

Cooperative Driving: A Comprehensive Perspective, the Role of Communications, and its Potential Development

Renato Lo Cigno^{a,*}, Michele Segata^b

^aDepartment of Information Engineering (DII) — University of Brescia, Italy

^bFaculty of Computer Science, Free University of Bolzano, Italy

Abstract

Inter-vehicle communications may have many reasons to be, but improving road safety and efficiency is arguably the only reason that may differentiate them from other communication infrastructures and justify a special effort in their study and deployment. This work overviews (some of) the past research on the topic to draw some lessons for the future, and tries to dissipate some of the fog that still veils the future of cooperative and autonomous vehicles: Can communications improve mobility or selfish-autonomous vehicles will dominate roads in the future? The paper is not a survey, but rather a critical analysis of what Cooperative Driving (CD) means and how communication is essential for some functions and useful for others, never detrimental. We dedicate a special part to platooning, as iconic application of CD, one of the most studied and also closer to be market ready, at least technologically. A final section discusses the potentialities of CD and what threatens its adoption.

Keywords: Vehicular Communications, Cooperative Driving, V2X

1. Introduction and motivation

Vehicular networks and cooperative driving are research topics that we can now hardly define *new*. Yet, after many years both fields remains actual and open, and the cross-disciplinary work that is needed to pursue the ambitious goal of improving road mobility and make it socially and economically sustainable is still largely not explored and extremely interesting.

Let's first of all clarify what this paper *is not*: It is not a survey on vehicular networks or any other acronym or synonym ever used for it, it is not a tutorial on autonomous and cooperative driving, and it is not a retrospective on (vehicular) distributed control systems. Our goal is to provide a systemic vision of the broad topic of cooperative driving, leveraging and revisiting some of the work done in recent years by us and many other researchers, discussing critical points needed for the adoption of the technology for the benefit of society, and trying to figure out the perspectives lying ahead and the areas where more research and innovation is needed to go beyond the state of the art.

The contribution of this work has several facets. On the one hand it provides a comprehensive overview of what we reckon Cooperative Driving (CD) to be, highlighting that the scope of CD has been artificially limited and restricted mainly because early research focused only on the cooperation of vehicles (cars, trucks), disregarding the interaction of vehicles with the other road users, motorcycles, bikes, pedestrians, and more. On the other hand it discusses the (essential) role of communications to

gain effective and safe cooperation, and stresses how the debate on which technology is the best for vehicular networking has relegated on the background a simple truth: One technology will never be able to achieve the sufficient reliability, and most of all dependability, to sustain life-saving technologies and applications. A special attention is finally given to platooning as it is so far the CD application that received more attention, even if it is a relatively simple one.

The remaining part of the paper is organized as follows. Sect. 2 provides an analysis and synopsis of CD with a wide perspective, highlighting how future smart cities and smart mobility cannot prescind from CD. Next, Sect. 3 presents a wide categorization of scenarios and applications where CD can benefit traffic and society. Sects. 4 and 5 discuss the role of communications in CD, highlighting the limitations of simple autonomous driving and reasoning on the characteristics that different technologies should (or may) have in relation to applications and actors within the scenario. Sect. 6 does a vertical dive into platooning, exploring the many proposals put forward and hinting to the possibility that different methods and controllers can co-exist on the road, a possibility that may open the market even without intervention of the regulators. Sect. 7 ends the paper with final considerations and reasoning on the work ahead in this exciting research field.

2. Cooperative driving: A synopsis

A lexical analysis of *cooperative driving* indicate there is a tautology: We all cooperate when driving, otherwise we crash with other vehicles. So, what are we talking about? Indeed, the recent evolution of the automotive sector has seen an enormous

*Corresponding author: Renato Lo Cigno, Dept. of Information Engineering, University of Brescia, Via Branze 38, 25123, Brescia, Italy. email: renato.locigno@unibs.it
Email address: renato.locigno@unibs.it (Renato Lo Cigno)

hype on *autonomous driving*. The Society for Automotive Engineering (SAE) has defined the levels of autonomy [1], but has not specified any communication requirement for autonomous vehicles¹. Outside the scientific community, Tesla CEO Elon Musk advocates for autonomous cars that drive using only cameras to mimic the behavior of human drivers². We are playing with words, and also the final statement we come to sounds like an oxymoron: Autonomous driving must be cooperative, and explicit communications can boost cooperation beyond any level reachable with pure inference. Lets elaborate more on this concept.

First of all, it is clear that autonomous driving refers to vehicles that drive without the intervention of a human being, not without interaction with the surrounding environment, other vehicles, and Vulnerable Road Users (VRUs). However, aiming at improving safety and autonomy of cars, the automotive industry is focusing much more on on-board sensors rather than considering even very simple communications based on beacons like Cooperative Awareness Messages (CAMs) [2] to distribute already defined application-specific messages therein or a richer set as defined by SAE [3]. The reasons of this attitude remain unclear. Fig. 1 provides four typical contexts of smart mobility, developed in more detail in 3, where we think CD is fundamental and where inference based on on-board sensors will be, in our opinion, always less efficient and less effective that cooperation based on explicit knowledge and communications.

The top drawing of Fig. 1 describes what is often considered the only application of CD: Platooning on a highway. We dedicate a specific section to platooning, as this is possibly the application that has received the most attention from the community, with the promise it carries to improve safety, reduce fuel consumption due to airdrag reduction, but most of all, even if not always stated, improve the infrastructure usage, reducing congestion and liberating authorities from the need to build new road infrastructures. We discuss there how platooning without communications is almost impossible, but most of all its impact on infrastructure usage, without communications, is irrelevant due to theoretical results on string stability.

The second row of Fig. 1 extends the idea of platooning to sub-urban and rural roads, where crossroads are present and where possibly VRUs are present in the scenario. Crossroads are a constant part of the scenario, and vehicles destinations are more varied and dynamic, requiring more frequent platoon formation and maneuvering.

The scenario in the third row of Fig. 1 envisages a situation

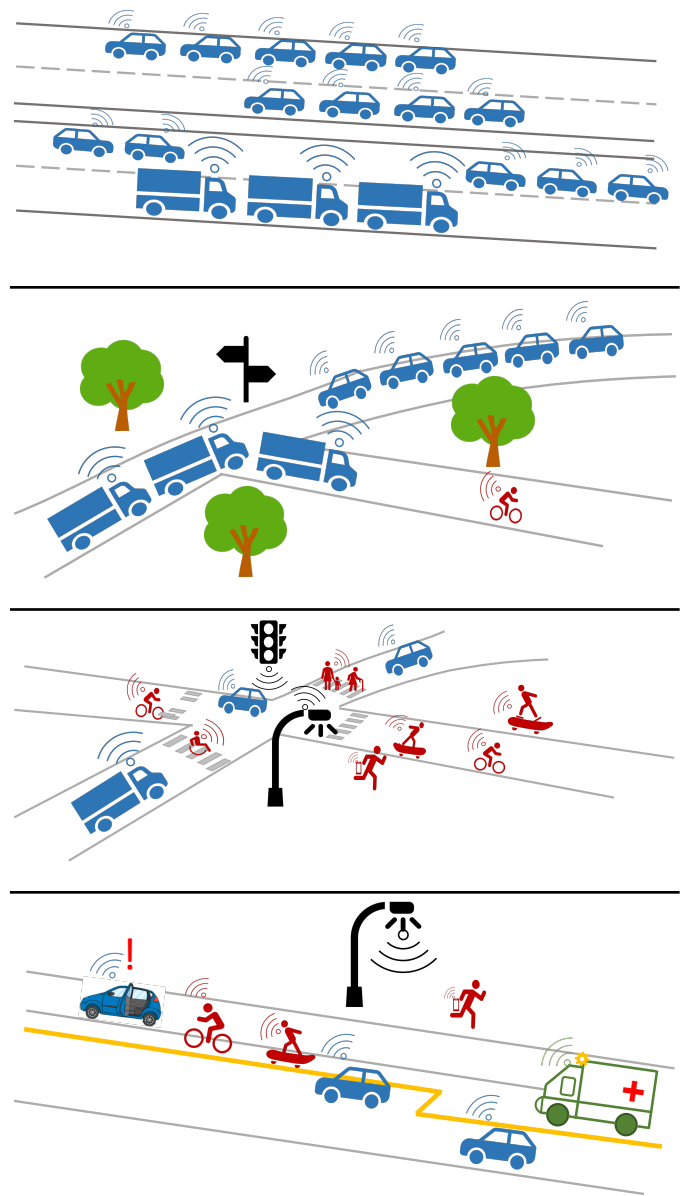


Figure 1: Examples of cooperative driving: Highway platooning on top; Sub-urban cooperative driving in the second row; Urban coordinated crossroad in the third row; and Lanes for a virtual infrastructure at the bottom.

where communication enables advanced, cooperative sensing and distributed machine learning leading to collaborative decision making. Urban scenarios are always more complex than highway or rural ones, and smart urban mobility implies co-existence on the same infrastructure of many different users, including bikes, e-kick scooters, and in general VRUs, who are very often the victims of road accidents, since they do not have the protection of the vehicle. Coordinating a crossroad may seem a simple task, but it is not, and it is fully part of a CD approach where vehicles interact with VRUs of many sorts, and where some of the actors, for instance elderly people, may not be part of the collaborative decision, but represent constraints of the decision problem and have to be properly sensed and communicated to all the cooperative actors.

¹An initial effort by SAE to define communication requirements for CACC systems is stuck since 2015 as work in progress and no information is available on the progress (<https://www.sae.org/standards/content/j2945/6/>).

²In Dec. 2021 Elon Musk declared that autonomous cars should rely only on cameras mimicking the human eyes (<https://www.businessinsider.com/elon-musk-demanded-cameras-over-radar-in-self-driving-cars-nytimes-2021-12?r=US&IR=T> - last visited April 2022), renouncing to radars, LiDARs (LiDARs) and any other technology, without even mentioning communications. The position spanned discussions and technical concern in the economic and regulatory world (<https://www.calcalistech.com/ctechnews/article/rkgdmipfq> - last visited April 2022), with re-positioning of industries that produce sensors and other ranging devices.

Finally, the bottom picture of Fig. 1 presents a more advanced and complex situation, where cooperation enables the definition of virtual lanes. In many places, e.g., historical centers, it is not possible to build physically separated infrastructures for VRUs, for instance a bike lane, very often marked with a simple yellow line, sometimes between the carriage way and parking slots: an extremely dangerous situation. Appropriate communication and cooperation empowers the concept of *virtually separated infrastructure*, in the example a virtual bike lane, whereby vehicles are appropriately informed of the presence of bike lane users and automatically respect the space dedicated to the virtual bike lane. Additionally, as shown at the right of the drawing, the virtual bike lane can double as an emergency lane, widening as an ambulance arrives and passes.

