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Dimensions of Cooperative Driving, ITS and Automation

Maytheewat Aramrattana[1,2], Tony Larsson[1], Jonas Jansson[2] and Cristofer Englund[1,3]

***Abstract*— Wireless technology supporting vehicle-to-vehicle (V2V), and vehicle-to-infrastructure (V2I) communication, allow vehicles and infrastructures to exchange information, and cooperate. Cooperation among the actors in an intelligent transport system (ITS) can introduce several benefits, for instance, increase safety, comfort, efficiency. Automation has also evolved in vehicle control and active safety functions. Combining cooperation and automation would enable more advanced functions such as automated highway merge and negotiating right-of-way in a cooperative intersection. However, the combination have influences on the structure of the overall transport systems as well as on its behaviour. In order to provide a common understanding of such systems, this paper presents an analysis of cooperative ITS (C-ITS) with regard to dimensions of cooperation. It also presents possible influence on driving behaviour and challenges in deployment and automation of C-ITS.**

I. Introduction

With its potential benefits to the transport systems as presented in [1], cooperative intelligent transport system (C-ITS) have recently received a lot of attention. For example, in Europe three large projects that have been dealing with cooperative systems are CVIS, SAFESPOT, and COOPERS. Cooperative Vehicle-Infrastructure Systems (CVIS) [2] focused on vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication issues. While, SAFESPOT [3] aimed to enhance road safety via a "safety margin assistant" concept, which detects critical situations in advance, and the use of a "local dynamic map". COOPERS [4] was focused towards providing safety related real-time information and cooperative traffic management through infrastructure-to-vehicle (I2V) communication. A comparative study of these projects is presented in [5]. SARTRE [6], another European project dealt with platooning applications, through the concept of increased "driver comfort". Five years after the previous competition in 2011 [7], the grand cooperative driving challenge (GCDC) 2016 will be arranged by the i-GAME project [8]. The objective is to speed up real-life implementation of automated driving and interoperability of wireless communication. Besides i-GAME, another ongoing project is AutoNet2030 [9], working towards cooperative automated driving technology based on a distributed decision-making strategy.

[10] present an architecture for cooperative driving of automated vehicles. It consists of three layers *a*) vehicle control layer; *b*) vehicle management layer; and *c*) traffic control layer. The vehicle control layer typically is individual for each vehicle. It is connected to sensing and actuating systems, it sends data from sensors and vehicle state variables to the vehicle management layer. It also receives steering and vehicle speed commands from the vehicle management layer. The vehicle management layer is also implemented in the vehicles, placed in the middle between the vehicle control and the traffic control layer. It determines the movement of each vehicle in the C-ITS, with the data from the vehicle control layer of neighbouring vehicles through V2V communication. It also receives information from the traffic control layer via V2I communication. The traffic control layer consists of two parts; physical and logical. The physical part is located in the infrastructure, it consists of physical equipment like traffic signals, communication access and relay nodes, and roadside units. The logical part deals with regulations, rules, manners, common sense, and ethics in the human society. Considering the two parts, common criteria must be defined and communicated to neighbouring vehicles through the vehicle management layer.

Within C-ITS, information is shared between many actors such as vehicles, infrastructures, cloud services, etc. However, only sharing information is not enough to be considered a C-ITS, cooperation and interaction between the actors in the system is also required. In order to have a common understanding of what we mean by C-ITS, this paper presents an analysis of the topic from different perspectives in Section III. Introduction to driving automation is presented in Section II. Section IV elaborates on dimensions of C-ITS followed by its deployment challenges in Section V. Finally, Section VI conclude the paper.

II. Levels of Automation

Recent research have focused on automated driving functions like adaptive cruise control (ACC), automated parking, etc. Levels of driving automation have also been defined by organizations such as SAE, BASt, NHTSA, and VDA. A comparison of these definitions is presented in Table I. Apart from ongoing research on automation functions like adaptive cruise control (ACC) and automated parking, several papers on cooperative systems in relation to automated driving concepts are published, see [10]–[13].

