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Lateral control assistance in car driving: classification, review and future prospects

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Abstract: This study puts forward a classification of driver lateral control assistance devices based on distinctions among several cooperative activities between the driver and the assistance devices. The proposed classification is based on prior work by Hoc, Young and Blosseville and Young, Stanton and Harris, who put forward related theoretical frameworks on human–machine cooperation with automation. The particular application here to lateral control allows for a human-centred categorisation of existing and potential (i.e. near-future) driver assistance devices. Four human–machine cooperation levels based on drivers' activities have been adopted. All of the proposed categories are reviewed in three steps. First, each device category is functionally defined. Next, the impact of the devices on driving behaviour is presented. A third part sums up the effectiveness of each assistance category, particularly with regard to accident data. The general conclusion synthesises the main insights for each human–machine category proposed and highlights a number of design recommendations.

1 Introduction

1.1 Background

Crash analysis data from several studies carried out in different countries suggest road departures represent a significant proportion of road casualties [1, 2]. A study of fatal crashes in Sweden, for instance, showed that about one-third of the crashes took place after a lane departure (see [3]). Bar and Page [4] reported that unintentional lane departure was responsible for about 40% of crashes and 70% of road fatalities (based on data from several European countries). In the USA, road departure crashes are among the most severe. Single-vehicle off-road crashes accounted for 17.3% of the 6.32 million police-reported crashes and 40.8% of all fatalities (see [5]). Lane departures are often a combination of several factors, such as road condition (slipperiness) and driver state (driver fatigue, alcohol). However, distraction seems to be a major cause of crashes (Royal, 2003) and can be considered as the main target of safety research.

The response to this has been recent technological progress with developing lateral control assistance devices. Thus, lateral control support for car drivers has become a growing field of interest for both engineers and cognitive ergonomists – with the latter keen to understand the interactions occurring between drivers and the assistance devices introduced to help them.

According to Young *et al.* [2], levels of automation within the car-driving domain are divided into two categories: 'vehicle automation' and 'driving automation'. Vehicle automation covers those devices with low level vehicle control and few human–machine interactions (e.g. anti-lock braking system (ABS) and automatic gearbox), whereas driving automation implies more human–machine interactions and even human–machine cooperation (see [6]).

Hoc *et al.* [1], on the other hand, put forward a four-level classification system for human–machine cooperation in the car. At the perception mode level, the assistance device acts as an extension of the sensorial organs (augmented perception). With the mutual control mode, the device provides evaluative feedback on driver behaviour when certain conditions are reached. In the function delegation mode, part of the driving task is delegated for a while to automation. Finally, in the fully automatic mode, automation controls the vehicle, either replacing a driver who is momentarily impaired or under the driver's supervision. In terms of human–machine interaction, all the automation modes described are cooperative modes. This theoretical framework has been preferred to others, because it emphasises the effects of car automation on human cognition. Links can be drawn with the classical skill-based, rule-based, knowledge-based taxonomy introduced by Rasmussen [7]. For instance, delegating the control of speed or steering to the automation amounts to shifting from a skill-based control to a rule-based supervision. Nevertheless, both theoretical approaches cannot be superimposed. For instance, augmented perception can be obtained by means of additional sub-symbolic information (improved sensory feedback) as well as additional symbolic information (numerical information, for instance). Parasuraman *et al.* [8], extending over the initial classification by Sheridan and Verplank [9], also proposed a model in which various levels of automation are crossed with four broad classes of cognitive functions (information acquisition, information analysis, decision and action selection and action implementation). The objective was also to evaluate criteria for automation design. This framework was mainly applied to supervisory tasks, such as air traffic control. In contrast, Hoc *et al.* [1] propose a more specific human–machine-centred approach of car driving, which emphasises operational control.

In the present paper, we apply the framework proposed by Hoc *et al.* [1] to the specific case of lateral control assistance devices. We also augment the cooperation model, primarily by considering a combination of Young *et al.*'s [2] classification with Hoc *et al.*'s [1] cooperation levels.

1.2 Revisiting frameworks for human–automation interaction

Within the cooperation model, the mutual control mode has been modified. Hoc *et al.* [1] further divided mutual control into four sub-categories (warning mode, action suggestion mode, limit mode and corrective mode). However, this sub-categorisation appears to be too specifically related to particular device characteristics (e.g. the limit mode is directly derived from specific devices that tend to limit drivers' actions under certain conditions). Therefore in the present paper, only two sub-categories are adopted, based much more on human–machine cooperation. The first is a warning mode, defined as a criticism of drivers' behaviour as with Hoc *et al.* [1]. Applied to lateral control, all devices issuing a lane departure warning fall into this category. Because some devices not only criticise drivers' behaviour, but also participate physically in the driving activity, a second sub-category called 'co-action' has been created. This remains part of the mutual control mode, but the driving activity is more deeply modified, and drivers are no longer able to ignore automation recommendations. In the co-action mode, drivers and assistance devices act together on vehicle control. All devices actively involved in vehicle steering control (lane-keeping assistance systems (LKAS)) can be classified in the co-action mode.

In the function delegation mode, Hoc *et al.* [1] distinguish between a mediatised and a control mode. According to Hoc *et al.*, ABS or electronic stability control (ESC) come under the mediatised mode, since such devices act as mediators between drivers' actions and car behaviour. While it does appear that part of the driving task has been delegated to automation when comparing vehicles with and without these devices, as ABS (and even ESC) become standard on new vehicles such devices are now more integrated by the driver as part of the vehicle dynamics. It could still be argued that ABS performs a delegated function because, before such a device was introduced, drivers were in charge of the activity now performed by the device, but it is a particular form of function delegation that becomes invisible for the driver and integrated as part of the vehicle dynamics. A parallel could be drawn with automatic gearboxes. When contrasting drivers' activities before and after the introduction of automatic gearboxes, it seems that automation now performs part of drivers' tasks. However, an automatic gearbox does not perform a delegated function; it is more of a device that is part of the vehicle controls. Thus, the vehicle automation classification as introduced by Young *et al.* [2] is more appropriate for describing this particular interaction between drivers and driving assistance.

In the proposed classification, the delegation function category includes only devices that drivers choose to use to delegate part of the driving task, for example delegation of longitudinal control with adaptive cruise control (vehicle speed and time headway with the lead vehicle being controlled by the device) and/or delegation of lateral control with a device capable of managing the car's position in its lane under normal conditions without any intervention from the drivers.

The fully automatic mode described by Hoc *et al.* [1] is technologically out of reach at present, since it would have to perform all lateral control activities such as obstacle avoidance and overtaking manoeuvres (and will therefore also involve speed control). For that reason, it will not be considered further.

