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How to ensure control of cooperative vehicle and truck platoons using Meaningful Human Control

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Vehicle cooperation, not vehicle automation, will yield the greatest benefits on road traffic. However, satisfactory human control over platoons of cooperative vehicles still has a large number of uncertainties and issues to be addressed. This paper aims to address these broader issues of control over a cooperative vehicle platoon by focussing on a truck platooning system as a case example, and taking the perspective of Meaningful Human Control (MHC) as control concept. MHC goes further than mere operational control as it addresses issues that exist in current system designs, and proposes improvements based on a novel and more encompassing set of conditions for control. These issues are addressed in regard to the vehicles and their Operational Design Domains (ODD), the role and ability of the drivers (both leading and following) and how these exist in regard to their road environment. We conclude that current advances are making progress, but that from a MHC perspective, issues still remain for the operational and tactical implementation of truck platoons and cooperative driving that need to be addressed in regard to ODDs and drivers. Furthermore, consideration of responsibility and liability aspects is required that stretches beyond nominal appointment thereof, as this does not satisfy important ethical and societal standards. This is demonstrated in the paper through two hypothetical cases focussing on issues on a system level and one further analysis which is focussed on the role of the driver in the platooning system.

Keywords: *cooperative driving, platooning, truck platooning, Meaningful Human Control*

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1. Introduction

With increasing vehicle automation development and advances in cooperative vehicle technology, truck platooning is often referred to as a concept that can lead the way for initial deployment in practice (Bhoopalam et al. 2017; Calvert, Schakel, et al. 2019). Vehicle platooning, or truck platooning when referring to trucks, utilises vehicle-to-vehicle (V2V) communications and (low level) automation technology to maintain short time headways and form a platoon of multiple following vehicles with coordinated longitudinal and sometimes lateral control (Calvert, Schakel, et al. 2019). Current platooning systems that already exist on roads can be considered low level automated systems with cooperative vehicle technology, aligning to SAE level 1 and 2 (SAE 2018). This level of vehicle automation entails that the vehicles can traverse roadway sections with automated longitudinal control for car following, in the case of SAE level 1, and additionally without the need for a driver to steer, in the case of SAE level 2. The car following and/or lane keeping is controlled by the automated driving system (ADS) that is present in each vehicle. The cooperative technology allows wireless communication between the vehicles, which allows them to drive in platoon formation with small time gaps as each vehicle receives information about speed, acceleration and other changes with minimal delay allowing the vehicle to respond with very short reaction times. For truck platooning, these short time headways translate to a reduction in the aerodynamic drag on the trucks, which in turn leads to a reduction in fuel consumption (Calvert, Schakel, et al. 2019). For higher levels of automation, stronger financial gains may be possible when labour productivity improvements may be realised (Vissers et al. 2018). A strong potential business case for truck platooning through the aforementioned mechanism, consistent investment in the trucking industry, as well as an already demonstrated proof of concept of truck platooning, make the trucking industry attractive for the initial application of vehicle platooning technology.

However, the introduction of (truck) platooning is not without its uncertainties. It also introduces some technical, psychological, and socio-political challenges (Calvert et al. 2018). With regard to operational traffic flow management, the blocking effect, such as near ramps, has been mentioned and studied as a potential hazard, especially for long multiple-vehicle formations (Calvert, Schakel, et al. 2019; Poorsartep and Stephens 2015). Reliability of connectivity between vehicles, which also includes cybersecurity, is being studied (Dadras and Winstead 2017; Petrillo et al. 2018; Jahanshahi and Ferrari 2018), while the broader safety concerns of heavy-duty articulated vehicles driving at such a close proximity remains a focus of other research (Axelsson 2017; van Nunen et al. 2017). In many ways, many of these investigations relate closely to the aspect of control. To a certain extent, this considers direct operational control, but in a broader sense it considers control over a wider system than just a driver in relation to their vehicle. The importance of human focused control has been recently highlighted to safeguard an as clear as possible attribution of accountability and moral responsibility in case of accidents caused by intelligent or automated machines. We therefore argue a broader system-based account of control that can appreciate the role of the multiple elements that cooperate in determining a system's behaviour and its potentially undesired consequences, which is the gap in literature we aim to address. Much previous and current research focusses either explicitly on the technical process of automated control, or on the human capabilities in control, but rarely on human control over a system that is functioning autonomously. Hence, in this paper, we review how human control can be maintained in cooperative automated vehicles (CAV), using the case of truck platooning, to highlight important considerations on a system level. For this, we apply the concept of Meaningful Human Control (MHC), which considers the extent to which, and in which sense, a human can maintain control over an automated system, even when not in (full) operational control (Santoni de Sio and Van den Hoven 2018). For the remainder of the paper, we will focus on truck platooning, while most of the described issues are equally relevant for vehicle platooning in general. The applied approach is described in Section 2, including a description of the concept of MHC. In Section 3, we analyse the control of a platooning system per human agent and flag up potential control issues. In Section 4, we discuss two hypothetical cases focussing on issues on a system level and one further analysis which is focussed on the role of the driver in the platooning system to highlight the findings from Section 3. This is followed by a synthesis of these results and recommendations to improve platoon control in Section 5.

2. Meaningful Human Control in the context of Connected Automated Vehicles

In this section, we explain the approach that is taken in this research to analyse current control over platoons, and truck platoons in particular. Before presenting this, it is necessary to first elaborate on the implications of automated systems, such as CAVs, for the attribution of responsibility. We will then explain how Meaningful Human Control (MHC) could contribute to address those gaps. Thereafter we highlight the relevance of MHC in the context of CAVs.

2.1 Responsibility gaps in automated systems:

Human controllers of automated systems can lose track of their role in the chain of command, ending up "out-of-the-loop". This is due to several factors, from the systems' fast and resolute decision-making capacity to the huge amount of information at their disposal. It has been argued that this process may give raise to "responsibility gaps" (Matthias 2004; Sio and Mecacci 2021). These are situations where an artificially intelligent, automated system causes a serious accident and no human being can be reasonably held morally responsible or legally liable (Santoni de Sio and Di Nucci 2016; Sparrow 2007). This problem, originally identified in regard to autonomous warfare (Horowitz and Scharre 2015; Roff and Moyes 2016), has been recently also investigated in the field of automated vehicles, especially after their recent involvement in road accidents (Calvert, Mecacci, et al. 2020; Dikmen and Burns 2017; Shepardson 2018). AVs have been argued to give rise to recognizable control gaps (Calvert, Mecacci, et al. 2020) and, therefore, responsibility gaps (Mecacci and de Sio 2019; Santoni de Sio 2016).

In his 2004 paper, Andreas Matthias argued that responsibility gaps put society in front of a dilemma. Either we give up innovation, and cease creating intelligent systems, or we give up human responsibility, with all the difficulties of the case. Some theorists have embraced the second horn of this dilemma, and theorised that responsibility gaps might be acceptable if a technology brings about sufficiently important benefits. After all, some say, these gaps might not even be a completely new thing, as also buildings and bridges sometimes collapse in events that are unpredictable and beyond human control, similar to the behaviour of automated intelligent systems (Simpson and Müller 2016). Other scholars have proposed different technical and legal solutions. Some of them, for instance, propose that explainability and transparency of AI could be the key to preserve a correct and clear attribution of human responsibility (Tsamados et al. 2021). Value-sensitive technical advancements might therefore lead to progressively addressing certain AI related responsibility gaps. Finally, others propose that new legal mechanisms might help dealing with responsibility gaps: examples are faultless liability systems (Schellekens 2018) and the attribution of legal personhood to artificial intelligent systems (Koops et al. 2010).

One of the authors of this paper has elsewhere (Sio and Mecacci 2021) delved into the limits and perks of these responses, but such discussion would be beyond the scopes of this paper. It will be enough to say that the idea of meaningful human control represents a further response to the dilemma between human control and autonomy presented by Matthias. In particular, MHC strives to reject the dilemma in its entirety, and proposes a normative and conceptual revision of the notion of control to make it applicable to highly, and even fully, autonomous systems. The particular instantiation of MHC that we will propose, we claim, could save both innovation and human responsibility, thereby–at least in part–overcoming an undesirable value trade-off.

2.2 *Meaningful human control*

The idea of MHC stems from the political debate about autonomous warfare, where the high stakes of the machine-mediated decision-making process makes extra important that the role of human controllers in the control chain remains clear and their actions fully accountable. Several different MHC theories have been produced by different scholars, practitioners, and other stakeholders. These theories consist of sets of standards, conditions, parameters, that promote a legally, ethically and societally acceptable form of human control. They apply to different sorts of intelligent machines, targeting case scenarios ranging from autonomous weapon systems to surgical robots to self-driving vehicles. Santoni de Sio & van den Hoven (Santoni de Sio and Van den Hoven 2018), and successively Mecacci & Santoni de Sio (Mecacci and de Sio 2019) have proposed a specific operationalisation of MHC for the case of dual-mode vehicles. This theory constitutes an ideal starting point to consider the case of truck platooning. Also, this theory has been elaborated (Calvert, Heikoop, et al. 2019; Calvert and Mecacci 2020a; Calvert and Mecacci 2020b) into a significant degree of detail, and several proposals have been made to make the normative requirements that it contains more usable and objectively quantifiable. Before returning to this, we will introduce the main requirements on which control is based within such theory.

