braking responses (Ho, Reed & Spence, 2006), and also decreased reaction times in rear-end collisions situations (Scott & Gray, 2008). Nonetheless, vibrotactile warning features are not accessible in most old cars.

IVISs will initially be available in the premium car segment. However, connected vehicle features have the potential to have a much larger safety impact thanks to retrofitting. Indeed, mobile phone applications are nomadic in essence and can provide such features to most drivers with older vehicles. The present paper addresses four connected vehicles features that are expected to provide significant safety benefits, namely, Emergency Vehicle Warning (EVW), Emergency Electronic Brake Lights

(EEBL), Roadworks Warning (RWW) and Traffic Condition Warning (TCW). This paper discusses some of the Human Machine Interface (HMI) design considerations for such features and reports on the findings of a driving simulator study aimed at evaluating the impact of these features on driving behaviour, user acceptance and usability. However, the particular features will be first briefly explained in more detail.

EVWs inform drivers about an approaching emergency vehicle in order to facilitate drivers to take timely and appropriate actions, e.g. giving way to the emergency vehicle by moving into the slow lane. EEBL warning systems aim to avoid rear end collisions which can occur if a vehicle ahead in the same lame performs an emergency braking (here defined as decelerations larger than 4 m/s^2), in particular when the vehicle is not clearly visible, e.g. when obscured by other vehicles ahead. Using V2V technology, EEBL warning systems alert drivers of a braking vehicle ahead before the driver may perceive the braking event otherwise.

From an HMI design perspective, there are two fundamental principles to consider, namely urgency and criticality. Whereas some connected vehicle features such as TCWs and RWWs (e.g. "congestion ahead", "roadworks ahead") require no urgent responses from the driver (i.e. urgency level 0), and hence no critical warning signals, other features, including EVWs and EEBLs, require more urgent driver responses to be effective and therefore benefit from attention grabbing human-machine interfaces. Urgency refers to the time within which the driver action or decision has to be taken if the benefit intended by the system is to be derived from the warning signal (ISO/TS 16951, 2004). It is categorised in four levels based on how quick drivers need to respond to the warning signal (Table 1).

Table 1 The four levels of urgency.

Urgency level	*Driver's rapidity of response*
3	Respond immediately (within 0 to 3 sec)
2	Respond within a few seconds (within 3 to 10 sec)
1	Response preparation (take action within 10 sec to 2 min)
0	Information only

Criticality is defined as the life-threatening consequences of a task (Hanson, Bliss, Harden & Papelis, 2014). Four levels of criticality have been defined (ISO/TS 12204, 2012), based on occupants injury and vehicle damage (Table 2). For instance, a forward collision warning that helps drivers avoiding a collision with a lead vehicle is considered level 3. Hence, EEBL warning systems can also be considered level 3 in terms of criticality. Concerning the EVWs, transporting injured individuals or reaching a destination to assist them also involves a level 3 of criticality. However, RWWs and TCWs do not involve such dramatic consequences, therefore their criticality level is 0.

Table 2 The four levels of criticality

Criticality level	*Severity*
3	Severe or fatal injury to occupants
2	Severe or possible injury to occupants
1	No injury to occupants but with damage to any vehicle
0	Neither injury to occupants but with damage to any vehicle

These warnings may be effective and assist drivers in more or less urgent and critical situations. For instance, previous studies recommended the use of faster auditory signals (e.g. 6 pulse/sec), a greater number of pulse burst units (e.g. 4 units) and high fundamental frequencies (e.g. > 1000Hz) to increase drivers' perceived urgency (Jerome, Monk, & Campbell, 2015). On the contrary, in order to decrease the perceive urgency when a situation was not highly critical, it was suggested to use slower auditory signals (e.g. 1.5 pulse/sec), a fewer number of pulse burst units (e.g. 1 unit) and low fundamental frequencies (e.g. 200Hz). However this additional in-vehicle information may not be accepted as it could be perceived as annoying or even distracting. Consequently, HMIs have to take into account what information is presented how and when in order to facilitate safe driving but also user acceptance.

User acceptance and acceptability of in-vehicle information and assistance systems are essential for several reasons (Burnett & Diels, 2014). Firstly, systems must be accepted if they are then to be used (i.e. a utility argument), such that the fundamental design goals for a system (e.g. safety, driving efficiency) have the potential to be met. Secondly, an understanding of acceptance is required when considering the closely related issues of usability and satisfaction. Considering connected vehicles will share users' data with other parties (e.g. local authorities, car manufacturers, other road users), it is also important to assess to what extent drivers accept their driving-related data to be used. If drivers refuse to share this data with one or different third parties, it may influence the app acceptance and its broad use amongst potential users.

The location of the HMIs conveying warnings should also be considered and be determined by the users' main characteristics and capabilities. For instance, individuals can detect detailed information only in their central or foveal vision. The visual area outside this foveal region is more sensitive to flashing lights and movements (Bhise, 2012, p.10). Moreover, approximately 90% of the driving task is considered to be visual task (Kramer & Rohr, 1982; Sivak, 1996; Spence & Ho, 2009). Therefore, locating the HMI in different positions in the vehicle may impact either drivers' readiness or distraction. For instance, the European Statement of principles on Human-Machine Interface (Godthelp, Haller, Harteman, Hallen, Pfafferott and Stevens, 1998) recommended such systems should not distract or entertain the driver, obstruct the driver's view of the road scenes, obstruct vehicle controls and displays required for the primary driving task, and should be positioned as close as practicable to the line of sight. To take full advantage of IVISs safety potential, further investigation on the warnings location are needed, based on the aforementioned guidelines.