Fig. 1 encapsulates the theoretical framework adopted for the subsequent review of lateral control assistance devices. The black arrow represents the ever-greater influence of

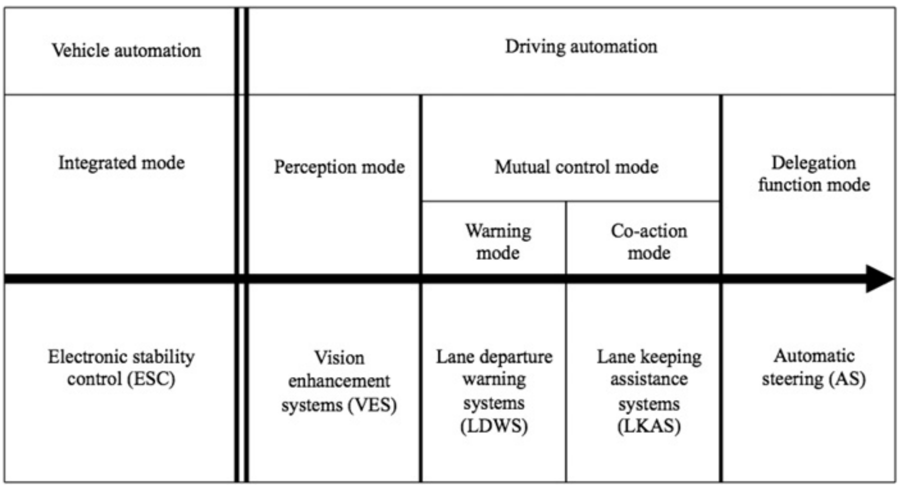

Fig. 1 *Integrated classification of lateral control assistance devices based on the theoretical frameworks of Hoc et al. [1] and Young et al. [2]*
The top line shows the level of human–machine cooperation while the bottom line shows the different assistance devices classified along these levels

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Table 1 From [10]: number of crashes in leading road-departure pre-crash scenarios (rounded to the nearest 1000, and 0.1%)

	Going straight	Negotiating a curve	Initiating a manoeuvre	Total
departed road edge	348 000 (36.4%)	111 000 (11.6%)	66 000 (6.9%)	525 000 (54.9%)
lost control	218 000 (22.8%)	162 000 (17%)	51 000 (5.3%)	431 000 (45.1%)
total	566 000 (59.2%)	273 000 (28.6%)	117 000 (12.2%)	956 000 (100%)

automation on drivers' activities. In the vehicle automation category there is little (or residual) interference between automation and drivers. Interference increases proportionally with the increase of automation intervention in the lateral control task. Vehicle and driving automation are considered here as two juxtaposed categories. A three-level classification inspired by Hoc *et al.* [1] comes under the driving automation category.

This paper discusses each human–machine cooperation mode via an assessment of available assistance devices. Device effectiveness (actual or expected) in reducing crashes will be presented for each category based on data from the United States' 1998 'general estimates systems' database (see [10]). The authors of this paper put forward six leading crash scenarios defined by two dimensions: the pre-crash motion of the vehicle (top row), and the nature of the road departure (left column). These categories were specifically defined following an analysis of single-vehicle off-road crashes. Table 1 presents the frequency of crashes with the six pre-crash scenarios.

Negative behavioural adaptation (BA), observed or likely to occur at the different human–machine cooperation levels, will also be presented. Driving assistance devices are expected to assist people while driving, but BA often occur as a consequence. The OECD [11, p. 23] defined BA in transportation as 'those behaviours which may occur following the introduction of changes to the road–vehicle–user system and which were not intended by the initiators of the change; BA occur as road users respond to changes in the road transport system such that their personal needs are achieved as a result'. The outcome is meant to be positive. For instance, drivers who often exceeded speed limits may become more prone to respect regulation when using speed regulators. On the other hand, negative BA can also appear, such the same speed regulators resulting in shorter time headways. Those unintended negative BA could overshadow positive BA or even lead to a deterioration of driving behaviour. Negative BAs that have been observed or are likely to occur, at the different human–machine cooperation levels will be presented in this paper.

2 Part 1: vehicle automation: ESC

2.1 Description of the assistance category

Several types of ESC devices have been developed, but its basic working principle is the same across all. ESC brakes one or more wheels (depending on the situation and specific device in question) to enhance vehicle controllability by preventing skidding in cases of understeer or oversteer. If the car understeers (i.e. the front wheels begin to skid), ESC decelerates the rear inner bend wheel (see left picture of Fig. 2). As a result, the car's heading is corrected, and the vehicle can safely continue to take the bend. If the car oversteers (i.e. the rear wheels begin to skid), ESC decelerates the front outer bend wheel (right picture of Fig. 2), which has the same benefits.

2.2 Impact on drivers

ESC could be helpful for drivers who over-estimate the speed in a bend and who turn the steering wheel too sharply. It can also be effective in low-friction conditions or where these situations are combined [12].

ESC is rather a new component of the vehicle for drivers to interact with. A parallel can be drawn with ABS. From the driver's point of view, such devices are part of the vehicle dynamics and do not invoke true human–machine cooperation. ABS was designed to avoid wheel locking during emergency braking by implementing cadence braking when necessary. With ABS, drivers' braking is optimised, and they can still effectively steer the car. Both ABS and ESC do not directly interfere with drivers' actions but rather optimise some drivers' actions without their necessarily knowing about it. This idea is supported by the fact that some drivers have limited knowledge and skill in the use of ABS [13–16].

The introduction of ABS can lead to BA in terms of risk homeostasis (see [17, 18]) at this level of automation. ABS use resulted in a significant reduction in time headway for Norwegian taxi drivers [19]. This reduction of the safety margins is a contributing factor for front-end collision crashes and can be attributed to drivers' adaptation to new vehicle dynamics with ABS.

If the concept of risk homeostasis is applied to ESC, it is easy to imagine that drivers will increase their speed in bends if they perceive that their vehicle can take bends more quickly. The only data available about BA to ESC are survey data [20]. The surveys conducted by these authors revealed that less than two-thirds of ESC car drivers were aware of the presence of the device. But among those that were aware of the presence of ESC, one-third reported noticing long-lasting changes in their driving behaviour related to the introduction of ESC.

In sum, from the driver's point of view ESC acts as an underground system. When drivers encounter a skid, ESC is automatically engaged. Drivers are not always aware of how it works or whether their vehicle is equipped and therefore do not always detect its intervention [20]. There is very little interaction between the device and drivers,

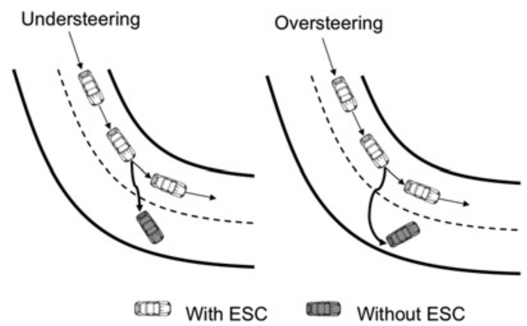

Fig. 2 *Effects of ESC for understeering (left) and oversteering (right)*

Table 2 Overview of the overall effects of ESC on crashes

Study	Data sources	Country	Specific conditions	Percentage of reduction
Bahouth [22]	accident analysis, before–after study	USA		12% of multiple vehicle frontal crash events
				53% of single vehicle frontal crash events
Farmer [23]	accident analysis, before–after study	USA		41% of single crash involvement risk
				56% in single vehicle fatal crashes
Farmer [24]	accident analysis, before–after study	USA	sport utility cars	32–37% of multiple-vehicle crashes
			cars	25% of multiple-vehicle crashes
Aga and Okada [25]	accident analysis, case control studies	Japan		35% of single car crashes
				30% in head of collision crashes
Thomas [26]	accident analysis, case control studies	UK		19% in fatal and serious injury crashes
			wet road	34% in fatal and serious injury crashes
			icy road	53% in fatal and serious injury crashes
Dang (2004)	accident analysis, case control studies	USA	passenger cars	35% of single vehicle crashes and 30% of single vehicle fatal crashes
			sport utility vehicles	67% of single vehicle crashes and 63% of single vehicle fatal crashes
Lie *et al.* (2004, 2006)	accident analysis, case control studies	Sweden		22% effectiveness
			wet road	32% effectiveness and 56% of serious or fatal crashes
			road covert with ice and snow	38% effectiveness and 49% of serious or fatal crashes