Santoni de Sio & van den Hoven's MHC theory is articulated into two main criteria called tracking and tracing (Santoni de Sio and Van den Hoven 2018). The extent to which they are fulfilled determines the degree (or quality) of human control that is possible at a given time. The first criterion, tracking, focuses on the nature of the relationship between human controllers and controlled system. It should be noted that a system is not intended here as just the automated machine, but includes all the relevant controllers, machines, and infrastructures. Human and artificial controllers are considered to be part of this system-at-large, and can exercise control from within the system. The fulfilment of the tracking criterion depends on the degree to which a system can "track" the different "reasons to act" of its controller(s) (Mecacci and de Sio 2019). We can immediately see how this criterion embodies MHC's innovative potential. Whereas classic control theories focus on the quality of the operational relation between a controller and a controlled system (Michon 1985), MHC theory proposes to base control not on a physical, directly causal relationship, but on a more abstract coordination. Namely, on the degree to which the behaviour of a system is aligned to and capable to covary with the different reasons to act of its controller, ranging from their intentions, to more encompassing and long-term goals, stretching up to their overarching moral values. The implication of the tracking criteria is that it allows consideration of controlling agents in a system even when they are not directly, i.e. operationally, in control. The rationale behind this becomes somewhat clearer if we consider that this theory of control is designed to grant a reliable, reliably retrievable, connection between designated human controllers and autonomous (even fully autonomous) machines, which by definition do not require any form of operational control. Also, the theory specifies that in considering the "reasons" of the controllers, we should consider them in their moral relevance, i.e. in their being relevant for a moral evaluation of the system's behaviour. This is the case because meaningful human control theory, as said, is meant to respond to the need of preserving human moral responsibility in those situations where "gaps" would otherwise occur.

Whereas the tracking criterion mainly focuses on the quality of the relation between controllers and controlled system, the tracing criterion concerns more closely the capacities of human controller(s) and the nature of their involvement in the chain of control. This criterion prescribes the presence of at least one person in the system design history or use context who can (i) appreciate the capabilities of the system–possessing adequate knowledge and skills–and (ii) their own role as target(s) of potential moral consequences for the system's behaviour. Such person(s) would be, within the–usually numerous–ones potentially involved in determining such behaviour, the most suitable ones to bear the controllers' role and the responsibility attached to it.

Both the tracking and tracing criteria have been recently further developed into more workable, i.e. less abstract, conceptual frameworks. The tracking criterion, as said, requires a reliable alignment between relevant human controllers' "reasons" and the behaviour of the controlled system. According to the theory, more than one agent, or even supraindividual agents, such as a company, a given society or a state, might satisfy the tracking criterion and thereby be considered, to the extent also the tracing criterion is satisfied, eligible controllers. To model the complex network of relations that govern the reciprocal relations among these different potential controllers, a model has been proposed, inspired by both psychological and philosophical accounts, where different kinds of "reasons" are ordered in a scale with respect to how closely they are reflected by–or how "proximal" they are to–a system's behaviour. This model, inspired by the tradition in philosophy of action, draws also inspiration from traffic psychology, and in particular to Michon's model of different classes of control: operational, tactical and strategic (Michon 1985). In Figure 1, we give a graphical description of our model. The most noteworthy novelty of the proximity scale is that it substantiates the general notion of "reason to act" into an ordered taxonomy that goes from the particular "intentions", very proximal–also temporally–to the behaviour of the system, through general goals and plans, to overarching moral norms and values, which are also importantly reflected by a system's behaviour, despite being laid down long before this is displayed. This allows one to appreciate the interests, and the relative controlling role, of stakeholders that sit far away from the actions of a system, i.e. designers, policy makers, etc. In fact, the scale, by spelling out and laying down in a bi-dimensional space different types of reasons, helps with identifying different (classes of) controllers, who might bear those reasons.

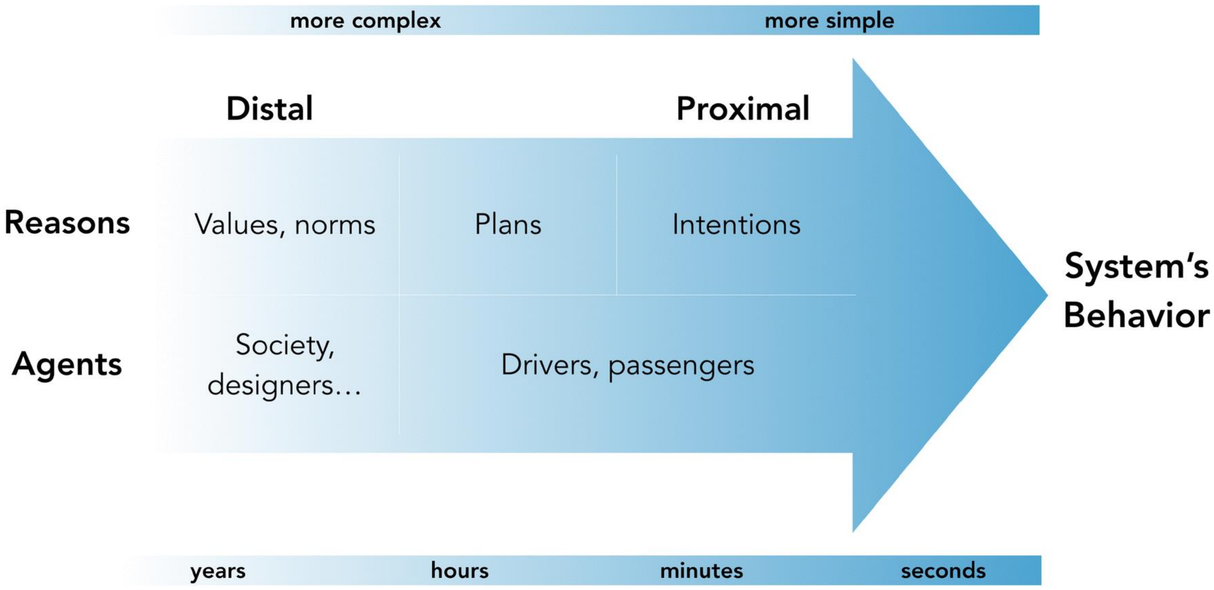


Figure 1. Proximity scale of reasons and agents. Reasons can be classified according to their proximity value. Proximal and distal intentions (plans) are typically temporally closer to a system's behaviour than values and norms. They are also simpler, in the sense that more complex reasons explain and affect a system's behaviour only through more proximal ones. Different agents can also be identified as typical endorsers of certain kinds of reasons.

2.3 *Notions of control for platooning*

Control is a term that can have different meanings to different people in different domains in which context is paramount. In this work, we refer to control from a sociotechnical perspective of influence over a system, and in particular here, over a connected automated driving system. Michon (1985) describes three levels of control that a driver can exert: strategical planning, tactical maneuvering and operational control. According to this, a system is under the control (in general terms) if its behaviour responds to an agent's (e.g. a driver) plans, maneuvers or operations. Correspondingly, an agent would lose control of a vehicle as soon as it does not respond anymore to any of those levels of control. We consider operational control therefore to entail the physical influencing of vehicle dynamics in through the chain of control. The chain of control indicates that there can be multiple sequential processes that follow one another. For example, a driver that turns a steering wheel influences the direction a vehicle travels, as the steering wheel is connected to the shaft and rack, which turns the angle of the wheels. This is a physical chain of control, which is proximal. A distal chain of control may be the design of an automated systems to obey a passenger's command to drive to a specific location. This last example is also an example of strategic control, as it focusses on planning rather than physical movement (operational).

This notion of control can bring about some interesting implications, especially when applied to intelligent systems. One of them regards the fact that this notion can apply to human and non-human agents alike. An automated driving system, for instance, can be deemed in operational control of a car for as long as there is a correspondence between the software operations and the car behavior (Mecacci and de Sio 2019). When considering automated vehicles, and especially when platooning, much existing research is focused on aspects relating to technical vehicle control and the interactions between platooning vehicles to perform optimally. Different approaches have focused on platoon stability (Barooah et al. 2009; Ploeg et al. 2014), while other have focused on the effect on traffic performance through improved intra-vehicle homogeneity (Guo and Yue 2011; Ploeg 2014; Shaw and Hedrick 2007) and vehicle spacing policies (Besselink and Johansson 2015; Dehlia Willemsen et al. 2020; Naus et al. 2010). The topic of human control for automated driving systems in which a human does not exert operational control is not broadly considered, at least not from the perspective taken with MHC (Beckers et al. 2019).