The following description will use SAE's definition as the basis. From level 0 to 2, the human driver has responsibility to monitor the environment. At level 2, the vehicle can take over steering, acceleration and deceleration in some driving modes. At level 3 and 4, the vehicle will monitor the environment, but only for some driving tasks. The differences

[1]School of Information Technology, Halmstad University, Box 823, 301 18, Halmstad, Sweden {maytheewat.aramrattana, tony.larsson}@hh.se
[2]the Swedish National Road and Transport Research Institute (VTI), SE-581 95, Linköping, Sweden jonas.jansson@vti.se
[3]Viktoria Swedish ICT, Lindholmspiren 3A, 417 56, Gothenburg, Sweden cristofer.englund@viktoria.se

TABLE I: Comparison between levels of automation released by SAE, BASt, NHTSA, and VDA.

	Organization			
Level	SAE	BASt	NHTSA	VDA
0	No Automation	Driver Only	No Automation	Driver Only
1	Driver Assistance	Driver Assistance	Function-specific Automation	Assisted
2	Partial Automation	Partial Automation	Combined Function Automation	Partial Automation
3	Conditional Automation	High Automation	Limited Self-Driving Automation	Conditional Automation
4	High Automation	Full Automation	-	High Automation
5	Full Automation	-	Full Self-Driving Automation	Full Automation

between 3 and 4 is the fall-back performance, in other words, who is responsible when the system fails. At level 3, the system still expect the human driver to handle the failure with a request to intervene. On the other hand, the vehicle will handle itself at level 4, for instance, when a failure occurs, the automation system still has to safely handle the vehicle. A request to the human driver may be made at this level, but if the driver does not respond, the system should be able to handle the situation. At full automation, level 5, the vehicle will handle all the driving responsibilities or tasks, including monitoring of the environment.

III. Cooperative ITS

In this paper, the scope of C-ITS encompass technical systems that applies to actors in the road transport system. Within this scope, C-ITS is defined according to the following definition:

Definition 1: C-ITS is a technical system that implements cooperative behaviour based on communication between two or more actors in the system.

Cooperative behaviour is in turn defined as:

Definition 2: A cooperative behaviour includes two or more actors working towards a common or mutually beneficial goal, purpose, or benefit; enabled by interaction and information exchange between the actors.

Cooperative behaviour involves actions such as sharing information, taking turns, following instructions from others, etc. Typical goals within the transport system context are, the improvement of safety and increased transport efficiency. When combined with driving automation, having more comfortable driving is another goal of C-ITS. The overall goal is to drive beyond the capability of a human driver or an autonomous vehicle. Thus, comfort as well as safety and efficiency are important goals. However, not every cooperative function must deal with all these goals. For example, a function like cooperative adaptive cruise control (CACC) can improve efficiency of the individual vehicles, but to be more efficient, vehicles could also drive closer to each other to reduce air resistance. This could however increase the risk of accident i.e. different goals can be in conflict with each other and may require different cooperative behaviours. Thus, applying the concept to the transport system needs to be considered carefully at different levels.

Apart from the exchange of system state information, interaction about intentions, planned behaviours, and agreements play an important role in C-ITS. In [14] cooperative driving is defined from a human-machine cooperation perspective, focused on the interaction between a vehicle and its human driver. They proposed five levels of cooperation for human-machine interaction. Those five levels deal with: *a*) *intention*; *b*) mode of *cooperation*; *c*) dynamic task and action *allocation*; *d*) the human-machine *interface*; and *e*) the *contact* between human and machine. Four out of the five levels were presented in the paper with an example of cooperative lane change scenario. Further evaluation of the concept was presented in [15].

A. Behavioural Perspectives

A critical review of different driver behaviour models is presented in [16]. According to the article, there are three levels of skill and control in driving, seen as a problem solving task: strategical, tactical, and operational. These three tasks relate to the driver's decision making and is often mentioned as basis for modelling of driver behaviour. The strategical level can be seen as a planning task, it involves things like cost and risk evaluation, route choice, trip goals. The tactical level is about deciding manoeuvres such as: overtaking, turning, gap adjustment based on the criteria made on strategic level. Moreover, negotiation is also involved at this level, for instance when making decision to cross an intersection, as well as monitoring of traffic since it is the basis for making decisions at this level. Lastly, the operational level handles more continuous and periodic routine tasks such as longitudinal and lateral control, based on environmental input. These are principles that any model of driver behaviour should take into account. Furthermore, information flow, switching and interaction between levels should also be considered. To bring this concept into C-ITS, the goal of cooperative functions could be on different levels but cooperative partners should have common goals on those levels to enable efficient cooperative behaviour.