because drivers do not need to understand the device to interact with it, and its effects are perceived as part of the vehicle dynamics. However, unexpected BA (i.e. risk homeostasis) may occur even with 'vehicle automation', which could reduce the effectiveness of the device if drivers do not fully appreciate its capabilities and limitations.

2.3 Crash reduction effectiveness

Studies dealing with the effectiveness of ESC fall into three categories according to the type of crashes studied. Table 2 summarises the studies conducted on the global effects of ESC on crashes, whereas Table 3 groups together those dealing only with loss of control crashes, and Table 4 presents crash analyses focusing on ESC pertinent crashes (loss of control and guidance problem crashes; see [21], for a comprehensive definition).

In Table 2, ESC reduced crashes and injuries by 12–67%. Large differences were observed depending on the type of crash, crash severity, type of vehicle and road conditions. Unsurprisingly, single vehicle crashes are more sensitive to ESC than multi-vehicle crashes. Loss of control events are reduced by 25–70% with ESC use (Table 3). Finally, ESC leads to a reduction of 22–54% of ESC pertinent crashes (Table 4) and an even greater reduction in the number of fatal crashes.

Erke [33] conducted a meta-analysis of eight studies from different countries to assess crash reductions with ESC. The results showed a large effect on single vehicle accidents, and an even larger effect on rollover accidents. Erke attributed these benefits to crashes related to loss of control. Not surprisingly, in head-on collisions ESC was found to be less effective because fewer crashes are attributed to loss of control in this type of crash. Finally, for multi-vehicle accidents, ESC was only significantly effective with respect to fatal crashes.

2.4 Conclusion and prospects

ESC first appeared in 1995 and is the first device devoted to lateral control that is widely available on cars (see [34]). According to the European Commission [112], 9% of

Table 3 Overview of the effectiveness of ESC on loss-of-control crashes

Study	Data sources	Country	Specific conditions	Percentage of reduction
Becker *et al.* [27]	estimation	Germany		45% of loss of control injuries
Yamamoto and Kimura [28]	test track experiment		slippery curves	40% of run out of lane events
Papelis *et al.* [29]	simulator			25% of loss of control
Unselt *et al.* [30]	accident analysis, case control studies	Germany		40% of loss of control crashes
Green (2006)	accident analysis, case control studies	USA	sport utility vehicle	70% of loss of control crashes
			male against female	NS differences

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Table 4 Overview of the effectiveness of ESC on ESC-relevant crashes

Study	Data sources	Country	Specific conditions	Percentage of reduction
Tingvall *et al.* [31]	accident analysis, before–after study	Sweden		22% of ESC pertinent crashes
Kreiss *et al.* [32]	accident analysis, case control studies	Germany		32% of ESC pertinent crashes
				56% of ESC pertinent fatal crashes
			correcting misclassification using a home made methodology	54% of ESC pertinent crashes
				78% of ESC pertinent fatal crashes
Page and Cuny [21]	accident analysis, case control studies	France		44% of ESC pertinent crashes

European cars were equipped with ESC in 2005, but this level is increasing very rapidly. For instance, ESC looks set to be compulsory in all new passenger vehicles by 2014 in Europe, following Australia, Canada and the USA. All studies dealing with ESC effectiveness agree on its positive effects on crash reduction although the situations where this device is effective are limited, insofar as ESC is only engaged when the car begins to skid and so can only have an effect on the 'lost control' crashes described by Najm *et al.* [10] (about 45% of crashes connected with road departures, see Table 1).

ESC has a special role to play in lateral control assistance as the only device that does not directly interfere with drivers. As such, it belongs to the vehicle automation category. ESC operates according to the 'last chance' law, in that it intervenes only once the car has begun to skid. Consequently, ESC is aimed not at prevention, but rather at correcting a vehicle's trajectory in critical situations once the driver has already made a driving error. The next step towards assisting lateral control is that of integrating the driver into the loop well before the critical situation occurs. However, this comes within the field of driving automation, which has more complex design issues relating to human–machine cooperation.

3 Part 2: driving automation

3.1 Perception mode: VES

3.1.1 Description of the assistance category: At this level of human–machine cooperation, automation could be described as an extension of perceptual systems. In practical terms, vision enhancement devices provide information so as to enhance the driver's visual perception of the driving scene. The rationale with respect to lateral control is to help drivers keep the vehicle in its driving lane by improving the visual information required to steer the vehicle.

Perception mode devices do not deliver warnings about the position of the vehicle in its lane. They make relevant information more easily accessible to the driver, but do not provide the driver with any sort of interpretation of that information.

3.1.2 Impact on drivers: Road markings can play a major role in helping drivers keep their vehicle on the road, as borne out by crash analyses: in 2003 75% of rural road crashes in the USA took place on two-way roads with no lane markings (see [35]). Based on the assumption that road markings are used by drivers to keep their vehicle on the road, devices that enhance the visibility of road markings have been developed.

For instance, illuminated in-pavement systems have been designed and implemented on some road sections in the USA and have been found to be effective for guidance purposes (see [36], for examples). Owing to high installation and maintenance costs, however, the system is only feasible for small road sections where there is the highest potential effectiveness for crash reduction (such as road tunnels).

To extend the enhancement of road-marking visibility more widely, in-vehicle technologies have been used in real-world driving conditions. Such information could be displayed either on the dashboard (head-down displays) or the windscreen [head-up display (HUD)]. Head-down displays mean the driver must stop looking at the road to retrieve the displayed information. Since the vehicle and lane markings are represented in a reference frame that differs from the perspective of the driver, the latter would also have to determine the significance of the symbolic representation before deciding to use it (e.g. the display shows a vehicle position close to the right lane boundary, which means I need to move over to the left). A head-down display device that shows the lane boundaries and the vehicle position within these lanes has been used and assessed on snowploughs. Drivers reacted positively to the device, reporting that it enhanced their confidence in adverse conditions. Furthermore, behavioural data showed that it took only a short time (about 4 min or less) to learn how to use the device (see [37]). Wide field-of-view HUD, on the other hand, are used to superimpose virtual road markings on the real-world scene (or to create road markings if there are no real ones). By enhancing the visibility of the road limits, these devices directly influence drivers' perception by guiding their attention to the enhanced part of the visual field. Several studies have looked at the technical development of such devices (e.g. Gorjestani *et al.* [38] for snowploughs and [39] for ground-based vehicles). Rakauskas *et al.* [40] used a device for highlighting lane boundaries to assist snowploughs working in low visibility conditions. Seat vibration and audio lane departure warnings coupled with forward collision warnings were combined with the vision enhancement system (VES). The assistance enabled drivers to maintain their lane position in low-visibility conditions at least as well as when visibility was good. Drivers also reported that they liked being able to see the lines of the road. Although snowploughs are driven at low speed and in conditions of very low visibility, these results provided a good demonstration of the value of enhancing the visibility of road markings by means of HUD. There are also more results to support this view.