When considering cooperative automated vehicle control, there are clear differences between platooning and non-platooning trucks. Operational control in a truck-platoon is present with the leading truck, which has direct influence over the movement of the following truck in the platoon. The following drivers have little to no operational control during platoon operation, which can in principle lead to questions regarding the locus of control, where responsibility lie, and questions in regard to safety. Current truck platooning systems – typically described as driver-assistive systems – require all drivers to monitor their own truck and remain in an active role. This is the case even if the drivers are not in operational control (Nowakowski et al. 2016), so that they can retake such control if a situation arises that requires so. It should be noted that these practices may change in the future due to regulatory changes. Transition of control has been a broadly discussed topic in recent years with researchers questioning the feasibility of many system designs to allow a safe and timely transition of control. If one considers the chain of control throughout an entire platoon, never mind the leading vehicle, even more questions may be raised regarding the extent to which the drivers of following vehicles are meaningfully able to retake operational control of their trucks. In fact, those scenarios are characterized by short headways and potential lack of explicit information that a human can reasonably absorb and process to the point of decision before a situation becomes critical. This ultimately throws up the question: who is actually in meaningful control, from a human perspective, and responsible at any given time?

This paper aims to address the broader issue of human control over a cooperative vehicle platoon, focussing on truck platooning as a case example, from the perspective of human influence over the platoon system. This goes further than mere operational or automated control and addresses issues that exist in current system designs and proposes improvements based on the concept of meaningful human control. This works focusses explicitly on how humans influence control on a system which is either fully or partially automated and in which there may be no or little physical control exerted by a human during large periods of operation. Therefore, we do not explicitly consider how the automated systems perform in regard to vehicle interactions or communication, but rather focus on how human reasons and intentions are suitably catered for and included when humans are more distal to control operations.

3. Methodology

The approach taken to evaluate the control of cooperative trucks from a human-technical perspective has a strong focus on the ability of the platooning system to perform to a certain expected level. When humans drive manually, there are certain levels of performance that are expected from them that adhere to regulations and laws of driving. Human drivers are also expected to exercise judgment in their decision making that is morally compliant with societally shared norms and values. Likewise, a technical system that operates (semi-)independently, while designed to overcome human drivers' performance limitations, is also expected to display a similar degree of performance, while there is also discussion on if they should display similar levels of intelligence and moral judgement. This originates from the way the technology is designed to function and also includes the environment in which it is designed to operate. To address the role and expected performance of each agent and technical system, we first describe the main agents involved in the control of a platoon system. For the technical system, this entails obtaining a clear picture of the Operational Design Domain (ODD) of the technical system, such that its capabilities and operational environment is well described. For human agents (e.g. drivers), this entails giving a clear overview of their tasks and (in)ability to carry out these tasks under varying conditions. This may also include consideration of other (human) agents that can influence the platooning system, such as traffic controllers of technical system designers. This first step is carried out in Section 4, and also addresses potential control issues that may already be present when viewed from the viewpoint of MHC.

Following on from the theoretical considerations of the system and its agents, we then consider a number of real and fictive (but realistic) examples of platoon control in Sections 5.1 and 5.2. These examples are aimed at demonstrating that consideration of platoon control under real conditions is not as clear cut as compared to a theoretical model at the system design stage, and that further consideration is required in specific situations and conditions. This is performed by considering the role of truck-drivers and how they currently perceive specific on-road situations and how they may act in similar future scenarios if part of a platoon of trucks. Furthermore, we consider how drivers perform in regard to platooning and what can be learned in regard to platoon control. Thereafter, we consider two case studies that demonstrate issues for operational control of a platoon and for tactical control that may be insufficiently addressed within the system design, either as part of the technical system or in regard to an agent's (i.e. driver) role in the system. The analysis of these experiments and cases is given in Section 5.3. After highlighting the roles and some potential issues that remain unaddressed, an expansive discussion is given in Section 6 in which we aim to summarise the main findings of the evaluation and give recommendations of areas that should be considered for the further development of platooning systems, not only from a technical point of view, but also from an ethical, human behavioural and regulatory point of view. An overview of the approach is shown in Figure 2.

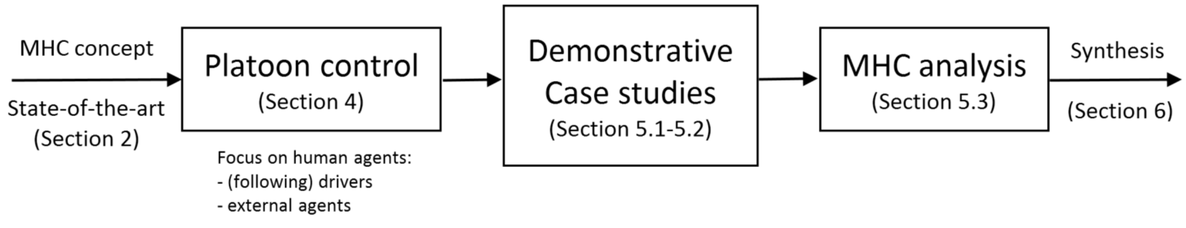


Figure 2. Applied approach to demonstrate the need for and the application of MHC to truck platooning

To further narrate how the analysis and example cases from Section 4 and 5 relate to MHC, we also point to the paper Calvert and Mecacci (2020a); (Calvert and Mecacci 2020b) (2020), in which MHC is taxonomised in regard to human control and interactions, and to Calvert, Heikoop, et al. (2019)

(2019), in which the core components of the driver, vehicle, infrastructure and environment are elaborated. To assist the readers, we have depicted the MHC taxonomy in Figure 3, with further details given in the accompanying paper.

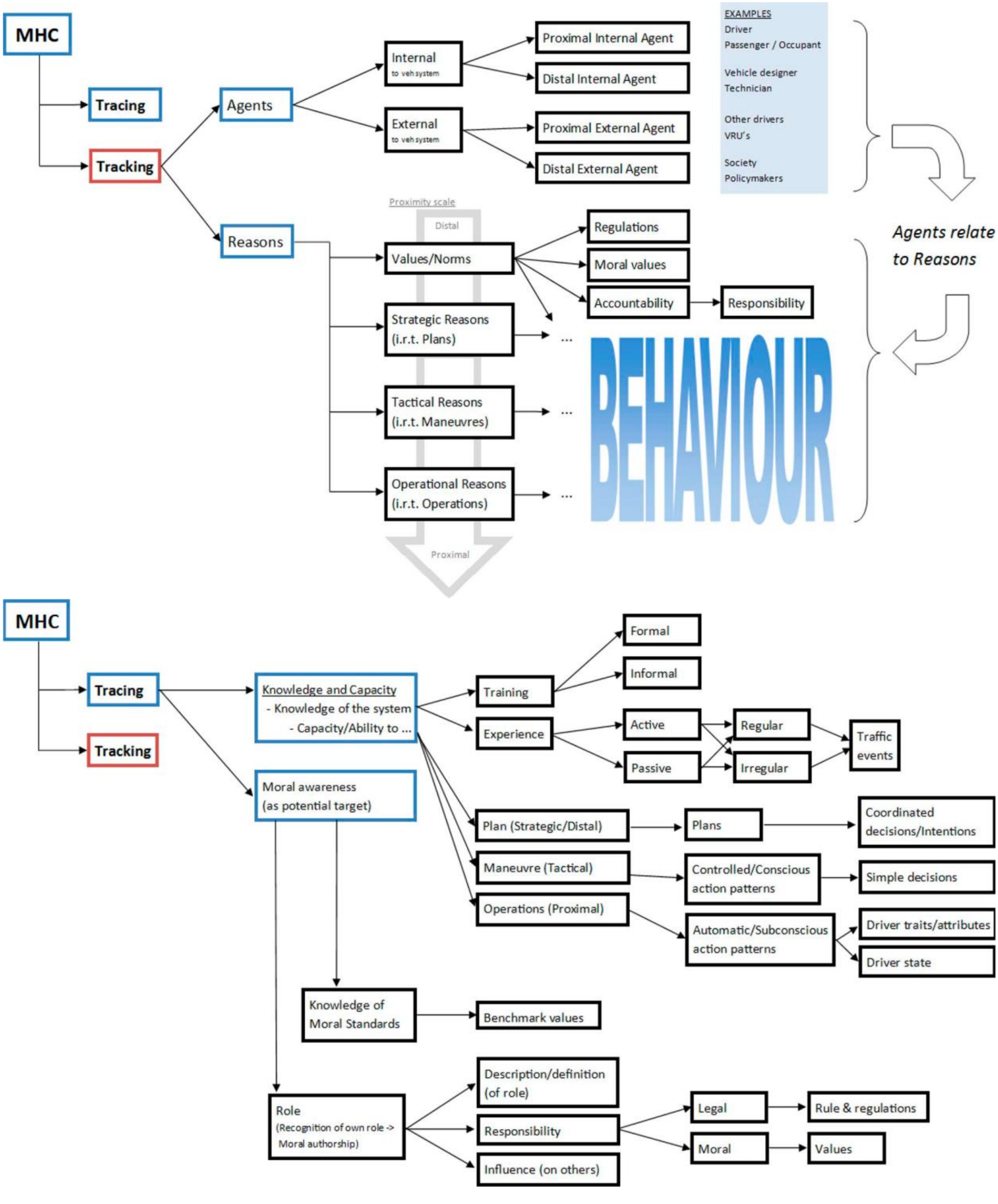


Figure 3. Taxonomy of the MHC tracking and tracing conditions for automated driving (Calvert and Mecacci 2020a; Calvert and Mecacci 2020b)

