Postprint

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Safety in Vehicle Platooning:
A Systematic Literature Review

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Abstract—**Vehicle platooning has been studied for several decades, with objectives such as improved traffic throughput on existing infrastructure, or reduced energy consumption. All the time, it has been apparent that safety is an important issue. Yet, there are no comprehensive analyses of what is needed to achieve safety in platooning, but only scattered pieces of information. This paper investigates, through a systematic literature review, what is known about safety for platooning, including what analysis methods have been used; what hazards and failures have been identified; and solution elements that have been proposed to improve safety. Based on this, a gap analysis is performed to identify outstanding questions that need to be addressed in future research. These include dealing with a business ecosystem of actors that cooperate and compete around platooning; refining safety analysis methods to make them suitable for systems-of-systems; dealing with variability in vehicles; and finding solutions to various human factors issues.**

Index Terms—**Road vehicles, platooning, safety, systems-of-systems.**

I. INTRODUCTION

SINCE the advent of automobiles, vehicles have been driven individually with each driver essentially pursuing their own goals. However, with increasing traffic and soaring energy costs, the potential benefits of cooperative driving were early on recognized (as described in a recent historical summary [1]). In particular, *platooning*, where the movements of a group of vehicles is coordinated, has been investigated for several decades. The main objective of platooning is to reduce the inter-vehicle distance considerably compared to what is considered advisable during manual driving. This is achieved by partly or fully automating the driving tasks. Among the potential benefits are a better use of the road infrastructure, by allowing more vehicles to use a given stretch of road, and improved energy efficiency by reducing aerodynamic drag.

A. Platooning safety

The degree to which these benefits can be achieved is proportional to the distance between the vehicles in the platoon. The smaller the distance, the more vehicles can be packed into the road, and the more aerodynamic drag is reduced. However, reducing the distance clearly also leads to issues regarding transportation *safety*. This fact is so obvious that almost any paper discussing some aspect of platooning would mention safety. Many of them recognize this as a problem, but some also point it out as an opportunity, claiming that automation could increase safety compared to manual driving [2]. However, it is striking when browsing the literature that even though safety is universally recognized, few clues are given on exactly what is needed to make platooning safe, and it is hard to find any systematic and comprehensive analysis of the subject.

It is worthwhile to briefly consider what safety really is. Many definitions have been proposed over the years, and most of them are quite similar and in accordance with the everyday use of the word. A broad definition is that safety is "freedom from accidents and losses" [3], whereas a narrower interpretation is "absence of catastrophic consequences on the user(s) and the environment" [4]. In the case of platooning, the most obvious consequences are related to loss of human lives or injuries, and this will be the primary focus of this paper, but the broader definition additionally considers other kinds of losses, which will also be studied, albeit more briefly.

The one big exception to the lack of safety analysis is the extensive study of string stability, which is the condition necessary to ensure that the vehicles in the platoon do not collide with each other as a consequence of disturbances in the control system [1]. However, this condition is mostly studied under normal cruising in the platoon, when all components are working as intended. It does not deal with component failures, and also not with other modes of driving, such as platoon formation or dissolution, disturbances from surrounding traffic, and so on. Control of string stability is thus a normal and intended condition, and analyzing it does not answer the question of what to do when something goes outside the bounds of normal operation. For this reason, string stability will not be considered further in this paper, but the reader is referred to already existing reviews on that subject, such as [5]. The objective of this paper is instead to complement the many results on string stability with a broader view on other aspects that also need attention in order to make safe platooning a reality.

Even though platooning can be seen as a next step in a sequence of increasingly more advanced driver assistance functions, including front collision warning, lane departure warning, and autonomous emergency braking [6][7], it introduces new elements not present in these applications, such

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as communication and co-operation, and there is a mixture of different communication types and both decentralized and central control. The platoon becomes a system-of-systems, whereas previous functions can be analyzed for an individual vehicle in isolation. This means that the safety analysis of platooning can only make use of analyses for earlier functions to a very limited extent.

The existing literature on platooning safety appears to be scattered and not covering all relevant aspects. There is thus a need to synthesize and evaluate what is known today on the subject, and that is the contribution of this paper.

B. Objective and Research Questions

The *objective* of this paper is to investigate what is known today about how to achieve safety in platooning, and identify gaps in that knowledge to provide guidance for future research. This will be achieved by studying the existing research literature to address the following five *research questions*:

RQ1. What characterizes existing literature on platooning safety?

RQ2. What are the characteristics of the applications studied in literature?

RQ3. What safety analysis methods have been used in literature?

RQ4. What hazards and failures have been identified in literature?

RQ5. What solution elements have been proposed in literature to improve safety?

C. Overview of Paper

The remainder of this paper is structured as follows. In Section II, the research methods for systematic literature review and systematic literature mapping are summarized, and it is described how they were applied in this research. This is followed by a presentation of the results identified after analyzing the literature, for each of the research questions. Then, in Section IV, the findings are discussed and gaps in the present knowledge are identified. After that, the validity of the findings are discussed in Section V, and finally the conclusions are summarized.

In order to make the study as transparent as possible, the research method and its validity is discussed fairly extensively. However, the reader who is primarily interested in the concrete findings may safely skip Sections II and V.

II. RESEARCH METHODS

In this section, the research methods for systematic literature review and systematic literature mapping will be discussed. First, the methods will be described in general, and then it will be detailed how they were applied in the study.

A. Overview of Systematic Literature Review Methods

A systematic literature review "is a means of identifying, evaluating and interpreting all available research relevant to a particular research question, or topic area, or phenomenon of interest. Individual studies contributing to a systematic review are called primary studies; a systematic review is a form of

secondary study" [8]. It is a method which is very common in medicine, but which has been increasingly applied to other fields, such as software engineering, in order to make better use of existing evidence.

A related approach is systematic mapping, which is a common alternative if "little evidence is likely to exist or that the topic is very broad" [8]. Whereas the focus in systematic reviews is to go in depth in the literature, and summarize findings, the goal of a mapping study is to give an overview and to identify the structure of a broader research area [9].

In practice, a certain study can contain elements of both these approaches, and this is also the case for this paper, where RQ1-2 will be treated primarily as a systematic mapping, and RQ3-5 will be studied in more detail in a systematic review. The process followed in the two methods is also similar in many respects, but can differ in the details. In summary, the two methods basically apply the following process, which is also the basis of this research [8][9]:

1. Define research questions and review protocol.
2. Conduct search for primary studies.
3. Screen primary studies based on predefined inclusion and exclusion criteria.
4. Extract data using a classification scheme and data collection form.
5. Synthesize data and present results.