Indeed Charissis and Papanastasiou [41] carried out a series of simulated driving experiments using a full-windscreen HUD to convey several types of information to drivers of passenger cars, including information about their lateral position. The lane symbol highlighted road markings and provided a 'virtual pathway' as a reference for the vehicle's position on the road. Ninety per cent of the drivers claimed that the system helped keep their stress levels down in poor-visibility conditions. The device also prevented fatigue, and almost all participants stated they would like to use it under poor visibility. More specifically, the lane symbol was judged 'extremely helpful' by about a third of participants and 'very helpful' by more than half (see [42]).

Using a driving simulator, Mars [43] showed that control of steering could be facilitated by enhancing the saliency of a single target point moving down the road. A visual beacon was added to the scene by means of a simulated HUD. The beacon was positioned in the vicinity of the tangent point, a specific point on the inner edge line that drivers frequently look at when negotiating a bend (see [44]). The data revealed that continuously tracking the tangent point was conducive to smoother steering control. The benefit was observed when the point of gaze was directed to the tangent point per se, but also when the beacon was shifted to the right or to the left (it sometimes indicated the lane centre, for instance). The suggestion is that enhancing the tangent point – or any point with the same dynamics in the visual scene – may be seen as a way of improving eye-steering coordination and, as a consequence, facilitating lateral vehicle control. In a follow-up experiment, Mars [45] showed that improved steering was only observed in good-visibility conditions when drivers were explicitly instructed to look at the visual aid. When no such instruction was given, only minor changes in steering control and gaze positioning were observed, suggesting that the real benefits of such a display should be expected in poor-visibility conditions.

Adaptive front-light systems (AFS) are another type of VES specifically devoted to night driving. These devices stem from an older concept used in 1967 by Citroën car manufacturers, who equipped their DS model with a system for adjusting the headlamps' horizontal and vertical positioning based on the vehicle's steering and suspension systems. More recently, several devices have been developed that adjust the headlight beam in response to steering wheel position, vehicle speed, suspension dynamics, visibility conditions and even road curvature, using GPS data (see [46, 47]).

AFS are of particular interest for negotiating bends. For a given bend, the headlight on the side of the inside edge line pivots in that direction to illuminate the path. Therefore it is easier for drivers to see the road markings. Several studies showed that AFS could increase the visibility of the visual scene (e.g. [48]). Furthermore, AFS have been found to improve drivers' eye movement patterns during night driving. Panerai *et al.* [49] showed that AFS increased the range of visual lateral scanning compared to conventional headlights. Actually, gaze patterns were similar to those observed in daytime conditions, with an increase of gaze behaviour ahead of the tangent point. In other words, AFS favours anticipatory gaze behaviour, which allows early detection of obstacles and a more anticipative motor control for steering.

A six-day driving simulator study focused on possible negative BA to AFS through the analysis of speed, responses to obstacles and steering behaviours (see [50]). A general speed increase was observed across the six days of the experiment, but this was also observed without AFS. With AFS, the drivers' speed profiles when approaching an obstacle were smoother than without AFS. Finally, AFS did not modify either steering movement speed or steering reversal rate. The results therefore did not reveal any clear negative BA. However, during the six days of the experiment, drivers only drove approximately 140 km in both rural and city environments. The authors cautiously concluded that such adaptations might need more time to appear.

3.1.3 Conclusions and prospects: VES are designed to improve drivers' perception of the lateral position of their vehicle. They make no judgment of driving behaviour, but simply facilitate the lane-keeping task. The benefits of VES are mainly to be expected in poor-visibility conditions (e.g. road covered in snow, absence of lane markings, tunnels, fog, heavy rain etc.). In terms of BA, the same rationale as developed for ESC could also apply here. Based on the risk homeostasis theory, it can be predicted that VES could cause drivers to reduce their safety margins, which would be apparent from an increase in driving speed round bends. VES could reduce lane departures in bends and on straight lines by improving lane boundary detection, but further studies are needed to assess the impact of VES on both crash reduction and negative BA.

3.2 Mutual control mode

Biester and Bosch [51] analysed drivers' verbal reports in a driving simulator experiment where drivers were required to perform standardised overtaking manoeuvres either manually, cooperatively, half-automatically or automatically. Drivers reported that they placed more trust in an assistance system and were more aware when they were in a cooperative control mode compared to manual, half-automatic or automatic control. What Biester and Bosch called 'cooperative control' corresponds to our mutual control category, where drivers and automation perform the same task in parallel – as with lane departure warning systems (LDWS) and LKAS. LDWS provides feedback on drivers' actions and LKAS devices share the vehicle control with drivers. Using an online questionnaire, Biester and Bosch also asked 509 drivers to rank 66 driving tasks, based on their desired function allocation between human and machine, from (1) manually to (7) full automation. It was found that drivers considered lane-keeping to be a task where both the machine and the human have almost equal rights. Consequently, lane-keeping has a high potential for cooperative activities.

3.2.1 Warning mode: LDWS: **Description of the assistance category**. *Rumble strip*. Most drivers have already experienced an infrastructure-based LDWS when driving over rumble strips. On roads equipped with rumble strips, drivers hear a sound and feel a vibration on the steering wheel and/or at the level of the car as a whole just as the vehicle is about to leave its lane. The positions of the strips are limited to the edge or centre of the road. A further description of different types of rumble strip may be found on the website of the US federal highway administration (see [52]).

A number of studies have demonstrated that edge rumble strips can reduce road departures (see [53–56]). To improve

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rumble strip efficiency, some American roads are equipped with rumble strips on the edges, coupled with an extra band of road separating the road from the shoulder. The effectiveness of these rumble strips was assessed by Morena [57]. Both rolled-in rumbles and intermittent rumbles reduced the number of drift-off crashes (defined as lane departures owing only to drowsy or distracted drivers) by 20%. An additional 19% reduction in drift-off crashes was observed when using a milled rumble strip.

No clear effect was found when rumble strips were placed in the centre of the lane so as to cut the number of unintended excursions to the opposite lane. Persaud *et al.* [58] found there was a 25% drop in head-on and opposing-direction sideswipe injury accidents after rumble strip treatment, whereas Räsänen [59] found no improvement in bend manoeuvring after a rumble strip was placed in the middle of the lane.

However, vehicle size and speed and whether drivers use their indicator before changing lanes are not taken into account with rumble strips. In contrast, a vehicle-based LDWS has the potential to be more flexible and adaptable to drivers and the driving context.