4. Human platooning control

Within the control of a truck platooning system, there are various human and technical agents, such as the technical systems themselves that can be identified that can exert control. As the considered systems are not fully autonomous, the truck drivers have a role to play and can exert operational control. There may also be other human agents, such as the operators in systems with fall-back control centres or even the very designers of the technical systems that, though indirectly or intermittently, are also involved in the control chain. The technical automated driving systems are designed in such a way that they are given control within their Operational Design Domain (ODD) and play an important role when considering system control. In this section, we give descriptions of some of the main control aspects within the system and will highlight potential issues that may arise in regard to control. In regard to ODD, the focus is on traffic systems that are applicable for truck platooning, which currently are constrained to road traffic and highways. This section focusses on the current practice and state-of-the-art to highlight the necessity to consider control from a different perspective. In the following section 5, these aspects are highlighted explicitly in regard to MHC in example cases.

4.1 Description of platoon control and potential control issues

4.1.1 Vehicle design and ODD

A (truck) platooning system, in its current most commonly considered setup, involves two or more vehicles (trucks in the case of truck platooning) that drive in close longitudinal proximity to each other by making use of cooperative and automated vehicle technology. At present, the leading vehicle is either fully human controlled or makes use of a low-level automated driving system, such as Adaptive Cruise Control (ACC), for longitudinal control. The following vehicles can be anywhere on the automated vehicle spectrum from in ACC-mode to full mode automated driving (Vissers et al. 2018). Following vehicles are ‘connected’ to the leading vehicle through wireless communication with the leading vehicle communicating driving details such as acceleration, speed and system settings, and status updates with minimum time delay. This allows the following vehicles to react almost instantaneous to longitudinal variations in the leader’s speed.

There are various research efforts and implementation initiatives that consider how (truck) platooning can and should be implemented. We will use the ENSEMBLE project as an example that originally discussed three levels of platooning (Vissers et al. 2018), before settling on a final distinction two levels of platoons (Dehlia Willemsen et al. 2020). These levels, “supported” and “autonomous”, differ in the level of automation for the following trucks and the Operational Design Domain (ODD) (for e.g. road type, driver role, fall-back conditions, etc.). Note that ODD is defined as the conditions under which a technology (in this case a vehicle or vehicle platoon) is designed to operate, which includes the physical environment, but also other aspects such as the system settings and driver roles. Table 1 gives an overview of some of the differences between the levels.

Table 1. Some differences in the ODD of different platooning levels (example adapted from ENSEMBLE (Vissers et al. 2018; Dehlia Willemsen et al. 2020))

	Supported platooning	**Semi-autonomous platooning[5]**	**Autonomous platooning**
Operational area	Triggered by driver in dedicated areas (e.g. highway)	Dedicated areas (e.g. highway)	Dedicated areas (e.g. highway + parking areas)
System & environment monitoring	System itself + Driver (environment)	System itself	System itself
Fall-back of the DDT (dynamic driving task)	Driver; as long it is safe and the driver can react in time	System (for x seconds)	System
Safe state	Fail-safe (driver in control after reaction time of the driver)	Stopped in ego lane or rightmost lane	Stopped in safe stop area (e.g. fuel station)

The ODD can be defined as the "operating conditions under which a given driving automation system, or feature thereof, is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics (Saberi et al. 2019)." The ODD of a platooning system is therefore vital, as it lays out the conditions when the system should be in normal working order. A technical system that can suitably operate within a properly defined ODD should in principle grant the desired control. Categories that are often considered with the ODD include infrastructure and road type requirements, vehicle specifications (both design status and current working state), environmental conditions and human driver requirements (Calvert, Heikoop, et al. 2019). Although we have not seen many examples of this, also traffic conditions may be a condition that could be included in the ODD (Aigner et al. 2018), e.g. no platooning in congestion (Calvert, Schakel, et al. 2019). Increasing numbers of examples of ODDs for platooning are beginning to appear (Transportation 2019; Crane et al. 2018), some based on scientific research or technical consultation, and some as a high-level guideline, all with differing levels of detail. Many of these descriptions focus either on the technical limitations of the system and/or on the infrastructure and geographical limitation of where (truck-) platooning is permitted. Both are valid and important to describe and, in most cases, do sufficiently cover the ODD of the system. It is however impossible to cover every eventuality that may occur, especially when either the technical system or the human driver/agent, or both are pushed beyond their limits. Following this challenge, there may be situations that push the system outside of the ODD that are difficult for the system to recognise. We do not presume that the system is intelligent (in the sense that it can think for itself) and therefore, the system will not recognise situations as being outside of its own ability to deal with. We may refer to these situations as false positives of ODD agreement. To clarify by means of an example: the accident involving a Tesla vehicle in autopilot mode that hit a crossing truck was caused by irregular light incidence that tricked the sensors into believing that there was no vehicle present ahead of the vehicle. The ADS was working in this case, but did not receive input that was sufficiently distinguishable (Calvert, Mecacci, et al. 2020). We could even take this a step further by considering elements of the automated system that could malfunction in a minor way and lead similarly to situations in which the ADS would not be able to operate, while the system itself may not recognise this. A major malfunction is easily detectable and would trigger an emergency procedure as defined in most ODDs, but a minor malfunction may not be recognised and lead to the same response.

[5] Note that *semi-autonomous platooning* was omitted form the final version of the ENSMBLE platooning categories.

A final challenge for the ADS that we would like to highlight is the case of intermittent 'flickering' in and out of the ODD and sudden unexpected situational loss of ODD. These may be situations in which the system recognises that it is outside of the ODD, but does not have sufficient time to warn a human driver or to act before moving outside of the ODD. This may either result in the activation of a safety/emergency action from the system and/or demand an immediate transition of control to the human driver. The danger here is that the system no longer can maintain control over itself, while the driver may not be ready or able to react to the situation with immediate effect. The role of the driver is viewed in the following sub-sections, but the role of the ADS herein should not be a hands-off one, but a 'deal with it to the best of its ability' one without overreacting. In some cases, the ODD may only be lost for a short time, therefore activation of an emergency stop may be over the top. An example that covers both cases is that of missing lane markings on a section or road. It may be that roadworks have been performed and that lane-markings have not yet been sufficiently redrawn, which would be a requirement of most SAE level 2 systems. Despite this may only occur for a short distance or intermittently, it remains a major problem for a system that relies on lane-markings.

4.1.2 Leading driver

The leading driver of a platoon has, from an operational point of view, probably the clearest role of all the drivers. Their vehicle operates with low level automation (e.g. ACC) such that the driver has an active role in steering or at the very least monitoring their vehicle's own ADS. This however may lead to undesirable situations, as research has previously shown, where a driver's driving tasks rapidly diminish as automation increases. A driver that has less operational tasks and greater monitoring tasks results in a lower cognitive demand, which is commonly known to lead to inattention and drop in driving performance (Louw et al. 2015; Parasuraman et al. 1996). Nevertheless, additional tasks may be assigned in regard to platoon control and they may also be expected to monitor the platooning system as well as the leading vehicle. This would mean that a certain amount of control is transferred to the leading vehicle and its driver. Note that merging and lane change control will still always reside with the following driver. Transfer of control can lead to a number of human factor challenges that are relevant for all drivers involved, whether in the leading vehicle or the following ones. Driver fatigue is often mentioned as a major issue in traditional truck-driving, although other psychological factors such as attitude and trust should not be underestimated (Poulter et al. 2008). However, there are two other issues that are especially relevant in regard to a driver's performance while platooning. The first is a loss of situation awareness and vigilance, due to a restricted vision of the road for the drivers in the following vehicles (Zhang et al. 2017). The second relates to the platoon lead driver, who now carries responsibility over the entire platoon, and possibly also operational control, which will inadvertently require a high level of trust (in the system and/or their own ability) (Hjälmdahl et al. 2017). The driver needs to have a comprehensive understanding of the system, of how it functions and under which conditions (ODD), as well as knowing when the system may require intervention and which interventions should be performed and how. Current (truck) platooning systems require a driver to maintain an active role, even if this means that they are not in operational control. They are required to monitor the system and their own vehicles performance, and if required, intervene and retake control is a situation arises that requires this or if the system makes such a request. The question of transition of control has been previously addressed a safety critical one that has yet to be satisfactorily solved (Axelsson 2017).