1.2 Research questions

The aim of the present driving simulator study was to investigate drivers' acceptance of connected vehicle features and their potential impact on driving behaviour. The features included EVW, EEBL, RWW and TCW warnings which were displayed on a mobile phone located near the line of sight. More specifically, these warnings were assessed in terms of their impact on driving manoeuvres and response times compared to situations where they were not shown to drivers. The EVW and EEBL warning features were considered amongst the most safety critical within the set of features evaluated. As a result, their effect on driving behaviour were expected to be more impactful than the less urgent RWW and TCW features. In addition, the effect of the location of the mobile phone on driving behaviour, usability and acceptance was also evaluated. In line with the above, the following hypotheses were formulated:

H1: Drivers would give way to the emergency vehicle more often when the EVW was displayed in the vehicle than when it was not.

H2: Drivers' braking or decelerating response times would be shorter when the EEBL was displayed in the vehicle than when it was not, especially when the vehicle performing the emergency braking was not clearly visible.

H3: Drivers exposed to the EEBL, RWW and TCW warnings would drive slower following the alert than those who were not exposed.

H4: The application displayed on the mobile phone would be considered usable and would be accepted by participants.

H5: The different locations of the HMI in the driver's line of sight would have an impact on usability, acceptance and driving behaviour.

2. Method

2.1 Participants

The sample consisted of 36 drivers holding a valid driver licence (15 females, age: *M* = 33.3, *SD* = 8.6, *MIN* = 21, *MAX* = 54). The drivers had 1 to 35 years of driving experience either in the UK or in the European Union (M = 12.8, SD = 8.9). They drove on average 5290 miles a year (min = 0, max = 20000, SD = 4362). They were free to withdraw from the study at any time. The participants were recruited amongst Coventry University students and staff. They received a 15 pounds voucher in compensation for their participation. They remained anonymous throughout the study.

2.2 Simulator equipment

The fixed-based driving simulator consisted of a car buck. A three channel HD projection system provided a full panoramic view onto the 220 degree curved projection screen. It provided an output of a seamless high quality 5760x1080px display resolution at 60Hz. The wing mirrors had 10" SVGA resolution LCD screens integrated, whereas a 32" LED HD screen was mounted at the rear to simulate the rear view. The speedometer was displayed directly on the curved projection screen. The software used for the simulation environment was OpenDS 4.0. The steering wheel was equipped with a force feedback steering control unit, and the buck was equipped with two bass shakers which converted the signals from the bass shaker amplifier into physical vibrations to be conducted throughout the automotive buck's framework in the cockpit area.

2.3 Human-machine interface

The visual HMI was shown in a mobile phone (size: 16:9; resolution: 720x1080px). The mobile phone was displayed in landscape mode. It was either located on the centre console or on the instrument cluster (see Figure 1). The symbols were displayed in the middle of the screen with a 720x728px size during 4 secs, on a black background (see Figure 2). All symbols were paired with an acoustic signal in congruence with the criticality of the use cases. Symbols and acoustic signals are described in Table 3, and were designed to match the urgency of each event (Jerome *et al.*, 2015). The symbols were also designed to ensure drivers would not misinterpret them (Payre & Diels, 2019). The RWW and TCW were not considered urgent, whereas the EVW and the EBBL were (ISO/TS 16951, 2004).

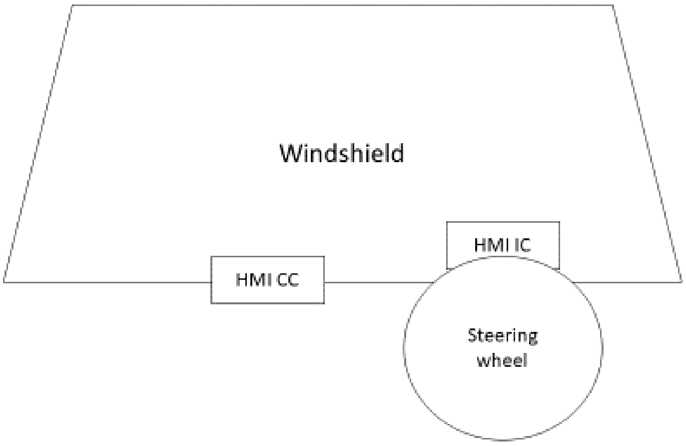

Figure 1 Sketch of the HMI locations. CC = centre console, IC = instrument cluster

Figure 2 Illustration of the EEBL displayed on the mobile phone

Table 3 Warnings visual and acoustic description

Warning	Urgency	Symbol	Acoustic signal
Roadworks	1/3		Two pulses within 0.6 sec, Frequency: 250 Hz
Traffic congestion ahead	1/3		Two pulses within 0.6 sec, Frequency: 250 Hz
Emergency vehicle	2/3		Two pulses within 0.6 sec, Frequency: 865 Hz
Emergency electronic brake lights	3/3		Four pulses within 0.65 sec, Frequency: 2000 Hz

2.4 Experimental design and procedure

Participants were welcomed and filled out a consent form. Subsequently, they received a general introduction to connected vehicles while seated in the driving simulator. Specific information about the driving simulator were given, such as the automatic transmission, the force feedback steering unit and the bass shakers. This introduction was followed by a 5 min practice drive to get familiarised to the simulator controls.

The main drive consisted of a 5 min drive on a 3 miles long two-lane motorway track, either with the HMI or without any HMI. Drivers were instructed to comply with traffic regulations. Besides, they were told they were late for a meeting and they had to make good progress. This instruction was meant to reduce variability in driving behaviour between participants and increase consistency in the traffic conditions and incidents they would encounter. In the HMI condition, participants were also told some information would be displayed on the mobile phone. They were not specifically informed about any of the alerts to avoid over-anticipation of hazards on the road. A mixed within and between subjects design with the between-subject factor *HMI* (with vs. without) and counterbalanced within-subject factor *EEBL visibility* (low vs. high) was used. They were distributed according to their age and gender into the six different experimental conditions (Table 4).

Table 4 Number of participants per experimental condition

	No HMI	**HMI**	
		Centre console	*Instrument cluster*
EEBL visibility: high then low	6	6	6
EEBL visibility: low then high	6	6	6

During the drive, the four warnings for the different connected vehicle features popped up in the mobile phone in the following order to control the driving environment as much as possible: Emergency vehicle warning (EVW), Roadworks warning (RWW), Traffic condition warning (TCV), and Emergency electronic brake lights (EEBL). These four use cases were all experienced by participants and are described in the following sections (Figure 4).