LDWS as an improvement of the rumble strip idea. LDWS are in-vehicle devices that monitor a vehicle's position in its lane and warn drivers when the vehicle is about to leave its lane. Types of LDWS currently available use road markings to determine the position of the car in its lane. A warning is issued to drivers if the car gets too close to the lane edge and the vehicle's indicators are not in use. The lateral distance between the car and the lane boundary is the main variable used to determine the onset of the warning, but a metric taking into account the vehicle speed (such as the time to lane crossing) could equally be used. The time to lane crossing is defined as the duration available for the driver before any lane boundary crossing (see [60] for more details). LDWS only inform drivers if the car is in a dangerous position – no automatic actions to avoid lane departure are carried out. Therefore drivers remain fully responsible for vehicle operations.

LDWS impact on drivers. Several studies assessed the efficiency of various LDWS. Most of them back the idea that such devices bring safety benefits. Under normal straight lines driving conditions, a reduction in lateral positioning variability and shorter steering wheel reaction times to lane departures were observed on a driving simulator (Tijerina, 1996). Shorter steering wheel reaction times were also reported for both auditory and vibratory LDWS (see [61, 62] for results obtained with sleep-deprived participants on a driving simulator; Navarro *et al.* [63] involving visual occlusion of the driving scene to cause lane departures). A reduction in the number, duration and magnitude of lateral excursions was also observed with both real and simulated driving conditions (see [61, 64–66]). All these studies tested devices that varied across several dimensions (e.g. the timing of signal delivery and sensory modality), which sometimes gave rise to differing conclusions.

Timing of LDWS: onset and gradual warning. The effects of LDWS onset on drivers' behaviours have not been extensively studied. Tijerina (1996) found that early onset resulted in more activations than late onset; however, it also led to fewer lane departures. Results obtained with other warning devices (forward collision warning systems) show that late warnings tend to reduce drivers' trust in automation whereas early warnings could be perceived as harmful, although the latter were actually more effective [67, 68]. Another important issue is that the perceived efficiency of the device is linked not only to device validity, but also to its onset. Lee *et al.* [69] observed benefits for both early and late forward collision avoidance systems compared with no assistance. However, the benefits were greater with early warnings. Generally, long duration of the alarm warning is considered more valid and thus evokes more responses than short-duration alarms (see [70]).

LDWS onset seems to be key for both the effectiveness and acceptability of the devices. Some studies have looked at warning-triggering algorithms that are a better reflection of drivers' current state. For instance, Batavia [71] proposed a training algorithm that takes account of road geometry and past driver behaviour. Detection of periods of inattention (drowsiness and distraction) could also significantly improve adaptation of the devices to drivers' state (see [72]).

To improve LDWS, a graduated warning system could be devised. Based on this idea, Rossmeier [73] assessed a two-level lane departure warning device on a driving simulator. An auditory rumble strip warning was heard first and followed, if drivers stayed too close to a lane edge, by a second warning noise (bell tone). This device was compared with a device that used the same auditory rumble warning but only once. The results obtained were similar in terms of reaction times, size of lane departure and number of lane departures. Questionnaire analyses revealed that the two-level device was considered too complex and too intensive, and hence irritating and startling. Nevertheless, when using the same two-level warning device in a driving simulator experiment, Rimini-Doering *et al.* [74] showed it to be more effective than a condition without any assistance.

Sensory modality, lateralisation and redundancy. The effects of LDWS could be modulated either by their location and/or the sensory modality used to deliver the warning signal. These two characteristics are closely linked. For instance, if the device uses the steering wheel to warn drivers, using the haptic modality is a necessity. Most of the studies reviewed above used an auditory LDWS rumble strip noise, with the sound emitted on the side of lane departure, with or without additional steering wheel vibrations.

Tijerina (1996) reported that both auditory and haptic modalities were more effective in terms of reaction times and corrections to stay in lane than when there was no assistance. On the one hand, several authors reported that auditory warnings tended to be marginally less effective than haptic warnings in terms of reaction times or magnitude of lane excursions (see [61, 73]; Tijerina, 1996). On the other, no differences were observed between auditory and haptic devices in terms of either steering wheel reaction times or duration of lateral excursion. This was the case for both lane departures induced by means of visual occlusion of the driving scene (see [65]) and those caused by a visually distracting task (see [74]). To sum up the comparison between auditory and haptic warnings, it is unclear that one sensorial modality is more effective than the other.

Concerning lateralisation, similar effects of directional and non-directional auditory LDWS have been observed with respect to both reaction times and maximum lateral deviation (see [73]). Directional warnings were found to interact in a complex way with both sensorial modality and hazard context (Tijerina, 1996). In short, directional LDWS have no clear benefits over non-directional versions, although the former might be useful in high-hazard situations. In addition, the same auditory warning for four different warning systems (frontal and rear collision warning, and left and right LDWS) was no different from four different auditory warnings in terms of either reaction time or accuracy (see [75]).

Providing the same information at the same time via two different sensorial modalities can reduce reaction time and is known as 'intersensory facilitation' (see [76], cited in [77]). When applied to automation, multimodality (visual and auditory) benefits were observed for aircraft pilots (e.g. Helleberg *et al.*, 2005). Following up on this idea, bi-modal LDWS devices have been tested, but no efficiency gain was found for either visual and haptic combinations (see [61]) or auditory and haptic combinations (see [65]). In addition, according to subjective assessments, the combination of auditory and haptic modalities might be a source of overload for drivers (see [75, 78]).

Acceptability and trust. Sounds associated with the sound of rumble strips have been most widely used, because they are more acceptable and allow faster reaction times than arbitrarily selected sounds of the same intensity (see [79]). Drivers' verbal reports revealed that both haptic and auditory sensorial modalities were more helpful and acceptable than the visual modality (see [61]). Tijerina (1996) also reported that haptic and auditory sensory modalities were appreciated. Sayer *et al.* [80] showed the haptic modality was appreciated because it does not alert the entire car and drivers find it less distracting. They also accept more false alarms with haptic than with auditory warnings (see [81] and unpublished data reported by Pohl and Ekmark [82]). On the other hand, drivers judged auditory warnings easier to understand. On the whole, drivers were lukewarm about the LDWS concept. However, when it was available, drivers preferred devices with directional signals rather than non-directional devices (Tijerina, 1996).

One simulator and one test-track study were carried out to assess the possible negative effects of inaccurate LDWS implementation in cars. Using an auditory LDWS, Rudin-Brown and Noy [83] observed a global improvement in lane-keeping – with both accurate and inaccurate devices, drivers approached the lane-edge zone less often with an LDWS than without. Drivers' trust in the device grew after LDWS exposure. The increase was greater with an accurate device than with an inaccurate one. Drivers' personalities also seem to have an impact on trust. Those with an external locus of control and low-sensation seekers tend to be much more trusting of LDWS, regardless of the device's accuracy. This could lead to over-reliance on the device. Rudin-Brown and Noy [84] found some drivers may have been relying on the device and therefore experienced larger lane displacements than other drivers. Despite the fact that very few studies have been conducted on inaccurate LDWS, some of the data collected with other devices (collision warning systems) indicate that incorrect warnings can dramatically reduce the benefits of the device (see [84, 85]). However, Lees *et al.* [86] showed that trust in a collision warning decreases when the warning does not match the context, but remains stable when it is redundant (i.e. when the driver has already detected the problem).