Ideally, this process is carried out sequentially, but in practice it is often necessary to go back and update previous steps as the researcher's understanding of the topic deepens.

B. Application of Method to the Platooning Safety Literature

It will now be described how the above process was used in practice in this study. The steps in the process will be presented in each of the following subsections.

1) Define research questions and review protocol

The research questions have already been identified in the introduction to this paper. Based on those questions, a review protocol was prepared that described how to perform the remaining steps. The details of that protocol will be provided below in the steps where they apply.

2) Conduct search for primary studies

The identification of primary studies is decisive for the quality of results, and it is often difficult to ensure that all the relevant papers have been included. In particular, the selection of databases and the formulation of queries is important.

The search was conducted in two incremental steps: first a regular database search was performed, to identify an initial set of papers. The database used for the initial step was primarily the Scopus citation database, which is provided by Elsevier, and is claiming to be the largest such database in the world. Both literature [10] and prior experience of the researcher indicated that this database was likely to provide a large set of relevant papers for the topic of this study. Even though Scopus indexes most of the literature from other databases, the IEEE Xplore database was also searched, since it is one of the most important sources for platooning literature. This precaution also increased the chance of finding very new literature.

In the field of this study, the terminology used is luckily quite

TABLE I
SUMMARY OF PRIMARY STUDIES

Lead author	Year	Context	Brief summary	Reference
Aki	2012	Energy ITS	Discusses the need for an improved brake system in platooning, based on results from driving simulator studies.	[11]
Alam	2014	Scania	Defines a safety criteria between vehicles in a platoon, and reports empirical results of real life experiments.	[12]
Alvarez	1999	PATH	Discusses how to define safety regions to deal with collisions between different platoons.	[13]
Featherstone	2009	CyberCars	Analyzes the frequency and severity of accidents in platooning and uses this to evaluate different design alternatives.	[14]
Hu	2016	N/A	Presents a recommendation scheme for rating if platoon leaders are trustworthy.	[15]
Jones	2013	FHWA	Analyzes human factors challenges related to CACC, and proposes research questions that should be studied further.	[16]
Kato	2012	Energy ITS	Describes an impact-absorbing bumper for platooning.	[17]
Larburu	2010	SARTRE	Analyzes interactions between non-platoon drivers and platoon drivers and evaluates HMI solutions.	[18]
Liu	2015	N/A	Performs theoretical analyses of traffic safety when automated and human driven vehicles are mixed.	[19]
Lu	2002	PATH	Discusses potential hardware faults, and their effect on string stability and thus on the safety of platoons.	[20]
Lygeros	2000	PATH	Discusses how a hierarchical platooning control architecture can be extended with fault handling strategies.	[21]
Michaud	2006	N/A	Investigates how different communication schemes between platoon vehicles affect the ability to perform platooning maneuvering and deal with failures	[22]
Mizuma	2001	Toyota	Describes safety evaluation of autonomous buses running in platoons.	[23]
Nilsson	2013	SARTRE, KARYON	Discusses how ISO26262 can be extended from a vehicle centric perspective to also cover cooperative systems.	[24]
Nowakowski	2015	PATH, Volvo	Discusses the main operational concepts of CACC, including formation, cruising, split, and abnormal conditions.	[25]
Ogitsu	2012	Energy ITS	Analyzes device failures in platooning, and describes a strategy for handling failures based on severity.	[26]
Scheuer	2009	CyberCars	Investigates platoon collision avoidance without relying on positioning or communication.	[27]
Switkes	2014	Peloton	Describes safety considerations in the commercial platooning system for trucks provided by Peloton.	[28]
Xu	2014	N/A	Discusses the value of different information to control platooning in a safe way.	[29]
Yamabe	2012	Energy ITS	Analyzes driving behavior for avoidance manoeuvers when the lead truck makes an emergency braking.	[30]
Zheng	2013	Energy ITS	Discusses driver behavior when dealing with system failures in the formation and separation of platoons.	[31]
Zheng	2014	Energy ITS	Evaluates driver behavior in an emergency braking situation using driver simulation and real vehicles.	[32]

well established, and therefore the query was simply "platooning AND safety". The search was carried out in June 2016, and can therefore be assumed to contain most papers published in 2015 or earlier as well as some from 2016. After conducting the Scopus and IEEE searches, the screening process described in the next section was applied to identify the relevant papers.

For the papers selected as relevant from Scopus, a complementary snowballing search [33] was conducted, in which references to and from those papers were followed to check for additional literature. First, backwards snowballing was done by going through the reference lists in all papers, and based on title only identifying those that appeared relevant. Those were added to the set, and the procedure was repeated until no more papers were found. Then, a forward snowballing was done, where instead it was studied what other papers refer to members of the identified set. This search was done using Google Scholar instead of Scopus, due to its convenient facilities for finding referring papers but also as a precaution against some papers not being available in Scopus. Again, relevant papers were added to the set, and backward and forward snowballing was performed on the added papers, until no more papers could be found.

3) Screen primary studies

The selection of primary studies was based on a review protocol where the following inclusion criteria were defined:
- Papers that explicitly do a safety analysis or report on hazards or technical solutions to improve safety.
- Papers in journals, conference proceedings (peer reviewed), and reports of normal academic standard.

In addition, the following exclusion criteria were applied:
- Non-English papers.
- Papers that just mention safety as an important aspect, but do not analyze it.
- Papers that only focus on limited aspects, such as control algorithms for vehicle motion control; macroscopic analysis of road systems; off-road vehicles; "manual" platooning; etc.
- Papers that are not accessible in full text from the normal research libraries or could be obtained in other ways.
- Preliminary reports, that were later followed by an extended version; typically this would be a workshop paper that later expanded into a journal article, and in that case only the latter was kept.
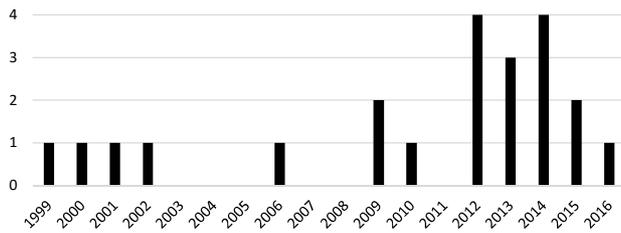- Non-scientific papers, such as commercials, pure
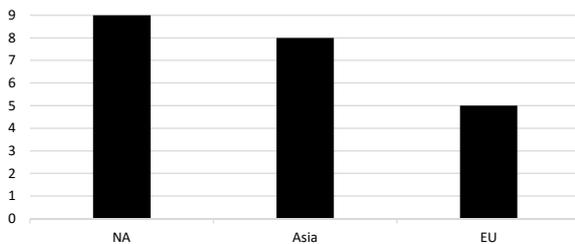
Fig. 1. Number of publications per year.

