Cooperation between drivers and automation: implications for safety

Jean-Michel Hoc*, Mark S. Youngb and Jean-Marc Blossevillec

aCentre National de la Recherche Scientifique and University of Nantes, IRCCyN, PsyCoTec, Nantes, France; bSchool of Engineering and Design, Brunel University, Uxbridge, UK; cInstitut National de Recherche et d’Étude des Transports et de leur Sécurité, LEMCO, Versailles, France

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The purpose of this paper is to develop a recently proposed framework of human–machine cooperation (Hoc, J.M., 2001. Towards a cognitive approach to human–machine cooperation in dynamic situations. International Journal of Human–Computer Studies, 54, 509–540) and apply it to the domain of in-car automation. Previous models of automation (e.g. Sheridan, T.B. and Verplanck, W.L., 1978. Human and computer control of undersea teleoperators. Cambridge, MA: MIT Man–Machine Systems Laboratory) delineate the roles of human and machine in a task-based manner and primarily from the viewpoint of machine requirements. However, with increasing arguments that automation should support the human operator rather than replace them (e.g. Young, M.S., Stanton, N.A., and Harris, D., 2007. Driving automation: learning from aviation about design philosophies. International Journal of Vehicle Design, 45(3), 323–338), Hoc’s (2001) framework offers a means of modelling the interaction from the perspective of teamwork – that is, from the viewpoint of human requirements. In the present context, the framework describes how both the driver and the automation can be considered as separate agents pursuing their own goals while trying to facilitate a common task, but who may interfere with each other positively (e.g. mutual control) or negatively (mutual conflict). Vehicle automation, as an area of fervent research in ergonomics at present, provides the opportunity to explore the framework and use it to interpret current and emerging research findings. It is suggested here that many of the psychological problems underlying the introduction of in-car automation are a result of suboptimal communications between human and machine, and the framework is used to propose directions for future research in this area.

Keywords: human–machine cooperation; automation; safety; car driving

1. Introduction

For a number of reasons, from marketing through to comfort and safety, technological research and development in vehicle automation are making rapid advances. As a result, various automatic systems that are designed to take over elements of the driving task have already been introduced (Dingus et al. 1997, Walker et al. 2001). These systems can operate at the level of vehicle control (e.g. automatic transmission) or at higher-level aspects of the driving task (e.g. collision avoidance; see Young et al. 2007). Furthermore, the level of intervention can range from being an information provider (e.g. future road
adhesion) to automatic diagnosis and response (e.g. collision avoidance systems, which intervene if the driver does not respond in time). As has been learned with similar systems in aviation (e.g. Stanton and Marsden 1996, Young et al. 2007), such automation can have huge implications for safety and performance, and thus modelling the interaction with the human operator is a paramount concern.

Task-based models of automation (e.g. Sheridan and Verplanck 1978) have neatly divided these levels of automation (LOA) according to what the human or the machine is doing. Such models have been developed with the aim of defining the machine’s tasks from the designer’s point of view rather than that of explaining the impact of automation on human performance, for example in terms of cooperation. Recently the overriding consensus in ergonomics research has been that automation should support the human operator as part of a team, rather than replace them (see, for example, Young et al. 2007).

The notion of driver support is sometimes taken to mean a by-passing of the human, who is seen as the main source of error and accident. This position has been rightly criticised by Stanton and Marsden (1996). The current authors’ interpretation of this notion is closer to that introduced by Malaterre and Saad (1987), referring to the undertaking of some components of a task or ensuring some redundancy for the fulfilment of certain functions. It considers the driver as the main entity in charge of driving and adopts progressive interventions in attempts to gain appropriate control from the driver, before taking over control completely as a last resort. If one considers a machine that is designed to support the human operator, this machine will positively interfere with the human activity in order to facilitate the human tasks and any common task. Positive interference can take several forms: perception enhancement; action suggestion; function delegation from the human to the machine; etc. Only when the major task requirements cannot be satisfied, the machine, if it is able to do it correctly, will take more control (e.g. automatic collision mitigation when the response must be applied faster than the driver’s response latency, when the machine can act much more quickly). This model has direct parallels in human–human cooperation.

Whilst a machine cannot exhibit full cooperative capabilities, Hoc (2001) argued that a machine can satisfy the minimal requirements of a cooperative situation:

Two agents are in a cooperative situation if they meet two minimal conditions. (1) Each one strives towards goals and can interfere with the other on goals, resources, procedures, etc; (2) each one tries to manage the interference to facilitate the individual activities and/or the common task when it exists.

(Hoc 2001, p. 515)

Nevertheless, at present one is left with an interim situation of cooperation between drivers and automation where both are able to control the vehicle at the same time, a situation that can result in possible interference in action. In contrast with other domains, such as aviation, rail transportation or industrial process control, the use of automation in cars (and its concomitant human–machine cooperation problems) is a fairly recent phenomenon. Consequently, the literature on human–machine cooperation within this domain remains comparatively underdeveloped, and yet the technological development of such systems continues apace. Whilst some reviews of in-car automation (Dingus et al. 1997) and its potential human factors issues (Walker et al. 2001) have been already published, and whilst the arguments for driver support are now being generally accepted, few are explicitly addressing vehicle automation from the perspective of human–machine cooperation. Yet cooperation is intimately linked with driver support and so there is a
clear need for a framework of human–machine cooperation in order to define a direction and strategy for future research in this field.

Hoc (2001) introduced just such a framework for approaching human–machine cooperation in industrial situations and in aviation. The present paper develops and applies Hoc’s (2001) framework to clarify some of the problems posed by relations between car drivers and in-car automation. Rather than the task work-based division of labour characterised in previous models (e.g. Sheridan and Verplanck 1978), the current approach illustrates a more teamwork-based allocation of function. The paper begins with a brief overview of the theoretical framework for cooperation, integrating the classical studies on human–automation relationships; after this the cooperation status of diverse LOA currently in use or under study is identified and the latest empirical findings in the domain of in-car automation are reviewed. The purpose of this paper is thus twofold: to review current research in vehicle automation; and to use that review to demonstrate the applicability of Hoc’s (2001) framework of human–machine cooperation. The paper closes by formulating directions and implications of this point of view for research and design within the car-driving context.

2. A functional approach to human–machine cooperation

After Hollnagel and Woods’ (1983) seminal work on ‘joint cognitive systems’, the wording ‘human–machine cooperation’ has gone beyond a simple advertisement label and is an invitation to transfer models of human–human cooperation to human–machine interaction. There are several reasons why it is important to consider the interaction in terms of teamwork and cooperation. First, the development of almost autonomous machines (such as the flight management system in aeronautics) is likely to interfere with human activities and pose potential cooperation problems. A second concern is humans’ spontaneous cooperation attitude when they are confronted with intelligent machines (Nass et al. 1996). This has led many authors to import social psychology concepts to approach this new human–machine type of relationship (e.g. the concepts of trust, complacency, dependability, etc.; see Parasuraman et al. 1993, Muir 1994, Lee and See 2004). Human–machine cooperation concerns relationships with computers (e.g. with natural language communication) as well as automation, more directly related to the control of the environment and with more concrete (sub-symbolic) and less abstract (symbolic) human–machine interactions. Thus, Hoc (2001) applied the concept of cooperation to enrich the human–machine (or computer) framework within the context of intelligent machines – from the point of view of their adaptive power.