Towards more than just a warning?. Different devices that do more than just warn drivers but without acting on vehicle control have been assessed in a variety of studies. Pulse-like steering torque devices, consisting of a steering wheel motion towards the lane centre with minimal effects on trajectory, were assessed by Suzuki and Jansson [73]. In a driving simulator experiment, these devices produced variable results. Some drivers corrected the car's trajectory in the direction indicated by the steering pulses. Others overrode the device and turned the steering wheel towards the lane departure direction rather than towards the lane centre. In a test track study, Hoc *et al.* [64] also reported large individual variability in responses to a pulse-like steering torque they called an 'action suggestion mode'. On the other hand, a device that gives small asymmetric steering wheel oscillations (towards the lane centre) was more effective than simple vibrations (delivered to the seat or steering wheel) and auditory warnings (see [65, 74], using a driving simulator). This 'motor priming' did not yield shorter reaction times than other LDWS devices assessed but increased the sharpness of the drivers' steering wheel correction after an unintended lane departure, with the result that the duration of lateral excursion was reduced. The results backed the idea that motor priming not only improves the situation diagnosis by informing drivers about a dangerous position in the lane, like any other LDWS, but also helps them perform the required correction by providing some directional motor cue to the hands via the haptic modality. As such, the motor priming device intervenes directly at the action level.

More recent experiments assessed whether drivers would be able to modulate or inhibit the effects of motor priming effects when necessary (see [87]). First, the question of how the effect of motor priming could be modulated by expected risk was addressed. Results showed that the lower the expected risk, the higher was the duration of the lane excursion. Second, it was demonstrated that drivers could inhibit their steering response and counter motor priming when the direction of the cue was erroneous. Thus, motor priming improved recovery manoeuvres, while drivers remained in full control of steering. This suggests a modulation of the effect of motor priming by higher levels of cognitive control.

Because motor priming makes only minimal corrections to the car's trajectory, it cannot be considered a LKAS. However, unlike devices that only provide simple warnings, motor priming acts at the action level and is therefore at the boundary between LDWS and LKAS.

Conclusion and prospects. LDWS do not physically act on vehicle steering but they interfere with the driver by providing critical feedback on their behaviour when the lateral position of the vehicle is deemed unsafe. Results suggest that an LDWS probably redirects drivers' attention to the steering task, causing them to analyse the visual scene and ultimately correct their trajectory. It is not surprising therefore that progressive warning devices appear to offer little promise of improving LDWS efficiency. The different sensory modalities (and multimodality) seem to have the same potential to redirect drivers' attention.

However, the haptic modality allows some directional information to be conveyed to the driver's hands (a motor priming device). It was found to be more effective than other LDWS because it intervenes directly at the action level, prompting the motor response, unlike other warning systems that only issue criticism of drivers' behaviour.

At this level of human–machine cooperation, negative BA would appear to be over-reliant on the device for lane departure risk assessment. Long-term studies are needed to indicate whether drivers rely on LDWS for lateral control risk assessment. If it is shown that they do, an increase in lateral position variability should be observed with LDWS. There might be a tendency for drivers to wait for the warning signal before adjusting their lateral position.

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Since 2004, Citroën C4 and C5 models are equipped with a lateralised vibratory seat warning. To date, no crash analysis data are available, but, according to Najm *et al.* [10], 48% of crashes related to road departure could be avoided by LDWS (pas clair). The crashes targeted by these systems are defined as 'departed road edge while going straight', or 'departed road edge while negotiating a curve' (see Table 1).

With their current design LDWS are highly dependent on road markings, and cannot be used where there are no markings. Furthermore, in poor driving conditions (such as fog, snow, ice or heavy rain), where strong effects could be expected, they are not always available owing to technical limitations (i.e. they are unable to detect lane markings).

3.2.2 Co-action mode: LKAS: **Description of the assistance category**. With LKAS, both the driver and assistance device act on the vehicle's trajectory. Several papers detailing the development of such devices have been published (e.g. see [88, 89]). This kind of device has been created to improve safety as well as facilitating the steering task by physically participating in it. As such, LKAS are as much comfort systems as safety systems.

At this level of human–machine cooperation, cooperation takes place at the action level, or more specifically, at the sensorimotor control level. It is important to note that drivers remain responsible for vehicle control at all times, insofar as these devices are dedicated to assisting steering but at no point do they have authority over the driver's judgement. Therefore provided that a force is applied on the steering wheel, it is always easy for drivers to override the device at any time.

LKAS impact on drivers. Tanida [90] assessed a device specially developed for expressway driving in Japan, known as 'Lane following assistance system' (LFAS), which detects the extent of lateral deviation from the lane centre and applies a proportional torque on the steering wheel. Subjective data revealed that drivers using LFAS felt less physically fatigued, less drowsy and more able to concentrate after a long period of driving than drivers without LFAS. Objective measurements showed that LFAS was able to maintain drivers' abilities to react selectively to information after a long period of driving, whereas without LFAS these abilities diminished.

Another device that uses a continuous force applied to the steering wheel was implemented by Steele and Gillespie [91] in a driving simulator. The device was designed to turn the steering wheel to bring the vehicle back into the centre of the lane, based on information received about the road geometry, and by calculating the steering wheel angle needed for good path-following performance. This desired angle is compared with the actual angle. Torque proportional to the difference between the actual and the desired steering wheel angle is then applied to the steering wheel. This device produces better following performance and visual demands are much lower (about 45% less, as demonstrated by the visual occlusion method; [92]) than with manual control. No evidence was found of a reduction in mental workload, although this could be owing to the fact that the driving task was relatively easy in the first place.

A similar device was used to assess steering performance, visual demand and availability of cognitive processing capacity (see [93]). When obstacles were placed in the middle of the road, fewer lateral positioning errors were recorded with the device than during normal driving. In terms of avoidance manoeuvres, drivers' behaviour was similar with or without the assistance device, but the number of collisions recorded was slightly higher with the device than without. This was attributed to the tendency for the device to keep the vehicle at the lane centre, precisely where the obstacles were placed. When the device was engaged, visual demands were reduced, and there was an increase in available cognitive processing capacities.

Conclusion and prospects. Like LDWS (warning mode), LKAS (co-action mode) belongs to the mutual control category, with the distinction that it physically acts on steering. Contrary to LDWS, LKAS devices are continually in action and as such, need to be integrated into the human sensorimotor control loops. LKAS are not only designed to help drivers, but also to act with drivers. This means that there is a clear intrusion of automation on the drivers' motor activities related to steering. In order to make the integration of these actions seamless, especially in bends, the control law of the system should be based on an adequate and adaptive driver model, which includes road preview and a representation of the neuromuscular system (see [94, 95]). Nevertheless, although the device and the driver share vehicle control in a proper sense, the driver always decides on the vehicle trajectory in case of disagreement between the two agents.