The latter two scenarios are more often described in the context of Artificial Intelligence (AI) [4, 5, 6], Edge Computing (EC) [7, 8] or more recently Edge Intelligence (EI) [9] and AI-Human interaction [10, 11]. We agree that they go beyond classical control of distributed systems or consensus theory, and they do require novel coordination approaches. Still, we claim that communication is essential for their possible success, and it is fully part of a CD approach, where autonomous vehicles dialogue with less-autonomous, human-centric mobility means, including all-human foot-goers, to empower smart mobility. One may be tempted to state that CD and smart mobility are synonyms, but we disagree, as this latter term is customarily used to identify also novel mobility models, technological improvements, and even simple informational systems allowing better choices and strategies for the end users, while CD strictly identifies situations where a local cooperation among sentient and communicating agents lead to better and safer mobility.

This simple discussion clarifies that cooperative driving is a broad topic with slightly blurred contours. At the same time it is clearly defined by all the situations where explicit communication can help (or is essential to) improve road mobility. Scenarios must include also the infrastructure and road users that are not on vehicles, and that are often the victims of accidents due to absent/bad traffic management. Identifying CD strictly with specific applications like platooning, virtual traffic lights, and similar contexts that include only vehicles reduces the scope of cooperation, artificially separating scenarios that are instead naturally intertwined, eventually limiting the advantages of cooperative road usage, specially in urban contexts where instead the advantages of smart, cooperative mobility can have the largest impact.

3. Applications and their requirements

The list of applications that falls under CD is long, and it does not make sense to try to enumerate them here. The goal of this section is to provide a coarse classification of applications, grouping them by their qualitative requirements, Sect. 4 starts from this classification to analyze what is the role of communications in the different application classes.

3.1. Highway driving

CD has often been limited to this area of application, mostly because of its simple layout and well defined concepts: separate carriageways, two or more lanes per direction, limited and controlled access to the infrastructure. Specific applications on highways can often be isolated, abiding to the traditional engineering *divide et impera* approach. Emergency braking, for instance, can be introduced independently of other applications or services. Indeed, many vehicles today have emergency braking assistance, mostly based on radars or cameras. Lane assist is very similar, the only form of coordination is between the vehicle and the infrastructure and not with other vehicles.

Simple platooning can also be introduced in total autonomy. Two or three trucks that form a “road train” traveling for tens of kilometers only need regulatory permission, as they do not really need to interact with the rest of the traffic in any way different from standard trucks, at least as long as the driving control is taken over by a “standard” driver (human or autonomous) for any action of maneuver that is not simply following the highway in packed formation.

Clearly as soon as we start reasoning in a broader context things change: How can vehicles enter and exit a highway without proper coordination? How do platoons form (or dismantle) on the highway? What is the best traffic configuration to maximize safety and minimize travel time?

Overall, we can clearly see a crescendo of coordination requirements, i.e., of substitution of human inference, as highway CD moves from elementary actions (lane following, braking), to more complex actions (driving vehicles very close one another to spare space and fuel), to smoothly merging and splitting flows of vehicles, properly distribute them along the infrastructure with strategic management of travel requirements, as for instance temporarily reduce (or increase) the cruising speed of isolated vehicles to form stable and efficient platoons. Some of these requirements have a local scope (surrounding vehicles, presence of lanes), while more complex ones have broader scope (many vehicles for joining / exiting the highway, splitting / merging flows at intersections). Traffic management, finally, requires data and intention collection (destination, desired speed, ...) and proper decision-making to fulfill the different demands.

Reliability of information and decision-making is always a requirement, but latency is not an issue: even an emergency braking due to an accident or similar can happen in hundreds of ms, and this is implicit in the dynamics of vehicles, where the mass inertia, and the protection of passengers from excessive acceleration dictate the maximal speed of intervention. Latency is not stringent, but clearly all the scenarios we discussed do have soft real-time requirements. An emergency braking action can start after a delay of 50 ms to 100 ms (less than this is prohibited by the mechanics of the brakes and vehicle), is still valid after 200 ms to 400 ms, but it is definitely too late after 2 s to 3 s. Merging at an highway entrance can have a space uncertainty of a few meters, translating in a latency for corrections commands of a few tens of ms, but definitely not seconds, at least not at highway speeds of 90 km/h to 130 km/h.

3.2. Rural and sub-urban driving

As soon as there are no separate carriageways and traffic has less access restrictions to the infrastructure, CD concepts become more complex and applications can be identified, but often blur one into the other. Road crossings and roundabouts require a coordination effort which goes well beyond highway platooning, and although very often applications are analyzed in isolation (see [12, 13, 14, 15]) it is clear that a platoon approaching a crossing naturally intertwines the two applications. Even a simple, e.g., two- or three-vehicle platoon driving a lightly loaded rural road may incur into additional requirements. How does a platoon behave, for instance, if a very slow vehicle, maybe a tractor or a bicycle occupies the lane? If it is a bicycle, moreover, it belongs to the category of VRUs, which are obviously present not only in urban environments but also in sub-urban ones, and they can be, in these scenarios, unpredictable and out-of-context.

Indeed, it is exactly the higher probability of out-of-context situations that create the most difficult challenges for CD, as they also do for human drivers and for autonomous vehicles as the few accidents with autonomous vehicles prove.³ Thus, compared to highway scenarios, suburban ones require more complex and sophisticated strategies, which means more data, collected with higher reliability, and improved situational modeling.

It is very important to understand that more complex and less predictable scenarios require more reliable and dependable information to allow decision making. Compared to highway scenarios, sub-urban ones do not require a smaller latency in data acquisition, nor necessarily a much larger quantity of data, but the quality of the information that can be retrieved from this data must be much better, and this applies both to transmitted data and to sensory data. If on-board sensory in a highway must distinguish between trucks, cars, and motorcycles, in a suburban scenario it must distinguish a moped from a bike, and a boar from hare at night: The former require emergency braking to avoid serious accidents, the second maneuvering to try to spare it, but it does not endanger a vehicle and its passengers.

3.3. Urban mobility

If in highway scenarios the concept of “CD application” is clear, and in sub-urban scenarios it is still valid, urban mobility does not easily lend itself to a clear subdivision into specific applications. Several papers have addressed the topic of urban platooning [16, 17, 18, 19], but it is clear that it is impossible to isolate any CD application from the others: How do we manage a platoon without considering crossroads and roundabouts in a city? How can we imagine CD applications that do not involve VRUs in urban scenarios? Fig. 1 in Sect. 2 envisioned a cooperative crossroad where all actors cooperate to make it safe and efficient. What has not been discussed there are the

wide implications of the scenario. It is clear that such scenarios go beyond the traditional engineering modeling, and require the widespread applications of Machine Learning (ML) and AI techniques. Several authors discussed these scenarios and their potential, envisioning different techniques and proposing potential solutions [6, 20, 21, 22], but clearly the topic is still wide open and in its infancy. As we and several others highlighted in previous works [9, 23, 24], the application of automatic inference techniques has to deal in this case with unprecedented requirements on latency, predictability (the outcome of the inference is a decision that influences all the actors in the scenario) and dependability. This latter point is often disregarded, or not fully discussed in works on cooperative urban mobility, but it is clear that any algorithm, be it classic, fuzzy, based on centralized or distributed learning, or whatever other approach one may take, the fundamental constraint it must respect is dependability in face of safety: If a vehicle has to stop, brake, or steer to avoid a VRU the decision must be consistent and correct. A reliability (correct decision) of 99.999 % is useless if the algorithm fails the single time when an error results in an accident with casualties. This is, in our opinion, the most challenging issue in urban mobility: To devise CD systems that are more dependable than human judgment.

In urban scenarios, however, there exist a number of applications that are related to driving at large, but do not imply real time cooperation. Parking lots management, route optimization, and many similar services benefit from a cooperative approach and in general require vehicular communications. Actually, the more autonomous vehicles are, the more they benefit from explicit coordination and cooperation with other vehicles and the infrastructure even for these simple “side” services.

3.4. Virtual infrastructures

In some ways related to all the scenarios discussed above, but conceptually separated, is the idea of virtual infrastructure. The idea of virtual traffic lights is possibly the first one that was discussed [25, 26], but it is still an open research topic [27]. However, as we depicted in Fig. 1 there are many other infrastructures that can be virtualized, at least in scenarios where the physical realization of the infrastructure is impossible, too complex, or simply too costly.

In general, all road signs can be virtualized, helping human drivers to be aware of them, and enormously simplifying the task of autonomous vehicles. Notice that virtualizing an infrastructure does not always imply that there are no physical indications. As in the example of the virtual bike lane in Fig. 1 the lane is marked with a suitable yellow line, the virtualization is an enhancement of a physically limited demarcation. Further examples extend to the “creation” of virtual emergency lanes in case of accidents where they are not available, i.e., in any road infrastructure but highways, the dynamic use of lanes in urban highways depending on traffic, we can call this *virtual Jersey moving* and any other situation where a specific infrastructure is needed either for a temporary laps of time, like roadworks, or where the virtualization can enhance the physical one or empower better services and applications.

³Vehicular accidents outside highways seems to be mostly related to misjudgment of uncommon situations as the analysis of accidents show (<https://www.iotworldtoday.com/2021/10/20/blame-the-humans-idtechx-finds-99-percent-of-autonomous-vehicle-accidents-caused-by-human-error/>). Often they are blamed to “distraction”, but it is highly probably that what is called distraction is indeed lack of training and experience: An uncommon situation was probably never seen before.

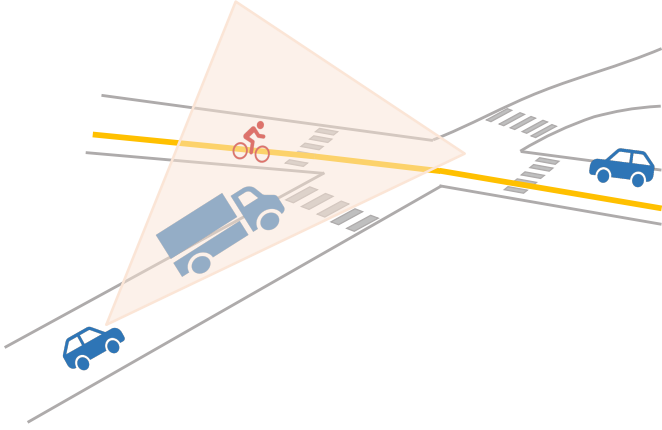


Figure 2: Communications are essential to protect VRU as on-board sensing can be limited by obstacles and impairments.

