A Taxonomy of Optimization Factors for Platooning

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Abstract—The technical maturity of autonomous driving enables the discussion of beneficial use cases to leverage its full potential. In this paper, we target one such use case: Platooning is the efficient convoying of vehicles by making use of self-driving capabilities and inter-vehicle communication. Many advantages arise from grouping vehicles in platoons with a small inter-vehicle distance, such as energy savings, congestion reduction, and safety improvements. However, due to the diversity of involved stakeholders, numerous objectives have to be balanced to leverage the full potential of platooning. Furthermore, these objectives also depend on various factors that influence their optimization. The vast majority of existent literature only targets a subset of related objectives and underlying factors. This paper provides an overview which categorizes objectives and influencing factors. Additionally, metrics for the evaluation of objective attainment are proposed.

1 INTRODUCTION

Recent developments in autonomous driving by companies such as Waymo, Tesla, or Uber open the stage for various new use cases. One of these is platooning, the efficient convoying of vehicles [1]. Energy savings, congestion reduction, or safety improvements only represent a small fraction of the numerous advantages resulting from leveraging self-driving capabilities and inter-vehicle communication [2].

Due to its various advantages, possible risks, and the involvement of numerous individuals and other context influences, the optimization of platooning represents a multi-objective and multi-constraint optimization problem. The scope of such objectives does not only vary from approach to approach but also differs for people, platoons, or societies [3]. Some objectives might be conflicting while others complement each other; some might represent objectives of single persons while others represent objectives of a whole platoon. For example, some drivers may tolerate an increased traveling time for higher energy efficiency while others prefer faster traveling instead [4]. Furthermore, the objective attainment depends on various influencing factors. For instance, weather, traffic, or vehicle characteristics have an influence on possible energy savings. Resulting from this diversity, also many respective evaluation possibilities exist.

While platooning research often refers to single aspects of this problem, this paper aims at providing a broad overview on optimization factors for platooning. Our contribution, which emerged from conducting a comprehensive literature review, is tripartite. First, we propose a taxonomy that presents objectives for platooning. Second, we describe different metrics for evaluating the objectives and identify factors that influence objective attainment. Third, we discuss possible conflicts between the three levels of our taxonomy, namely individual vehicles, platoons, and global traffic. The paper puts the basis for future work on platooning optimization, highlighting the key aspects that should be considered when realizing the algorithms that will manage platoons according to specific objectives.

The remainder of the paper is organized as follows: First, we introduce platooning and related concepts in Section 2. Then, we provide an overview of related work and classify our contribution in the field of platooning research in Section 3. Next, we describe the conducted research methodology in Section 4. We then present platooning objectives and their evaluation in Section 5 and address related influencing factors in Section 6. Afterwards, we discuss the objectives and the dependencies between objectives and influencing factors in Section 7. Finally, we conclude with an outlook on prospective research topics in Section 8.

2 BACKGROUND

Autonomous driving may partially solve the issue of safety by reducing the likeliness of human errors, but it can do very little to understand the environment beyond its local sensing. Research showed that cooperative driving provides additional benefits to autonomous driving as communication enhances the perspective of vehicles and informs each vehicle on the intended behavior of others [1], [5]. Platooning is a cooperative driving technology where (partially) automated vehicles drive in close formation with gaps of 3 to 10 m supported by inter-vehicle communication [1].

Drag reduction represents one of the main advantages of platooning [6]. The slipstream effect allows to save fuel by reducing the air friction at the front as well as disrupting the turbulent flow at the tail (see Figure 1). This means that

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Manuscript received November 15, 2018; revised January 10, 2020; accepted April 13, 2020.

even the platoon leader profits from positive aerodynamic effects. Vehicles at the center of the platoon, however, have larger benefits than head and tail vehicles. An imbalance in the different levels of objectives (i.e., individual vehicle versus platoon or global optimization) can occur due to the position of vehicles within the platoon.

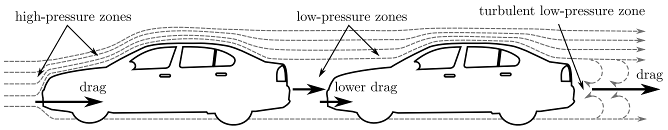

Fig. 1. The figure shows the slipstream effect [6]. The first car experiences a drag effect at the front, the second one at the rear through turbulences. However, both benefit from the slipstream as drag effects either at the front or at the rear are eliminated.

Further advantages include energy savings, increased traffic flow through homogenization, increased capacity through shorter security distances, and safety and comfort benefits. Energy savings of up to 16% and increased efficiency directly emerge from drag reduction [7]. Additionally, better traffic flow and improved capacity of up to 200% of existing road infrastructure reduce congestion [8] and, hence, avoid the need to build new costly roads. Furthermore, replacing traditional drivers' tasks, like steering or reacting to traffic, with automated, computer-driven driving control enhances driver comfort and safety.