A driver will most likely require additional training and an updated understanding of the systems capabilities (Vissers et al. 2018; Janssen et al. 2015), not unlike that of an airline pilot, who must interact with a semi-autonomous system (Young et al. 2007). For a transition of control (ToC) event in which the driver must retake operational control, this can be initiated by the driver themselves if they deem the conditions require it, but a ToC request can also be made by the ADS. In the case that inattention is present, this may form a problem as regaining situation awareness takes time. For example, for the appropriate comprehension and projection of a vehicle's speed difference with your own can take over 20 seconds (Lu et al. 2017). Therefore, a take-over request time could be at least 20 seconds in some cases, while other research has found varying levels of required time for different drivers under varying circumstances, on average approximately 6 sec (Eriksson and Stanton 2017), which demonstrates a further uncertainty in relying on driver in these cases. Such high takeover times may prove critical and inappropriate if the ADS finds itself out of its ODD and in need of immediate intervention (as discussed in section 3.1.1). It is with regard to partial automation, in which drivers are deemed to maintain levels of control from a viewpoint of monitoring, that there may be concerns over meaningful control in practice. This has previously been identified and discussed in other works (Calvert, Mecacci, et al. 2020) and will be carried forward in consideration of the operationalisation of MHC (Simeon C. Calvert and Mecacci 2020; Calvert and Mecacci 2020b).

To aid the driver in additional platoon tasks, a well-constructed Human-Machine Interface (HMI) is vital. This allows the driver to interact with the platoon's system and to be kept in the loop on the systems performance (Vissers et al. 2018; Adell et al. 2008; Carsten and Martens 2019). Indications appear to be that drivers themselves desire information on immediate operational and tactical manoeuvres (Sadeghian Borojeni et al. 2016), such that the transition from manually driving to automated driving and vice versa is transparent for the driver (Vissers et al. 2018). This allows drivers to anticipate when intervention may be required and/or when it may find itself out of the ODD. The leading driver will always have the option to disengage the system. One further difficulty of an extended HMI is that it in itself can be an added distraction, as was indicated during previous pilots (Sadeghian Borojeni et al. 2016). The HMI console and interaction with it can act as an additional task, which has been shown to lead to deterioration of primary driving tasks (Calvert, Schakel, et al. 2020). Much research has been performed on good HMI design for automated and cooperative systems and can be found in (Carsten and Martens 2019; Lu et al. 2016; Sadeghian Borojeni et al. 2016; Naujoks et al. 2017). Another point touched upon for the ADS system is that of an unclear transition of control in such circumstances that the system may be (temporarily) out of the ODD. Depending on the reaction of the ADS, a driver may either proactively retake operational control, or wait to view the ADS' response and react to that. If the ADS does maintain control outside of its ODD or makes an immediate ToC request, then the driver would need to respond. There are many different permutations that may lead to an unclear ToC or mode confusion and uncertainty of who or what is actually in operational control. This could potentially be one of the most dangerous situations that could occur and certainly is one that is undesirable.

4.1.3 Following drivers

Drivers in the following vehicles are expected to have a very different role to the one in the lead vehicle. For supported platooning (see Table 1) with CACC for following vehicles, they will still be required to steer their truck and therefore have operational tasks as well as a monitoring role. Longitudinal control is completely transferred to the platooning system. With autonomous platooning, the driver is only present as a back-up and is not required to take control. Initially the ENSEMBLE project also defined an intermediate level of semi-autonomous platooning (Vissers et al. 2018) in which the driver is not required to perform any operational driving tasks during platooning and merely has a monitoring role in which they are required to retake control for specific manoeuvres (e.g. complex lane changes) or platoon disengagement. Each of these levels puts different degrees of demands on the driver. If the following driver is steering, they are doing so without a direct visual view of the road ahead (Sadeghian Borojeni et al. 2016). It is likely that they will have an indirect view through cameras mounted to the front vehicle, however this does change their perception of the environment and may place a greater task demand load on the driver (Funke et al. 2007; Zhang et al. 2017). In the case that the driver has no operational tasks, the same issues in regard to inattention become relevant, especially when a ToC request is made or is necessary under certain conditions. As described for the leading driver, it may be a matter of many seconds before a driver can cognitively become sufficiently aware before being able to retake control. Some views on platooning have even claimed that the following drivers may even be able to completely disengage from their driving tasks and perform other tasks or even sleep (Heikoop et al. 2017; Mok 2019). However, this would ensure that the driver is completely disconnected from the driving task and would ensure that the only operational human control would be exerted by the leading driver. This leads us to the area of responsibility. In conventional terms, a driver is deemed to be responsible for their own vehicle. Currently in most jurisdictions, this still applies. In the case of a following vehicles driver, they have no control whatsoever for the higher levels of platooning and fairly limited for the others. When considering the following driver's perspective, it is important to understand the chain of control within a truck platoon, which can lead to questions such as: "Who is (ultimately) in control, and where does it leave me?", "If the lead vehicle driver is in control, what influence do I have on my own truck while in the platoon?", and "Would it be of any meaning for me to keep paying attention, since I am not in actual control?".

These questions are important for the further development of truck platooning systems, and especially for the human-machine-interface of the systems. Through these processes, some level of meaningful human control can be improved in the core of ADS design. For example, from the moment a truck joins a platoon, operational control over their truck is transferred from them to both the ADS and the lead driver (tactically and strategically). At the point that a following driver wishes to leave a platoon, the opposite control process is executed, and the driver will retake the wheel and pedal control (gas and braking) of their own vehicle. There is a challenge here to have these transitions clear and overt to everyone involved (i.e., traceable), in order to avoid (amongst other things) mode confusion, which entails human cognitive confusion in regard to the status of a system (Stanton and Marsden 1996), and a potential loss of meaningful human control.

Meaningful human control can be increased for following drivers through certain considerations, although additional processes may be needed. For a system to respond to the intentions of the driver, it is not responsible to presume that a (following) driver can react with a very short reaction time. Remember that some platooning systems are designed for time-headway below 1 second, which encroaches a human's basic reaction time. Therefore, control of the vehicle for emergency situations that require such a short response time would not lie with the following driver, but rather with the ADS and the leading driver, who may have a greater ability and opportunity to intervene, as they are actively engaged in the driving task. Beyond the physical reaction time, a following driver will require time to cognitively readjust, which will take many seconds and sometimes even more than 20 seconds (Eriksson and Stanton 2017).

4.1.4 External agents

Platoon control, and certainly operational control, but also MHC, will often stem from a human driver or system designers. MHC also considers the influence of a less explicit form of control, distal control. This pertains to proximal agents, like the drivers, as well as to distal agents, like designers and institutions, that can be seen as "external" to the system. Distal control refers to non-operational control adhering to human reasons such as values and general goals, as described in Section 2.1. Although we will not overly focus on these influences in this paper, as they are less direct and better addressed in a normative, policy-oriented discussion, they should not be ignored completely. External control will most likely be exerted on a strategic or tactical level. On a strategic level, one may consider the influence that a truck company's logistical planner has on trucking operations, or the influence that road authorities have when implementing strategic plans that may influence the routes that a truck can take, the speed it may drive, or the lanes that it may make use of. In the context of truck platooning, this may also be directives on locations and roads that platooning is permitted on with specific conditions in regard the ODD of a system. Especially on this higher strategic level, many indirect agents may play a role. For instance, achieving optimal coordination with traditional vehicles and vulnerable road users implies that the behaviour of those agents must be accounted for, as well as the extent to which they can / are willing to adapt to the behaviour and needs of an automated truck platoon. Without going into detail, if we make an abstraction, and take 'society' as a single overarching agent, the influence that this agent plays, through exertion of societal values and norms, has a direct influence of how policy is applied and strategy is developed on a governmental level and that of road authorities. On a tactical control level, control may be exerted by on road conditions. Traffic management centres generally maintain an overview of traffic operations and in many cases will exert measures to relieve congestion, act upon incidents (such as accidents), and to promote traffic flow and safety. On the ground, police and road authority agents may be doing something similar on a smaller scale, e.g. in the vicinity of an accident. For the broader context of MHC, these distal influences on traffic and cooperative driving do play a role, but one that is highly contextual and hence difficult to generically substantiate for operational and tactical control, as we focus on in this paper. A more thorough treatise of these distal influences can be found in philosophical works such as (Mecacci and de Sio 2019).

4.2 Summary of potential control issues

In this section, we have given a description of control issues for platooning with focus on the case of truck platooning, and a viewpoint of MHC. This highlights a number of current issues that remain in regard to the application of truck platooning, and cooperative driving in general, that are relevant and need consideration as a wider implementation of these technologies approaches. In Table 2 below, we summarise the main points that were found and made in this section categorised by agent.