The framework proposed by Hoc (2001) is based on a functional rather than structural approach and is not aimed at describing relational structures between cooperative agents, such as distribution of authority (Millot and Mandiau 1995) or competencies (Schmidt 1991) between agents. Its main objectives are to identify, analyse, implement and support cooperative activities. These are considered to be additional to private activities when moving from an isolated individual activity to a collective activity. For example, function allocation is a cooperative activity and would be unnecessary if an agent was working alone. However, although function allocation, for example, in terms of LOA (Sheridan and Verplanck 1978), can be analysed in terms of cooperation, it is far from encapsulating the main cooperation aspects of the human–automation relationships.

The framework proposes that cooperation is an activity of interference management between non-independent tasks distributed among several agents. In line with
Castelfranchi (1998), interference can be considered both as positive and negative. It reflects the fact that the goal of one particular agent has something to do with that of another agent and each can either facilitate or disrupt the other. Interference is managed in order to facilitate the individual tasks or the collective task as it stands. Cooperation does not always imply a perfect symmetry between the diverse agents. Sometimes there are strong reasons for giving priority to the facilitation of one particular agent’s task. In-car human–machine cooperation is supposed to give priority to the driver’s task (at least in normal circumstances).

In order to manage interference, the framework decomposes the cooperative activities involved into three levels (Figure 1), which broadly relate to the operational, tactical and strategic modes of driving (cf. Ranney 1994), as one moves up the hierarchy. The lowest level is cooperation in action, where the cooperation activity is directly related to action and corresponds to a local, concrete and short-term interference management. For example, when the driver turns the steering wheel too much and when there is a risk of spin, electronic stability program (ESP) intervenes on the wheels’ rotation speeds to avoid a spin. This operational level includes what Young et al. (2007) termed vehicle automation.

The second level is cooperation in planning, where the cooperation activity is more remote from the concrete action and aims at maintaining a common frame of reference (COFOR) between the agents. For example, when a collision avoidance system would not be acceptable to the driver if the two agents do not agree on the analysis of the risk of collision. Here, there are parallels with the tactical level, which correlates with Young et al.’s (2007) driving automation. However, the COFOR is more about a shared understanding of a situation, including plans and function allocation, rather than the specific decisions that are taken.

The highest level is meta-cooperation and consists of maintaining long-term models of oneself and of the partner, on the basis of training and experience.

Figure 1. Cooperation activity levels. COFOR = common frame of reference; ACC = adaptive cruise control; ESP = electronic stability program.
2.1. Action level

At the action level, interference management is restricted to the short term, with minimal anticipation of the agents’ goals. The positive or negative outcomes of interference are highly related to overall performance. Interference occurs when the tasks are not independent. This means that the tasks can be, for example, in precondition relations (one being necessary to perform another one), in interaction relations (the two being performed simultaneously) or in redundancy relations (the same goal can be reached by any of the agents). Interference can take the form of mutual control when an agent checks another agent’s activity to give back an evaluation (e.g. a warning). So, interference is not always negative, it can be deliberately instigated to improve effectiveness. After its appearance at the action level, interference can also trigger cooperative activities at the other cooperation levels (e.g. common plan elaboration in order to resolve interference on a longer term basis).

The removal of interference during the course of action can be considered as a means of reducing unnecessary (task-unrelated) workload. That is, whilst it is desirable to optimise task workload in order to avoid underload (cf. Young and Stanton 2002), managing the automation becomes an additional and undesirable task if interference is not efficient (by way of illustration, the flight crew of modern airliners have been colloquially thought of as computer operators rather than pilots). The other levels of cooperative activities, because of their ability to abstract and to anticipate, are likely to restrict interference in action; that is, to resolve it beforehand. However, the cooperative activities, at whatever level, are also a means of adapting to unforeseen situations and so interference is sometimes desirable. For instance, mutual control is recommended in aircraft cockpits because it is impossible to anticipate every possible error produced by a complex interaction between the agent, the machine and the situational context (Wiener et al. 1993).

Initial (pre-task) planning in order to render the diverse agents’ tasks independent (and hence minimise interference) thus has a limited validity. Some workload cost (in terms of real-time interference management) must therefore be paid to gain adaptation power.

Ergonomics has traditionally been more sensitive to the negative aspects of human–machine cooperation than to the positive ones within the car-driving context (Neboit 1995, Brookhuis et al. 2001). As far as safety automation is concerned, most systems are designed to intervene at the action level in critical situations, which are sources of stress. Current devices have been found to reinforce the negative effects of stress on attention load, on executive control, on selective attention and effort (Matthews and Desmond 1995).

As is the case in other domains, then, automation can have undesirable and unexpected effects on human behaviour and performance, some of them being unconscious and intervening at the action level (Parasuraman and Riley 1997, Hoc 2001). Within the context of driving automation, these effects have been qualified by the term ‘behavioural adaptation’ (Organization for Economic Co-operation and Development 1990, Rudin-Brown and Parker 2004), covering every (positive or negative) unexpected change in behaviour caused by automation. In dynamic situations, human operators mainly control their efficiency; that is, the ratio between acceptable performance and its cost in terms of cognitive resources (Hoc and Amalberti 2007). What is acceptable depends on the priority levels allocated to the diverse performance variables. The introduction of some driver support can change the cognitive costs or the priority levels allocation. Unconsciously, two kinds of phenomena can develop at the action level – by-passing and complacency.

First, if human–machine interference is perceived as costly, without gain in terms of performance, the driver may unconsciously by-pass automation. For example, drivers are
likely to occupy the left (overtaking) lane more with adaptive cruise control (ACC; trying to ensure a desired cruise speed while maintaining an acceptable time headway (THW; time to collision with a lead vehicle if it stops suddenly)) than without this device (Nilsson 1995, study on a simulator; Saad and Villame 1999, study in real conditions). This behaviour enables drivers to reduce the discomfort produced by the speed variations not absorbed by ACC in the right lane. In addition, it reduces the difficulties encountered when overtaking a vehicle, ACC being likely to reduce the speed when the driver needs a strong acceleration.

Second, when a machine takes care of part of the functions implied in an activity, there is a decrease in human operator performance in failure detection, described as a complacent behaviour (Parasuraman et al. 1993, Moray 2003). Beyond this behavioural definition, the interpretation in terms of cognitive and cooperative activities possibly implies three successive levels of negligence. First, the operators may neglect the information necessary to perform the automated function. Second, they may neglect the supervision of the machine. Third, they may omit to improve the machine performance by some complementary action. When the machine performs a safety function (e.g. THW control with ACC), complacency can result in lowering the priority of safety in performance evaluation. Complacency can be reinforced by the fact that automation can give the driver the feeling that there is no hazard in critical situations because it suppresses anxiety signals and encourages the driver to take risks beyond those accepted in non-assisted situations (Amalberti 1999). This phenomenon has frequently been described. Vision enhancement devices when driving in fog have been shown to result in increased speed (Stanton and Pinto 2000), and an anti-lock braking system (ABS) has been shown to result in increased speeds and decreased THW to lead vehicles (Heino et al. 1995, Hoedemaeker and Brookhuis 1998, studies on simulators reproducing highways; Sagberg et al. 1997, on taxi drivers operating between town and airport).