Fig. 2. Number of publications per region.

opinions, etc.

The screening was first performed on title, abstracts and keywords, and for those papers that appeared potentially relevant, the full papers were browsed to ascertain the fulfilment of the criteria.

The initial Scopus and IEEE searches resulted in 204 papers. After screening, 15 papers remained. Then, snowballing was applied, and 7 more papers were added, leading to a total set of 22. The primary studies are summarized in Table I. In the table, the column "Context" identifies if the work was carried out as part of any of the major platooning research projects, or by a company.

In addition to the primary studies, that comprises the literature where the safety aspects of platooning is central, a large number of other papers that contain some valid information, but has a different focus, were retained. These are used as complementary references throughout this paper.

Among the papers considered, there is a large number that only mention safety as an important aspect, but do not deal with it further. There are also many papers that discuss the control algorithms for maintaining the appropriate distance between vehicles and to achieve string stability. However, as already discussed this can be considered to be a normal situation, whereas safety analysis is primarily concerned with situations when something goes wrong, and those papers were in general also excluded.

4) Extract data using a classification scheme

The identified 22 papers were classified based on the following scheme:

- *Administrative information*: Paper ID; Title; Selection method (Scopus, IEEE, or based on snowballing to/from another paper); and Brief summary.
- *RQ1 – Literature characteristics*: Authors; Year; No. of citations; Venue type (journal, conference/workshop, report); Venue; Country; Region.
- *RQ2 – Application characteristics*: Platooning objective; Application area; Special assumptions.
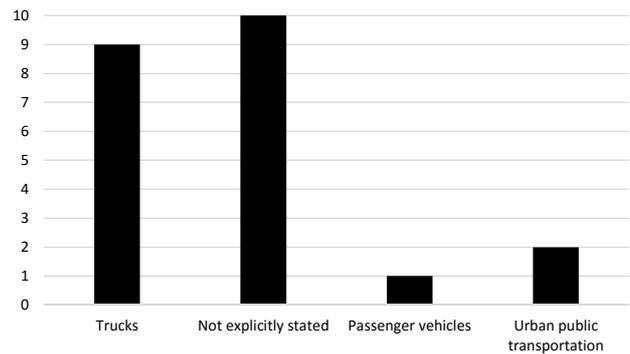

Fig. 3. Number of publications per application area.

- *RQ3 – Safety analysis method*.
- *RQ4 – Hazards, failures*, etc.
- *RQ5 – Technical or managerial solutions*.

A data collection form was used consisting of a table with one column for each category, and one row per paper. Each cell in the table contained the data for that paper and category.

5) Synthesize data and present results

The data was synthesized by cross-reading the papers by column to identify the data that provides input to each research question. In some cases, the data was grouped into subcategories based on what was actually found. This will be illustrated in the next section, where the results are analyzed.

III. RESULTS

The results of the study will now be presented, and each of the five research questions is reported in a separate subsection below.

A. Characteristics of the Literature

The characteristics of the literature is useful to distinguish the overall structure of the research in the area. For platooning safety, as mentioned above, the literature consists of 22 papers that have been published between 1999 and 2016 (see Fig. 1). The paper authors were fairly evenly distributed between the regions North America, Europe, and Asia (see Fig. 2). The Asian papers were mainly from Japan, the North American mostly from USA, whereas the European were from Sweden, UK, Spain, and France.

As Figure 1 indicates, there are two groups of papers, one around the turn of the century and the other during the last five years, and when digging deeper into the papers, it was revealed that this corresponds to different research programs in various countries. The first group of papers are mostly from the USA, and are related to the PATH project at the University of California at Berkeley, whereas the more recent papers stem from the Energy ITS initiative in Japan [34], and from different European research projects, such as SARTRE, GCDC, COMPANION, Chauffeur, CyberCars, and KONVOI [35][36].

It is also interesting to see where different papers have been published. Out of the 22 selected publications, 7 were from journals, 13 from conferences, and 2 were reports from institutions. 7 of the conference papers were from the Intelligent Transport Systems World Congress series, and 3 journal papers
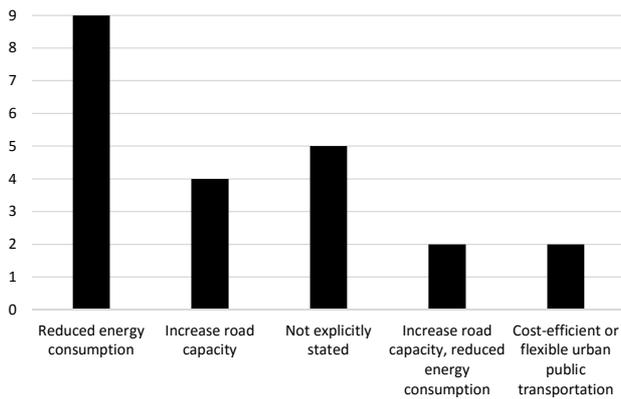
Fig. 4. Number of publications per platooning objective.

were from the IEEE Transactions on Intelligent Transportation Systems. These were the only publication venues with more than one publication. The papers have received in total 258 citations, giving an average of 12.3. However, the two oldest papers from 1999 [13] and 2000 [21] contribute with 44 and 62 of those citations, respectively, and the remaining papers thus have an average of only 7.6 citations. Both the relatively small number of relevant papers, and the low citation scores, indicate that platooning safety has not been an area that has received much attention.

In total, 68 different persons appear as authors in the papers. Most of them only have a single publication, but several of the Japanese papers come from the same team, consisting of Nakano, Suda, Yamabe, and Zheng (co-authoring four somewhat overlapping papers), and sometimes also including Aki and Nakamura (two papers each). In addition, X. Lu and Tsugawa have contributed with two papers each.

B. Application Areas

Platooning has been mainly considered for two application areas: passenger cars and heavy trucks. As shown in Fig. 3, the truck application is dominant, and has been the clear focus during recent years. A number of papers do not state explicitly what area they are focusing, but in the earlier papers it appears that passenger cars were emphasized, and in some publications it also appears that a mix of cars and trucks are considered. In addition, there are two papers focusing on urban public transportation systems, namely [23] which focuses on buses, and [27] which targets small electrical vehicles.