4. Role of and opportunities for communications

We have deliberately not discussed communications or networking in Sect. 3, because we think this discussion deserves a place of its own. The qualitative requirements we set categorizing applications were in term of information latency, data reliability and quality, and so forth, without discussing the source of this information and data or how it is collected.

The automotive industry trend seems to point toward autonomous driving fully based on on-board sensors, limiting the role of communications to telemetry and software upgrades. We recognize the role of on-board sensors, from cameras to radars, LiDARs, and any other device that can help a vehicle to perceive its surroundings and monitor other actors (vehicles, VRUs, obstacles, etc.) on stage, but we think that communication is essential for proper cooperation.

There are two main reasons that make communication essential. First of all, communication can distribute information beyond the sensing range of a single vehicle, thus extending the perception of any decision-making algorithm. This seems to be fully recognized, at least implicitly, by all the works that deal with cooperative sensing, distributed learning, and similar concepts (see for instance [28, 29, 30]). The second reason, elementary and foundational for proper cooperative driving, is that through communication vehicles and humans can exchange facts, intentions (e.g., trajectories), and certain data, while in many cases sensors can only retrieve indirect information that is interpreted by an ML structure to infer behavior.

The first reason is sort of obvious, as exemplified in Fig. 2, where a truck blocks the visual line between a bike, with right of way, and a car. Any distraction or judging mistake based on missing (or false) sensing may lead to a collision, with fatal consequences for the VRU. These situations have been analyzed in many works (see for instance [31, 32]), but how to properly coordinate vehicles, VRUs, and other road users is still a fully open question.

As a second example to appreciate the difference between sensor-only and cooperative driving solutions, we show the results for an emergency braking scenario obtained with PLEXE [33]

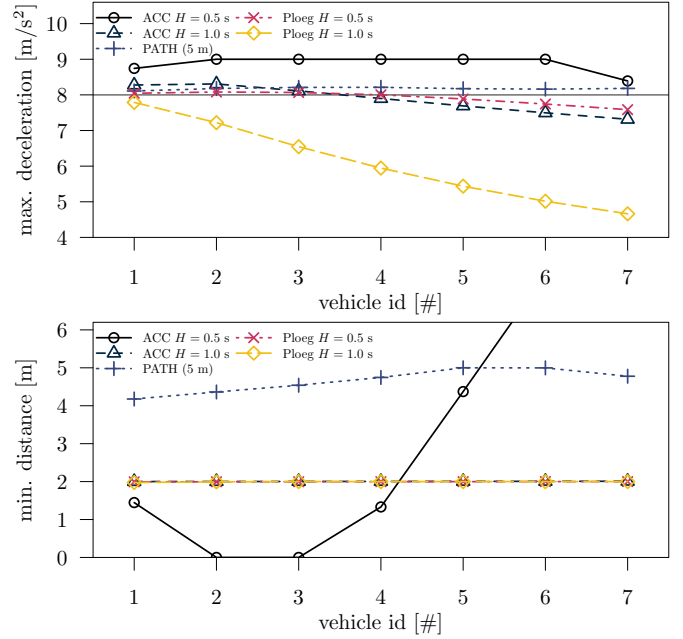


Figure 3: Reaction to emergency braking (braking deceleration 8 m/s^2) of a group of 7 automated vehicles with and without communications; top plot maximum deceleration, bottom plot minimum inter-vehicle distance during the maneuver.

for a string of 8 vehicles. The automated vehicles drive at a constant speed of 100 km/h following a common leader using one of the control algorithms later described by Eqs. (1) to (3) in Sect. 6. The first vehicle brakes with a deceleration of 8 m/s^2 reaching a complete stop. We test both a sensor-only based solution (Eq. (1), namely an Adaptive Cruise Control (ACC)) and the cooperative driving-based solution designed by Ploeg (Eq. (2), a Cooperative Adaptive Cruise Control (CACC)) with time headway of $H = 0.5 \text{ s}$ and $H = 1 \text{ s}$. In addition, we consider the cooperative driving CACC developed within the California PATH project (Eq. (3)), which uses a constant inter-vehicle gap of 5 m . In addition, we enforce a physical deceleration limit of 9 m/s^2 , realistic for commercial light vehicles and larger than the actual braking deceleration. The headway time is the “distance” in time from the preceding vehicle. A smaller H corresponds to a more aggressive driving style, but also to smaller distance between vehicles leading to reduced fuel consumption and more efficient infrastructure utilization.

The Ploeg CACC replicates the same vehicle following algorithm of standard ACC, but, since it is communication-enabled, it works based on the driving inputs of the vehicle in front (certain data) instead of using the measures coming from a radar device (or a set of cameras, results would not change) that are necessarily delayed compared to driving inputs, and affected by measurement errors. The PATH CACC is instead a more sophisticated system, allowing a constant distance between vehicles independent from the cruising speed thanks to the use of information coming not only from the vehicle in front, but also from the first vehicle of the string. Refer to Sect. 6, for the formal definition of the controllers and their parameters.

Fig. 3 shows the results in terms of maximum measured decel-

eration and distance, for each follower vehicle in the string. For the sake of clarity, the acceleration plot displays a horizontal line marking the constant deceleration of the first vehicle (vehicle 0). We start by observing the behavior of the ACC for a time headway of 0.5 s. The deceleration of the majority of the vehicles hits the physical limit causing vehicles 2 and 3 to collide with their predecessor. When there is a collision PLEXE stops the simulation, so the minimum distances of the other vehicles are not significant. Comparing these results to Ploeg (same time headway), we can see that all vehicles roughly brake with the same deceleration and all stop at the stand-still distance (2 m). The PATH CACC performs similarly in terms of deceleration: Vehicles safely come to a halt with a stop distance always larger than 4 m.

The key result is that an aggressive ACC system leads to rear-end crashes, as shown by the minimum distance equal to 0 m in the lower plot of Fig. 3. The same does not happen with Ploeg’s CACC with $H = 0.5$ s, showing that the use of communication naturally solves a problem even without changing the behavior of the system. The minimum distance of 2 m for both Ploeg’s CACC and for ACC with $H = 1.0$ s is the desired stand-still distance between vehicles. The acceleration on the top plot also shows how the PATH CACC maintains a constant deceleration for all the vehicles, equal to the deceleration of the first vehicle. To use the ACC in a safe configuration we need to resort to a larger time headway, as shown in the results for $H = 1$ s. In that case, the ACC safely brings the vehicles to a stop, but if we look at the acceleration for Ploeg using the same time headway, it becomes progressively smoother towards the tail of the string. So, not only cooperation can guarantee safety at smaller inter-vehicle distances, but it also increases comfort for larger gaps.

The second reason has been less discussed and seems often ignored in the debate on autonomous and cooperative driving, with an implicit reasoning that “sensed data” is more reliable than “communicated data”. We disagree, and we think with good reason. Let’s start from a tragic event that killed Elain Herzberg in March 18, 2018 in Tempe Arizona while she was traversing a road pushing her bike outside a crosswalk.⁴ Forensic analysis defined that sensors on board had actually “seen” Ms. Herzberg, but the system failed to recognize the situation as dangerous and requiring emergency braking. In other words, the sensed data was there, but the inference (or AI) algorithm interpreting them somehow stalled and did not take the right decision. Needless to say that a simple CAM stating the presence of a pedestrian or bike would completely solve the problem: Certain data, no ambiguity to stall on.

The example above is possibly extreme and due to infancy problems of self-driving. Maybe, but while someone like Elon Musk thinks that autonomous vehicles should drive exactly like a human being, we think that CD should do much better than that: Recall that 95 % of car accidents involve human errors [34]. Explicit coordination based on communicated data and *decisions*

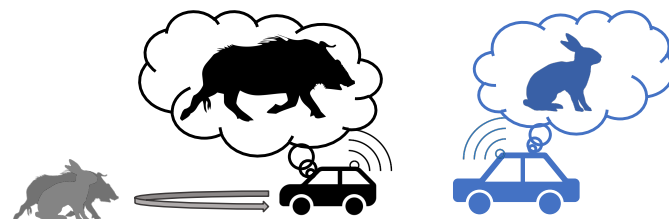


Figure 4: An obstacle, possibly a wild animal, is detected by one car that communicates with a following one: What data should be exchanged and how should it be used?

is fundamental to reduce, ideally to zero, errors and wrong decisions. We stress here the concept of *decisions*, i.e., actions that are going to be undertaken by road users. To highlight this concept we use an example stemming from arguing at a Dagstuhl seminar [35], and use it to discuss what data should be exchanged among CD actors and how do they use it to take driving decisions.

The Boar & the Hare. Consider the situation depicted in Fig. 4. Two cars are following each other possibly with low visibility. The one in front detects, by radar or cameras, a shape in front of the car, a wild animal or other, difficult to distinguish in low visibility. The following car, brand new and luxury, cannot obviously detect the obstacle, thus should be informed by the car in front, cheaper and older. This is a typical case for cooperative perception, but what data should the cars exchange? Many think that cars should share raw data (radars & cameras & beyond), so that each car can build its own perception of the environment and act consequently, with the implicit thought that luxury cars will have better systems and decide for the best, giving vendors commercial advantage. This is however a selfish attitude, not a cooperative one, and may lead to dangerous situations. For instance, the AI-based perception of the car in front leads to think the obstacle is a wild boar, thus collision should be avoided at any cost, and prepare either for emergency steering or emergency braking. The system of the following car, instead, decides that the obstacle is a hare, prepares to try to avoid it, but its ethics system considers that a collision is possible and preferable to maneuvers considered more dangerous.

It is evident that different processing on the same raw data can lead to diverging decisions when *inference* is involved, and diverging decisions can lead to stalls and very dangerous situations. Ideally, the two actors should exchange both raw data and decision-making steps, leading to a common decision with distributed learning and processing, but until this is not feasible, possibly simple, pre-processed information also requiring less resources are preferable.

The role of communications for the general coordination problem is enabling the distributed intelligence system that can finally lead to a really smart and safe mobility environment. In other words, communication is a necessary condition, but not a sufficient one, as the modeling and analysis of the entire system is still beyond the state of the art, even though AI research is starting to address it. Recently some works started investigating

⁴A good summary of the accidents and its aftermath is reported on wikipedia https://en.wikipedia.org/wiki/Death_of_Elaine_Herzberg last visited: May 2022.