2.2. Plan level
At the plan level, interference is managed at a more abstract and anticipative level and depends on the generation and maintenance of a COFOR. Roughly, a COFOR is composed of shared representations (between the agents), which help to facilitate the activities situated at the action level. In fact, these representations are complementary rather than identical – that is, different but non-contradictory (Loiselet and Hoc 2001). It is a common fact in ergonomics that each agent must be assisted by external representations that are presented in a suitable format for this particular agent’s action. Thus, the same ‘abstract’ information must be presented differently to several agents in relation to their own tasks. For example, the designer of in-car automation may use numerical variables such as adhesion or lateral acceleration, but the driver is likely to prefer translations of these measures in terms of sensations rather than numbers, especially when effectiveness at the level of sensorimotor loops is concerned, which can aid mutual situation understanding.

COFOR does not only include representations of the environment (spatial and context awareness), but also of the team’s activity (e.g. common plans and goals, function allocation, etc.). It is directly analogous to concepts of distributed situation awareness (cf. Stanton et al. 2006), which essentially refer to the COFOR as the transmission of knowledge around the various agents in the system. The quality of that knowledge and the communication channels thus directly influence the generation and maintenance of
the COFOR. For instance, it is relatively easy to create conditions for shared awareness of the external situation, since the knowledge is readily available (although the information format must be suitable). On the other hand, it is much more difficult to maintain a shared representation of the team’s activity or goals – for example, whether the machine can recognise the human’s intentions – since this knowledge is often covert. A driver who intends to leave a road at a junction or overtake another vehicle should not be negatively interfered with by a lane departure warning system. Within the context of collision avoidance, some progress has been made in order to infer the driver’s mental state, both from human behaviour and from external situation analysis, using sensors and scene analysis (Bellet 2006, Bellet and Tattegrain-Veste 2004).

Communication between the agents in the system is therefore a crucial component of generating and maintaining an effective COFOR. Humans must communicate their intent to the machines via their actions; the machines must similarly communicate their status and activities to the humans. Only through these clear and open communications can situation awareness be truly shared and the interaction optimised. Poor situation awareness can be the major cause of difficulty to return to manual control – a problem frequently mentioned in human–automation studies. Whilst a COFOR can be enriched by activities at the action level, it is largely generated and maintained at this plan level. Given the time constraints of car driving, maintaining an existing COFOR should be the primary goal, because generating a COFOR from scratch, even partly, implies demanding communications between agents to negotiate an agreement (Karsenty 2000).

This level of cooperation has not yet been directly addressed within the car-driving context. Nonetheless, it has the potential to be one of the most promising areas of research in the near future. For example, if automation exerts a mutual control on the driver’s activity, it will be understood and accepted by the latter only if the two agents share the same situation analysis and task goals. As has been already stated, that shared understanding is wholly dependent on communication between the agents in the system (human and machine) and, in many ways, this adds to the promise for this area of research.

2.3. Meta level

At the meta level, the experience of cooperation within the team is exploited to facilitate the activities of the previous levels – for example, by using models of the other agents and of oneself. At this level, trust in automation and in one’s relations with automation, together with self-confidence, can be calibrated through the use of models elaborated by experience (Muir 1994, Lee and See 2004).

Although there is not an abundance of research on this question in the car-driving literature, the few studies that are available show the importance of this level. Within this context, where the shift between manual and automatic control is not as sharply defined as within other domains, the main subject of trust is neither the machine nor the driver, but rather the interaction between the two. Rajaonah et al. (2003) have shown that the driver’s model of interaction with ACC plays an important role in the development of trust. A component of such a model can be elicited from the fact that, when overtaking, drivers learned to turn the wheel earlier with ACC than without, in order to avoid being slowed down by ACC. This demonstrates their understanding of, and trust in, the consistency of the interaction with ACC. Trust should not be considered as a stable state. It can develop with experience from a blind faith (mistrust) or an absolute doubt (distrust; cf. Parasuraman and Riley 1997) to an enlightened or appropriate trust (Lee and See 1994). Appropriate trust
allows the driver to distinguish between situations where the system can cope (trust is well founded) and situations that may be beyond the capacity of the system.

The lack of precise model of the machine can lead to an over-generalisation, so that the machine can be utilised outside its validity domain. For instance, Stanton and Young (1998) found an increase in the number of accidents in an ACC simulator study where the lead vehicle stops suddenly. They account for the phenomenon with the fact that drivers tend to assume, incorrectly, that ACC includes a collision avoidance function. Such findings are supported by recent work by Kazi et al. (2005), who found that trust over time developed in parallel with drivers’ conceptual models of the ACC system. These models, even when wrong (e.g. including a collision avoidance function), crystallised after a few days using ACC and this was associated with a stabilisation of trust in the system. Thus, experience does not necessarily translate to accurate cooperation at the meta-level; indeed, it can even be counterproductive.

Another case for considering the driver’s model of automation as an important factor in interaction concerns the effects of ABS in accidents. Traditionally, risk homeostasis (Wilde 1982) has been proffered as an explanation, but the variability in results suggests that it is not the only phenomenon at work. For example, Broughton and Baughan (2002) have shown that ABS reduces the number of accidents involving young drivers, but not those involving women and older drivers. They suggested that the latter group does not operate the device properly because of an incorrect model of the device. As with ACC, then, appropriate use of ABS depends on a good model of the system’s operation. Training for ABS use has proved to be efficient (Mollenhauer et al. 1997).

Last, but not least, an inappropriate machine model can lead to automation surprises, which have been well documented in the aviation domain (Sarter and Woods 1992, Funk et al. 1999). The unexpected behaviour of the car in these situations can be a source of stress.

3. Cooperation modes between driver and automation

Within each cooperation level, which have been described in Section 2, several cooperation modes are considered in the present section (Table 1). In the perception mode, the machine is just a perception enhancement device (e.g. use of a head-up display (HUD) in order to highlight a lead car in fog). With the mutual control mode, the machine is able to criticise the driver’s behaviour in terms of adaptation to the current situation (e.g. pedal resistance when the speed is too high). For the function delegation mode, the driver decides to delegate one of the driving functions to the machine (e.g. speed control with ACC). Finally, the machine may take over control, with the full automation mode. These cooperation modes are not only a matter of LOA, but they also imply cooperation activities, as will be described in the rest of this section.