When it comes to the objective of platooning, a similar pattern can be seen. In the early work focusing on passenger cars, the main goal has been to deal with road congestion by packing cars closer together and thereby making better use of existing road capacity. Later, this has shifted to instead improving energy consumption, through reduced aerodynamic drag by running closer to each other, and this effect is more prominent for trucks. Fig. 4 details the number of papers for each of these objectives. In addition, the paper addressing urban public transportation [23] has a focus of providing a cost-efficient alternative to light rail systems, which is unique to that paper.

Different projects and papers also make varying assumptions about the context of platooning [35]. In particular, there are differences when it comes to assumptions about the infrastructure, where early work assumes an automated highway system with dedicated lanes and sophisticated road-side traffic control systems [13][21][23][35], and sometimes also the use of magnetic guidance embedded in the road [20][23]. The more recent publications tend to assume mixed traffic on existing highways, and in some cases even non-highway scenarios dealing with intersections [16][19].

Another set of assumptions deals with the functionality, and in particular the level of automation. Some publications assume full automation, where both longitudinal position (acceleration) and lateral position (steering) is considered, whereas others limit themselves to only longitudinal control, which is sometimes referred to as Cooperative Adaptive Cruise Control (CACC). In some cases, the length of the platoon is very restrictive, even down to only two vehicles [28], and some assume (explicitly or implicitly) more or less equal vehicle configurations [12].

Understanding the application area and its objectives is clearly important when analyzing safety, since not meeting the objectives constitutes a loss, which is included in the broad definition of safety presented in the introduction [3]. In addition, the assumptions about context and functionality need to be understood to determine to what extent a certain solution is also valid in a different situation.

C. Safety Analysis Methods

An important aspect of developing safe systems is what methods have been used to analyze just how safe they are. In the literature on platooning, safety related analyses have been conducted on two different levels. The first is the level of system safety, where the objective is to understand the safety of the whole system as a consequence of how it is integrated from its components, with its users, and in its environment. Typically, methods in this area deal with identifying hazards, and understanding how failures can lead to hazards and possibly accidents. The second level deals with specific aspects, either a certain component, a certain kind of damage, or a limited part of functionality. These methods are not substitutes for doing the system safety analysis, but can provide valuable input in order to better understand certain parts of the system. In the following subsections, these two levels will be discussed.

1) System safety

A large number of methods have been proposed in the field of system safety. Some of them, such as Fault-Tree Analysis (FTA), Failure Mode and Effects Analysis (FMEA), and Hazards and Operability Analysis (HAZOP) have been in widespread use for decades [37]. In the automotive industry, as well as in others, functional safety has lately been in focus, through the introduction of the generic IEC61508 [38] and the automotive specific ISO26262 [39] standards. In functional safety analysis, hazards are identified, and based on their severity, probability of exposure, and controllability, a Safety Integrity Level (SIL; or Automotive SIL, ASIL, in the case of ISO26262) is determined. This classification is then used to

determine what means are needed to achieve the necessary safety, for instance through a decomposition of safety requirements to redundant units. The interest in these standards in industry is partly due to a need to certify products, or in other ways being able to prove that best practices have been followed when it comes to product liability.

In the primary studies, it is surprising to see that only two papers mention any of the established system safety analysis methods. Of these, Nilsson et al. [24] discuss how ISO26262 could be used to analyze cooperative systems, using platooning as an example, and they conclude that the current standard is insufficient when going beyond a single vehicle. In particular, they identify the severity classification of hazards as an issue, claiming that the current scale with three severity levels defined in the standard is limited to hazards involving life-threatening or fatal injuries to a few persons, whereas platooning could potentially involve many vehicles. Consequently they propose a fourth severity level, to handle the death of tens of persons. It then also becomes necessary to introduce a fifth ASIL level.

The other paper that mentions established methods [23] is using IEC61508 together with FTA, and this choice is motivated by the application area of bus platooning as a replacement for light rail transportation, and by the fact that those methods are commonly used in the railway domain. However, the paper is very brief on how the methods have been applied.

A third paper is also relevant to the area of system safety [14]. It studies how vehicle spacing in platoons can lead to casualty risks, which are analyzed using the Abbreviated Injury Scale (AIS) based on the collision speed, resulting in probabilities for fatalities. The use of restraints, such as seatbelts and airbags, are also included in this analysis. These probabilities are used to determine the consequences in terms of fatalities in a national transportation system, and by relating that to the risks that exist in current systems a tolerable risk level can be defined.

2) Specific aspects

Turning to the papers that discuss analysis of more specific aspects, the applied methods can be subdivided into three main groups: theoretical analyses, simulations, and tests.

In the group of theoretical analyses fall approaches based on control theory, including the identification of safety regions to avoid that one platoon collides with another in an automated highway system [13]. Related to this is also a game theoretic analysis of safety distances within a platoon [12], and a theoretical analysis of traffic safety in situations where some vehicles are automated and others are human driven [19]. Finally, one paper performs a logical reasoning to determine how combinations of device failures can be managed by a proposed handling strategy [26].

Among the simulation approaches, driver simulation is the most prominent, and has been used in a series of related papers [11][30][31][32] which investigate the capability of human drivers to take over control in case of a failure, in particular in an emergency brake situation. It has further been used to assess how the presence of platoons influence the headway distance behavior of manual drivers [18]. Driving simulation is also mentioned [2] as an important method for determining human

factors issues in CACC, together with other techniques such as microsimulations of traffic and field studies including road tests. Other simulations are also included, such as the mathematically oriented simulations to validate theoretical results [15]. Related to simulations is also the use of robotic model cars to investigate how the communication schemes influence platooning maneuvers [22].

Finally, when it comes to actual testing, road tests have been used by several authors (e.g. [12][28][32]). Road tests can be either naturalistic field studies on public roads, or on closed test tracks. Tests have also been applied to evaluate specific solutions, such as collision tests for a protective bumper design [17].

D. Hazards, Failures, and Human Factors

As mentioned in the previous section, the identification of hazards is an important part in most system safety analysis methods, and it is therefore interesting to see what hazards are considered in the primary studies, and this will be the topic of the first subsection. Then, an analysis follows of what technical failures can lead to those hazards, and finally, it is discussed what human factors issues have been identified.