Table 2. Issues and challenges for cooperative truck control per considered agent

Vehicle design (and ODD)	**Leading driver**
- Difficulty in recognition of ODD - 'Flickering' in and out of ODD - Gaps in ODD description - Technical system capability may be outside of ODD - Lack of detail on emergency procedures for system outside of ODD	- Driver fatigue and distraction (incl. HMI) - Loss in Situation awareness and vigilance - Insufficient driver trust - Driver knowledge of the platooning system - Requirements for additional driver training - Long transition of control time (6-20s)
Following driver	**External Agents**
All items mentioned for the 'Leading driver', plus - Increased degradation of perception - Disconnection from driving task - Unclear transfer of responsibility and liability - Lack of influence over system (intentions)	*All items mentioned for the 'Vehicle design', plus* - Inadequate traffic regulations and management - Need to achieve coordination between road users and platoons

5. Case studies

With some of the main control issues highlighted, further clarity and evidence for some of these issues is given in this section, especially in the context of MHC. We do this through consideration of cases and a driver experiment. The use of case studies, describing situations in which control over a platoon may be less than optimal when considering MHC are described. These highlight some of the main challenges that are being faced in regard to symbiotic control of a cooperative automated system, such as the platoons that are considered here.

5.1 Case 1: Operational: Work zone

The first case that we consider is that of a truck-platoon on a two lane motorway driving on the right hand lane, with traffic flowing in an uncongested state. The platoon consists of three identical trucks in platooning mode, in which the leading truck makes use of ACC for longitudinal control and the driver has control of the steering. The following trucks are automated for longitudinal control (ACC) with Lane Keep Assist (LKA) present and active. At a certain location on the motorway, a work zone is present on the outer right hand lane resulting in a lane drop from two to one lanes and requiring a lane change from the right to left lane, similar to the picture shown in Figure 4.

Figure 4. Demonstration of a work zone lane drop case

Although the leading driver correctly observes the work zone, they anticipate that the ADS is still within its ODD and expects the truck to perform a lane change manoeuvre without intervention. However, as the platoon approaches the work zone, the driver of leading truck starts to become concerned that the work zone has not been properly detected and decides to retake lateral control and performs a sharp evasive steering manoeuvre to force the truck into the left hand lane a few tens of metres before the work zone is reached. The leading driver does so successfully and safely, and proceeds to drive on the left hand lane passing the work zone. Prior to reaching the work zone, the drivers of the following trucks are equally aware of the work zone, but with operational control of the platoon residing with the leading vehicle, they continue to monitor their vehicles and are not in operational control. However, at the point that the leading truck driver performs the evasive manoeuvre to the left lane, the ADS of the following truck sends out an immediate ToC request as the parameters of the evasive manoeuvre performed by the leading truck are outside of the ODD for a truck to be performed automatically due to safety (i.e. a sharp and abrupt steering action of a heavy truck). With only 1.5 seconds to react before reaching the work zone (ca. 30 metres at 20 m/sec), the driver of the first following truck is unable to retake control and perform an evasive manoeuvre in time after the ToC request and ploughs into the workzone, followed by the second following truck, resulting in an accident.

Analysing this case using MHC, we consider both the tracking and tracing conditions as described in Section 2.1. The tracking condition, in regard to the extent that the system complied with each controller's intentions, can be viewed from a distal and proximal perspective. The distal intentions, i.e. the drivers' general goals, are met for this case as the platoon is en route and compliant within its ODD to the wishes of the drivers, designers and others on a strategic level. On a proximal level, the system still meets the main intentions of the human agents. The system cannot perform the emergency manoeuvre, but doing so would be outside its ODD. However, for reasons that are inherent to truck platooning in general, we observe that following drivers' more distal, tactical decisions are underrepresented. For instance, the following drivers had no say in deciding whether to trust the ADS capacities or to override its control while approaching the work zone. This might be a minor problem here, for as long as we acknowledge that the leading driver bears full responsibility for such decisions. Furthermore, this manoeuvre is situational rather than by intention, therefore the system still generally responds to the main reasons of the human agents.

For the tracing condition, the ability of an agent to exert control over system, we need to consider the main agents involved: the leading driver, the following drivers, and the ADS designers. The leading driver eventually needs to perform an emergency manoeuvre, which they successfully manage. However, this was required because the driver did not have a correct understanding of how the ADS would perform under the prevailing circumstances. The ADS remained in operational control in a situation that obviously seemed to be outside of its ODD, hence proper control, or rather control according to the definition of MHC, appears to be diminished. The following trucks drivers were required to monitor their vehicles and did so correctly. However, when required to retake control within a very short timeframe, they were unable to do so. At that moment, MHC was not present, regardless of who was in operational control (the driver at the point of ToC), as the driver was cognitively and physically unable to exert control over its vehicle. Could then, the human designer of the ADS be considered to exert control over the vehicles? The answer to this is also negative, as the system was designed with a specific ODD in mind, which the trucks went outside of. Therefore, the ADS was not designed to deal with this situation and transferred control (both operational control and MHC), while MHC could not be transferred (even if operational control could be).

This case demonstrates that although operational control was always present somewhere in the system, MHC was not, and hence undesirable outcomes can occur. The lack of MHC in the case was (mainly) on the tracing conditions and the ability of a human agent to exert control over the system (platoon) or sub-section (vehicles) thereof. It should also be noted that this lack of MHC, due to the lack of driver's capacities, was also present before that accident; however this may not have been apparent at that stage of the trip.

5.2 Case 2: Tactical: Route choice

In a second case, we consider a situation that focusses more on the tactical level of driving, e.g. manoeuvring, rather than operational level as in the previous case. A highly automated truck-platoon with five trucks is scheduled to deliver s consignment to a large seaport. However, there appears to be some confusion about their planned route, as there have been some road closures in recent weeks. Despite this, the platoon has a planned route and proceeds to follow this route. However, while approaching an earlier exit than was planned, the leading driver makes an on-the-spot decision to take this exit, as he expects that this may lead to the platoon avoiding some of the possible road closures. Some of the drivers in the following trucks realise that the platoon is about to take a different exit to the one that was planned and quickly retake control of the steering and ensure their own trucks continue on the motorway and exit at a later off-ramp as planned. Some other drivers in the platoon remain oblivious and continued to follow the leading truck. The detour taken by the leading driver was not a wise choice and the platoon ends up stranded in a suburban area. The trucks that continued onto the planned exit reached the seaport at the allotted time window, while the leading truck and its followers did not. The trucking company's operations manager is enraged and holds all the drivers that didn't reach the port on time responsible, especially as the drivers that left the platoon and took the planned route did make their cut-off time at the seaport.

According to the concept of MHC, there are different conditions that each set of drivers must have satisfied to be deemed in control of their individual vehicle, or in some cases in control of the whole platoon. Starting with the leading vehicle and driver: it may be fair to state that they appear to have operational control over the platoon, which can also supported by the concept of meaningful human control supports to a certain extent. In regard to the tracking condition, there were clear reasons for the driver to steer the platoon off the motorway at an earlier exit, and we will assume that the whole system was designed and able to respond accordingly. Therefore, this condition does appear to be satisfied. In regard to the tracing condition, it is also reasonable to presume that the leading driver is capable of understanding how the platooning system was designed to operate. In principle, the only relevant functionality that the leading driver needed to understand was that his truck was guiding the platoon and setting the route for the other trucks. It is also fair to presume that the drivers are highly trained professionals that should be prepared for such eventualities as rerouting. Furthermore, there is no reason to assume that the leading driver was not able to understand that he may be considered morally responsible for the effects of his actions on the behaviour of the platoon. The lead driver explicitly decided not to take the exit, while knowing that other trucks would follow and could therefore reasonably be held responsible for that decision. The tracing condition therefore also seems to be satisfied.