Developing safety devices within a context where the driver should remain the main entity in charge of driving means that automation should intervene sparingly. For example, within the context of truck automation, Biester (2005) has shown that a ‘cooperative’ mode where the driver and the machine act together produces a better situation awareness and trust than a semi-automatic mode where there were shifts between manual and automatic control. This presents a challenge when trying to design for cooperation, since the automation should clearly be subordinate to the driver. Automatic protection systems that are designed to take over control in critical situations do not follow this model. Before looking for such highly invasive interventions in a fully
Table 1. Cooperation framework demonstrating levels of cooperation against modes of cooperation, using a hypothetical design of a lane departure warning system to illustrate definitions in each cell, from the machine’s viewpoint.

<table>
<thead>
<tr>
<th>Mode of Cooperation</th>
<th>Meta level</th>
<th>Plan level</th>
<th>Action level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perceptual mode</td>
<td>Models of driver perceptual capabilities (e.g. limits of vision)</td>
<td>Compensation of drivers' limits of vision (e.g. blind spot warning)</td>
<td>Vision enhancement on head-up display (e.g. display of perceptual cues of road curvature)</td>
</tr>
<tr>
<td>Mutual control mode</td>
<td>Efficiency of feedback modality to elicit appropriate driver responses, e.g. Auditory, Tactile, Haptic</td>
<td>Knowledge of driver’s intentions (e.g. overtaking instead of an erroneous lane departure) with feedback only if no turn signal used</td>
<td>Implementation of appropriate feedback for the circumstances, e.g. Lateral auditory alarm, Motor priming on steering wheel, Steering wheel resistance</td>
</tr>
<tr>
<td>Function delegation mode</td>
<td>Model of driver behaviour and mental models (with emphasis on driver’s action and controlling function on request)</td>
<td>Delegation of activities to machine (Feedback of system mode and acceptance of instructions from the driver)</td>
<td>Execution of driver’s requests (Lane-keeping assist, Active steering)</td>
</tr>
<tr>
<td>Fully automatic mode</td>
<td>Model of driver workload and task demands</td>
<td>Agreement of criteria for dynamic allocation of function</td>
<td>Adaptive lateral collision avoidance system</td>
</tr>
</tbody>
</table>
automatic mode, lighter interventions should first be explored. These have previously been described as LOA (cf. Sheridan and Verplanck 1978), which is commonly accepted even in recent studies (e.g. Endsley and Kaber 1999, Kaber and Endsley 2004).

The LOA typology describes the full range of automation, from fully manual control to fully automated control. The intermediary steps are formulated in terms of symbolic information processing from supporting solution generation to supporting solution execution. Whilst LOA essentially explains the modes from an engineering perspective, there are obvious cooperation issues at stake in car driving concerning cooperation modes between the two extremes. Thus, the levels of automatic intervention need to be formulated in different terms – that is, in cooperation terms. This paper relates the intervention modes to human–machine cooperation and, following the theoretical framework presented above, classifies them in terms of cooperation modes in order to make their psychological implications more salient. As with the traditional LOA hierarchy, the modes from the least to the most active machine are presented. The lower levels concern diagnosis activity (e.g. mutual control) and action preparation, while the higher levels cover function delegation. However, even the least active machine, which just provides the driver with information, can be very intrusive when information enters into sensorimotor loops and triggers drivers’ actions.

3.1. Perception mode

In the perception mode, the machine is utilised as an extension of the sensorial organs. However, perceptual information can be either symbolic or sub-symbolic. At the symbolic level, for example, drivers are used to consulting their speedometer, which they interpret in terms of regulation or action. At this level, the sensorial information (form) alone is not sufficient for processing it (e.g. ‘50’). An interpretation activity is needed to reach the relevant meaning or content, which is not always perceivable (e.g. 50 km/h does not have the same meaning as 50°C). Symbolic processing is serial and, therefore, very costly in terms of attentional resources. In addition, the information that is processed is discrete (i.e. not continuous) and this is not compatible with smoothness of action. Inasmuch as car driving involves a strong sensorimotor component, the main question to consider is what function symbolic information has in the sensorimotor loop (from perception to action, and from action to feedback). Sub-symbolic processing, as opposed to symbolic processing, only deals with perceptions, without needing interpretation. For example, it has been shown that the speed travelled whilst negotiating a bend is controlled in order to maintain lateral acceleration at an acceptable level (Reymond et al. 2001). Sub-symbolic processing is parallel, much less costly than symbolic processing in terms of attentional resources and response time and can include continuous information.

The distinction between symbolic and sub-symbolic visual information has been stressed in a study of the effect of hazard road signs when approaching bends (Milleville-Pennel et al. 2007). Road signs revealed an effect on symbolic information processing, triggered by explicit processing such as a verbal evaluation of hazard or of curvature. However, there was no effect on sub-symbolic information processing, triggered by implicit processing underlying the concrete production of a steering wheel angle. More especially, the road signs did not reduce the well-known bias of underestimating high curvatures. In another fixed-base simulator study, Milleville-Pennel (2006) has inserted black strips both on the top and the bottom of the windscreen, these strips being submitted to tilts in bends in relation to the virtual lateral acceleration. When the participants were...
not informed of this modification of the visual framework, compared to what they could see in a real car, they reduced their speed. Thus, the sub-symbolic processing of the visual information was efficient. However, when the participants were informed beforehand, this effect not only disappeared but the reverse was observed. Participants increased their speed, interpreting the information as an illusion without relation to safety.

In any case, the perception mode must be considered as a cooperation mode since it is designed to interfere with the driver’s activity. It is mainly a question of choosing the best human–machine interface, either in terms of an appropriate code (form/content) to support symbolic processing or an efficient sensorial modality to easily trigger action. Some attempts have been made to transfer the ecological interface design principle (Vicente 2002) to car driving in lane change manoeuvre support (Lee et al. 2006), trying to produce direct coherence between perception and interpretation. These first results are promising but need reinforcement. Vision and audition have been favoured within the domain, whereas the haptic modality, which integrates tactile information along time, has been neglected. Information types may be utilised successively. For example, when approaching a bend, speed advice can be produced at the symbolic level since there is sufficient amount of time for the driver to plan at this level. Conversely, when negotiating a bend, there is no time to process this kind of information and it would be more appropriate to simply draw the driver’s attention towards information that is crucial for the sensorimotor loop and can be directly perceived. For example, Land and Lee (1994) have shown that the (tangent) point where the curve reverses on its inner side is critical. Visual enhancement of the tangent point has proved to be of some benefit for trajectory control in certain conditions (Mestre et al. 2004, Mars 2006). When visual conditions are very bad, at night or in fog, vision enhancement can reproduce part of the useful visual information, especially for anticipating speed control when approaching bends (Ward et al. 2004). However, some biases are identified, such as the underestimation of slow speeds or the overestimation of high speeds, the former being reduced by the enhancement of speed perception (by dashed lines). More generally, too simple a transfer of the HUD principle from aviation to car poses various problems – size and distance distortion, attentional capture, much more complex visual environment (Ward and Parkes 1994, Parkes et al. 1995, Pauzié 1995, Tufano 1997, Baldwin 2002). The resolution of these types of problem is necessary in order to avoid transforming a positive interference into a negative one.