1) Hazardous situations and losses

The most prominent hazard is, as was already described in Section 1.A, that one vehicle in the platoon runs into a preceding vehicle [12][14][17][30][31], and in particular this becomes an issue when the first vehicle needs to perform an emergency brake. A variation of this is when the lead vehicle of one platoon runs into the last vehicle of another platoon [13][14], and avoiding this becomes a part of the system's functionality when considering automated highways. In most cases, it seems to be the goal of the authors to completely avoid collisions, but interestingly, Alvarez and Horowitz [13] define safety as the "absence of collisions [...] that exceed a given relative velocity threshold." Although the consequences of a low impact collision might be very small, it is questionable if such occasional bumping would be acceptable for the vehicle occupants.

Another commonly mentioned hazard is cut-in situations, where other vehicles change lanes to end up in the middle of a platoon [25][28][30][32]. It appears that these situations are unavoidable in real traffic environments, and have to be dealt with by increasing the distance once a cut-in occurs, splitting the platoon, and later rejoining when the vehicle has disappeared.

Other potential hazards related to avoiding collisions include driving off the road as a consequence of trying to avoid a collision by steering [31]. This is a situation that could appear when the lead truck suddenly changes lane to avoid a stopped vehicle or debris in the roadway ahead. Reaction time for following vehicles could be very short, and they may not have space to also change lanes [25]. It is also noted [30] that with short inter-vehicle distances (e.g. 10 m), there is not enough room for a truck to avoid a collision by steering. Further, the safety goals of the system should include no unintended full braking in platooning at cruise speed, and no sudden unintended full acceleration in platooning at low speed [24], since the

system would be actuating the brakes and accelerator. (If steering is also automated, a similar safety goal for that would need to be included, although that is not mentioned in the study.)

So far, the hazards have mainly been associated with the narrow view of safety focusing on accidents that endanger humans. However, the broader definition of safety introduced earlier also considers other kinds of losses, which would mean failing to meet the objectives of the system. As seen above, in many of the papers the objective is reduced energy consumption, and two risks related to this goal have been identified in the CACC application [25]: Firstly, there is a risk that inaccuracies in (manual) steering of the following vehicles would increase drag and result in a smaller gain in energy consumption; and secondly, cut-ins could very well prove to be so common that the energy consumption effects are minimized.

2) Technical failures and consequences

One reason for hazards leading to accidents is a technical failure in a component. Some papers evaluate what component failures would need to be considered in the safety analysis, and the components enlisted are:

- *Sensors*, such as radar, laser, camera, speedometer, tachometer, position and magnetometer [20][26];
- *Actuators*, such as steering, accelerator, and brake [20][26];
- *Inter-vehicle communication* [11][20][25][26];
- *Computation* [11][26];
- *Internal communication networks*, such as CAN buses [20];
- *Driver interfaces* [21][26]; and
- *Infrastructure* [21].

Lu and Hedrick [20] also propose a priority order among some of these which includes four levels, and can be used for fault management. Interestingly, they include also software in this priority order, but explicitly state that this is outside the scope of their analysis. The same restriction is made in another paper [21], and these are the only two places where software problems are mentioned in the primary studies.

Having identified individual component failures, it also becomes possible to consider interactions between several failures. One example is how to deal with a mismatch between a forward distance sensor and the inter-vehicle communication, which could be caused either by a cut-in or a GPS error [25]. Another inconsistency could occur between the state perception of different vehicles in the platoon, which could lead to them making incompatible decisions, such as full braking of some vehicles and maintaining cruise speed of others [24]. During join or split manoeuvers, they could also end up with different views on who is the platoon leader [25].

Two papers discuss the general handling of failures [21][26], both identifying a number of levels with immediate stop of the vehicle as the most severe, and no special handling needed as the least severe (with some smaller variations between the papers when it comes to the intermediate levels, due to different application contexts).

A particular technical failure is a deliberate manipulation of the system through cyber-attacks. This is discussed in the context of a concept where users can rate platoon leaders [15]. In that case, the attacks are primarily aiming to provide unjustified trust in a leader, but other cyber-attacks could be considered for platooning applications.

3) Human factors

Most approaches to platooning still give an important role to the human driver, to supervise the automated parts and sometimes also actively perform some functions, such as steering. Human factors is thus an important area, and Jones [16] has summarized the challenges in the context of CACC. Some aspects have to do with the introduction of automation, where it is questionable to what extent humans will actually use it, and what levels of trust and reliance they will give it. One study [18] investigates how following drivers perceive the distance gap, and conclude that they start to feel uncomfortable when the gap reduces to below 16 m, and that they feel unsafe when it is below 7 m.

A particular concern here is the increased responsibility of the lead vehicle driver [25]. It is clearly important that following drivers can trust the lead vehicles, and one suggestion is to introduce a scheme, were users can rate the behavior of lead drivers, and the data can then be used to recommend to others whether to join a platoon with that leader, or not [15].

The performance of the human driver is also an issue [16], and includes driver behavior during lane-changing and car following manoeuvers; and possible increases to brake response time (although simulation studies indicate response times around 0.6s [30][32]). Jones [16] also discusses the possibility of poorer human performance when supervising automated systems than when driving manually, and potential carryover effects, such as using a shorter time gap when driving manually after having used platooning. One study has investigated how the mere presence of platoons influence the headway of non-platoon drivers, and the simulator studies indicate a "contagion" effect when driving next to a platoon [40].

Driver workload is a special concern [18], and there is on the one hand a risk that platooning would reduce the workload, leading to underperformance and tempting the driver to take on secondary tasks [16]. On the other hand, there are indications that steering with limited forward vision could impose a very high workload, rapidly leading to fatigue [25]. Overall, driver situational awareness is an issue for the following vehicles [18], in particular when cruising is interrupted by joining vehicles, splitting of platoons, cut-ins, or system failures [25].

It is also interesting to study the effects on other traffic that do not participate in platoons once platoons are introduced. Larburu *et al*. [18] evaluates, using driving simulators, how long the platoons can be without being regarded as a disturbance by other road users, and conclude that up to 15 vehicles in a platoon is acceptable.

E. Solution Elements

Almost all of the primary studies discuss various elements of the technical solution, and there is almost general agreement of a minimum set of devices needed. This set consists of inter-vehicle communication; some kind of sensor for measuring

distance to the vehicle ahead; and actuation of at least accelerator and brakes, and also steering if lateral control is automated. To this set, different papers propose a wide variety of additional solutions in order to enhance safety or otherwise improve the system. In the following subsections, the proposed solutions will be reviewed, with a focus on those addressing safety. The structure of the section is a result of grouping the data extracted from the primary studies into a set of related topics.