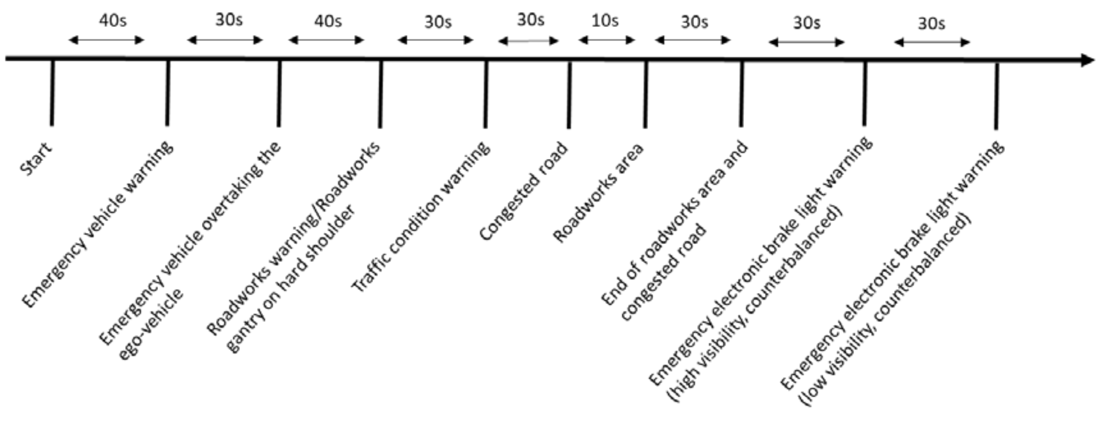

Figure 3 Timeline of the events occurring during the scenario.

All of the V2X applications and associated event occurred on a straight section of the road to control for the driving conditions and associated driving demand (i.e. workload) between participants.

Finally, after this simulator run, participants answered a questionnaire composed of the System Usability Scale (SUS, Brooke, 1996), different sets of questions on acceptance, willingness to buy, driving-related data sharing and socio-demographic variables.

In the following sub-sections, the four use cases experienced by the all participants are introduced and illustrated.

2.4.1 Emergency vehicle warning

The ego vehicle was located on the left lane, or slow lane, of the two-lane motorway and started accelerating up to 70 mph. The traffic was free flowing, and two vehicles were ahead on the left lane, travelling at 55 mph. After 500 m, an emergency vehicle (i.e. ambulance) spawned on the road on the right lane (i.e. fast lane) behind the ego vehicle and travelled at a speed of 95 mph. At the same moment the emergency vehicle warning was triggered for participants in the *HMI* condition. In this set-up, the emergency vehicle had to brake to avoid any collision with the ego vehicle if participants had decided to overtake the two vehicles on the left lane (Figure 5). Participants were free to either overtake the vehicles on the left lane or to stay behind them.

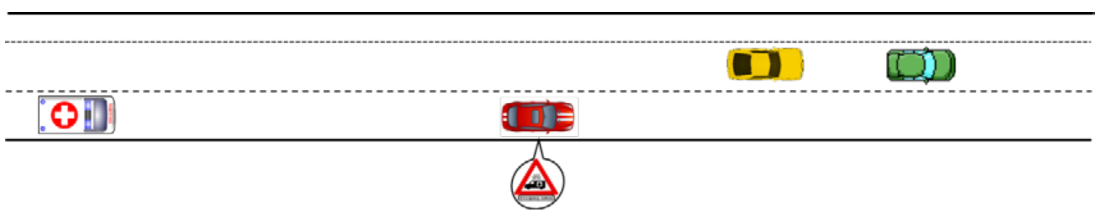

Figure 4 Plan view of the EVW scenario showing the approaching emergency vehicle (i.e. ambulance) in the fast lane with the ego vehicle (i.e. vehicle indicated by the EVW warning symbol) ahead. Here, the ego vehicle is in the process of overtaking two vehicles in the slow lane.

2.4.2 Roadworks warning

One mile before a roadworks area, a sign was displayed on the hard shoulder in compliance with local traffic legislation regarding the distance between a roadworks sign and the roadworks area (Highways England, 2016). The roadworks area consisted of a 200m section where the hard shoulder was closed by cones. When the car reached that sign, the RWW was displayed in the vehicle for participants in the *HMI* condition. Another road sign was displayed on the hard shoulder 500 m after the first sign, but that one was not displayed using the HMI. The roadworks area consisted of cones located along the hard shoulder lane mark for a 100 m. A construction truck was located in this area. A *Roadworks End* sign was displayed 100 m after the construction area on the hard shoulder, in compliance with the traffic legislation. This warning sign was not displayed on the mobile phone.

2.4.3 Traffic congestion warning

Approximately 5 secs after the RWW (i.e. depending on the ego vehicle speed, usually very close to 70 mph), the TCW warning was displayed subsequently for the participants involved in the *HMI* condition. The traffic was congested 500 m after the warning was displayed, with vehicles travelling at 35 mph in both lanes, precisely where the roadworks area was.

2.4.4 Emergency Electronic Brake Lights

All participants experienced the two experimental conditions of the EEBL warning (high vs. low visibility). On the left lane a commercial vehicle drove at 45 mph, and two cars on the right lane were travelling at 65 mph to allow the ego vehicle to catch up. The ego vehicle was 200 m behind the EEBL cars, with slight variations on the inter-distance depending on its speed. In the high visibility condition (Figure 6), the ego vehicle (i.e. the vehicle with the EEBL icon) was directly behind the vehicle performing the emergency braking (i.e. the vehicle with the exclamation mark >4m/s^2 = 8.9 mph/sec) and thus was able to see the brake lights turning on. The emergency braking was performed for 2 sec, as a result the vehicles' speed decreased to 47 mph.