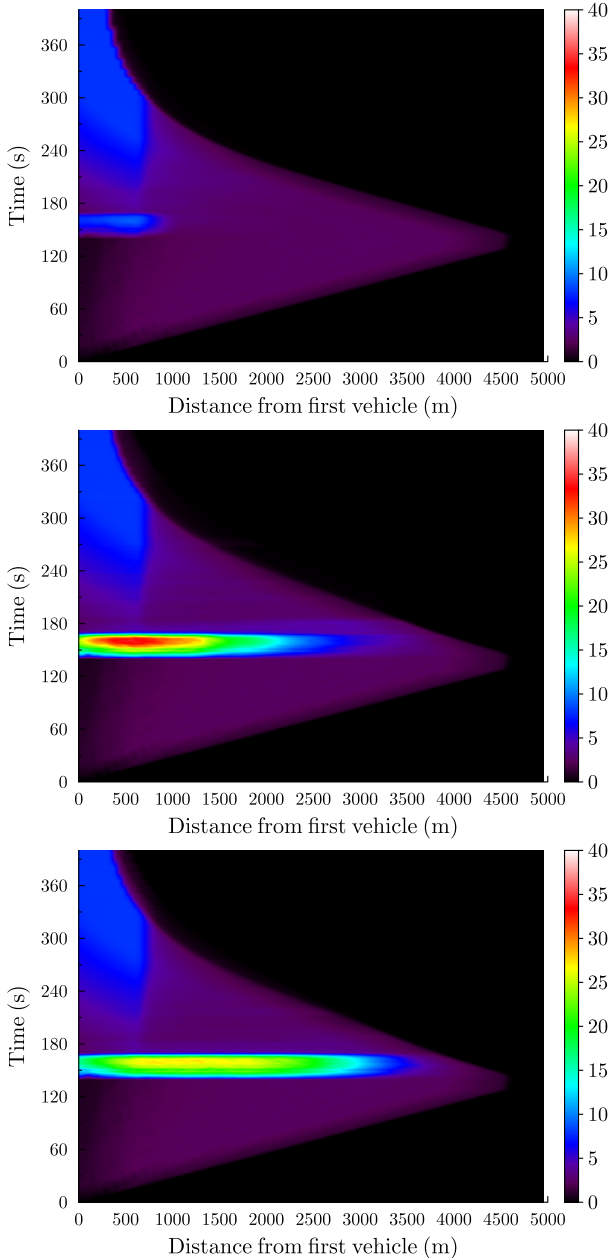


Figure 5: Channel load measured during an emergency braking event using different re-propagation algorithms, i.e., single hop (top plot), 5 hops (middle plot), 5 hops with data aggregation (bottom plot). © 2013 IEEE Reprinted, with permission, from [37].

this different role of the network, i.e., the support for intelligent distributed systems, for the generic case [36], and even for the specific context of intelligent mobility [8, 9] starting to unveil the complexity of the problem and how information can be collected, distributed, and used to build real CD scenarios for future mobility.

5. What Technology?

Communication is essential for CD, but what technology should we adopt to support it? Direct Short Range Commu-

nications (DSRC) and 802.11p have been around for nearly 20 years now, but they are still not widely adopted. 5G and in general Cellular V2X (C-V2X) architectures promise support and services for smart cities, smart mobility, and hence CD. Which technology between the two is best has been debated hotly, and we shall not repeat that debate here, as it is mostly driven by commercial interests. The curious reader can find information, pros, and cons of technologies in the literature, for instance [38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48].

What we want to discuss here is whether a single technology may suffice the requirements set forth in Sects. 3 and 4 and in general how different communication needs are supported by different existing or emerging technologies. Let’s start from an elementary question that, however, we deem has not yet an answer, nor has been studied and analyzed deeply enough: What is the “communication channel” in vehicular networks?

The question seems even weird without specifying the technology, but indeed there are common characteristics to all radio technologies where propagation and limited directivity imply that any communication occupies a portion of bandwidth, time and space in the vicinity of the transmitter. Consider Fig. 5, reported from [37], a paper dealing with emergency braking. Vehicles send CAMs with a frequency of 1 Hz, and increase the frequency to 10 Hz when the deceleration exceeds a certain threshold. The plots refer to 802.11p technology, and report the load on the channel (measured busy time) as color code versus space and time during a braking maneuver for three different message relaying strategies. Without entering into undue detail, the key message is that it is impossible, and indeed wrong, to reason in terms of “communication channel”, carrying out the traditional steady-state analysis performed for communication systems and networks. The communication channel is local to each CD actor and continuously variable in time and space, thus the effectiveness, reliability, and dependability of communications can only be evaluated in relation to the application they support: Is the communication network suitable for the application or not? Any other metric, from latency, to packet loss, to throughput is mostly irrelevant. Hence the technology (or technologies) good for CD is the one that fulfills the above requirement, measured at the application level: all other considerations are useless. In the example we use, the only critical question is whether vehicles receive enough information to trigger smooth braking or not, and the Medium Access Control (MAC) and information scheduling should be aware of this goal, otherwise the resource management system may fail its goal. Notice that qualitatively the result reported in Fig. 5 apply to any radio technology, say below 20 GHz to 30 GHz, independently of the channel management scheme or MAC protocol, as it indicates the communication requirements of a certain application and how it changes with the dynamics of the application. Clearly a more efficient channel management can yield better results with the same amount of resources. Still the general problem of defining what is the communication channel remains, and the answer is unfortunately very complex, as the status of the common pool of (radio) resources used for the communications changes continuously in space and time jeopardizing the traditional modeling and design of transmissions and networks.

Revisiting the role of communications, it is clear that every application and scenario has different requirements, but what they all share is the need for reliability, and extreme dependability. Any CD application incurs, every now and then, in situations where the lack of information or its staleness may end up in accidents and possibly casualties. It is evident that no single technology can ensure such dependability. It is not a matter of how good or reliable the technology is, but simply the presence of a single point of failure that makes single-technology communications not dependable enough for most CD applications, as interfaces may fail, and deliberate attacks to the infrastructure or radio jamming may not be excluded.

Any application, from highway platooning to infrastructure virtualization, needs basic, local, broadcast message distribution (beaconing) that form the fundamental informational layer of presence and characterization of the CD actors. Then requirements change with the goal of the application or service. The basic beaconing should be as independent as possible from any infrastructure, ensuring that basic communications work in any situation. It can be provided by traditional 802.11p or 5G sidelinks, but in this latter case the MAC protocol and scheduling must be appropriately changed to avoid the wireless blindspot problem [49, 50] that currently heavily hampers the use of sidelinks out of coverage. Actually, using both technologies that are naturally available in smartphones and can easily and cheaply be introduced in any CD On-Board Unit (OBU), would immediately reduce the single point of failure problem. Reduce, not solve, as being both traditional radio technologies they are both subject, e.g., to jamming.

What other communication technologies can be added to CD heavily depends on the application and the actors considered. Sect. 6.1 analyzes an example for highway platooning, using as additional technology Visible Light Communications (VLC). The advantages of using multiple communication technologies integrated in a single networking architecture are rather obvious: Improved reliability and dependability, increased capacity, latency reduction. The technology of choice is instead less obvious. Cars and trucks can be easily fitted with VLC [51, 52, 53, 54, 55, 56] or modulated radar [57, 58] that can dynamically activate point to point, high-capacity channels with surrounding vehicles. For instance, if a radar detects an object, it can immediately try to setup a communication channel assuming the object itself is endowed with the same technology. Additional technologies for VRU, specially pedestrians and bicycles are instead more difficult to conceive and fundamental research is needed to understand the best way to integrate multiple, independent communication technologies for these users. Surely, whenever a CD actor is under 5G cellular coverage, appropriate infrastructure-based communications can immediately provide access not only to a structured and reliable communication networks, but also to all the services that are being conceived for smart mobility based on Mobile Edge Computing (MEC) and similar technologies [59, 60, 61, 62, 9].

6. A zoom on platooning

One specific CD application that attracted the attention of industry, academia, and the general public is platooning. For platooning, we mean an application that groups vehicles in road trains where the first one leads the platoon and the members follow each other at a distance smaller than the safety distance that needs to be kept by human drivers, bringing benefits in different ways. These includes a better use of the road infrastructure by increasing its capacity (thanks to smaller inter-vehicle distances) which, in turn, can reduce traffic jams and fuel consumption due to smoother flows. In addition, aerodynamic drafting also reduces fuel consumption. With respect to safety, this is improved “by definition”, because distance is automatically maintained by a control system, provided that all the required data is fed to such system. Finally, it reduces driving stress, as the driving burden is relieved from humans, and this is specially important for professional drivers and commuters.

Platooning draws the interest of the community because it is an application with a partial solution to the problem of the first day roll out, that is, what benefit would the first customer of a connected vehicle have if the vehicle could not communicate with any other? Platooning was initially conceived for freight trucks, where the aerodynamic effects could make freight companies save fuel. When renewing their fleets, companies would buy new trucks in batches to immediately benefit from such application. After reaching a certain market penetration for trucks, customers of private cars could immediately benefit from that as well, as they could “connect” to platoons of trucks on highways.

The fundamental building blocks of platooning, on top of which all the ecosystem is built, are lateral and longitudinal control. Lateral control deals with steering, aiming at keeping the vehicle within the lane. This can be done either by installing magnetic markers under the asphalt [63], by tracking the preceding vehicle through sensors [64], or designed together with longitudinal control [65]. Regardless of the method, sensor-based solutions are enough to solve the problem and it is thus regarded as a “simpler” problem. Communications and trajectory prediction can improve the system, possibly with the cooperation of digital twins running in the infrastructure cloud [66, 67].

On the other hand, longitudinal control deals with regulating the speed of vehicles to maintain a desired gap between them. This has attracted the attention of the research community much more, and new solutions are still being developed. The working principle of longitudinal control consists in gathering information from one or more vehicles belonging to the same platoon and using such data to accelerate or brake the vehicle to regulate the gap.

In its simplest form, such control law can be the one of a standard ACC, which is now commonly available in production cars. An ACC simply measures the distance to and the relative speed of the preceding vehicle and computes the desired acceleration to maintain a so called “constant time headway”, i.e., the time that elapses between the passage of two consecutive vehicles in any point in space is constant. This translates into an actual distance that increases with speed to account for measure and

actuation delays, as it should be for human drivers to account for reaction times. In [68] we find an ACC control law defined as

$$u_i = -\frac{1}{H} \left[\underbrace{(x_i - x_{i-1} + l_{i-1} + H v_i + d_{st})}_{\text{distance error}} + \lambda \underbrace{(v_i - v_{i-1})}_{\text{speed error}} \right]. \quad (1)$$

In Eq. (1), x_i , v_i , and l_i are the position, the speed, and the length of vehicle i in the platoon, respectively, while H is the time headway. Equation (1) acts by minimizing the distance error, i.e., the deviation of the actual distance from the desired distance and the speed error, with λ is a weight between the two error components. The desired distance is computed considering the time headway H and the current speed v_i : as the speed increases so does the desired distance. d_{st} is called stand-still distance and it simply avoids the distance to go to zero when vehicles come to a complete stop. The output of the equation u_i is the desired acceleration, i.e., the command that is sent to the engine or the brakes. The command translates into an actual acceleration only after a certain actuation delay.