As elaborated in [14] and [15], human-machine interaction is important for cooperative systems as long as the human driver is still involved in the driving task. Furthermore, at the early stage of C-ITS deployment, some vehicles might not have any communication and automation capabilities at all, some might have automation but not communication, and just a few would have both. How to communicate the intention between those three differently equipped categories of vehicles? How would the driving behaviour of autonomous vehicles be perceived and processed by the human driver in a manually driven car without communication? And vice versa. Those are important question from behavioural perspectives that needs to be addressed.

[17] investigated the effects of automation on tactical driving behaviour, depending on the trust in the system. Most

driving automation today works at the operational level, in which the function (when allowed to take over from the driver) handles longitudinal and lateral control, for example, ACC or lane keeping assist functions. On the tactical level, automation can be involved, e.g. in self-parking systems, but usually the vehicle only provides information to help the driver make decisions about driving tasks. Navigation systems are mentioned in [17] as one example of a function aiding strategic tasks, still it does not take control of the vehicle. Within C-ITS, automation of tactical tasks such as crossing of intersections is possible as presented in [11], [18], [19]. Furthermore, [20] elaborate on the possibility of having automation at the strategic or tactical level.

B. Structural Perspectives

From a structural perspective, actors in C-ITS consists of components aimed for: *a*) communication; *b*) sensor fusion; *c*) environment perception; *d*) decision making; *e*) actuators; and *f*) human driver interaction. Figure 1 illustrate these components from structural perspectives in relation to the driving tasks presented in section III-A.

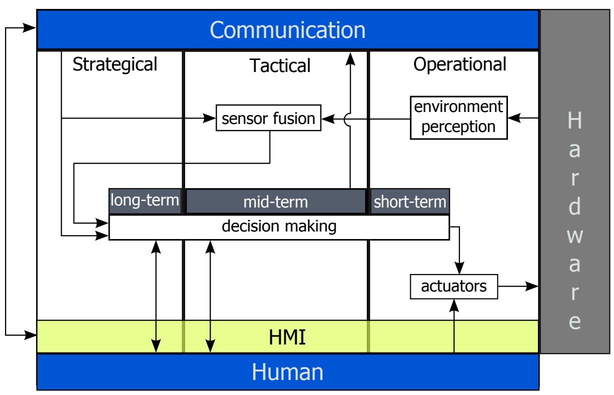


Fig. 1: Vehicle/infrastructure actors internal structure.

Access to one or more mechanisms for wireless communication is one of the key factors that enable C-ITS. Reliable and standardized communication techniques providing sufficient coverage and quality of service in different environments is an important enabler of C-ITS, and may eventually be achieved through a combination of vehicle-to-vehicle and vehicle-to-infrastructure (V2X) and cellular communication systems. ETSI [21], The European telecommunication standard institute, has published two technical specifications [22],[23], defining two types of messages namely cooperative awareness message (CAM) and decentralized environment notification message (DENM) respectively. These two message types are intended for the European C-ITS applications. CAM periodically provide information of presence, position and basic status of an ITS-station to neighbouring stations located within a single hop distance. Some use cases provided in [22] are: emergency vehicle warning, intersection collision warning, speed limit notification, collision risk warning, etc. If higher frequency is needed to ensure low reception latency after first contact, DENM with situation specific communication attributes can be used, e.g. providing road hazard warning related information. According to [23], examples of events that would trigger DENM are: collision risk warning, precipitation, road-work warning, accident, emergency electronic brake light, etc. In conclusion, these messages provide the basis for the communication protocols used in C-ITS. However, it still require some enhancements and extensions regarding application level information. For example, the need to include and standardize vehicle behaviour information as pointed out in [24]. Besides wireless communication, other alternatives such as light and sound signals from vehicles, messages on traffic signs, car horn, etc. are also included in this part. These alternatives are usually used to communicate intentions between cooperative partners as well as to interact with vehicles lacking wireless communication capability.

The sensor fusion part combines information from communication and environment perception. Usually this part implement a filter to certify information. The filter should detect false information and then ignore that information or inform the higher level about the failure. Thus, failures in sensing and communication are also handled in this part.