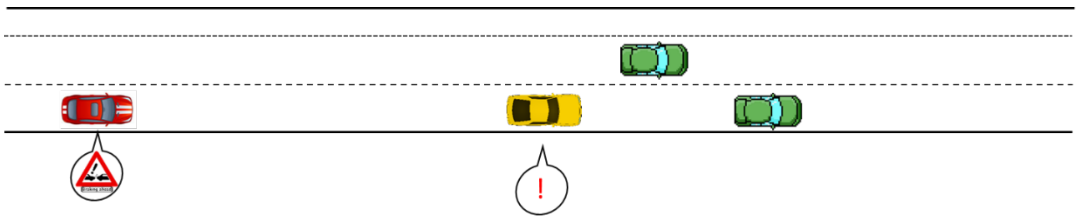

Figure 5 Illustration of the EEBL high visibility condition: The exclamation mark shows the emergency braking vehicle with brake lights directly visible to the ego vehicle approaching from behind.

In the low visibility condition (Figure 7), a vehicle between the ego car and the emergency braking car ahead was obstructing the participant's view. Hence, participants could not see the brake lights of this vehicle as soon as it started braking. The vehicle in between pulled in the left lane after the emergency braking to allow the ego vehicle experiencing the high visibility condition. These events were counter-balanced to avoid any order effect. Participants in the *HMI* condition experienced the warnings whereas those in the *no HMI* condition did not.

Between the two EEBL events, vehicles on the right lane accelerated to travel at 70 mph. The second EEBL event was triggered approximately 30 sec after the first EEBL.

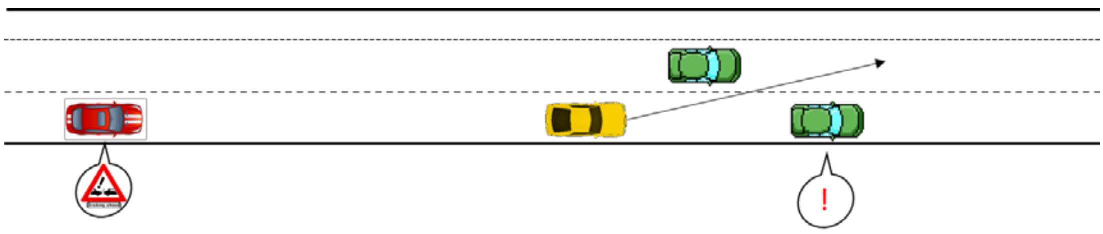

Figure 6 Illustration of the EEBL low visibility condition. The exclamation mark shows the emergency braking vehicle with brake lights not visible to the ego vehicle approaching from behind.

3. Measures

3.1. Questionnaire

The first section of the questionnaire consisted of the System Usability Scale (SUS, Brooke, 1996) to assess the usability of the four connected vehicle features among participants who experienced them (n = 24). Regarding data sharing and acceptance of the in-vehicle app, participants were asked the following questions in the second section (i.e. a 5-point Likert scale ranging from *1: Strongly disagree* to *5: Strongly agree*). The order of the questions was randomised across participants to avoid any order effects:

- *I would mind if an app would replace the gantry and road signs,*
- *I would mind if the driving-related data collected by my car was shared with other road users,*
- *I would mind if the driving-related data collected by my car was shared with other parties (manufacturers, local authorities).*

The following additional usability questions on the specificities of the app were asked:

- *The warnings' location in the vehicle was appropriate;*
- *I would like to be told what the warnings mean before seeing them while driving;*
- *I had enough time to see the warnings on the mobile phone;*
- *I had been distracted by the warnings;*
- *I found the signs were congruent with what happened on the road.*

Finally, the following socio-demographic information was asked: gender, age, driving experience and familiarity with managed motorways (i.e. Yes or No question).

A picture of the M42 in the UK was provided in case drivers were not familiar with this managed motorway.

3.2. Driving behaviour

The first measure of interest was the manoeuvre performed by participants in response to the emergency vehicle warning (EVW) event. Participants could give way to the emergency vehicle by either staying on the slow lane (i.e. left lane) or stopping the overtaking manoeuvre and reverting to the slow lane. They could also overtake vehicles therefore hindering the emergency vehicle to make good progress.

The second measure was the response time during the EEBL events. It was measured from the moment the EEBL was triggered to the moment participants either braked or decelerated.

The third measure was the mean speed of the participants' vehicle calculated during a 10 sec timeframe after the RWW, the TCW and the EEBL events were triggered. The rational supporting that timeframe is the level 2 urgency criteria (ISO/TS 16951, 2004), which was how fast drivers need to respond to a driving signal (e.g. level 3 = respond within 0 to 3 sec; level 2 = respond within 3 to 10 sec).

4. Results

4.1. Usability and data-sharing

Overall, the app seemed to be considered usable. Participants from the *HMI* condition rated how appropriate was the warnings' location (*SD* = .77), the willingness to be told what the warnings mean (*SD* = 1.19), if they had enough time to see the warnings (*SD* = .75), to what extend the app could be distracting (*SD* = .98) and eventually if the signs displayed on the mobile phone were congruent with what happened on the road (*SD* = .69) (Figure 8).