Simply looking at its working principle, it seems that an ACC can be used for platooning: In reality this is not the case. To implement automated following at a close distance the time headway H should be small, but this cannot be arbitrarily chosen because if H is too small compared to actuation delays, the platoon might experience instabilities and thus become unsafe. In general, the time gap between two consecutive vehicles cannot be smaller than 1 s, which translates into a inter-vehicle distance of roughly 36 m at 130 km/h.

This is why the community worked towards the development of CACCs, which extend ACCs by considering additional data obtained through communication: As anticipated in Sect. 4, this can have astonishing performance compared to ACC, making platooning a simple, yet very convincing example of what cooperative vehicles can do more than vehicles basing their decisions only on sensors. Communication enables vehicles to perceive objects beyond their field of view and to gather information about such objects, but it also allows to share intentions and future actions, empowering easy and reliable prediction, which is not possible with sensors such as radars, LiDARs, or cameras.

To see why we briefly introduce two CACCs. The first one, defined in [69], employs a constant time gap policy as an ACC, but thanks to communication the time headway can be drastically reduced. The control law for vehicle i is defined as

$$\dot{u}_i = \frac{1}{H} \left(-u_i + \underbrace{k_p (x_{i-1} - x_i - l_{i-1} - H v_i - d_{st})}_{\text{distance error}} + \underbrace{k_d (v_{i-1} - v_i - H a_i)}_{\text{speed error}} + u_{i-1} \right), \quad (2)$$

where a_i is the acceleration of the vehicle, while k_p and k_d are gains for the two error components. Equation (2), as Eq. (1), considers a distance and a speed error, but also an additional component that is the desired acceleration of the preceding vehicle \dot{u}_{i-1} . This is the value computed by the control law of the preceding vehicle that is still to be sent for actuation, thus it

can only be obtained by means of communication. This value cannot be measured, because it is the acceleration the vehicle will implement in the near future. This control law can thus anticipate the behavior of the preceding vehicle and, as a result, the time headway can be drastically reduced to roughly 0.5 s without compromising the stability and the safety of the system.

The second example, defined in [63], considers not only the data of the preceding vehicle but of the leading one as well. In particular, the control law is defined as

$$u_i = \alpha_1 a_{i-1} + \alpha_2 a_0 + \underbrace{\alpha_3 (v_i - v_{i-1})}_{\text{speed error (prec. vehicle)}} + \underbrace{\alpha_4 (v_i - v_0)}_{\text{speed error (lead. vehicle)}} + \underbrace{\alpha_5 (x_i - x_{i-1} + l_{i-1} + d_d)}_{\text{distance error}}. \quad (3)$$

We skip the definition of the α_i gains, the interested reader can find them in the original article [63]. The important aspects to notice here are two. The first one is that Eq. (3) exploits the acceleration (a_0) and the speed (v_0) of the leading vehicle, which can only be obtained by means of communication. The second, and most important one, is that the desired distance is fixed (d_d) and does not depend on the cruising speed. It can indeed be proven that, when considering information from the leading vehicle as well, the platoon is safe and stable even under a constant spacing policy.

The two cooperative control approaches described before are simple, yet very convincing examples of what cooperative vehicles can do more than vehicles basing their decisions only on sensors, giving an additional reason for attracting so much attention. These are just two examples of many different proposed approaches. Changing the communication pattern, also known as Information Flow Topology (IFT), or the control approach can lead to different performance. For example, there are controllers using a common reference speed rather than the speed of the leader, either considering information about the preceding vehicle [70] or the preceding and the following vehicle [71]. Additional approaches are based on consensus and they consider arbitrary IFTs, meaning that vehicles can potentially exploit data received from any other member of the platoon [72, 73].

We also find approaches based on optimization, i.e., the control action is not computed in a ‘‘classical’’ way but rather considering a future time horizon and choosing the action that minimizes some parameters by solving an optimization problem. An example is the work in [74], using a control framework known as Model Predictive Control (MPC). The benefits of using such an approach is that we can consider comfort/consumption metrics directly within the control law. In [74], the control law is defined as an optimization problem and, besides minimizing distance and speed error, the formulation also includes acceleration and jerk, which are related to consumption and comfort. They can also consider constraints, so it is possible to limit, for example, the maximum acceleration.

The authors of [75] take a completely different approach. In particular, their control law tracks a certain speed profile that is defined in the space domain, rather than in time domain. The idea is that each vehicle should have a specific speed depending on their position on the road rather than always having the same

speed. The aim is to compute and track the most efficient speed profile, which depends on the position because of the slope of the road. As a result, the control law is also defined in the space domain, and the information that vehicles share are not to be used as soon as they are received, but rather when a vehicle is close to the point where that information was generated: Basically, data packets can be seen as breadcrumbs left by vehicles on the road as they travel.

The list of CACCs we describe here is clearly not exhaustive, but it gives an idea of how large the solution space actually is. Yet, even with such huge body of literature and despite more than 30 years of research, platooning has not yet seen the light. The reasons are several. First of all, the large set of proposed CACC solutions opens up a problem: which one is to be adopted? The answer to this question might actually be “many of them”, because different manufacturers might choose different ones which, in turn, requires to understand the behavior of heterogeneous formations. Only recently we find studies that define new stability properties for the analysis of heterogeneous platoons [76, 77]. We also look into the problem empirically in [78] by studying the safety and the efficiency of mixtures of CACCs. We report here some preliminary results. In particular Fig. 6 reports the results for a 4-vehicle platoon where the members use a combination of the PATH (PA) and Ploeg (PI) controllers. The label on the x-axis indicate the controller used by the second, the third, and the fourth vehicle. The top plot measures, for each vehicle, the maximum acceleration deviation from a vehicle located in the same position but using an ACC. The negative deviations shown in the plot indicate that the absolute value of the acceleration when using ACC-only platoons is smaller. This result, which might seem negative at first, needs to be carefully interpreted. Indeed, the largest deviation is measured for a homogenous platoon of PATH-only vehicles: it is not a mixed platoon. The reason is that the ACC smoothly dampens oscillations due to its large time headway, while PATH employs a constant spacing policy and thus behaves more rigidly because the vehicles need to replicate the behavior of the leader to maintain the fixed gap. The more we measure this metric towards the tail, the larger becomes the deviation, but this is to be expected. The important observation is that, when considering mixed platoons, the deviations are no larger than for a PATH-only platoon, thus suggesting that mixing controllers does not cause unexpected phenomena. The bottom plot, instead, measures the maximum distance deviation from a vehicle located in the same position but using an homogeneous CACC formation. The maximum measured deviation is roughly 15 cm for a Ploeg controller, which uses a inter-vehicle distance of 15 m (0.5 s at 100 km/h). This minimal distance deviation plus the results on the acceleration indicate that such mixtures of controllers seem indeed safe, but we are far from a definitive answer.

Finally, Fig. 7 shows the throughput measured on a 10 km ring for different vehicle densities. The throughput is measured for homogeneous formations as well as mixtures of the PATH and Ploeg CACCs, for market penetration rates of 25 % and 75 %. For comparison the graph shows also the theoretical free-flow and the baseline throughput, the latter obtained in all ACC-driven vehicles in the simulation. Besides showing

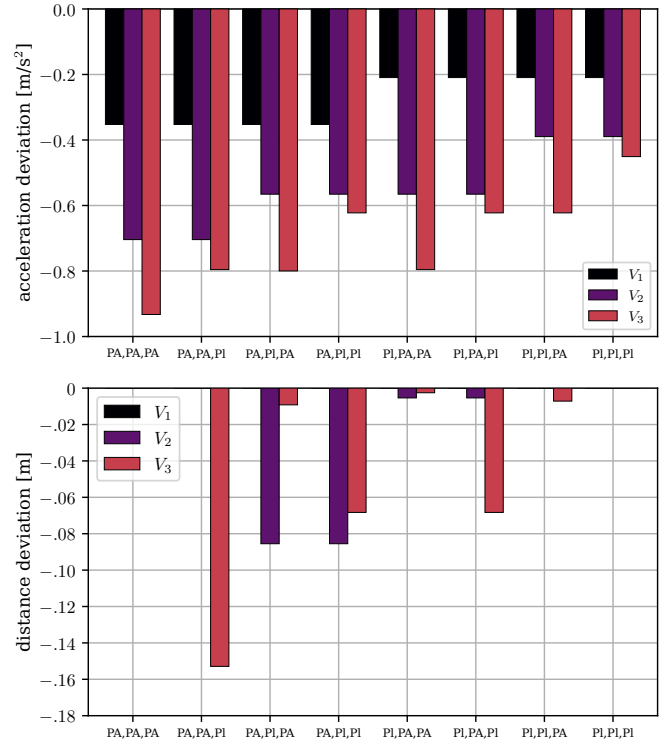


Figure 6: Acceleration and distance deviation for a 4-vehicle platoon using a mixture of PATH [63] and Ploeg [69] controllers (pictures adapted from [78]).

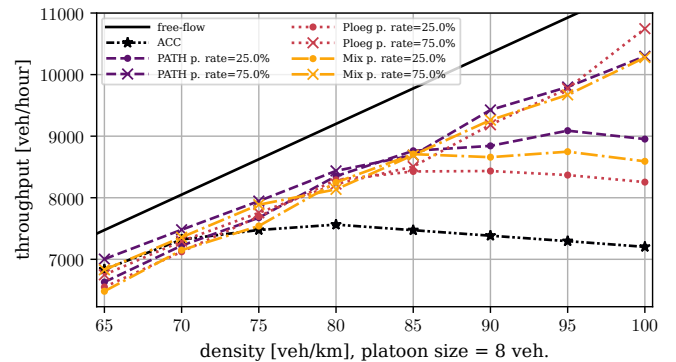


Figure 7: Road throughput measured on a 10 km ring, for 8-vehicle platoons in homogeneous and mixed compositions of PATH [63] and Ploeg [69] controllers, for different market penetration rates. The figure also shows the theoretical maximum (free-flow) throughput and the baseline throughput (only ACC-driven vehicles). The picture is adapted from [78].

the well-known results on throughput improvement, by looking at the curves for a 25 % penetration rate, we can see that the throughput for a mixture of CACCs lies exactly in between the PATH-only (shorter gap) and the Ploeg-only (larger gap) curves, indicating that mixing different controllers might affect throughput simply due to different inter-vehicle distance, and that this does not induce unexpected side effects. As for Fig. 6, the results are preliminary, but they give positive indications and suggest it is worth investigating in this direction.