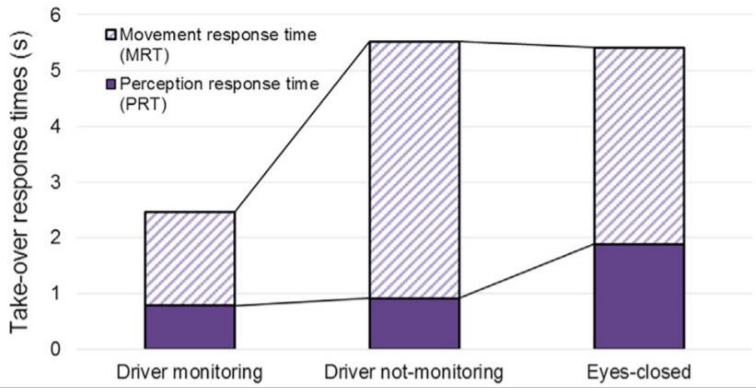
This case highlights a diminished capacity of the whole system-platoon to track the intentions of the following truck drivers, their MHC being thereby diminished. This, however, is not recognized by the company, which represents in the story a classic operational control theory. From a tracking perspective, the whole platoon is designed to maximise its responsiveness to the leading trucker, both from a proximal (operational interventions are at all times possible) and a distal (the platoon will try to go where the leading driver wants, within the boundaries of its ODD) perspective. However, MHC theory highlights how the following drivers, although supposed to be only in control of their own truck, and seemingly so from a classic control perspective, they are actually not meaningfully in control. This is because, although the following truck's ADSs are designed to effectively respond to the most proximal intentions, i.e. directly operating on the controls, the more distal intentions of the following drivers, i.e. to remain on route, are underrepresented, i.e. the ADSs will not automatically respond to them, but only react to direct input. This might be limitedly fine for as long as a conscious design decision is made in that direction. However, MHC allows appreciation of at least two important facts. The first one is that there might be an important discrepancy in the degree of control that might be overlooked while adopting a more operational notion of control. The following drivers in the story are all deemed equally responsible by the fictional company because they could -in principle- steer away and take the right exit, especially as some of them actually made it. But this possibility has to be considered in the light of a disadvantageous design (from a tracking perspective) and the difficulty of regaining operational control with very short advance notice (from a tracing perspective). The second important aspect that MHC let us appreciate is that, in overlooking the possibility for the following drivers to properly assess the more distal intentions of the platoon, and consequently the behaviour of their own truck, safety concerns might be raised. In fact, the unexpected turn created surprise and mixed reactions in the following drivers, potentially leading to dangerous scenarios.

5.3 Truck driver analysis

The previous cases give anecdotal descriptions of the relevance and necessity of MHC. With full scale truck platooning not yet in operation and as on-road pilots in critical situations are not ethically feasible, other types of experiments are carried out to gain insights into how truck drivers may respond to control events in truck platooning as well as how they perceive their role. We focus on aspects of control that are relevant to assist evaluation of driver capability and interaction with the system. We do this based on four main components of the tracing condition that relates to the driver as a human agent in the system (Calvert, Heikoop, et al. 2019) (Simeon C. Calvert and Mecacci 2020; Calvert and Mecacci 2020b). These are driver ability (i.e. capacity) to perform control tasks, the knowledge to do so, knowledge of moral standards and an awareness of their own role and its moral responsibility. The connections of these four aspects to MHC theory was given in Figure 3 and can be viewed there for reference.

5.3.1 Driver ability

A first aspect we wish to touch upon is that of driver ability to respond to situations in a timely fashion. If a driver is required to perform certain actions, then they must be able to cognitively and physically react from a human perspective. For transition of control (ToC) in automated passenger vehicles, much research has already been performed (Eriksson and Stanton 2017; Zeeb et al. 2015; Merat et al. 2014; Varotto et al. 2018). This literature shows that on average it can take a driver 1.5-15 seconds to retake manual operational control after a request to do so. Eriksson and Stanton (2017) point out that drivers take longer to resume control when under no time pressure and that driver is occupied by a secondary task exhibit larger variance and slower responses to requests to resume control. They also point out that there is often a large spread in ToC times (between 2.8 and 23.8 s in their experiment), such that average ToC times do not tell the whole story. A recent experiment carried out on the ToC that explicitly considered truck drivers while platooning is described by Zhang et al. (2019). This was a driving simulator experiment in which 22 professional truck drivers participated. It focussed on their ability to retake manual control of their trucks from different starting conditions, e.g. while monitoring, while distracted, and while relaxing (with eyes closed). The reaction time required to retake manual control was separated into the perception response time (PRT) and movement response time (MRT), with their results shown in Figure 5. This result showed that even when monitoring the system, drivers required between 2-3 s on average to retake control, while when not monitoring this rose to above 5 s on average. The authors also found that drivers, even after retaking operational control, still required upwards of 10 s to fully engage in the operational driving task. This is a strong indication that while operational control has transferred from the ADS to the driver, MHC is still suboptimal as for quite a while thereafter.



	Mean (SD)	Median	Min.	Max.	IQR
PRT					
Driver Monitoring	0.78 (0.14)	0.80	0.43	1.10	0.10
Driver Not-monitoring	0.91 (0.35)	0.87	0.17	1.77	0.33
Eyes-closed	1.89 (1.66)	1.43	0.80	7.73	0.64
MRT					
Driver Monitoring	1.67 (0.49)	1.58	0.95	2.97	0.60
Driver Not-monitoring	4.61 (1.40)	4.07	2.75	7.74	2.01
Eyes-closed	3.53 (1.90)	3.48	1.19	8.31	2.85
TRT					
Driver Monitoring	2.45 (0.53)	2.37	1.75	3.80	0.69
Driver Not-monitoring	5.53 (1.39)	5.36	3.62	8.54	1.86
Eyes-closed	5.42 (2.44)	5.43	2.19	11.31	3.43

Figure 5. Difference in perception response time (PRT) and movement response time (MRT) for transition of control (from (Zhang et al. 2019))

5.3.2 Driver system knowledge

Being involved in operational control, or any control, in a platoon system, requires a good understanding on the systems capabilities and limitations. Although truck drivers are well trained and experienced professionals, additional training may be required to be able to properly interact with the system. In the case of truck platooning, several considerations exist that need proper training, namely that of the changing driver role, dealing with short time headways, and entry- and exit manoeuvres to and from the platoon (Nowakowski et al. 2015). Part of this is also the driver's ability to trust the system, as this is also vital to maintain symbiotic control (Nowakowski et al. 2015). One of the major components to increase trust is to have an appropriate mental model of the system that can be trained (Beggiato and Krems 2013; Heikoop et al. 2017). An insufficient, incomplete, or inappropriate mental model can lead to mistrusting the system or even trusting it too much, and thereby misusing it, which can lead to dangerous circumstances. Therewith, training drivers to obtain an appropriate mental model that can lead to appropriate use of the system should be based on a trackable system, one of the conditions to ensure meaningful human control over an autonomous system (Santoni de Sio and Van den Hoven 2018). If a system is trackable, meaning that it is designed to follow its human controller's (moral) reasoning as much as possible, its human driver will be naturally more able to fully grasp the workings of the system, thereby developing an appropriate mental model, and as such, meaningful human control over the automated driving system. Given that many novel knowledge-based behaviours arise during automated driving (Heikoop et al. 2019), it is clear that providing relevant training on driver system knowledge is of paramount importance.

5.3.3 Driver moral responsibility

The last two aspects of control that we consider are more abstract in nature, yet nonetheless relevant for control, and specifically relevant to be deemed in control. These are the recognition of a driver's own role as a possible target of moral responsibility, and their ability to understand what is morally correct. As described in Section 2.1, to be under MHC, a human agent should also have a sufficient understanding of their own role, including the moral responsibility that it carries. MHC is concerned with a broader notion of control that includes ethical and legal aspects, as well as certain common practices of attribution of accountability and moral blame. These practices are important to consider, especially since they play a big role in determining moral and legal consequences of potential unwanted outcomes, such as accidents and general misbehaviour. Consider, for instance, a situation where a driver displays reckless or undesirable behaviour while controlling a truck, ultimately leading to an accident. Once questioned about the reasons of such behaviour, the driver is found to be not only completely unaware that the behaviour was inappropriate, but also unaware that they were supposed to be in charge, or actively responsible, for preventing that accident. This can lead to at least two consequences. Firstly, a diminished moral responsibility and in turn a potentially reduced legal liability. In fact, there is a clear absence of mens rea (intention to harm or even a knowledge of wrongdoing). This could ultimately lead to those responsibility gaps that a meaningful form of control, once established should contribute to minimize. Secondly, a diminished active responsibility would decrease a driver's commitment to the task, attention, and careful evaluation of the consequences of their actions. This, in turn, might result in decreased quality of control and potential safety hazards. Although this is perhaps an extreme example, we hope it serves to elucidate that the extent to which a driver is aware of their controller's role and of the moral consequences of their actions, is an element that can ultimately modulate the quality of their control over a vehicle. In conclusion, certain ethical, legal and societal aspects of a driver's relation with their vehicle should play a part in evaluating the quality and nature of control that can be ultimately exercised over it. In this regard, MHC gives a perspective that includes elements that no other notion of control in vehicle development or analysis has yet included, but really should consider.

6. Synthesis, discussion and recommendations

In this section, we will reflect on the analysis that has been performed in this paper and will discuss some of the main points that are most relevant and still need addressing. As argued throughout, this will be performed from the viewpoint of MHC, but we will also take a step back and review the relevance of doing this from that viewpoint.