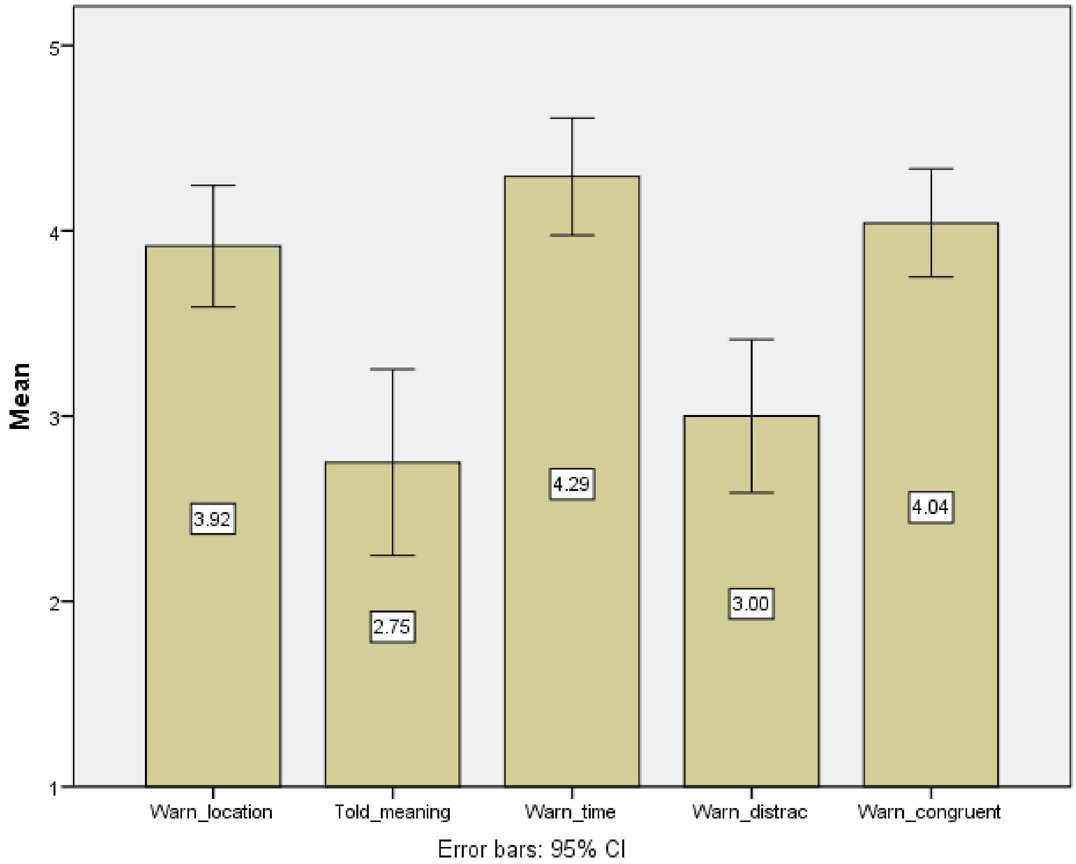

Figure 7 Mean score for the in-vehicle app usability (n = 24, error bars show the confidence interval).

The mean SUS score was 82.4 (n= 24, *SD* = 8, *MIN* = 67.5, *MAX* = 97.5), which is interpreted as excellent (i.e. overall score of 6 out of 7) according to the SUS adjective rating scale based on 1000 SUS surveys (Bangor, Kortum & Miller, 2009).

On average, the 36 participants declared they would mind if the gantry was replaced by an in-vehicle app (*M* = 3.7, *SD* = 1.2, *MIN* = 1, *MAX* = 5). Similarly, they declared they would mind if using such an app was mandatory (*M* = 3.6, *SD* = 1.2, *MIN* = 1, *MAX* = 5).

Regarding their own driving-related data, they declared they would mind sharing it with other parties (*M* = 3.6, *SD* = 1.3, *MIN* = 1, *MAX* = 5), but they would be less reluctant sharing with other road users (*M* = 2.2, *SD* = .87, *MIN* = 1, *MAX* = 4). They would spend on average £4.23 to get the app (*SD* = 8.5, *MIN* = 0, *MAX* = 30).

4.2. Manoeuvres during emergency vehicle warning

Amongst drivers exposed to the EVW, 75% of them gave way to the emergency vehicle whereas none of them did when they were not exposed to the EVW. A chisquare test of independence was performed to examine the relation between giving way to the emergency vehicle and the HMI. Participants who were shown the EVW (n=24) gave way significantly more often than those who were not (n=12); $X^2(1, 36) = 18$, $p < .001$ (Figure 9). None of the participants stopped the overtaking manoeuvre and reverted to the left lane.