3.2. Mutual control mode

In the mutual control mode, the machine is designed in such a way that it can interpret information in terms of limits to be respected in relation to risk assessment. Thus, it can provide drivers with feedback on their actions (mutual control) in terms of exceeding limits. Three sub-modes can be envisioned, all with different degrees of invasiveness. The warning mode and the action suggestion mode are restricted to (interpreted) information transfer, without any action taken on the vehicle itself. The limit mode, although under the driver’s control, introduces more constraints, for example by creating pedal or wheel resistance. A fourth possibility (correction mode) would be to let the driver go beyond the limit and then to make the required correction. Little human factors research has been devoted to this latter mode, so it will not be considered here (although it is a potential fruitful area for future research). An appropriate COFOR between the machine and the driver is crucial in order to sustain the mutual control mode.
3.2.1. Warning mode

Here, warning is not taken in the sense of information provided on the car’s technical state (e.g. a fault), but as a criticism of the driver’s actions. Two interesting experiments (Lee et al. 2002) involving distracted and non-distracted drivers on a motion-based simulator have shown the positive effect of an early collision avoidance warning. This type of result was confirmed by Abe and Richardson (2004, 2005, 2006). In Lee et al.’s experiments, whilst the early warning did not reduce the response time directly (braking response), it did, however, give the driver more time to carry out a situation analysis (redirecting attention) and action preparation (increase in the speed of accelerator release). An experiment using a lane departure warning shows that the warning could produce an effect on action preparation before the visual situation analysis (Rossmeier et al. 2005). This mode has also been shown to present a positive border effect. Although used only for a brief period of time, a warning on short THW can durably lengthen THW for several months after the suppression of the warning in the car (Ben-Yaacov et al. 2002, Shinar and Schechtman 2002). In addition to its warning function, this device could simply enable the driver to learn to evaluate THW in qualitative terms that are relevant to driving. However, this positive effect only seems to be observable when it is related to safety (e.g. collision avoidance or THW control) and not simply to road regulation (e.g. stop violations) (de Waard et al. 1999). Thus, the availability of a COFOR between the driver and the machine is a very important issue. If the risks assessed by the driver and those assessed by the machine are very different, the effectiveness of the warning could be greatly restricted. This fact is very well illustrated by an experiment on collision avoidance warning (Lees et al. 2006). False alarms (e.g. noise from the sensor) lead to hesitant responses and a decrease in trust because the driver does not see anything consistent with the warning in the context. Conversely, useless warnings (e.g. when the driver has already identified the problem) are well managed because they are consistent with the context.

In the same context of collision avoidance, this kind of warning mode has nevertheless proved to be efficient in relation to false alarms and low detection rate (Maltz and Shinar 2004). Although it produced more decelerations as the false alarm rate increased, the level of detection rate did not have any adverse impact on behaviour. Bliss and Acton (2003) found that reliable warnings had an impact on response frequency and accuracy, provided that they emit localised information compatible with the location of the obstacle to be avoided. However, they noticed that the warning did not always ensure collision avoidance. In one of the experiments cited, the best score in terms of actual collision avoidance was observed with a 50% warning reliability.

The warning mode has also been evaluated in critical situations while taking a bend in order to avoid lane departure. Suzuki and Jansson (2003) have shown that auditory warning and steering wheel vibration were efficient in reducing response time and maximum lateral deviation in critical situations, but only in comparison with other types of support and not with a control situation (without support). More recent experiments (Hoc et al. 2006, Navarro et al. 2007) have qualified this conclusion, in comparison with a control situation, on the basis of the delay in returning to the lane centre, showing that the mode (lateralised sound in the direction of the deviation and steering wheel vibration) might only be efficient within certain contexts. In particular, the effect of the warning was modulated by the driver’s risk evaluation.
3.2.2. Action suggestion mode

When the warning mode is present on a control (e.g. a pedal or wheel), by using the haptic modality appropriately it could become an action suggestion and, therefore, could be more effective in emergency situations, acting as motor priming. This superiority of action suggestion is compatible with some empirical results concerning collision avoidance and lane departure (Tijerina et al. 1995, 2000). In the study cited above, Suzuki and Jansson (2003) have evaluated this kind of mode by means of the application of torque to the steering wheel. The results were not conclusive because, for some participants, the stimulation produced the opposite effect. Hoc et al. (2006) implemented the suggestion mode on a test track by an asymmetric vibration on the steering wheel, triggering a response in the appropriate direction. Although the effect was positive, it was not significant due to the fact that individual differences were greater than for the warning mode. In addition, the stress produced by a road departure was likely to mask the effect of the action suggestion, underlining the importance of context in determining mode effectiveness. However, Navarro et al. (2007) found a clear-cut effect of motor priming by an asymmetric vibration of the steering wheel, suggesting turning toward the correct direction in a simulator study. The effect of motor priming was much greater than an auditory or haptic warning mode. However, like the warning mode effect, the action suggestion mode effect was modulated by the driver’s risk evaluation. Thus, in parallel with the direct (sub-symbolic) effect of motor priming on action, there is a possible (symbolic) effect of diagnosis on the action level, capable of reducing or increasing the effect of motor priming in relation to risk assessment. This result is important because triggering an irrepressible action in a wrong situation could create negative interference.

The importance of COFOR was stressed by Sato et al. (2003) in an experiment on lane-keeping support. The action suggestion mode was shown to be less efficient than its combination with the display of the recommended trajectory on the visual scene, so that the intervention of the device was justified by the actual deviation.

3.2.3. Limit mode

With the limit mode, the intrusion into the control of a vehicle becomes clear. For example, when approaching the limits of the envelope of acceptable speeds, any action taken by the driver on the pedal that would lead the vehicle outside the envelope will encounter resistance. This type of mode has been evaluated for speed control over long-term use (about 6 months) and has produced positive effects on speed reduction (Várhelyi et al. 2004), on behavioural improvement with regard to other road users and a slight increase in THW (Hjälmðahl and Várhelyi 2004). However, these authors have gathered some evidence of behavioural adaptation towards complacency when using a limit mode, since when the device became inactive, the drivers did not comply with speed limits.

3.3. Function delegation mode

The cooperation modes considered under the function delegation category go beyond simple mutual control. They correspond to a lasting function delegation from the driver to the machine. In the mediatised mode, the machine takes a control as an order to be implemented using a procedure that covers a certain period of time. In the control mode, the machine controls a parameter, thus allowing the driver to take charge of the others.
The desired value can be decided by the driver or by the road manager. There is also a need for an efficient COFOR maintenance to be sure that the drivers know the current function allocation and the decisions of the road manager.