6.1. Platooning with multi-technology communications

The analysis in [78] relates to measurable safety performance, which is still an open issue. The standard approach for guaranteeing safety in CACC literature is to prove basic properties such as string-stability, i.e., guaranteeing that errors occurring at the head will not be amplified towards the tail. This property, however, is proven in perfect conditions, meaning absence of packet losses, but it is not yet completely understood to which extent CACCs are safe under packet losses and how to properly deal with them. In [79], the authors extend the CACC in Eq. (2) to perform a graceful degradation in presence of packet losses, in particular by using the real acceleration a_{i-1} of the preceding vehicle estimated through the radar rather than the desired one u_{i-1} , showing better performance than simply switching to an ACC. In [80] the authors prove string-stability properties under network impairments, but for mathematical tractability network problems are treated as a delay. However, in broadcast-like local networks, delays are always very low but packets might get lost, so the information is either received immediately or not at all. In [71] we perform a little step forward by designing a CACC with proven safety, i.e., by defining the characteristics of the vehicles and the network in terms of the maximum number of consecutive losses, we derive a lower bound on the minimum safety distance: if the conditions hold, then vehicles cannot get closer than that bound. The limitation is that this assumes vehicles starting from a steady-state, otherwise the bound cannot be guaranteed.

To reduce the chances of packet losses and to make the system more robust, one possibility is simply to consider redundancy as offered by multiple communication technologies. For example, we can replicate the information flow over multiple interfaces [56]. In [33] we propose to use more than a single communication technology to improve robustness and to monitor the state (in term of availability) of the other communication interfaces, introducing a fallback mechanism that increases inter-vehicle spacing and switches to a different CACC if deemed necessary. We show here the comparison between a single- and a multi-technology approach by testing a fallback mechanism that switches from the PATH CACC to a standard ACC. For the single-technology case, when a network failure is detected, we simply switch from one cooperative controller to a non-cooperative one. In the other case, we exploit the redundancy provided by the additional communication interfaces and gradually increase the gap of the CACC to the one required by the ACC before switching to the latter algorithm.

Fig. 8 shows the difference in vehicle dynamics between the two approaches. In particular, the left plots show the result for a single-technology approach, while the right plots for a multi-technology solution. The duty of the fallback mechanism is to bring the inter-vehicle distance from 5 m to roughly 35 m, which is the distance corresponding to a time headway of 1.2 s at 100 km/h (including a 2 m stand-still distance). For the single-communication solution, the abrupt switching from one control algorithm to the other causes much stronger deceleration, even if the leader is driving at a constant speed as in this case. Further analyses in [33] show that if a network failure occurs while vehicles are required to brake in response to an event, collisions occur.

The response to a network failure of a multi-technology solution is much smoother, because vehicles can exploit the additional communication means to maintain the string of vehicles safe and stable while increasing the gap.

While the solution in [33] shows the potential of multi-technology cooperative driving, it also opens a new research path. The study, although promising, is based on empirical results. Solution with proven safety (at least probabilistically) are yet to be found, and this provides a huge research opportunity and challenge, which is however a required step before such applications can see the light.

6.2. Platooning beyond control

What we discussed so far only concerns longitudinal and lateral control, which are the basic building blocks of platooning. Yet, an additional reason for which we still do not have platooning on roads is that we need higher levels for coordination. Longitudinal and lateral control maintain a platoon, but platoons need to be formed by means of maneuvers, and to “instantiate” maneuvers we need a decision layer. The decision layer needs to orchestrate vehicles, collecting planned trips, driving preferences, vehicle categories, etc., and decide what is the best way to group them to satisfy both passengers’ requirements and the goals of platooning with respect to green transportation, meaning reducing the environmental footprint. This is far from being a simple problem to be solved, because the number of objectives that need to be considered is huge. In [81] we perform a literature review listing all the potential optimization objectives and all the factors that might influence them. Indeed, not only the problem is complex from an optimization perspective, but a solution can be influenced by internal factors (such as vehicle characteristics) or external factors (such as the weather).

While some of these aspects are technological, others concern economic sustainability. It is not yet clear how to sustain platooning from a business perspective. Some companies are still actively working on truck platooning, while some other like Daimler believe truck platooning has no clear business case⁵.

While we find discussions on potential business cases for truck platooning, business cases for private vehicles are still completely missing. In principle, the business case is saving public money. The EU estimates that traffic congestion costs amount to 1 % of the GDP [82], while healthcare and rehabilitation related to road accidents account for 3 % of the GDP [83], so reducing traffic congestion and accidents reduce public spending for governments by a large amount. The problem is how to transform such savings into incentives for the users involving the private sector as well, considering also how much contribution each vehicle made. For example, in a platooning fleet, vehicles in the middle are the ones that save the most fuel, so incentives need to account for that and, through technology, potentially enable changes of role while driving, e.g., changing the leader [84], or exchanging recharging benefits for electrical vehicles.

⁵<https://www.supplychaindive.com/news/Daimler-platooning-autonomous-truck-CES/545524> last visited April 2022.

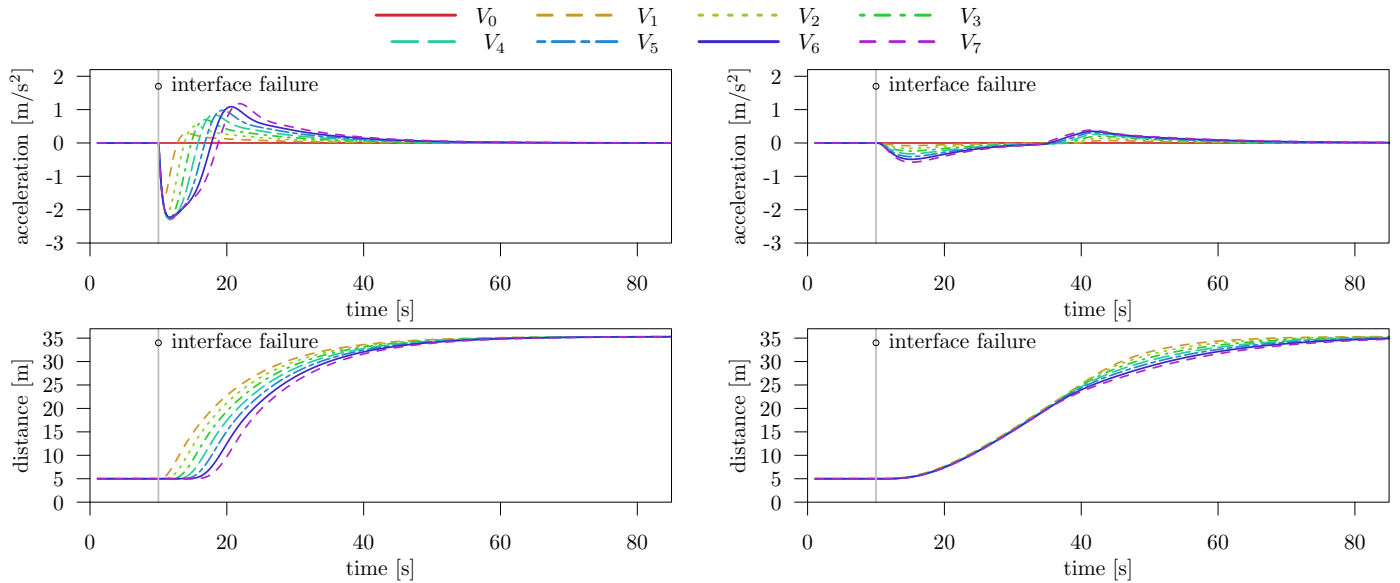


Figure 8: Acceleration and inter-vehicle distance for the members of an 8-vehicle platoon using single communication technology (left plots) and multiple communication technologies (right plots) switching to sensor-only driving (ACC) in the presence of a network failure (pictures adapted from [33]).

7. Final Discussion

What is the future of Cooperative Driving (CD)? Just a side-notch of autonomous vehicles for smoother highway traffic or a novel paradigm for mobility?

We have revisited the notion of CD, highlighting how it is central to many visions of future *smart living*, from mobility, to cities and generally shared spaces. Furthermore, we have argued that without explicit communications among all actors of the different scenarios cooperation remains based on inference, or more colloquially guesses, leading to errors and contrasting decisions that lead to accidents, sub-optimal use of the infrastructure, and possibly casualties, specially when VRUs are part of the scenario. This said, what lies ahead remains difficult to predict, mainly because we deal with a complex problem which requires not only a technical or engineering solution, like, e.g., going to Mars, but involve economy, societal changes, and proper regulation.

Multi-technology communications to improve dependability seems unavoidable for the success of CD, but economic stakeholders are instead fighting each other to define the *winning technology*, trying to monopolize the revenue space on CD, with the risk of missing the opportunity altogether.

Governments and infrastructure operators should be enthusiastic pushers of CD: Road accident victims cost as much as 3% of national GDP in developed countries and improved traffic efficiency allows avoiding to build new infrastructures, costly and socially contrasted. Instead, regulations and investments from these stakeholders are lagging behind: After nearly 20 years from its standardization simple and cheap 802.11p technology to diffuse CAM messages is still not mandatory in new cars and almost no road operator installed experimental Road-Side Units (RSUs) to distribute safety information.

Research is producing a vast amount of results on many as-

pects and facets of CD and lately is also trying to tackle the subject from an inter-disciplinary perspective, specially recognizing that the complexity of the problems at stake requires a holistic view, and new ways of exploiting the advances of ML, automatic inference, and AI to build the appropriate reasoning systems that can lead to autonomous and cooperative decisions with levels of reliability and dependability superior to those of humans. We all admit human errors, but not (rightly) technology ones. Still, CD is mainly considered an engineering and economic subject, thus trans-disciplinary approaches involving legal, societal, and behavioral studies are few and sparse. CD is not yet another technology that, if successful, will be enthusiastically adopted by users. It is a complex transition toward a different way of conceiving transportation and public spaces, thus it requires a properly designed path for its introduction and social acceptance.

Just as we were writing this paper, advocating for explicit communications to empower Cooperative Driving (CD) the Editors in Chief of *IEEE Intelligent Transportation Systems Magazine* and *Transactions on Intelligent Vehicles* wrote an editorial column [85] warning that lack of understanding and proper communication jeopardize the trust in autonomous driving. They provocatively close the column asking if autonomous vehicles with the auto-pilot on should display a red flashing sign warning all other road users.

We think that in the third millennium there are more advanced communication technologies than flashing signs!