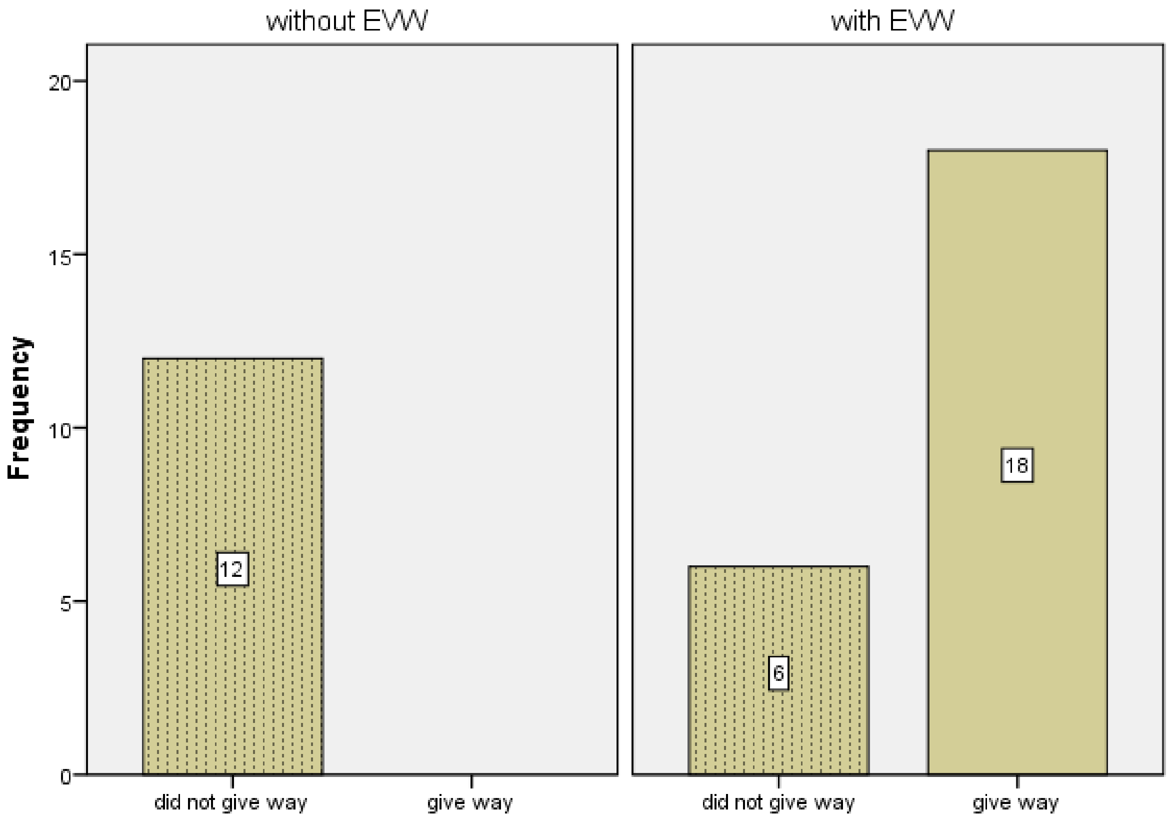

Figure 8 Number of participants who gave way to the emergency vehicle without EVW (left) and with EVW (right).

4.3. Response times during EEBL

Among the 36 participants, six were removed from the data set since they were not driving in the lane where the EEBL occurred: three from the high visibility condition and another three from the low visibility condition. One participant was from the *no HMI* condition whereas the five others were from the *HMI* condition.

Two independent-samples ANOVAs were conducted to compare the braking and decelerating response times in the *HMI* and *no HMI* conditions. In the high visibility condition, participants who were shown the HMI had significantly shorter response times than those who were not shown the HMI ($F(1,32) = 16.34$, $p < .001$, $\eta^2 = .35$). Similar results were observed in the low visibility condition, $F(1,32) = 17.67$, $p < .001$, $\eta^2 = .36$ (Figure 10). Two paired-samples t-test were conducted to compare the mean speeds in the *HMI* and *no HMI* condition. There were no significant differences in the scores for both the *HMI* (*t*(18)=.000, p=1.0) and *no HMI* conditions (*t*(10)=-.87, p=0.41).

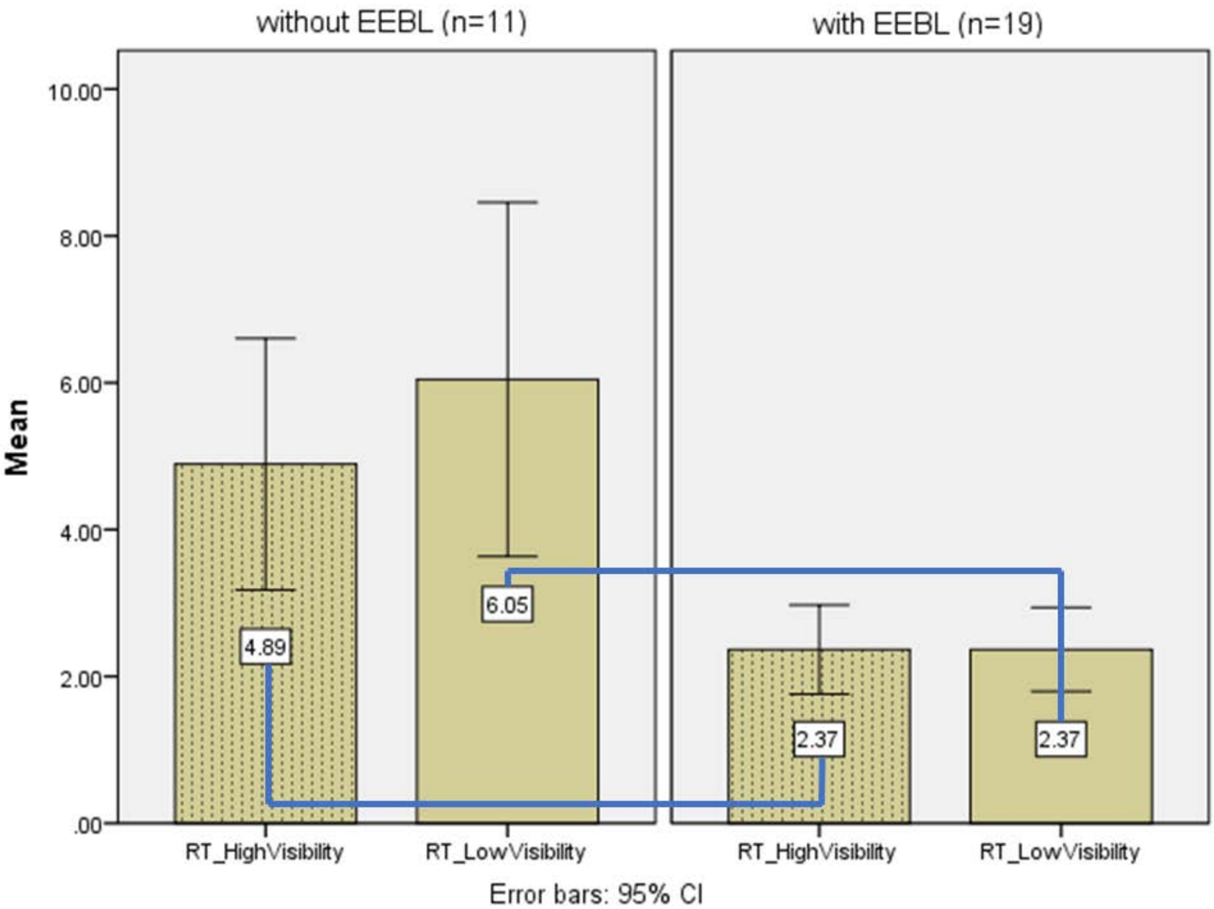

Figure 9 Mean response times in seconds for braking or decelerating during both EEBL events (error bars show the confidence interval, plain blue lines the significant differences in scores between conditions).

4.4. Mean speed

Regarding RWW and TCW, the ANOVAs conducted showed no statistical differences between conditions. Drivers from the *HMI* condition drove at a similar speed compared to those from the *no HMI* condition, for both the RWW ($F(1,35) = .99$, $p = .755$) and the TCW ($F(1,35) = 1.78$, $p = .191$).