3.3.1. Mediatised mode

In this mode, the driver’s action on a control will not have a direct effect on the car’s behaviour. It will be taken by automation (acting as a mediator) as an order to implement in safe conditions. ABS and ESP are typical examples of this mode and thus the mediatised mode can be seen to operate on Young et al. (2007) vehicle automation systems. Nevertheless, this mode stretches beyond such a dichotomous classification, since it can be difficult to draw the line between what constitutes vehicle automation and what is driving automation. As a case in point, the importance of the driver’s understanding of the functioning of ABS in order to avoid surprise and to ensure that the device is triggered satisfactorily has already been described. This mode is usually considered as efficient. Although some negative border effects of ABS have been reviewed, the data available from accident analysis are compatible with a reduction in accidents when the car is fitted with ESP (Page and Cuny 2006).

3.3.2. Control mode

Delegation is more long lasting in the control mode than in the mediatised mode and its triggering does not use the same control as that used in manual control. There is no risk of confusion, but the driver must know how the device can be engaged or disengaged. ACC is a typical example of the control mode. The driver defines a cruise speed and a THW and the device controls the longitudinal dimension of driving, leaving the driver in charge of the lateral dimension. The control mode is closer to traditional automation conditions found in other domains, such as aviation, than in those already discussed and hence raises some of the more traditional concerns, such as mental workload (e.g. Young and Stanton 2002), situation awareness and other automation biases (e.g. Stanton and Young 1998).

With ACC, Ward et al. (1995) have identified some form of complacency and Stanton et al. (2001) have evoked a similar phenomenon. A difficulty when returning to manual control has been shown to arise in collision avoidance in a fixed-base simulator, using either an ACC or active steering (AS; aimed at taking bends automatically) device alone or using the two together (fully automatic mode, see below) (Stanton et al. 2001, Young and Stanton 2007). When AS is active alone, there is a slight increase in collision frequency in comparison with manual control. This could be related to a difficulty in returning to manual control. When ACC alone or ACC with AS are concerned, the increase in collision frequency is considerable. When there is a device failure, the driver’s braking reaction time increases with the assistance devices. According to the authors, difficulty in returning to manual control could be related to complacency as the drivers relied upon the system to take care of driving tasks they ordinarily would have performed manually. Whilst this might be referred to as the ‘out of the loop’ phenomenon (Kaber and Endsley 1997), in the current context it could be considered as ‘over-delegation’. Some results let one think that, if the complacency phenomenon is a disengagement of the driver from the delegated function, it can extend beyond the function and take the form of a general attentional deficit (Young 2002, theory of malleable attention; Young and Stanton 2007).
Hoc et al. (2006) have also shown complacency in an evaluation of an automatic device for lateral control with haptic feedback on the steering wheel. In a situation where the device intervention was invalid (obstacle skirting), difficulties in reverting to manual control were observed; similarly, drivers tended to neglect visual information that was useful to accurately control lateral trajectory in bends. A simulator experiment confirmed the difficulty in returning to manual control (Navarro et al. 2008). However, in this case, a global analysis of gaze locations showed only minor changes in angle from the tangent point, but in favour of an increase in anticipation of the oncoming traffic. The most likely explanation of the difficulty was therefore the time needed to shift from supervision to control.

Complacency can also be sensitive to contextual factors. For example, Seppelt et al. (2005), in a simulator study of ACC, have shown a lower difficulty in wet weather conditions (when the sensors actually failed) than in high traffic conditions (reaching the limits of easy braking).

However, these drawbacks associated with the control mode should not hide the positive effects. Stanton et al. (2001) showed that AS (lateral control) alleviated the workload and argued that lateral control is more burdensome than longitudinal control. Young and Stanton (2004) validated this result for ACC when the traffic flow has a variable speed. Although a reduction in workload is positive, complementary measures must be taken in order to avoid problems of underload or workload homeostasis (e.g. Young and Stanton 2002). Reducing workload could result in the loss of task-directed attentional resources, generating difficulties in returning to manual control (Young 2002, theory of malleable attention). However, Sayer et al. (2005) have not found any effect of this kind with forward collision warning or ACC. Results related to situation awareness when driving with ACC are not coherent either: some authors identify a decrease in situation awareness (Stanton and Young 2005), others an increase, especially when ACC is combined with mobile phone use (Ma and Kaber 2005). Finally, the safety benefits of ACC have been proved by a decrease in interactions with other road users and an increase in safety margins (Sato et al. 2006).

3.4. Fully automatic mode

With the fully automatic mode, automation takes overall charge (at least in terms of guidance) of car driving. It is reasonable to consider two cases where this mode has relevance. In the first case, the driver is identified as being unable to control the vehicle, for example emergency braking occurring in the absence of any driver actions. In the second case, the risks are seen to be very high, for example automatic lateral control through tunnels. In this case, returning to manual control could pose very serious problems. First, reverting to a ‘normal’ situation, where the system can return to manual control, must be identified. Second, information needed by the driver to manually control the car must be defined. The aim is to avoid the well-known ‘human out of the loop’ difficulty (Kaber and Endsley 1997). For the moment, research on car-driving support has not addressed the fully automatic mode. A possible reason for this fact could be that applications are postponed because drivers are not prepared to operate in this kind of situation. They are not yet trained to supervise a car. However, it could be envisioned that professional drivers receive specific training for supervising full automation and for being prepared to return to manual control when needed (Brookhuis and de Waard 2006). In any case, the design of appropriate human–machine interfaces is necessary (Skottke et al. 2006).
4. Research and design implications

Although research on car-driving support has been widely increasing over the last few years, especially after the European DRIVE programme and, more recently, the French ARCOS and PREVENSOR programmes or the European AIDE programme, too little effort has been devoted to multidisciplinary approaches between psychology or ergonomics and engineering sciences within this domain. Two research topics look very promising. First, human behaviour at the sensorimotor level should be investigated further because, for the most part, driving support interacts with the driver at this level. Second, since the driver will remain the main entity in charge of driving for a long time, the common action of the human and of the machine on the environment raises important cooperation questions that should be addressed more extensively in the future. Through the diverse cooperation modes it has been shown that the three cooperation activity levels are implicated. So, this paper will now take stock of the state of the art presented and outline some research and design implications in relation to these levels.

4.1. Cooperation in action with car-driving support

ABS and ESP are good examples of successful attempts to enter into the sensorimotor driving control loops. However, this type of integration of automation into the execution behaviour cannot be effective in every case. ABS is not a collision avoidance device, whilst ESP is not a lane-keeping assistance device. Other cooperation modes are now being explored and raise more detailed questions in terms of human–machine cooperation, especially shared control, which combine the driver’s and the machine’s controls in order to reach a safe trajectory.

The use of the haptic communication channel in order to trigger an appropriate action must be investigated further. Sometimes, it could induce large individual differences, so that individual calibration is needed. The benefit of this mode is in suggesting an action without imposing it and keeping the driver in the action loop. However, attention should be devoted to the driver’s supervision capabilities when the action suggested by the device must be inhibited. In other words, inappropriate interference in action (incorrect action suggestion) should not jeopardise positive interference at the planning level (integration of the driver’s correct situation analysis).