According to existing research, LKAS appears to offer promise as an assistance device. However, further development is needed to clarify its impact on driver behaviours when skidding or avoiding obstacles. Further studies to address drivers' subjective assessment of this type of device are also needed. Finally, assessment negative BA will be required. Indeed, in straight lines or bends of low curvature, drivers may consider that the LKAS is autonomous and able to steer the car independently of the driver's input. This misconception would be characterised as over-reliance on the system, which may lead to dangerous situations. With respect to accident prevention, and despite the different support philosophies between LKAS and LDWS, they both target the same crashes. LKAS devices are also expected to contribute to loss of control crash reduction because they act continuously on the steering wheel (see Table 1).

3.3 Function delegation mode: AS

3.3.1 Description of the assistance category: With automatic steering (AS), lateral control of the vehicle under normal conditions is fully delegated to automation. AS is a type of automation that substitutes drivers on lateral control under normal driving conditions (see [96]) in order to alleviate the number of tasks drivers are loaded with.

Some AS devices have been developed for roads with a special lane marking at the centre of the driving lane (see [97]), but most are based on the detection of existing lane markings (e.g. [98–101]). In any case, the device computes the vehicle's position relative to the road markings and then implements the best steering wheel angle to keep the vehicle in its lane.

Fig. 3 describes a simplified standard AS device operation. Drivers can switch the AS device on or off at any time (dotted double arrow on Fig. 3). When the system is active (AS on), it keeps the vehicle in a safe position in its lane without any intervention from the driver. From the driver's viewpoint, the device takes over steering wheel control. If the driver disagrees with the device and wants (or needs) to act on the vehicle trajectory, they just have to turn the steering wheel to return to manual control. When they turn the steering wheel the system switches into standby and leaves the

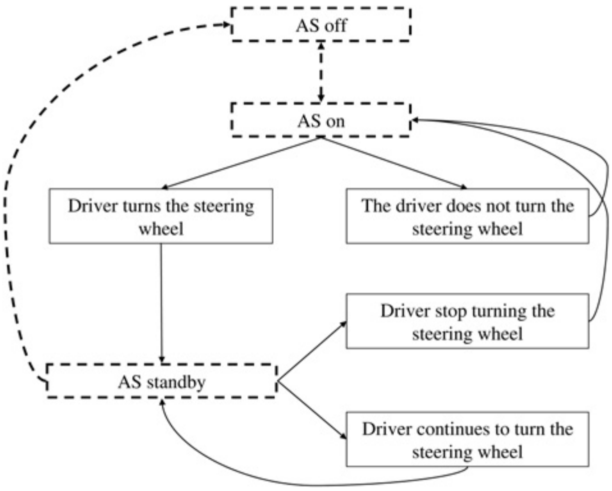

Fig. 3 *Three possible AS device states and transitions between them*

driver fully in control of the car. AS stays in standby as long as the driver acts on the steering wheel – otherwise the AS resumes automatically.

It is important to note that this device is not designed to avoid obstacles. The system cannot detect obstacles on the road and no programme is able to command obstacle avoidance. These detection and avoidance tasks are the drivers' responsibility.

3.3.2 AS impact on drivers: Despite the fact that it substitutes the driver, this kind of automation could be considered as 'soft protection' (see [102]). 'Soft protection' is defined in contrast with 'hard protection', where a hard protection philosophy is not devoted to helping drivers but in correcting their potential mistakes by having ultimate authority over their actions. As a consequence, when the hard automation device decides to perform an action, the action is performed regardless of what the driver intended. AS is clearly 'soft protection' assistance since drivers have the full authority to override the device at any time.

When engaged, a reliable AS device guarantees no lane departures as long as the driver maintains speed within the limits of vehicle adhesion to the road. Technical feasibility for such devices has now been reached and AS could have particular relevance for certain dangerous road sections. For instance, AS could be engaged temporarily so as to prevent lane departures in tunnels that could have severe consequences.

Chang [97] conducted a field performance assessment of an AS device he previously developed (see [103, 104]). This experiment showed that the device generated more stable trajectories than an experienced driver.

With AS, drivers delegate part of their steering activity to the system. Consequently, they can allocate more resources to the other driving tasks. This assertion is valid if the size of attentional resource pools is assumed to be fixed (see [105, 106]). However, the malleable attentional resource pool theory (see [107]) argues that underload can lead, via attentional shrinkage, to performance degradation. As a result, the introduction of assistance that reduces mental workload does not necessarily translate into benefits for the driver.

Such a mental workload reduction was observed in two studies with AS (see [96, 107]). Conversely, another experiment showed no significant differences compared to a manual condition or to a combination of lateral and longitudinal control assistance (see [108]). Overall, it seems that AS could reduce mental workload, especially because the critical driving scenarios used by Desmond *et al.* [108] probably influenced drivers' subjective ratings of mental workload.

This mental workload reduction seems to accompany degradations in performance when returning to manual control in both real world and simulated driving environments (Desmond, 1998; [63, 64]). Such has been observed when drivers need to return to manual control because the automation has reached its limit of validity (e.g. obstacle avoidance). Hoc *et al.* [64] reported greater steering wheel amplitude and longer skirting times for obstacle avoidance with AS than without. Navarro *et al.* [63] found greater steering wheel amplitude and maximum rate of steering wheel acceleration leading to larger lateral gaps on the left lane during obstacle skirting with AS than without. Moreover, time to collision (to the obstacle) was reduced with AS compared to an unassisted condition.

According to [107], this could be linked to driver underload. But degraded performance was also found by Desmond *et al.* [108] without an associated reduction in workload. The latter study focused on driver fatigue during long drives. In order to explain their results, they argued that AS is likely to result in undermobilised effort for fatigued drivers. Another possible explanation is complacency (see [63, 64]), already well described in other human–machine cooperation situations (see [109, 110]). It can be defined as the disengagement of the driver from the delegated function. Such a phenomenon could be related to negligence of information (mostly visual) usually used for manual control.

3.3.3 Conclusions and prospects: A clear distinction can be drawn between mutual control and function delegation. With AS the driver is replaced, and it is the device itself that manages the task usually performed by the driver. Drivers' activities are therefore considerably modified, and AS could modify the driving task per se. These changes bring with them a high risk of negative BA. There is a risk that the driver might disengage himself from the delegated function (i.e. steering) and consequently succumb to being 'out of the loop'. This has been described previously as the 'complacency phenomenon'. With AS, a double mechanism is at play when the driver needs to override the system (for obstacle avoidance, for instance), s/he must decide to return to manual control before performing the corrective manoeuvre. This may add some critical delay in response.

In theory, and according to the crash classification devised by Najm *et al.* [10], all accidents except for those related to 'manoeuvre initiating' are targeted by AS, providing drivers respect speed limits (since excessive speed could lead to vehicle road adhesion capacities being overstretched). However, AS also introduces some new difficulties when drivers have to revert to manual control, and it could even cause some new types of crashes. The difficulties created by these devices are owing to a combination of different factors: underload, complacency and the under-mobilisation of effort.

Future work should address the question of how to counter these difficulties in returning to manual control. To keep the driver in the loop, a solution may be to provide continuous information on lateral positioning, or even to enhance the information needed to return to manual control. When

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reaching such a high level of automation, it might also be reasonable to include an obstacle avoidance function to the AS device. However, even if an avoidance manoeuvre is technically achievable, it is harder to take into account incoming traffic (including speed) in emergency situations. Further technical developments are required in that respect before cars including AS will be available on the market. Nevertheless, each assistance device is reaching its limits of validity in certain conditions. Knowing that, the results presented with the AS device in its actual state are valuable to understand drivers' behaviours at this level of human–machine cooperation.