Similarly with the aforementioned response times section, six participants were removed from the data set since they were not driving in the lane where the EEBL occurred: three from both the high and low visibility conditions. One participant was from the *no HMI* condition whereas the five others were from the *HMI* condition.

Two independent-samples ANOVAs were conducted to compare the mean speed in mph between both experimental conditions. In the high visibility condition, participants who were shown the HMI had a significantly slower mean speed than those who were not shown the HMI, $F(1,32) = 6.42$, $p = .017$, $\eta^2 = .17$. Similar results were observed in the low visibility condition, $F(1,32) = 7.12$, $p = .012$, $\eta^2 = .19$ (Figure 11).

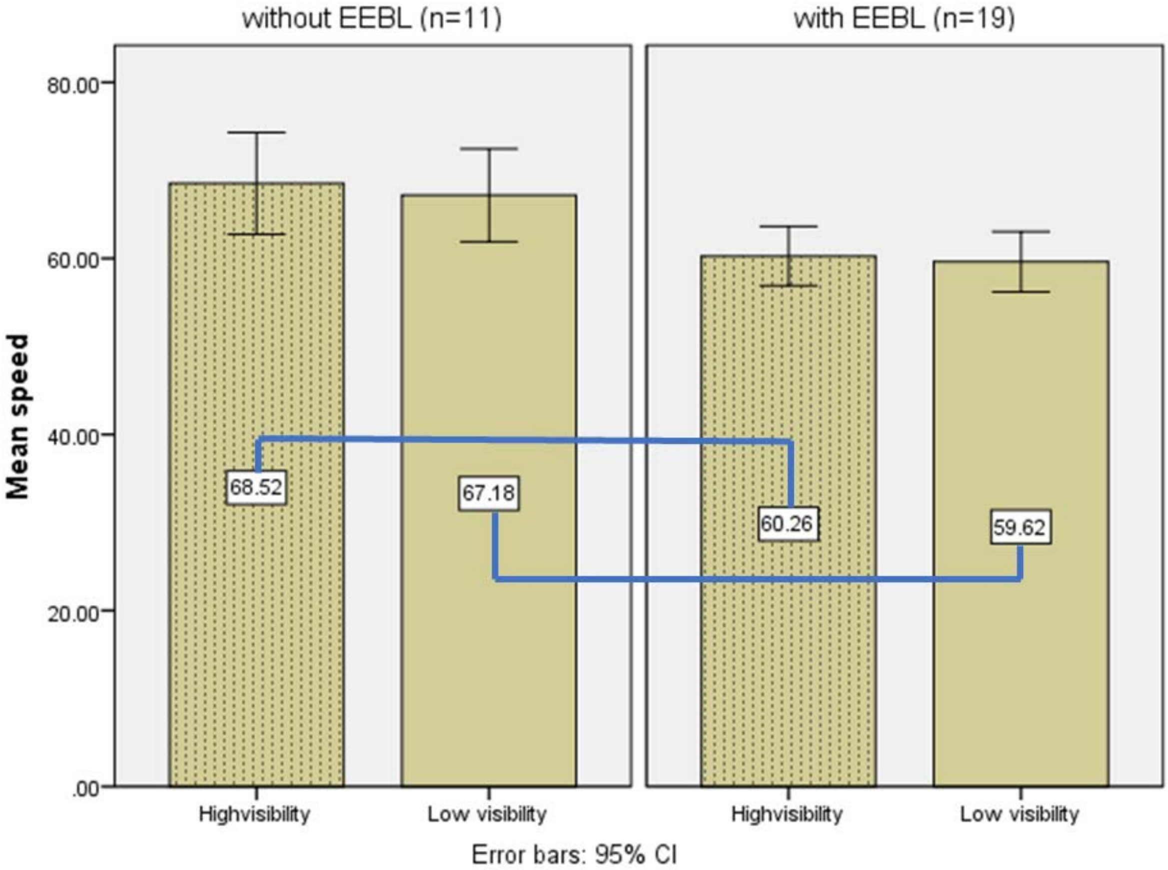

Figure 10 Mean speed in mph of the participants' vehicle during a 10 sec timeframe after both EEBL events (error bars show the confidence interval, plain blue lines the significant differences in scores between conditions).

4.5. HMI location

An independent-samples ANOVA was conducted to compare the driving behaviour and questionnaire measures depending on the HMI location (i.e. centre console vs. instrument cluster). No significant differences were found between these two experimental conditions for any of the measures collected (Table 5).

Table 5 ANOVA analysis comparing the HMI locations: instrument cluster vs. centre console

Dependent variable	*F*	*df**	p value
Warning location	1.11	1	.3
Difficulty to comprehend	.46	1	.5
Display time	4.11	1	.06
Distraction	1.61	1	.22
Congruency	.78	1	.39
SUS score	.674	1	.42

Gantry replaced	1.51	1	.23
Mandatory app	.04	1	.85
Sharing with other parties	2.4	1	.14
Sharing with other road users	3.77	1	.07
Mean speed after RWW	1.87	1	.19
Mean speed after TCW	1.15	1	.30
Give way during EVW	.001	1	.98
EEBL response times high visibility	.68	1	.42
EEBL response times low visibility	.003	1	.96
EEBL mean speed high visibility	.001	1	.98
EEBL mean speed low visibility	1.72	1	.21

* Degrees of freedom

5. Discussion

5.1 Driving behaviour

The objectives of the present study were to assess the influence of additional safety-related in-vehicle information (i.e. a mobile phone app) on driving behaviour, and to evaluate if this information conveyed via a mobile phone was accepted and considered usable. The warnings consisted of an icon displayed on a mobile phone paired with an acoustic signal. The EVW and EEBL icons tested during this study had not been used in a driving simulator study before.