1) Sensors

As already mentioned, forward-looking distance sensors are part of most platooning concepts. However, there are large variations in the sensor setup, both when it comes to technology and redundancy. Often, a radar is considered as the primary sensor [25][26][28]. However, it may not be sufficient to deal with all situations, and one suggestion is to complement it with a broad field of view sensor to detect cut-in situations [25]. Another proposal is to complement the radar with a laser sensor to provide redundancy [26].

For lateral control, further sensors are needed, and several alternatives have been proposed, such as magnetic sensors that measure the presence of magnetic nails in the road [13][20][23], or a combination of camera and laser sensors to detect lanes [26]. On a more coarse grained level, positioning sensors such as GPS are also needed [28].

This sensor setup could be complemented in different ways, and one proposal is to also include backward-looking sensors [24]. The purpose of such a sensor is not clearly stated in the paper, but one possible use could be to keep track of surrounding traffic to improve situational awareness in lane-change manoeuvers. Another suggestion is to include a laser scanner to identify the road surface conditions and lane markings [11].

As an alternative or complement to using redundant sensors, a proposal is to use sensor fusion to make estimations of missing data [20]. However, the study does not give precise information about which sensors to fuse, and how to do it.

Finally, there are also approaches that do not assume a forward-looking distance sensor, but instead rely on communication of the different vehicle's positions to achieve a similar objective [42].

2) Actuators

The system will need to actuate acceleration, braking, and potentially steering, and the main focus in the primary studies regarding actuation is how to provide redundancy. It is suggested to use a redundant secondary brake system [11], and to use both two brake actuators and two steering actuators [26].

There are also discussions about how to integrate the platooning related actuation with other vehicular systems. In one study, the platooning system is designed as an add-on solution for trucks [28], and it then becomes an issue how to integrate with the vehicle's existing brake system, and what the requirements are on that system. Another issue is blending of automatic and manual braking [30], and it is suggested to provide an override-braking mode, where the system brakes automatically until the driver takes over the braking.

3) Communication

Inter-vehicle communication is part of most approaches to platooning, and it is motivated by the need for string stability, where the delays induced by having only forward-looking sensors would cause instability as a deceleration of the lead vehicle propagates down the platoon. With communication, the lead vehicle can communicate its status directly to all the follower vehicles [1]. Control algorithms can also be designed to use the communication protocols in order to make all the vehicles in the platoon converge to their desired velocities and inter-vehicle distances in an efficient way [43].

As for sensors and actuators, it is suggested that redundancy may be needed in inter-vehicle communication [20][24], and one suggestion is to complement radio communication with optical communication to achieve this [26]. This can use infrared [44][45] as well as visible light [46].

However, inter-vehicle communication is not the only kind suggested, and in automated highway systems, vehicle-to-roadside communication may also be needed [23]. Cellular communication is suggested for long-range needs, such as for coordinating vehicles prior to platoon formation [25] or for interacting with a central traffic controller [28].

Another need is communication to the drivers, as opposed to communication between the automation systems. Two studies [25][28] introduce the idea of feeding video streams from a forward-looking camera in the lead vehicle to the other vehicles, to improve the situational awareness of the followers. Also, there could be a benefit of allowing drivers to communicate their intentions, such as to leave the platoon or change lanes [25], and this can be achieved through voice communication [28].

It is worth noting that although most studies acknowledge the need for communication, they are typically vague about the details of that communication, such as what information is transferred, how often, to whom, etc. A basis can be existing ETSI standards for cooperative awareness messages, but these do not appear to be sufficient for platooning [47]. In addition to distance and vehicle speed, information about braking events are also highly valuable [29]. One study, which investigates situations where some vehicles are autonomous, and others are driven by humans, implicitly assumes that the autonomous vehicles need to have access to the driving mode of the surrounding vehicles to predict their behavior [19]. The update rate, which is often assumed to be static, can under some circumstances make more efficient use of the bandwidth by instead sharing data only when needed [46]. (However, this could have consequences on the ability for a receiving vehicle to detect communication failures.)

It is also not universally accepted that communication is needed, and some studies argue that sensor solutions are sufficient for collision avoidance [27]. However, others have investigated different communication schemes, including non-communication, unidirectional or bidirectional communication with the vehicle before and/or after; and centralized where all vehicles share the same information [22]. A clear conclusion is that approaches without communication are insufficient, and this is also supported by [29].

4) Computation

The platooning functionality would typically be realized by software running on computers. However, there is only one study that discusses safety related solutions to this [26]. Their proposal is to provide fail-safe Electronic Control Units (ECUs) with two CPUs and a comparison circuit, for the longitudinal and lateral control systems.

5) Protection

So far, the solution elements have mainly been aiming at avoiding failures that could lead to accidents. However, accidents may still occur, and then protective devices could be used to mitigate the effects. The only suggestion in this direction is to equip platooning trucks with a redesigned bumper using a pneumatic cylinder to absorb energy when the vehicles in the platoon collide [17].

6) Management

In addition to component related solutions, some of the hazards may require solutions that are on a managerial level, and here two such issues will be discussed, namely how to handle differences in vehicle configurations within the platoon, and the need for central control systems.

Although not always explicitly stated, many of the studies appear to make an assumption that the vehicles in a platoon have similar capabilities, in particular when it comes to braking. If this is not the case, the differences need to be handled to avoid situations where a lead vehicle brakes harder than the followers are able to [25]. This problem becomes particularly pronounced for trucks, who can have huge differences in weight depending on if they are loaded or not. In principle, two solutions are put forward to this. The first is to order the vehicles in the platoon according to brake capability, with the least capable taking the lead [12][28]. The other option is to limit the brake force of the lead vehicle to that of the least capable in the platoon [11]. However, both these solutions assume that brake capability can be accurately estimated, but it is not explained how this should be achieved.

Although many studies on platooning focus solely on the interactions between the vehicles in the platoon, there are also a few that introduce the idea of a central control system [23]. This can be used both to enforce safety criteria, including road and weather conditions, which can be delimited using geo fencing where platoon formation has to be approved by the central system [28]. The same central element can be used for other services, such as coordinating the movements of vehicles so that they actually meet up prior to platoon formation [28], and to manage economic transfers between the vehicles to compensate for the lower benefit in terms of energy reduction for the vehicle leading the platoon [25]. This central controller could also collect data and provide analytics capabilities that could benefit both fleet managers and highway officials, to optimize future operations both in terms of safety and efficiency [28], and be used for collecting user ratings of platoon leaders [15]. Some concepts also assume that there are road side units that communicate locally with the vehicles [15], and can manage e.g. scheduling in intersections [19].