We start with issues relating **to truck platoon and cooperative driving ODD**. With the past and current pilots that have been performed for truck platooning, of which some have been mentioned in this paper, an increasing amount of attention has been placed on the importance of the ODD to define what a platooning truck should be able to do and under which conditions. There are excellent examples for this. However, it is nearly impossible to define a completely all-inclusive detailed ODD that covers everything, as it is equally impossible to define each circumstance that a vehicle may find itself in. The importance of a clear and consistent ODD for MHC has been demonstrated in this paper and is an important part of ensuring MHC in vehicle system operation. The definition of the ODD needs to be both generic, in the sense that it covers the entirety of situations on a high level of description, and detailed, in the sense that it explicitly indicates those aspects that are within and outside the ODD. Consistency and standardisation for ODDs is also important to ensure that infrastructure and vehicle ODD classification is aligned. Having custom designed ODDs and corresponding infrastructure design will lead to difficulties over a broader scale when trucks and cooperative vehicles traverse a larger area over multiple different types and designs of infrastructure with different types and setups of trucks and technological development. To an extent, this may not be unavoidable, but nevertheless efforts must be made to reduce a patchwork of ODD and infrastructures to maximise the chance that no mismatch occurs. This will also place demands at the door of road authorities, to maintain a consistent road layout and quality, which may limit 'flickering' in and out of the ODD, but in itself cannot prevent it. Interaction with other vehicles and prevailing traffic conditions will also influence this, and may mean that (for a long time) dedicated or adjusted infrastructure may be required. These are challenges that remain and need addressing as implementation continues. For cooperative vehicles that do leave their ODD and need (immediate) transition of control to a human driver or vehicle management centre, a new procedure may be required as expecting a driver to retake immediate control, with current estimates of 6-20 seconds to do this, showing to not be sufficient in many cases. On the vehicle side, this entails ensuring that there is a fail-safe procedure in place that ensures that a truck remains driving in a safe way, even when it is out of its ODD. Options to perform an emergency stop or pull immediately over to the hard shoulder will not always be suitable or possible and should not be the entirety of the back-up options. On the driver's side, there is also much that can be done, which we will now also elaborate on.

The **role of the driver** in a cooperative (truck or car) platoon crucially changes compared to regular non cooperative driving, or even automated driving. The common adage of changing from an active controller to a passive monitor holds even more truth in a cooperative platoon as compared to single-vehicle automated driving, as due to the limited view ahead, the 'driver' is basically left with staring at the back of another truck. During single-vehicle automated driving, one could at least look ahead, anticipate upcoming critical situations, or maintain the vehicle's trajectory. Solutions to increase the possibilities to actively monitor are being undertaken. For instance, a 'see-through screen' fitted to the back of the leading truck in front and displaying the field of view at the front of the platoon through cameras, allows a driver to follow the platoon's trajectory and oncoming dangers [21]. This can result in higher monitoring time and less severe responses to critical situations. Also HMIs displaying various types of information are being developed (e.g., (Adell et al. 2008; Carsten and Martens 2019; Sadeghian Borojeni et al. 2016)). However requirements for a driver of a following truck in a cooperative platoon to maintain meaningful human control over their vehicle remains an open issue. For instance, does a see-through screen increase the chance of an appropriate response to a critical situation? How does this translate when applied to multiple trucks in a platoon? Is detailed information on speed, distance, trajectory, et cetera of any relevance to a driver inside a platoon? How much time does the driver need to regain appropriate situation awareness to reclaim manual control over his vehicle, and can any type of prior information assist in that process? One has to wonder whether truck platooning is in any way trackable, or able to become trackable to a certain extent. Following a truck at a distance of 0.6 s, which is close to human reaction time ('Human benchmark'), in principle goes against human nature. Can we expect a driver to comfortably sit in their truck during such circumstances? A major issue here is whether the driver can trust their truck, its automated driving system, as well as the lead driver. This can be increased by suitable driver training that enable the driver to fully understand the workings of the system, as well as what to do during which circumstances. Currently, truck drivers are being trained to drive with various ADAS, but platooning is a step beyond. This requires special training, where one major element would be how not to drive. For this, we could learn from aviation (Young et al. 2007), where pilots have been trained for decades to fly their plane with extensive autopilot support. With professional truck drivers, such an intensive training, ideally encompassing quick regeneration of situation awareness, would be appropriate. As proper situation awareness can take up to 20 seconds (Lu et al. 2017), there appears to be plenty of room for improvement to enable a feasible, meaningful time to take over manual control.

Another main difference between platooning and regular non-cooperative (automated) driving resides in where **responsibility and liability** lie, especially between leading driver, following driver and vehicle owner/manufacturer. In cases of manual or lowly assisted driving, responsibility for controlling a vehicle's behaviour is commonly attributed to the driver, who is clearly and univocally identified. This applies in the sense of active responsibility, i.e. it is a designated driver's duty to control a certain vehicle, and in the sense of passive responsibility, i.e. the driver may be culpable if the vehicle spins out of control. This only holds to the extent that the vehicle operates within its ODD. Increasing automation progression may shift the burden of responsibility towards car manufacturers. This is due to the fact that the vehicle itself is designed to plan and initiate actions that might lead to undesired outcomes. As demonstrated in the cases, part of the gaps in control–and hence in responsibility–are generated by unclear, or unsuccessful, division of tasks between the driver and the automated technologies. Platooning, and cooperative driving in general, are characterized by multiple agents over which tasks and responsibility need to be distributed. Moreover, although the leading and the following drivers generally have similar tasks and responsibilities (keeping the truck on road, getting the vehicle to a destination, etc.), these change dynamically with the situational context. This means for instance that the leading driver can be considered actively and passively responsible for the whole platoon only when the automated platooning system is engaged, but they become responsible for their own truck immediately afterwards. This is similar for the following drivers, whose own truck's behaviour is fully under their operational control only when the platooning system disengages. All of the drivers bear different responsibilities that dynamically change in virtue of the status of the whole system-platoon. Truck platooning presents a particular case in driving automation that challenges well established practices of attribution of responsibility and liability by creating a qualitatively more articulated network of agents whose role and responsibility varies over time and context.

Meaningful Human Control is essential to properly consider control in a cooperative vehicle setting. In fact, it allows one to access a more nuanced set of criteria for control that allow a better characterisation of active and passive responsibility for each single driver of a cooperative driving system. As we showed in section 4, the MHC approach, can rely on more stable and relatively non contextual elements to evaluate the quality and degree of control and responsibility for each of the cooperating drivers. Identifying intentions and reasons to act according to their proximity value is for instance valuable, because more distal intentions, e.g. general goals, are by their nature more stable and context independent reasons for action. This, in turn, allows a better clarification of the loci of control and the extent to which every single agent should be deemed responsible and worth of blame in case of unwanted outcomes. Moreover, the increased complexity of the system, brought about by the introduction of multiple cooperatively controlling agents, introduces the need for further coordination, which cannot be achieved merely at an operational level. Rather, this must be structured around a shared set of values, intentions and general competencies, investigated and promoted by the tracing condition, that have to be aligned as much as possible across the different drivers in order to make the system-as-a-whole solid and reliable. All in all, MHC brings about the opportunity to consider a broader spectrum of elements that encompass both the driver(s) in a generalised theory of control and the larger socio-technical context within which truck platoons are deployed. This includes multiple stakeholders (e.g. manufacturers, traffic authorities) as well as the broader societal values and norms that regulate their responsible use.

7. Conclusions

In this paper we have addressed the broader issues of control over a cooperative vehicle platoon, focussing on truck platooning as a case example, from the perspective of the platoon system. This goes further than mere operational control and addresses issues that exist in current system designs and proposes improvements based on the concept of meaningful human control (MHC). While, platooning system, both for truck and passenger vehicles, are being developed and implemented, open issues remain in regard to their control. These have been discussed on an 'agents' level, considering the vehicle design, leading and following drivers and possible external agents. As part of this, we discuss two hypothetical cases focussing on issues on a system level and one further analysis which is focussed on the role of the driver in the platooning system. Current Operational Design Domains (ODD) for truck platoons give a broad and comprehensive description, but it remains almost impossible to cover every circumstance. Fall-back options for emergency procedures need to be watertight, while platoons may 'flicker' in and out of their ODD, which either may lead to non-platooning or incidental exceedance of the ODD. General difficulties in the roles of drivers have been well documented, with issues remaining for driver fatigue, distraction and other losses of situation awareness when interacting with an automated system. Furthermore, we have highlighted a need for driver training and a greater knowledge of the systems to meet conditions of MHC and avoid unexpected control gaps in operation. On a legal level, we highlight issues in regard to where responsibility lies from an operational point of view. We argue that nominal liability may in many cases not be reasonable, especially where obvious gaps in control exist. We conclude that MHC allows one to access a more nuanced set of criteria for control that allow a better characterisation of active and passive responsibility for each single driver of a cooperative driving system. While doing this, we have highlighted and discussed the aforementioned issues and challenge both industrial and research domains to consider the issues carefully to support the introduction and further development of the technology in practice.

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