Vision enhancement devices can implement cooperation at the perception level. A better knowledge of perceptive mechanisms could result in the design of sensorial communications from automation to the driver by the means of HUDs or proprioceptive devices (e.g. stimulations on the seat). HUD can attract the driver’s attention to important aspects of the visual scene (e.g. hazards) in order to produce an appropriate response. Proprioceptive devices can reinforce the haptic perceptions that are currently subdued by modern chassis designs intended to reduce lateral acceleration. If the aim of such a reduction is laudable because there is a better adhesion, suppressing lateral acceleration can lull the driver into thinking that there is no risk while the car is reaching its limit of adhesion. This can result in accidents related to inappropriate risk perception.

Most of the studies to date have dealt with a restricted range of mutual control cooperation modes, mainly the warning mode and the action suggestion mode. Few human factors studies have been published on the limit, correction or shared control modes. Before reaching the function delegation mode, which can trigger complacency
effects and difficulties in returning to manual control, partial intervention of automation could be efficient. The limit mode can introduce a signal of threshold reaching on the relevant control, which in turn acts directly at the action level. The correction mode can correct an inappropriate driver action (e.g. overshooting). Moreover, with shared control, each partner (driver and automation) can correct the other. However, these modes pose the question of acceptability of a device intervening in the driver’s control of the situation.

A better knowledge of sensorimotor mechanisms can also inform the design of automation calibrated to an optimal human style of driving. This design method, which favours ‘human-like’ devices in order to increase their acceptance by the users, has been applied in other domains where human–machine interaction develops at more symbolic levels (Amalberti and Deblon 1992, Boy 1995). Here, also, knowledge on sensorimotor mechanisms can be of great help for identifying perceptual cues used by the driver in order to evaluate diverse types of risk. A convergence between the driver’s risk evaluation, in good attentional conditions, and the automation’s risk evaluation can result in a better acceptability of the latter by the former.

Human factors studies at the cooperation in action level should also compare efficiency on the basis of workload and performance criteria, and individual and social acceptability judgements. Most of the time, these two types of studies are done separately. Design decisions should not be made on the sole basis of one of these aspects. Human activity is controlled at several levels interacting with each other. An appropriate effect at one level (e.g. action) can be jeopardised by a bad effect at another level (e.g. planning or meta-cooperation).

4.2. **Cooperation in planning with car-driving support**

The importance of the elaboration and maintenance of a COFOR has been stressed. As already shown, it consists of a shared situation awareness including awareness of the available resources engaged by the agents. It should integrate the information needed for coordination between the two agents (i.e. What will happen? Who will do what? Who is dealing with what and why? etc.).

Whilst safety devices are considered crucial, the development of devices for comfort can be questionable when they erase or override information that is useful to the driver’s risk evaluation process. Designers should not allow drivers to think that there is no risk when the devices are brought into play for safety reasons. For example, the aim of designing safer and more comfortable cars correlates with the erasing of most of the proprioceptive information needed by the driver in order to manage safety (cf. Walker *et al.* 2006). In order to establish a policy based not only on comfort, with the designing of automation that looks to reinforce hazard signals rather than erase them, further studies are necessary (Amalberti 1999). However, as soon as safety devices intervene by anticipation (e.g. ACC), without any particular hazard signal, the confusion between safety and regulation imposition may render automation inefficient. The transmission of necessary information to the driver is crucial for COFOR maintenance. Throughout, this paper has underlined the importance of communication in maintaining the COFOR and it is clear that such communication should be a two-way channel. Automation must not keep for itself a piece of information useful to its partner; similarly, the driver’s actions and intentions must be transparent to the automation. Models of distributed situation...
awareness (e.g. Stanton et al. 2006) demonstrate that performance is wholly dependent on knowledge transfer amongst agents. It has been a truism for some time now, but if automation can act more as a human team member (cf. Norman 1990), then one is more likely to achieve efficient support.

Such communication probably needs to be of a more direct fashion than symbolic warnings. The studies cited on mutual control through warnings clearly question the respective efficiency of warnings based on a shared representation (or compatible representations) of risks or on some regulation that is not considered by the driver to be related to risk. For example, if drivers are entirely out of touch with hazard signals, they might be inefficient because they are likely to be interpreted as regulation imposition rather than the means to improve driving safety. The respective effects of mutual control modes (warnings, action suggestions, etc.) need to be examined more closely, as do the types of contexts in which negative interference could be minimised. Demonstrating to the driver why a warning is relevant, perhaps through direct ecological design techniques (e.g. Vicente 2002), could be key to improving acceptance.

The complexity of the situation analysis performed by automation is not comparable to that which is performed by the driver. Except in extreme cases, where automation takes charge of most areas of driving, automation will only perform a specific driving function. Thus, the driver will be responsible for many other functions that may interfere with the automated ones, necessitating a much higher level (strategic) perception of the task, which could increase workload and stress. In order to adequately resolve such interference, the question of which is the priority function must be posed. If the priority function is under the driver’s control (e.g. cooperation with another road user), it is convenient to avoid bothering with this function. Conversely, if the priority function is performed by the machine (e.g. imminent accident), any possible actions on the part of the driver that are capable of jeopardising the automation functioning should be avoided. That is why an incremental triggering of cooperation modes can be judicious. For example, in curve negotiation, the warning mode may be adequate when there is no certitude that the driver’s action is priority. But, when the imminence of an accident can be identified with certainty, a more active mode becomes relevant. Action priority is a crucial piece of information in the COFOR between agents. Shared control could be an efficient concept for this purpose.

Any automation intervention is likely to be rejected if the agents’ current representations (CR) are too far from each other. It may be quite easy to communicate the automation’s CR to the driver, although the information format must be chosen carefully to make the driver aware of a certain risk level. On the other hand, it still seems too difficult a task to enable drivers to communicate elements of their CR to automation. Apart from real-time collection and the interpretation of a driver’s behaviour, such an explicit transmission could introduce an overload. Bellet and Tattegrain-Veste (2004) have focused their efforts on real-time diagnosis of driver behaviour, ensuring that it intervenes at the right time and at the right level within the collision avoidance task, partly relying on intention recognition. As was alluded to earlier, this could be an exciting area for future research as sensor and instrumentation technologies improve the potential quality of communications between driver and vehicle.

4.3. Meta-cooperation with car-driving support

Car manufacturers would prefer automation solutions that do not need specific driver training. It is unlikely that considerable progress could be made in car-driving support if
one simply relies on learning by doing. Some training solutions have shown potential in helping drivers to develop an appropriate model of automation, in order to reduce misuse, disuse and abuse (e.g. with ABS). However, the benefits and formats of this type of intervention need to be more widely investigated. The aim is to facilitate the construction of a simple and relevant model of automation by the driver. Thus, it would be more prudent to develop design solutions that can enable drivers to construct and maintain a model of the human–machine interaction. The key in calibrating appropriate trust, maintaining shared situation awareness and the all-important COFOR is clear and consistent communication between the agents in the system. As stated previously, communication channels are two-way – the driver needs to communicate his/her intent and his/her actions to the machine while understanding what is going on inside the machine’s head, and vice versa. The role of back-channel information such as sensorial feedback should be considered (Wiese and Lee 2007).