7) System architecture

In many studies, the scope of the platooning system is the participating vehicles, and in that case, the system architecture becomes fairly straight-forward: a few technical elements, such as sensors and communication is added, and this is used by a distributed control system with software allocated to the participating vehicles. However, as was described in the previous subsection, there are compelling arguments for also introducing a centralized element in order to make platooning successful in practice. This makes the system architecture a bit more intricate, and requires a more thought-through strategy for how different elements should interact.

The need for clear architectural principles was realized already in the early work on platooning in the context of automated highways [13][49]. Here, a hierarchical architecture was proposed, where different layers would be responsible for vehicle dynamics; regulation of platoons; coordination between platoons; and also with higher levels for controlling traffic flow etc. This control hierarchy was complemented with three additional hierarchies [21]: A sensor hierarchy provides sensor information at different levels of abstraction; a capability monitor hierarchy collects fault information at different levels of abstraction; and a performance monitor hierarchy collects environmental conditions at different levels of abstraction, and determines various performance factors. Depending on the capabilities and performance of sensors, actuators and communication, different control functions at the next level may become available or unavailable. In a similar way, different control models can be selected based on the control of a supervisor [50].

IV. DISCUSSION

The previous section summarized the literature on platooning safety, based on the various perspectives introduced in the research questions. In this section, the findings from the literature will be discussed, and in particular, there will be an emphasis on what it takes to do safe platooning in practice. After all, literature describes results based on research prototypes or technology demonstrators, with only one exception [28], which describes a commercial system designed as an add-on for trucks. This particular example also gives many insights into practical implications, introducing some solution elements that are typically not present in other studies, such as video and voice communication between the trucks, and a centralized traffic controller dealing with all kinds of services, including safety. There are clearly also many other practical issues to resolve, not the least important being how to deal with economic incentives and transactions [25].

Whereas the previous parts of the paper have been objective accounts of the literature, this section is an outlook based on interpretations of the author.

A. Overall Concepts

When looking at the literature, it appears that the hazards are fairly well understood, and in particular risks related to collisions within platoons, and interactions with other traffic, including cut-ins. What is apparently far less clear is what functionality and overall system architecture is needed, and there are almost as many variants as there are papers, including

automated highways with dedicated lanes vs. ad hoc platooning in mixed traffic; full platooning including automated lateral control vs. CACC; the use of a central controller with cellular communication vs. only onboard systems with dedicated short-range communication, etc. There is clearly a need to analyze these alternatives, not only from the ability to meet the objectives of platooning, but also from a safety perspective.

B. Platooning Business Ecosystems

One of the greatest neglects in the literature is how platooning will be developed and operated in practice. On the highway, there are vehicles of many brands, and operated by many individuals and fleet owners. It seems clear that for platooning to gain widespread use, it is not sufficient to restrict the formation of platoons to vehicles of one brand and operated by one fleet. On the contrary, there will be a business ecosystem forming, where vehicles of different brands and models will need to interact. This in turn requires new actors, such as standardization bodies that define the interoperability requirements, and service operators that are responsible for shared infrastructures such as cloud-based traffic control centers. As pointed out in [51], this kind of ecosystem poses challenges when it comes to safety, since responsibilities become unclear, and there could be a need for special agreements to clarify responsibility for safety between developers [24]. Possibly, there will be a need for certification bodies, standardized tests, and regulations, to make such ecosystems function in practice, and many of the safety solutions will be managerial and organizational rather than technical.

C. System-of-Systems Safety Analysis

In the literature, the lack of application of established methods for system safety analysis to platooning is striking. Possibly, this is due to a lack of applicability of those methods to the kind of system-of-systems that cooperative driving functions exemplify [24]. But if that is the reason, new or improved methods for dealing with safety for systems-of-systems are urgently needed.

At the same time, many studies propose technical solutions to address safety, such as redundancy in sensors, actuators, and communication. But with the lack of a thorough safety analysis, it is hard to see why those solutions were selected. Can the redundancy be motivated from a clear safety need, or were they just put in based on the misconception that redundancy is always better than no redundancy? Starting with a system safety analysis, it becomes possible to evaluate which technical solutions are most cost-effective in achieving real safety.

A particular issue is that the safety of software is completely neglected. As discussed in the previous subsection, it is likely that platooning will be developed based on certain standards, meaning that each vehicle OEM (or their suppliers) will implement their own solutions. This introduces a whole new range of safety issues, related to interoperability, misunderstandings of requirements, or simple mistakes. Mitigations are needed, and would mostly be process-related rather than technical.

Cyber-security is only discussed in one paper [15], but it is clear that the communication channels used in platooning opens up many possibilities for manipulating the systems, and those manipulations can affect the safety as well. There is thus a need to consider security also as part of the safety analyses.

D. Vehicle Variability and Estimation

In the platooning ecosystem, there will be vehicles of many kinds, with their varying implementations of the functionality. But they will also vary in other respects, and in particular their capabilities and performance. A special concern discussed above is related to braking capability, and the suggested approaches all assume an ability to estimate this capability. But there is a lack of models in general to provide the control systems with estimates of the capability, and a lack of understanding what accuracy is required and can be provided by such models. Ideally, such models should be self-tuning to avoid manual errors during calibration (perhaps similarly to the suggestion for steering in [52]).

Diagnosis of faults provides comparable challenges, which several papers assume can be done as a basis for fault handling strategies. Under certain conditions, those faults will also be of interest to the other vehicles in the platoon, but to what degree will one vehicle be willing to trust the estimate of others? Possibly, there is a need for providing fusion functionality for the estimates, meaning that several vehicles together build a joint estimate of the overall status of different parts of the platoon. This however introduces extra complexity and associated risks.

A special case of variability applies to trucks. In long-haulage operations, of the kind mostly using the highways, the typical truck is a tractor-trailer combination. However, these parts are typically manufactured by different companies, and the tractor has only limited information and controllability of the trailer. In practice, this means on the one hand that estimations will become more difficult, due to lack of information about the trailer, and on the other hand that certain technical solutions could become infeasible. This is for instance the case with special bumpers [11], or if there is a need to place sensors or communication equipment on the trailer.