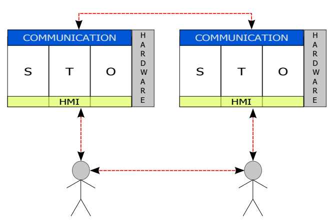
Environment perception or sensing could exist both in vehicles and infrastructures. Vehicles in C-ITS are usually equipped with sensors such as radar, camera, light detection and ranging (LiDAR), global positioning system (GPS), etc. A goal for this part is to perceive information about surroundings e.g. to detect and locate other vehicles, vulnerable road users (VRU), obstacles, cooperative partners, lane markings, etc. In case the vehicles maintain a local map of the surroundings, another goal is to locate itself in the environment through these sensors.

Decision making is an important part of C-ITS to select upon strategy and tactics of the systems based on the information gathered via sensors and communication. C-ITS can have either centralized decision making parts placed in the infrastructure or in a vehicle responsible for a group of vehicles. Alternatively, the decision making could be distributed and decentralized among vehicles and infrastructure. In a complex system both could be used at the same time in combinations such as distributed over the country but centralized within local areas. Decision making can be divided into short-term, mid-term, and long-term decision making. For instance, short-term decisions are, e.g. manoeuvres for collision avoidance, lane change, etc. They usually need information from the communication module in real-time, otherwise it could be dangerous to the system. For example, the driver receive the notification about a manoeuvre too late, and could not react in time, which might lead to an accident. On the other hand, route choice of a trip is an example of long-term strategic decision making.

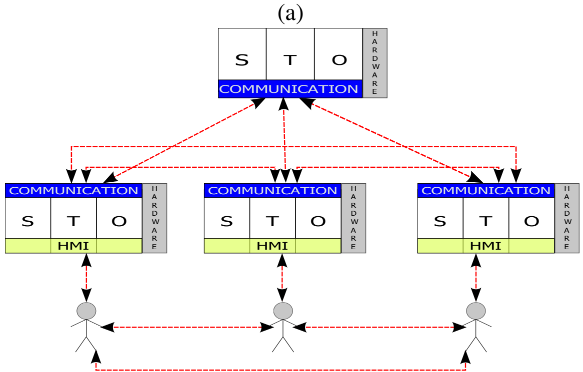
At the highest level of automation, actuators, i.e. throttle, brake, and steering wheel, would be totally controlled by the system. However, at the lower level of automation, the human driver is still involved and have effects in this part as well. Especially at levels that are partly automated, the human drivers will have interactions with the decision making part via human-machine interface (HMI) possibly including haptic feedback by force on steering wheel. Moreover, according to the "convention on road traffic" from Vienna 1968 [25], which aim to set up international uniform traffic rules, *"every driver shall at all times be able to control his vehicle or to guide his animals"*. Thus, if the future policy will follow this rule, the human driver shall always have priority to decide and override the manoeuvre decided by the system.

Lastly, the human driver, interact with the system through its HMI. The human driver, responsible for all driving tasks, has the highest priority to decide and override the decisions from the automation system. Still, some systems such as advanced emergency braking system (AEBS), or anti-lock braking system (ABS), the system override the human driver's decision. By interactions between the human driver and the system through HMI, the driver will understand the intention of the system and vice versa. Moreover, having access to the communication part allows the driver to make requests to cooperative partners as well as to respond to requests. For example, as elaborated in [14], in the cooperative lane change scenario, although the request is initiated by the software function in a vehicle, the driver in another vehicle could decide, and confirm through HMI to the first vehicle that the request is accepted.

IV. Dimensions of Cooperative ITS



(a)



(b)

Fig. 2: Cooperative ITS with two and four actors respectively, interactions are indicated with red dotted lines.

Cooperation between two actors in C-ITS is illustrated in Fig. 2a with the red dotted lines representing possible interactions. The hardware box includes sensors, actuators, communication devices, computers, and user interfaces. There is usually at least one vehicle among the actors, and the other could be another vehicle or a road side unit. In case of cooperation between a vehicle and infrastructure, there is no interaction between the human operators. Cooperation between the vehicle and the infrastructure is usually aimed to assist the driver of the vehicle by providing extra information. In other words, it is typically a one-way communication from the infrastructure to the vehicle. Examples of use cases defined in [26] are: speed limit notification, traffic condition warning, point of interest notification, etc. The next step is when both actors are vehicles. This step includes more advanced scenarios such as cooperative lane change, motorway merging, intersection crossing, etc. Once the number of actors increase, the systems become more complex as illustrated in Fig. 2b. Moreover, if the vehicles are operating at different levels of automation, the interaction become even more complex.