In line with previous findings (Graham, 1999), results showed that the urgent IVIS, i.e. EEBL and EVW, had a positive impact on driving behaviour. Indeed, drivers exposed to the EVW feature gave way to the ambulance significantly more often than those who were not exposed (H1). This result filled a gap in the research literature as EVWs impact on drivers' behaviour had not been much investigated in driving simulator studies. When the EEBL warnings were displayed in the vehicle, response times were decreased on average by 2.8 sec when the braking vehicle ahead was visible, and by 3.5 sec when the braking vehicle was not clearly visible compared with the *no HMI* condition (H2). EEBL warnings seemed to be more efficient in low visibility conditions, which is a new finding observed in the present study. Similarly, mean speed measured during 10 sec after the EEBL decreased by 7 mph when the braking vehicle ahead was visible, and by 7.2 mph when the braking vehicle was not clearly visible compared with the *no HMI* condition (H3). These results could be explained by drivers' potentially improved better situation awareness when exposed to the app-based warnings. The icons and the acoustic signals may have enhanced the three levels of situation awareness, namely: perception of the situation (e.g. a hazard is oncoming for EEBL, an emergency intervention is ongoing for EVW), comprehension (e.g. an emergency vehicle will pass me for EVW; a vehicle ahead is braking harshly for EEBL) and projection (e.g. I have to give way to the emergency vehicle for EVW; braking will prevent further accident for EEBL).

Regarding RWW and TCW, displaying these less urgent warnings did not influence drivers' mean speed. The road signs may have mitigated the effect of these in-vehicle warnings on drivers' behaviour as they both were redundant with the road signs. In addition, the road signs were visible before being displayed on the mobile phone, which may be sufficient to warn drivers of these non-critical oncoming events. The auditory signals for these features were not designed to be perceived as urgent or critical, which may also explain the lesser effect on participants' behaviour. Eventually, it may be assumed drivers' situation awareness was not enhanced regarding roadworks and traffic congestion events.

5.2 Usability and acceptance

The app was also considered usable and accepted (H4). However, participants seemed not to be ready to replace the hard gantry with an IVIS, and be compelled to use it. Although mobile phones allow older cars to get V2V and V2I safety systems, having a cell phone charged at all time and set up as a mandatory in-vehicle display might be a drawback in the adoption of nomad in-vehicle applications. An alternative would be to integrate the features into embedded systems to avoid drivers having multiple active displays within their vehicle. Comparing the app acceptance whether used on a phone or integrated in an embedded system could help understanding which platform matches drivers' need and expectations the best depending on the car driven. Concerning privacy, participants declared they were keen to share their driving-related data with other road users, but not with third parties (i.e. manufacturers, local authorities). Data sharing seemed to be accepted as long as drivers' information was shared within the app-users community. Manufacturers and local authorities should take this result into consideration as individuals might not accept being tracked during their journey, even for safety purposes. These answers were based on a survey therefore they may not reflect users' acceptance and perceived usability of the app after longer and more frequent interactions. For instance, many satnav and GPS applications already share users' data with various parties to feed the app but also for commercial purposes (e.g. suggesting points of interest). There seems to be a trade-off between privacy and usefulness: the higher the perceived value of the app, the lesser concern regarding privacy.

5.3 HMI location

There was no impact of the HMI location on neither driving behaviour nor usability (H5). One explanation could be that both locations were located close to the central line of sight, inducing a very little difference in the visual perception of the symbols. Participants only had to swiftly glance at the mobile phone display, which is potentially an easy task as they did not have to spend extended periods of time looking at the display to perceive the symbols. In addition, visual attention does not need individuals to glance directly at a target. This capacity is called covert attention. It consists in paying attention to an object in someone's visual field without making eye movement (Posner, 1980). This capacity could also improve with experience, for instance familiarity with GPS or traffic navigation apps. Another explanation could be that the acoustic signals displayed with the signs already increased drivers' readiness to respond to oncoming hazards and events, as previously demonstrated in a simulator study (Liu, 2001).

5.4 Limitations and further discussion

The response times during the EEBL event in the *no HMI* condition seemed quite high (i.e. 4.89s in the low visibility condition, 6.05s in the high visibility condition). This result may be supported by the relatively large distance between the ego vehicle and the vehicles braking ahead in the same lane (i.e. 200m). The simulated environment could also support these result as participants may have not clearly perceived the vehicles ahead were strongly breaking.

Braking or decelerating might not be the best actions to perform during an EEBL event. Another appropriate manoeuvre could be to swerve into another lane to avoid the braking vehicle if the traffic allows it. Further research should investigate such use cases, in which drivers have different options as to handle this critical and urgent situation.

These insights could be discussed in the light of the risk homeostasis theory (Wilde, 1982), which assumes some people opt a level of risk perceived as personally acceptable. If a situation is perceived to be safer, drivers may engage in riskier activities, for instance texting while driving if their car is equipped with dynamic warning features. To mitigate potential hazardous behavioural adaptation, designing in-vehicle warning systems must take into consideration drivers' attention and off-road glances. The HMI should be able to get the driver back into the loop or deactivate the additional warnings when they lead to a decrease of drivers' attention on the road.

Perceived usability and driving behaviour could be different depending on cross-cultural differences. Legends displayed on the supplementary plate are in English, and that could be an issue in terms of comprehension for non-native English speakers. Moreover, road safety policies are different internationally in regard of what drivers should do to let emergency vehicles pass through traffic.

6. Conclusion

Results showed that new features such as EVW and EEBL, with the highest levels of urgency and criticality, could possibly enhance safety and facilitate emergency vehicles access to their intervention location. IVIS have the potential to increase drivers' situation awareness and help them anticipating hazardous situations with different levels of urgency and criticality. However, road signs are still efficient for warning drivers of oncoming non-critical nor urgent events. The asset of nomadic devices is allowing older automobiles to be equipped with connected safety features conveying information on either urgent or critical events. The caveat is that the potential of in-vehicle connected safety features depends on how many drivers use them and on the quality of the connected road infrastructure. Further on-road studies are required to assess the impact of these features on safety and better understand drivers' acceptance and behavioural adaptation over a longer period of time.

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