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References

- [1] SAE On-Road Automated Vehicle Standards Committee, Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles, Standard J3016 Revision 2018-06, SAE (6 2018).
- [2] European Telecommunications Standards Institute, Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service, EN 302 637-2 V1.3.1, ETSI (9 2014).
- [3] SAE Int., Dedicated Short Range Communications (DSRC) Message Set Dictionary (J2735_201603), Tech. Rep. J2735-201603, SAE (3 2016).
- [4] J. Li, L. Yao, X. Xu, B. Cheng, J. Ren, Deep reinforcement learning for pedestrian collision avoidance and human-machine cooperative driving, *Elsevier Information Sciences* 532 (9 2020).
- [5] M. Bieshaar, S. Zernetsch, A. Hubert, B. Sick, K. Doll, Cooperative starting movement detection of cyclists using convolutional neural networks and a boosted stacking ensemble, *IEEE Transactions on Intelligent Vehicles* 3 (4) (2018).
- [6] I. König, M. Bachmann, M. Bieshaar, S. Schindler, F. Lambrecht, K. David, B. Sick, G. Hornung, C. Sommer, Traffic Safety in Future Cities by Using a Safety Approach Based on AI and Wireless Communications, in: ITG-Symposium on Mobile Communication - Technologies and Applications, Osnabrück, Germany, 2021.
- [7] F. Hagenauer, C. Sommer, T. Higuchi, O. Altintas, F. Dressler, Vehicular Micro Clouds as Virtual Edge Servers for Efficient Data Collection, in: 23rd ACM International Conference on Mobile Computing and Networking (MobiCom 2017), 2nd ACM International Workshop on Smart, Autonomous, and Connected Vehicular Systems and Services (CarSys 2017), Snowbird, UT, 2017.
- [8] F. Malandrino, C. Chiasserini, G. Dell’Aera, Edge-powered assisted driving for connected cars, *IEEE Transactions on Mobile Computing Early Access* (01) (5 2021).
- [9] F. Dressler, C. F. Chiasserini, F. H. P. Fitzek, H. Karl, R. Lo Cigno, A. Capone, C. E. Casetti, F. Malandrino, V. Mancuso, F. Klingler, G. A. Rizzo, V-Edge: Virtual Edge Computing as an Enabler for Novel Microservices and Cooperative Computing, *IEEE Network To appear* (2022).
- [10] S. Amershi, D. Weld, M. Vorvoreanu, A. Fournay, B. Nushi, P. Collison, J. Suh, S. Iqbal, P. N. Bennett, K. Inkpen, J. Teevan, R. Kikin-Gil, E. Horvitz, Guidelines for Human-AI Interaction, in: ACM CHI Conference on Human Factors in Computing Systems (CHI’19), 2019.
- [11] W. Xu, From automation to autonomy and autonomous vehicles: challenges and opportunities for human-computer interaction, *ACM interactions* 28 (1) (2021).
- [12] S. Joerer, B. Bloessl, M. Segata, C. Sommer, R. Lo Cigno, A. Jamalipour, F. Dressler, Enabling Situation Awareness at Intersections for IVC Congestion Control Mechanisms, *IEEE Transactions on Mobile Computing (TMC)* 15 (7) (6 2016).
- [13] G. Boquet, I. Pisa, J. L. Vicario, A. Morell, J. Serrano, Analysis of adaptive beaconing protocols for intersection assistance systems, in: 14th Annual Conference on Wireless On-demand Network Systems and Services (WONS’18), 2018.
- [14] G. Boquet, I. Pisa, J. Lopez Vicario, A. Morell, J. Serrano, Adaptive beaconing for rsu-based intersection assistance systems: Protocols analysis and enhancement, *Elsevier Vehicular Communications* 14 (2018).
- [15] A. Gholamhosseinian, J. Seitz, A Comprehensive Survey on Cooperative Intersection Management for Heterogeneous Connected Vehicles, *IEEE Access* 10 (2022).
- [16] J. Lioris, R. Pedarsani, F. Y. Tascikaraoglu, P. Varaiya, Doubling throughput in urban roads by platooning, in: 14th IFAC Symposium on Control in Transportation Systems (CTS 2016), Istanbul, Turkey, 2016.
- [17] T. Hardes, C. Sommer, Towards Heterogeneous Communication Strategies for Urban Platooning at Intersections, in: 11th IEEE Vehicular Networking Conference (VNC 2019), Los Angeles, CA, 2019.
- [18] T. Hardes, C. Sommer, Dynamic Platoon Formation at Urban Intersections, in: 44th IEEE Conference on Local Computer Networks (LCN 2019), Poster Session, Osnabrück, Germany, 2019.
- [19] S. W. Smith, Y. Kim, J. Guanetti, R. Li, R. Firoozi, B. Wootton, A. A. Kurzhanskiy, F. Borrelli, R. Horowitz, M. Arcak, Improving Urban Traffic Throughput With Vehicle Platooning: Theory and Experiments, *IEEE Access* 8 (3 2020).
- [20] S. Smith, Smart infrastructure for future urban mobility, *AI Magazine* 41 (1) (4 2020).
- [21] M. Malinverno, G. Avino, C. Casetti, C. F. Chiasserini, F. Malandrino, S. Scarpina, Edge-Based Collision Avoidance for Vehicles and Vulnerable Users: An Architecture Based on MEC, *IEEE Vehicular Technology Magazine* 15 (1) (2020).
- [22] S. B. Prathiba, G. Raja, K. Dev, N. Kumar, M. Guizani, A Hybrid Deep Reinforcement Learning For Autonomous Vehicles Smart-Platooning, *IEEE Transactions on Vehicular Technology* 70 (12) (2021).
- [23] F. Dressler, F. Klingler, M. Segata, R. Lo Cigno, Cooperative Driving and the Tactile Internet, *Proceedings of the IEEE* 107 (2) (Feb. 2019).
- [24] Z. Mahrez, E. Sabir, E. Badidi, W. Saad, M. Sadik, Smart Urban Mobility: When Mobility Systems Meet Smart Data, *IEEE Transactions on Intelligent Transportation Systems Early Access* (2021).
- [25] C. Avin, M. Borokhovich, Y. Haddad, Z. Lotker, Optimal virtual traffic light placement, in: 8th International Workshop on Foundations of Mobile Computing (FOMC 2012), Madeira, Portugal, 2012.
- [26] M. Ferreira, P. d’Orey, On the Impact of Virtual Traffic Lights on Carbon Emissions Mitigation, *IEEE Transactions on Intelligent Transportation Systems (TITS)* 13 (1) (3 2012).
- [27] A. Jame, M. Rapelli, C. E. Casetti, Reducing pollutant emissions through Virtual Traffic Lights, *Elsevier Computer Communications* 188 (4 2022).
- [28] R. Deng, B. Di, L. Song, Cooperative Collision Avoidance for Overtaking Maneuvers in Cellular V2X-Based Autonomous Driving, *IEEE Transactions on Vehicular Technology* 68 (5) (2019).
- [29] Y. Yuan, R. Tasik, S. S. Adhatarao, Y. Yuan, Z. Liu, X. Fu, RACE: Reinforced Cooperative Autonomous Vehicle Collision Avoidance, *IEEE Transactions on Vehicular Technology* 69 (9) (2020).
- [30] S. B. Prathiba, G. Raja, N. Kumar, Intelligent Cooperative Collision Avoidance at Overtaking and Lane Changing Maneuver in 6G-V2X Communications, *IEEE Transactions on Vehicular Technology* 71 (1) (2022).
- [31] J. J. Anaya, E. Talavera, D. Gimenez, N. Gomez, F. Jimenez, J. E. Naranjo, Vulnerable Road Users Detection Using V2X Communications, in: 18th IEEE International Conference on Intelligent Transportation Systems (ITSC 2015), Las Palmas de Gran Canaria, Spain, 2015.
- [32] M. Segata, R. Vijeikis, R. Lo Cigno, Communication-based Collision Avoidance between Vulnerable Road Users and Cars, in: 36th IEEE Conference on Computer Communications (INFOCOM 2017), International Workshop on Smart Cities and Urban Computing (SmartCity 2017), Atlanta, GA, 2017.
- [33] M. Segata, R. Lo Cigno, T. Hardes, J. Heinovski, M. Schettler, B. Bloessl, C. Sommer, F. Dressler, Multi-Technology Cooperative Driving: An Analysis Based on PLEXE, *IEEE Transactions on Mobile Computing (TMC) Early access* (2 2022).
- [34] A. Davila, M. Nombela, Platooning - Safe and Eco-Friendly Mobility, in: SAE 2012 World Congress & Exhibition, Detroit, MI, 2012.
- [35] O. Altintas, S. Banerjee, F. Dressler, G. Heijenk, Inter-Vehicular Communication Towards Cooperative Driving (Dagstuhl Seminar 18202), Vol. 8-5, Dagstuhl, Germany, 2018.
- [36] J. Pan, L. Cai, S. Yan, X. S. Shen, Network for AI and AI for Network: Challenges and Opportunities for Learning-Oriented Networks, *IEEE Network* 35 (6) (2021).
- [37] M. Segata, R. Lo Cigno, Automatic Emergency Braking - Realistic Analysis of Car Dynamics and Network Performance, *IEEE Transactions on Vehicular Technology (TVT)* 62 (9) (Nov. 2013).
- [38] V. Vukadinovic, K. Bakowski, P. Marsch, I. Dexter Garcia, H. Xu, M. Sybis, P. Sroka, K. Wesolowski, D. Lister, I. Thibault, 3GPP C-V2X and IEEE 802.11p for Vehicle-to-Vehicle communications in highway platooning scenarios, *Elsevier Ad Hoc Networks* 74 (2018).
- [39] R. Molina-Masegosa, J. Gozalvez, M. Sepulcre, Configuration of the C-V2X Mode 4 Sidelink PC5 Interface for Vehicular Communication, in: 14th International Conference on Mobile Ad-Hoc and Sensor Networks (MSN 2018), Shenyang, China, 2018.
- [40] A. Bazzi, G. Cecchini, M. Menarini, B. M. Masini, A. Zanella, Survey and Perspectives of Vehicular Wi-Fi versus Sidelink Cellular-V2X in the 5G Era, *MDPI Future Internet* 11 (6) (May 2019).
- [41] F. Eckermann, M. Kahlert, C. Wietfeld, Performance Analysis of C-V2X Mode 4 Communication Introducing an Open-Source C-V2X Simulator, in: 90th IEEE Vehicular Technology Conference (VTC 2019-Fall), Honolulu, HI, 2019.
- [42] V. Mannoni, V. Berg, S. Sesia, E. Perraud, A Comparison of the V2X Communication Systems: ITS-G5 and C-V2X, in: IEEE 89th Vehicular Technology Conference (VTC2019-Spring), 2019.