E. Human Factors

The fact that there will still be human drivers involved in platooning poses many challenges, which are summarized by Jones [16], who also points out directions for future research in this area. It is clear that the role of the driver needs clarifications, and this also includes the responsibility and liability of drivers in case of accidents. To what extent can the lead driver be held responsible for accidents involving the following vehicle? And to what extent can the following driver be held responsible in a situation where they need to rapidly move from supervising the automated system to driving manually? To achieve safety, there may be the need for training and certification of drivers, as well as updating legal requirements. Also, there could be a need for technical solutions to help accident investigations. In this way, legislators and law enforcement also become actors in the ecosystem.

V.   Validity of Results

As with any other empirical study, there are many threats to the validity of the findings in this paper as well. Some of the more prominent ones will now be discussed, together with the actions taken to mitigate them.

The first question one should ask is whether all relevant literature has been found. Of course, given the immense amount of scientific publications each year, there is always the risk that some publications were missed, for instance through the selection of search string. In this particular study, the terminology is luckily fairly well established, both regarding platooning and safety. Then comes the question whether the selected database is adequate. In this case, Scopus was used, since it is the largest bibliographic database available, in combination with IEEE Xplore. A drawback of Scopus is that it has a focus on recent literature, primarily after 1995. To deal with this potential threat, a complementary search approach was used, where snowballing of references was applied. This approach is insensitive to the search strings, and also to the choice of database when it comes to backwards snowballing. For forward snowballing, a different database was used, namely Google Scholar, and this was partly to ensure that also literature outside Scopus had a chance of being identified. All in all, it is likely that the majority of relevant papers have been identified. As an extra security, various ad hoc searches have been performed in Google Scholar, without revealing any additional primary studies. Having found a set of potentially relevant studies, there is also the screening, which is potentially subject to bias. In this case, the risk was reduced by having well-defined inclusion and exclusion criteria in a predefined study protocol, giving guidance to the researcher. Also, a threat is that the selection was done based on title, abstract and keywords rather than full papers. However, it would have been infeasible to read the complete set of papers. Still, in some situations when the verdict was uncertain, the full papers were studied before deciding on excluding certain studies.

A second question is whether the research literature represents all the available knowledge. There is always a risk that valuable knowledge does not get published, and one reason could be publication bias, meaning that positive results are more likely to be published than negative ones. In this case, solutions that do not work might not get published. However, this could still carry important information relevant to a safety analysis. Also, there is a risk that a sponsor chooses to withhold a certain result, either because it presents a commercial opportunity, or because it presents a risk to an existing product. This could be the case with safety problems that have been discovered. However, given that platooning development is still mostly in a pre-commercial phase, these risks are probably also small.

A third question is whether data has been extracted and interpreted in a correct way. Here, there is always room for subjectivity from the researchers involved, and there are no guarantees that correct interpretations have been made in all situations. However, the researcher has almost 15 years of industrial experience from the automotive domain, and thus a solid understanding of the concepts involved, which reduces this risk. Also, the moderate size of the literature base has made it possible to study each paper in more detail than would otherwise have been possible. Finally, the extraction has been done using a predefined data collection form based on a set of clearly defined research questions, which also reduces the risk of oversights.

A final question is whether correct conclusions have been drawn from the material. In this particular study, the literature has mainly been summarized, with only little interpretation and judgement. Therefore, the risk is probably small that incorrect conclusions have been drawn in the larger perspective, although smaller details could possibly have been missed or misunderstood.

VI.   Conclusions

Vehicle platooning has been a subject of research for a long time. However, to take platooning from research prototypes and technology demonstrators to large-scale deployment, it is imperative to prove that they are sufficiently safe. Therefore, it is interesting to summarize the evidence that has been collected on platooning safety over the many years of research, and it is a bit surprising to find a lack of systematic analysis, and only a number of scattered results. The paper addressed five research questions, and the answers to each of them will now be summarized.

A.   What Characterizes Existing Literature on Platooning Safety?

22 primary studies have been identified between 1999 and 2016, with authors from North America (9), Asia (8 papers), and Europe (5). The total number of authors is 68, but only a few of them have contributed to several papers. The primary venue for publications in the field is the ITS World Congress (7 papers), followed by IEEE Transactions on Intelligent Transportation Systems (3 papers).

B.   What Are the Characteristics of the Applications Studied in Literature?

The primary studies fall into two groups. The early, mostly American, research focuses on automated highway systems with passenger cars, with the objective of reducing congestion. More recent research, mostly in Japan and Europe, instead focuses on trucks traveling on normal highways, with the objective of reducing energy consumption.

C.   What Safety Analysis Methods Have Been Used in Literature?

There is a clear lack of systematic safety analysis using well-established methods. Only two studies mention commonly used safety standards like ISO26262 or IEC 61508, and a possible explanation is that these standards are insufficient to deal with cooperative systems. In addition, there are many papers that address particular concerns with relation to safety, using theoretical analyses, simulations, and testing.

D.   What Hazards and Failures Have Been Identified in Literature?

The most prominent hazards are related to the risk of a

vehicle in the platoon running into the preceding vehicle, and another commonly mentioned risk is that caused by cut-ins from surrounding traffic. There are many potential technical failures that can cause these hazards, such as failures in communication, computation, sensors, actuators, position, and infrastructure. Also, there is a large set of human factors that can cause hazards, including risks related to the introduction of automation, driver workload, and situational awareness.

E. What Solution Elements Have Been Proposed in Literature to Improve Safety?

The platooning functionality will rely on sensors, actuators, computation, and communication, and the primary safety solutions are to provide redundancy in these areas. However, the effects of this are unsubstantiated. In addition, there have been proposals for managerial solutions, such as a centralized traffic control system with various functions, and architectural patterns consisting of layers with clear separation of responsibility.

F. Outlook

Even though the literature is scattered, and no paper gives more than a fragment of the total picture when it comes to platooning safety, they complement each other in a good way, and the contribution of this paper has been to synthesize an overall view of what is known on the subject.

It is clear when looking at the results that there are gaps in the knowledge, and in particular when it comes to putting the concepts into practical use on a broad scale. The best concept for platooning is still not clear, and many different variants have been tried over the years. In selecting which way to go, safety must be an integral part of the decision. It must also be understood that there will form a business ecosystem around platooning, with many different actors cooperating and competing with each other, and this raises important issues related to safety, due to interoperability requirements and shared responsibilities. There is apparently a lack of applying appropriate safety analysis methodology for this scenario, and an approach suitable for systems-of-systems is needed. In practical implementations, many issues also persist related to variability in vehicles, and to human factors.

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