4 Conclusions

The purpose of the present literature review was to combine two existing frameworks related to car automation and to apply the resulting classification to lateral control assistance devices. All the assistance devices presented throughout the paper have the objective of assisting drivers in the lane-keeping task. Therefore longitudinal assistance devices, such as forward collision warning systems or adaptive cruise control, have not been included. This does not mean that lateral control should be considered as independent from longitudinal control. Most of the benefits recorded with lateral control assistance devices would probably be mitigated by higher speeds. The proposed classification could be used as a future framework for a similar literature review on longitudinal control assistance devices.

The assistance devices presented in this article span a wide range of design philosophies and have been assessed using a whole rack of different methodologies and measures, which can make comparison across studies difficult. Accordingly, both objective measures (e.g. steering response times, driving speed, lateral position) and subjective measures (e.g. questionnaires or interviews) have been reported. Both types of data complement each other, the former allowing the evaluation of system efficiency, the latter being related to drivers' preferences, trust and acceptability in the tested devices. In addition, the evaluation of assistance devices can be performed in simulated environments or real-world experiments. Driving simulation is often favoured because it offers a good compromise between experimental control (accurate reproducibility of events across experimental conditions and participants) and ecological validity. Plus, simulated experiments are less expensive than real-world ones and drivers can be confronted with hazardous situations without real risk. Nevertheless, real-world assessments are always needed because of limitations in simulator fidelity and the richness of variety in real-world situations.

The proposed theoretical framework allowed us to classify devices dedicated to improving lateral control according to their impact on driver behaviour rather than on the machine operations. The assistance device classification and proposed review offers a number of design recommendations and insights into crashes targeted by the different categories of assistance device. The classification may be useful for design purposes because it provides simple indications about the type of negative effects that might be expected depending on the human–machine cooperation level being considered.

In designing assistance devices that fall into the vehicle automation category, designers avoid the question of human–machine interaction. For example, devices like ESC, act on vehicle dynamics without interfering with drivers. ESC acts according to the last chance law and intervenes (largely) unbeknown to drivers when their vehicle encounters a critical situation. A few years after its introduction, ESC has been show to be effective in loss-of-control crashes resulting in a drop in even multi-vehicle and head-on collisions. Therefore this kind of intervention is to be recommended when targeting very specific crashes, but designers should pay particular attention to possible negative BA in terms of risk homeostasis at this level of automation. In other words, if vehicle dynamics in bends are improved, care must be taken to ensure drivers do not increase their driving speed. If such a tendency is observed, drivers should be informed and/or warned about inappropriate speeds, for example, via curve speed warning systems.

Other devices have to be developed to mitigate a broader range of crashes that vehicle automation devices are unable to reduce. To that end, designers need to intervene prior to, or immediately prior to the onset of a critical situation, which means they will need to address the human–machine cooperation challenge. All the devices that fall into the driving automation category involve human–machine cooperation. Driving automation was subdivided into three main cooperation modes (Fig. 1).

The first of these driving automation modes, the 'perception mode', enhances drivers' visual capacities. These devices have the potential to improve the perception and the control of lateral positioning without any evaluation of risk. They should be used when designers are keen to draw drivers' attention towards certain elements of information and to prevent critical situations well before their potential onset. At this human–machine cooperation level, designers need to ensure that use of the device does not disturb visual strategies that are useful for perform other driving tasks. Inattentional blindness effects might be observed if drivers focus too much on a particular point of the visual scene (see [111]). For instance, if the visibility of a given cue positioned on the road is enhanced, drivers might focus on that particular point and miss critical visual information such as a pedestrian crossing the road. As another example, when improving visibility with AFS, risk homeostasis may also lead to an increase of driving speed while taking bends. Thus, the designers' challenge is not only to determine the information that should be augmented, but also to find a good way of displaying it without eclipsing other elements present in the driving scene. Ideally, a dynamic enhancement of different elements in the driving scene depending on the driving context could be imagined.

Warning mode assistance devices deliver a signal when the vehicle position becomes dangerous. Activation occurs as soon as the driver has to be informed of the need for a situation diagnosis. Thus, warning mode devices can be recommended when designers are keen to act on the situation diagnosis before the actual onset of a critical situation. Several studies indicate the potential safety benefits of warning mode devices, but these results need to be corroborated by real road departure crash analyses. Designers need to be aware that the effects of these particular devices on drivers are sensitive to several factors including the sensorial modalities used, and the timing, location and reliability of the warning given. At this level of human–machine cooperation, negative BA appear to be over-reliant on the device used for lane departure risk assessment, in which case there might be a tendency for drivers to await the warning signal before adjusting their lateral position. So as to avoid such a negative adaptation, the warning signal needs to be perceived as a warning drivers do not want to face very often. Motor priming seems to be a very promising device. As well as being highly effective, verbal reports indicated that drivers would prefer to avoid it (see [74]).

With the co-action mode, keeping the vehicle in its lane becomes an activity that is physically shared between the device and the driver (i.e. the action performance is shared). In this category, the action of the device is continuous and intervenes at the action level, blending in with the human sensorimotor loops. Although it remains to be proved, the direct action of the device on vehicle trajectory could help to avert some loss-of-control crashes, especially on straight roads. Co-action mode devices are a good option when designers are keen to assist drivers physically rather than simply attract their attention by enhancing some elements of visual information or by warning them. By using physical assistance, a reduction in the number of crashes is naturally expected. However, this physical assistance comes with the risk of negative BA if drivers consider LKAS to be a correcting device that takes over the task of steering. Drivers will therefore let LKAS steer the vehicle instead of sharing control over it. In design terms, drivers must always be physically involved in the steering task. For instance, the device needs to cut out, after a warning, whenever drivers remove their hands from the steering wheel for a certain length of time.

In the function delegation mode, designers could ensure that the delegated task will be correctly performed when the driver is removed from the action loop. With respect to lateral control, the device replaces the driver as far as steering is concerned. Drivers therefore need to supervise the automation operations and perform all non-delegated activities. Function delegation mode devices are theoretically able to avoid road departure crashes (except for those related to a manoeuvre initiation) and reduce the number of loss-of-control crashes. With this kind of automation, when drivers want to return to manual control, the new task of deciding to retake control appears prior to the control itself. In an event of an emergency situation, drivers' responses might be delayed. Then, new crashes related to that type of complacency could emerge. Drivers may disengage themselves from the delegated function because they are no longer controlling it and only supervising control. At that level of human–machine cooperation, drivers should always be aware of the automation's capacity to perform the control. Continuous and graduated feedback could be delivered to indicate how secure the assistance device is in its operations. Furthermore, anticipatory warning signals should be addressed to drivers in case of malfunction. This might be complemented by the enhancement of the visual zones useful for lateral control. Therefore fleeting use of this human–machine cooperation mode could be recommended in very high-risk zones (e.g. tunnels) as a way of improving safety but without giving enough time for negative BA to occur.

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