- [43] C. Campolo, A. Molinaro, F. Romeo, A. Bazzi, A. O. Berthet, 5G NR V2X: On the Impact of a Flexible Numerology on the Autonomous Sidelink Mode, in: IEEE 2nd 5G World Forum (WF-5G 2019), Virtual Conference, 2019.
- [44] M. Karoui, A. Freitas, G. Chalhoub, Performance comparison between LTE-V2X and ITS-G5 under realistic urban scenarios, in: IEEE 91st Vehicular Technology Conference (VTC2020-Spring), 2020.
- [45] F. Romeo, C. Campolo, A. Molinaro, A. O. Berthet, Asynchronous Traffic on the Sidelink of 5G V2X, in: IEEE International Conference on Communications Workshops (ICC Workshops 2020), Virtual Conference, 2020.
- [46] T. Shimizu, B. Cheng, H. Lu, J. B. Kenney, Comparative Analysis of DSRC and LTE-V2X PCS Mode 4 with SAE Congestion Control, in: 12th IEEE Vehicular Networking Conference (VNC 2020), Virtual Conference, 2020.
- [47] A. Bazzi, A. O. Berthet, C. Campolo, B. M. Masini, A. Molinaro, A. Zanella, On the Design of Sidelink for Cellular V2X: A Literature Review and Outlook for Future, IEEE Access 9 (7 2021).
- [48] I. Soto, M. Calderon, O. Amador, M. Uruña, A survey on road safety and traffic efficiency vehicular applications based on C-V2X technologies, Elsevier Vehicular Communications 33 (2022).
- [49] A. Bazzi, C. Campolo, A. Molinaro, A. O. Berthet, B. M. Masini, A. Zanella, On Wireless Blind Spots in the C-V2X Sidelink, IEEE Transactions on Vehicular Technology (TVT) 69 (8) (Aug. 2020).
- [50] M. Segata, P. Arvani, R. Lo Cigno, A Critical Assessment of CV2X Resource Allocation Scheme for Platooning Applications, in: 16th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2021), Virtual Conference, 2021.
- [51] S. Rajagopal, R. D. Roberts, S.-K. Lim, IEEE 802.15.7 visible light communication: modulation schemes and dimming support, IEEE Communications Magazine 50 (3) (2012).
- [52] M. Uysal, Z. Ghassemlooy, A. Bekkali, A. Kadri, H. Menouar, Visible Light Communication for Vehicular Networking: Performance Study of a V2V System Using a Measured Headlamp Beam Pattern Model, IEEE Vehicular Technology Magazine 10 (4) (2015).
- [53] S. Ishihara, R. V. Rabsatt, M. Gerla, Improving Reliability of Platooning Control Messages Using Radio and Visible Light Hybrid Communication, in: 7th IEEE Vehicular Networking Conference (VNC 2015), Kyoto, Japan, 2015.
- [54] M. Segata, R. Lo Cigno, H.-M. Tsai, F. Dressler, On Platooning Control using IEEE 802.11p in Conjunction with Visible Light Communications, in: 12th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2016), Cortina d'Ampezzo, Italy, 2016.
- [55] S. Ucar, S. Coleri Ergen, O. Ozkasap, IEEE 802.11p and Visible Light Hybrid Communication based Secure Autonomous Platoon, IEEE Transactions on Vehicular Technology (TVT) 67 (9) (Sep. 2018).
- [56] M. Schettler, A. Memedi, F. Dressler, Deeply Integrating Visible Light and Radio Communication for Ultra-High Reliable Platooning, in: 15th IEEE/IFIP Conference on Wireless On demand Network Systems and Services (WONS 2019), Wengen, Switzerland, 2019.
- [57] M. S. Amjad, M. Schettler, S. Dimce, F. Dressler, Inband Full-Duplex Relaying for RADCOM-based Cooperative Driving, in: 12th IEEE Vehicular Networking Conference (VNC 2020), Virtual Conference, 2020.
- [58] C.-H. Wang, O. Altintas, C. D. Ozkaptan, E. Ekici, Multi-Range Joint Automotive Radar and Communication using Pilot-based OFDM Radar, in: 12th IEEE Vehicular Networking Conference (VNC 2020), Virtual Conference, 2020.
- [59] T. Higuchi, J. Joy, F. Dressler, M. Gerla, O. Altintas, On the Feasibility of Vehicular Micro Clouds, in: 9th IEEE Vehicular Networking Conference (VNC 2017), Turin, Italy, 2017.
- [60] Z. Xiang, F. Gabriel, E. Urbano, G. T. Nguyen, M. Reisslein, F. H. P. Fitzek, Reducing Latency in Virtual Machines: Enabling Tactile Internet for Human-Machine Co-Working, IEEE Journal on Selected Areas in Communications 37 (5) (May 2019).
- [61] F. H. P. Fitzek, S.-C. Li, S. Speidel, T. Strufe, M. Simsek, M. Reisslein (Eds.), Tactile Internet with Human-in-the-Loop, Academic Press, 2021.
- [62] N. Cha, C. Wu, T. Yoshinaga, Y. Ji, K.-L. A. Yau, Virtual Edge: Exploring Computation Offloading in Collaborative Vehicular Edge Computing, IEEE Access 9 (Jan. 2021).
- [63] R. Rajamani, H.-S. Tan, B. K. Law, W.-B. Zhang, Demonstration of Integrated Longitudinal and Lateral Control for the Operation of Automated Vehicles in Platoons, IEEE Transactions on Control Systems Technology (TCST) 8 (4) (Jul. 2000).
- [64] S. Solyom, A. Idelchi, B. B. Salamah, Lateral Control of Vehicle Platoons, in: IEEE International Conference on Systems, Man, and Cybernetics (SMC 2013), Manchester, United Kingdom, 2013.
- [65] R. Kianfar, M. Ali, P. Falcone, J. Fredriksson, Combined longitudinal and lateral control design for string stable vehicle platooning within a designated lane, in: 17th IEEE International Conference on Intelligent Transportation Systems (ITSC 2014), Qingdao, China, 2014.
- [66] S. Thormann, A. Schirrer, S. Jakubek, Safe and Efficient Cooperative Platooning, IEEE Transactions on Intelligent Transportation Systems 23 (2) (2022).
- [67] H. Du, S. Leng, J. He, L. Zhou, Digital Twin Based Trajectory Prediction for Platoons of Connected Intelligent Vehicles, in: IEEE 29th Int. Conf. on Network Protocols (ICNP), 2021.
- [68] R. Rajamani, Vehicle Dynamics and Control, 2nd Edition, 2012.
- [69] J. Ploeg, B. Scheepers, E. van Nunen, N. van de Wouw, H. Nijmeijer, Design and Experimental Evaluation of Cooperative Adaptive Cruise Control, in: 14th IEEE International Conference on Intelligent Transportation Systems (ITSC 2011), Washington, D.C., 2011.
- [70] A. Ali, G. Garcia, P. Martinet, The Flatbed Platoon Towing Model for Safe and Dense Platooning on Highways, IEEE Intelligent Transportation Systems Magazine 7 (1) (Jan. 2015).
- [71] G. Giordano, M. Segata, F. Blanchini, R. Lo Cigno, The joint network/control design of platooning algorithms can enforce guaranteed safety constraints, Elsevier Ad Hoc Networks 94 (Nov. 2019).
- [72] M. di Bernardo, A. Salvi, S. Santini, Distributed Consensus Strategy for Platooning of Vehicles in the Presence of Time Varying Heterogeneous Communication Delays, IEEE Transactions on Intelligent Transportation Systems (TITS) 16 (1) (2 2015).
- [73] S. Santini, A. Salvi, A. S. Valente, A. Pescapè, M. Segata, R. Lo Cigno, Platooning Maneuvers in Vehicular Networks: a Distributed and Consensus-Based Approach, IEEE Transactions on Intelligent Vehicles (T-IV) 4 (1) (Mar. 2019).
- [74] R. Kianfar, P. Falcone, J. Fredriksson, A Receding Horizon Approach to String Stable Cooperative Adaptive Cruise Control, in: 14th IEEE International Conference on Intelligent Transportation Systems (ITSC 2011), Washington, D.C., 2011.
- [75] B. Besselink, K. H. Johansson, String Stability and a Delay-Based Spacing Policy for Vehicle Platoons Subject to Disturbances, IEEE Transactions on Automatic Control 62 (9) (Sep. 2017).
- [76] Y. Zhou, S. Ahn, M. Wang, S. Hoogendoorn, Stabilizing Mixed Vehicular Platoons with Connected Automated Vehicles: An H-infinity Approach, Elsevier Transportation Research Procedia 38 (2019).
- [77] Y. Qin, S. Li, String Stability Analysis of Mixed CACC Vehicular Flow With Vehicle-to-Vehicle Communication, IEEE Access 8 (Sep. 2020).
- [78] M. Segata, L. Ghiro, R. Lo Cigno, On the Progressive Introduction of Heterogeneous CACC Capabilities, in: 13th IEEE Vehicular Networking Conference (VNC 2021), Virtual Conference, 2021.
- [79] J. Ploeg, E. Semsar-Kazerouni, G. Lijster, N. van de Wouw, H. Nijmeijer, Graceful Degradation of Cooperative Adaptive Cruise Control, IEEE Transactions on Intelligent Transportation Systems (TITS) 16 (1) (Feb. 2015).
- [80] S. Oncu, J. Ploeg, N. Van De Wouw, H. Nijmeijer, Cooperative Adaptive Cruise Control: Network-Aware Analysis of String Stability, IEEE Transactions on Intelligent Transportation Systems (TITS) 15 (4) (Aug. 2014).
- [81] T. Sturm, C. Krupitzer, M. Segata, C. Becker, A Taxonomy of Optimization Factors for Platooning, IEEE Transactions on Intelligent Transportation Systems (TITS) 22 (10) (2021).
- [82] European Commission, Roadmap to a single European transport area: towards a competitive and resource efficient transport system, 2011.
- [83] WHO Regional Office for Europe, European status report on road safety: towards safer roads and healthier transport choices, 2009.
- [84] V. Lesch, C. Krupitzer, K. Stubenrauch, N. Keil, C. Becker, S. Kounev, M. Segata, A Comparison of Mechanisms for Compensating Negative Impacts of System Integration, Elsevier Future Generation Computer Systems 116 (3 2021).
- [85] L. Vlacic, F.-Y. Wang, Let Us Reinststate the Public Trust in the Safety Benefits of Automated Vehicles [Editor's Column], IEEE Intelligent Transportation Systems Magazine 14 (2) (2022).