The communication, which enables interaction and leads to cooperation, can be divided into three levels: *a*) human interaction; *b*) one-way wireless communication; and *c*) two-way wireless communication. Today, interaction between human drivers by means of conveying vehicle behaviour is performed via turn signal, vehicle horn, vehicle direction and position, etc. To enable interaction and communication within the transport system, drivers combine vehicle behaviour with eye contact and body language. Moreover, FM-radio sometimes acts as a road side unit providing warnings regarding traffic information. However, as of today, none of the above can communicate with automated vehicles. Thus, the one-way and two-way wireless communication provide channels to interact with and between automated vehicles. Normally, in one-way communication the warning would be sent to the vehicles and it depends on the driver or the automation system to react to the information. Hence, the action rely on the driving behaviour of the driver or the system. With two-way communication, more interaction such as acknowledgement and negotiation is possible. Therefore, it would be able to utilize the benefits of C-ITS.

Although complexity of C-ITS can be defined by many different factors as mentioned above, in this paper, the three dimensions considered important are: *a*) the number of cooperative actors; *b*) the driving task (planning horizon); and *c*) the scope of cooperative benefits.

Starting from two actors, which is the basis of C-ITS, adding more actors to the system will result in a more complex system as illustrated in Fig. 2b. Interaction between actors in the C-ITS is typically realized through wireless communication. More actors will require more reliable communication, more bandwidth and maybe even broader communication range. Furthermore, handling uncertainties created by the actors will also be an issue.

The cooperative function and its interaction behaviour also influence the complexity, depending on which kind of driving tasks it solves, i.e. operational, tactical or strategical. Moreover, depending on the function, different type of interaction is required. For example, CACC operates at the operational level and once the platoon is set up, no interaction between drivers is required unless there is a failure. On the other hand, cooperative lane change, which operates at the tactical level, requires interaction between vehicles and drivers at many different stages e.g. making lane change request, the driver determines situation and accept/reject the request, etc.

Another perspective is to classify the function based on its goal, i.e. comfort, economy, and safety. Comfort represents typical driver's assistance systems such as intelligent speed adaptation, traffic sign recognition, wrong-way driving warning, etc. Economy has the goal toward more efficient usage of road space and fuel consumption. For instance, CACC, platooning, highway merge function, etc. Lastly, functions with safety as the goal, usually have the highest complexity due to time and reliability constraints. For example, cooperative intersection collision avoidance systems (CICAS), cooperative lane change, etc.

Cooperative functions may sometimes fulfil two or more goals. The scope of these cooperative goals would have a significant impact on complexity. The scope is divided into three different levels: global, local, and individual. The global scope would give more priority to achieve better traffic flow and reduce congestion. For example, optimizing traffic flow of a whole highway. While, intersection, highway merging, cooperative lane change are examples at the local level. Although some "self-interested" agents could cheat and take advantage of cooperative systems as presented in [27], cooperation to make way for an emergency vehicle is a good example at the individual level.

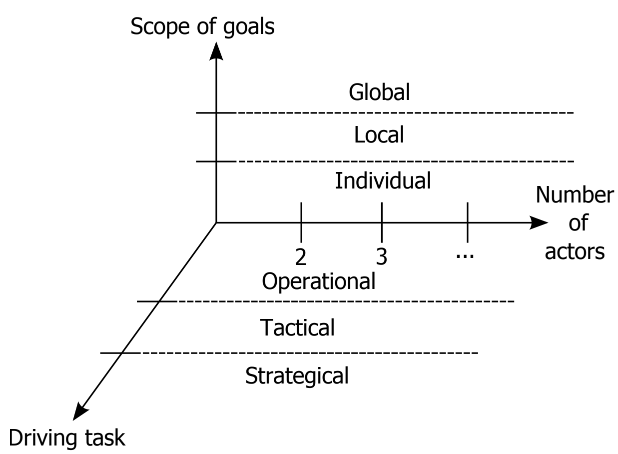


Fig. 3: Dimensions of cooperative ITS

Figure 3 illustrate three dimensions of cooperation. The complexity and the need for communication and cooperation grows as the system move away from the origin in any dimension. Automated driving functions help the C-ITS to achieve cooperation and vice versa.