Apart from with ACC, function delegation has not been investigated in depth, possibly because many difficulties are anticipated. The main difficulty is the unavoidable limitation of automation validity. It is quite impossible to design completely robust automation capable of facing every situation. Thus, returning control to the driver is a key question for function delegation. Although this has been partly addressed in the literature, the complacency effect should be studied more extensively as one cause of difficulty in returning to manual control. Behind these problems, drivers’ training is a key question because they need to know the validity domain of the devices. Studies on complacency should be developed further in order to suggest ways of increasing perceptual identification of the problems (situation awareness), of improving supervision conditions, of improving the return to manual control or correction of automation actions. Relationships between complacency, malleable attentional resources and the vigilance decrement should be investigated further in order to understand the mechanisms behind these cognitive phenomena and to derive efficient interventions.

In relation to situated mental models of automation and human–automation interaction, research on trust development along time should be engaged. Most of the time, within the car-driving support area, trust is evaluated without any reference to situations where trust is justified and to situations where trust should be low. This calibration of trust is a key aspect of human–machine cooperation.

As seen earlier, cooperation does not only introduce negative interference but also positive interference (e.g. mutual control). However, in order to ensure the expected positive effect, two conditions need to be satisfied, to which too few studies are devoted – information temporality and format. Both conditions imply that the machine or, at least, the machine designer has a correct model of the driver, more precisely a model of the main cognitive control modality used by the driver when the machine intervenes (Hoc and Amalberti 2007). The choice of temporality is related to a cognitive control dimension contrasting anticipative control (with a prominence of internal data) and reactive control (more importance given to external data). In the first case, automation intervention must occur early on. For example, in curve negotiation, the intervention could be an action suggestion in terms of approach speed. In the second case, intervention should take place in real time, providing the driver with sensorial information compatible with human routines. Whereas interference with a reactive control must only be sub-symbolic, in the case of anticipative control it may be both symbolic and sub-symbolic. The identification of what kind of information and when it must be given is relevant to the maintenance of the COFOR between agents.
5. Conclusion

This paper has advanced a framework for human–machine cooperation (based on Hoc 2001) on the following premises:

- The current consensus in ergonomics is for automation to support, rather than replace, the driver.
- Task-based models of division of labour with automation (e.g. Sheridan and Verplanck 1978) can result in conflicts between human and machine, where both are trying to control the system at the same time.
- The principle of driver support is dependent on optimal human–machine cooperation.
- Vehicle automation is an area ripe for research in human–machine cooperation, as the LOA technology is developing at a rapid pace.

As such, the purpose of this paper was to develop Hoc’s (2001) framework of human–machine cooperation in a new domain (vehicle automation), to provide an up-to-date review of research in vehicle automation and to propose future directions in research that emphasise the driver support perspective. The cooperation model makes distinct predictions from more traditional task-based models (e.g. Sheridan and Verplanck 1978) and different levels or modes of cooperation may be appropriate for different subtasks of driving. Future research needs to explicate these effects and determine the implications for vehicle automation design, such that one moves towards a position of truly cooperating with and supporting the driver.

Whilst benefiting from knowledge accumulated in other domains, such as aviation, human–machine cooperation in vehicle automation still raises a number of questions. For some of these, knowledge already available in other domains or in car driving itself will make it possible to provide designers with reasonable answers. However, many empirical questions still need to be answered regarding the cooperation framework proposed in this paper. Some questions are yet to be addressed, for example how drivers become familiar with (and hence develop an appropriate model of) safety automation that is seldom used while driving under ordinary conditions. For these reasons, the human–machine cooperation research domain will be enriched by further development and resolution of studies on this question in the car-driving domain.

Many vehicle automation systems are ostensibly designed to support the driver. However, in most cases these are actually only serving to assume those elements of the driving task that have been possible to automate and that could affect the cognitive performance of the driver (Young et al. 2007). This does not form a cooperative system, since the driver then often has to deal with managing the automation as well as his/her driving task. True driver support should act as a human co-driver – providing advice when needed, assistance when necessary, but largely remaining in the background and invisible under normal conditions. When it does intervene, it needs to be on the basis of valid and efficient communication regarding the spatial context of the vehicle and the driver’s goals and intentions in order to optimise the output of the human–automation team. Support provided to the driver by various cooperative devices therefore requires more or less costly technical efforts. Although adequate sensors are now accessible for some measures (e.g. short THW, lateral position in motorways, lateral and longitudinal acceleration), others remain relatively inaccessible (e.g. quality of adhesion to the road, measure of visibility). In addition, some technical features of the devices, such as reliability and accuracy, are all the more essential since
the devices intervene in high-risk contexts. In order that usable devices are developed, research must take into account both the technical and social costs. The framework presented in this paper can help to understand the social costs; the future research directions that have been suggested can explore the technical options in order to optimise cooperation in vehicles of the future.

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References


About the authors

Jean-Michel Hoc is a cognitive psychologist in ergonomics, Research Director at the French National Research Centre (CNRS), head of the PyCoTec research team (psychology, cognition, technology) within IRCCyN (Research Institute for Communications and Cybernetics in Nantes) and head of a national CNRS network in cognitive ergonomics. He is co-editor of the journal Le Travail Humain. His research team is studying cognitive activities brought into play within dynamic environment supervision and
control, more specifically stressing the integration of human operators into automated systems and production of results directly usable within cognitive modelling (cognitive and sensorimotor control) or human–machine cooperation design. Car driving, and planning and scheduling, are his main application domains.

Mark S. Young is a research lecturer in the School of Engineering and Design at Brunel University, UK, and Programme Director for the new MSc in human-centred design. He received a BSc in psychology and a PhD in cognitive ergonomics, both from the University of Southampton. His research interests focus on the human factors of transport systems, particularly with advanced vehicle technologies and automation. He spent 2 years working in industry for the Rail Safety and Standards Board, applying his experience to research and regulations for the UK rail network. Before joining Brunel in October 2004, Mark was a Visiting Fellow in the Department of Aviation, University of New South Wales, Australia, working on a Royal Society fellowship. Mark is a registered member of the Ergonomics Society, a member of the British Psychological Society, a Registered Practitioner of the Higher Education Academy, is Chair of the Ergonomics Society’s External Relations Committee, and sits on the vehicle design working group for the Parliamentary Advisory Council for Transport Safety (PACTS). He also jointly received the 2006 Hodgson Prize and Bronze Award from the Royal Aeronautical Society for co-authorship of a paper in The Aeronautical Journal.

Jean-Marc Blosseville is a theorist in car-driving automation (perception and control) and Research Director at the French National Research Institute in Transportation and Safety (INRETS). In 1999, he created the Laboratory on Interactions between Vehicle, Road and Driver (LIVIC) as a joint laboratory of INRETS and French National Research Institute in Public Works (LCPC) aiming at designing driver support systems and automatic driving. He is the author of several methods and patents dealing with measurement, modelling and control of road traffic. In 2007, he created a new research supply unit, the Laboratory of Cooperative Mobility Measurement (LEMCO) at INRETS. He is now the head of this unit.