V. Challenges

So far most research within cooperative driving and C-ITS deal with vehicles having the same level of automation. For instance, vehicles in the systems are all equipped with similar sensors, vehicles operate at the same level of automation, in other words, they have the same capabilities. On the contrary, considering real driving situations, cars with different capabilities are mixed in the traffic. There are many challenges already, even in current traffic situations, where driver's behaviour is a major difference. In the future traffic environment, where new and old cars meet, we would expect vehicles equipped with automated driving applications and communication facilities driving smoothly alongside older vehicles. Besides levels of automation, communicating vehicles from different companies, or different software version of the same cooperative function are other interesting scenarios. Seamless cooperation and interaction between such diverse vehicles are one of the challenges in C-ITS deployment. Apart from cooperation in the systems, interacting with non-cooperative vehicles, telling that there is cooperation, or automation going on, may sometimes be necessary. For example, using a special light signal to inform non-cooperative manually driven vehicles.

Safety is another important issue to address, which can be seen from many perspectives. First, perception failure or malfunction in a vehicle may mislead other vehicles in the system by feeding wrong information into the system. This issue is one example of hazardous events that could occur in the vehicle according to the standard ISO 26262 [28]. With more automation involved in the system as mentioned before, perception failure create risks which could lead to hazardous events. For instance, automated braking systems that suddenly brake the vehicle, or a lane keeping aid function that perform incorrect steering. Another perspective is safety, related to the transition to manual driving if the automation fails. For example, with an automated driving function like CACC, the driver might not always pay attention to the driving tasks. If the system fails and requires the driver to intervene in order to prevent hazardous events, one risk is that the driver is not alert enough to handle the situation. Thus, it could lead to an accident. There are some studies that already considered this issue, for example, [29] propose an architecture that separate applications into manageable and easy to test pieces and also use a communication protocol for collaborative vehicle control.

The larger the C-ITS becomes, the broader and more reliable communication coverage is needed. With such different capabilities as pointed out above and diversities among manufacturers, a standard set of rules are needed, especially in describing the behaviour of cooperative vehicles as elaborated in [24]. The paper used platooning, emergency vehicle warning and intersection scenarios as examples to illustrate lack of common abstraction to describe cooperative vehicle behaviour, for example, it is not clear in the current standard message format how the vehicles should manoeuvre.

One way of representing automation in cooperative driving is to apply the concept of multiagent system (MAS). Agents have suitable characteristics to represent actors in transport systems, which are autonomy, collaboration, and reactivity, as elaborated upon in [30]. Agent technology in traffic and transport systems are presented in [30]. Modelling and simulation are usually the main focus of agent-based applications. However, despite the long list of examples, only a few applications are implemented and deployed in real-world traffic. In conclusion, there are plenty of examples that relate cooperation with automation. Numerous promising simulation results were reported from those projects. Yet, only few were realized in real-world demonstrators. Thus, closing the gap between the simulation world and the real one is another challenge to be considered.

Last but not least, testing of cooperative driving functions is a challenging task within the area. C-ITS introduce numerous new possibilities and scenarios, testing all of them is nearly impossible. Therefore, ensure that "sufficient" tests have been done is seen as another challenge.

VI. Conclusion

This paper first presented C-ITS from two different perspectives: behavioural, and structural. From the behavioural perspective, C-ITS can operate or assist the driver on three levels of driving tasks: *a*) strategical *b*) tactical and *c*) operational. From the structural perspective, components within the actors in C-ITS, in relation to the behavioural perspective, are presented.

Moreover, the main factors to be considered for C-ITS classification are proposed as three dimensions of C-ITS: driving task, scope of goals, and number of actors. The scope of goals is the result of actors' behaviour and may be limited by the structure of the actors in the system. The number of actors reflects on connections and interaction complexity of the structures in the system. Besides, the relation between the driving task dimension, the behaviour perspective and the planning(time) horizon to solve the driving tasks, is seen as another perspective. Lastly, the challenges in the C-ITS deployment are also elaborated upon.

Interactions between cooperative partners and their drivers are a major contributor to successful cooperation. Especially automated coordination between vehicles with different capabilities is seen as one of the challenges.

In spite of the perspectives and challenges covered in this paper, implementing C-ITS is a great challenge with many issues. The presented analysis of C-ITS and dimensions of driving cooperation in relation to levels of automation is intended to provide a basis for future works regarding C-ITS.

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