To realize platooning in practice, we need a set of components and technologies, which include control systems, communication, and high-level management. Control systems for platooning have the duty of controlling the vehicles and, in general, have two components, i.e., longitudinal and lateral control. Longitudinal control accelerates and brakes the vehicle to maintain a target distance to the front vehicle, while lateral control takes care of steering the car to keep the vehicle inside the current lane or to track the front vehicle. Communication is a fundamental component of platooning as it is useful for lateral control, and essential for longitudinal control and for coordinating the vehicles (e.g., creating, joining, and leaving platoons). As an example, the well-known Adaptive Cruise Control (ACC), which is now available on several production vehicles, bases its decisions only on the information provided by the radar, i.e., distance and relative speed to the front vehicle [9]. The consequence of using only the radar is a large inter-vehicle gap that is required to avoid "*string instabilities*", which is the amplification of distance errors towards the tail of the platoon.

To ensure string-stability, the headway time H must be large enough to account for the "*actuation lag*", which is the time it takes the engine to realize the acceleration command computed by the controller. The CACC exploits wireless communication to share data among platoon vehicles, which is the reason why this control system is named "*cooperative*". Platoon vehicles also use cameras, lidars, or radars to maintain precise gaps to preceding convoy members, but exploiting leader status thanks to communication drastically increases the performance, as all vehicles in the platoon simultaneously know what the first vehicle is about to do. This allows to reduce the inter-vehicle gap without compromising string-stability and thus safety. For an in-depth view of the concepts in this section, it can be referred to [6], while [9] offers a mathematical study on vehicular control systems. [10] classifies platooning literature regarding obstacle detection and collision avoidance, communication, protocols, string stability, and challenges.

To control platooning, decisions about maneuvers and their execution have to be taken. Our taxonomy intends to support the optimization of these decisions. We therefore provide a brief overview of the essential platooning maneuvers below. The overview summarizes the platoon operations discussed by Maiti *et al.* [11]. Figure 2 visualizes the platooning process on a highway.

Finding a platoon. First, platooning options have to be searched. Available platoons and potential platooning participants are identified via vehicle-to-vehicle or vehicle-to-infrastructure communication (e.g., [12]). Here, literature divides between spontaneously joining the next platoon and identification of the best available platoon [13]. The first option is usually applied if many vehicles are available for platooning and have homogeneous properties. In contrast, the second option is preferable in settings in which platoons have heterogeneous properties (e.g., varying velocities) and, hence, the nearby vehicles or platoons might not provide the best performance regarding the coverage of the driver's objectives. Out of the available options, the optimal platoon for joining is chosen.

Joining a platoon. After identifying a suitable platoon, a vehicle has to communicate with the platoon (mostly, this refers to the leader of the platoon) to negotiate the details of how to join the platoon, i.e., how to connect with the platoon. As a vehicle either drives in front of or behind the target platoon, the vehicle either has to accelerate for catching up the platoon or decelerate until the platoon reaches the vehicle. Also stopping the vehicle in order to wait for the platoon to arrive might be an option. However, due to the stop's time-consuming nature, a dynamic join on the street is preferable. The join procedure includes decisions on the intra-platoon position of a vehicle.

Maintaining a platoon. This includes keeping the inter-vehicle safety distance between platoon members, controlling overtaking processes as well as merging and splitting of platoons. On-going search for platoons that better fit a driver's preferences can also be present in settings with heterogeneous properties (e.g., varying velocities) for platoons.

Leaving and dissolving a platoon. A vehicle may leave the platoon in order to stop platooning or to join another platoon (e.g., due to its route or the availability of a platoon that better fits the vehicle's objectives). In some situations, a platoon is dissolved. It must not only be decided when and where to dissolve but also if the platooning for the vehicles ends or if and how new platoons will be formed.

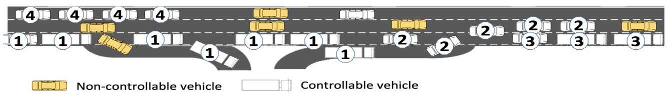

Fig. 2. A vehicle joins a platoon (2) which overtakes another platoon (3). Another vehicle also leaves a platoon (1). Non-controllable vehicles are driven by humans and cannot join platoons.

3 RELATED WORK

Several studies cover platooning in general or its objectives and influencing factors in specific. While some analyze both areas to explicitly provide a respective overview, others deal implicitly with the areas as part of another research goal, e.g., platoon formation. As all types of work are relevant for analyzing potential objectives and influencing factors, we present in this section (i) the most important platooning projects in research and industry, (ii) the most relevant research papers focusing platooning optimization with focus on platooning objectives and influencing factors, and (iii) related platooning surveys. Finally, we identify the research gap that this paper addresses.

3.1 Platooning Projects

Numerous platooning projects exist. The most prominent research projects are *SARTRE* [8], *Energy ITS* [14], *COMPANION* [15], *DRIVERTIVE* [16], *KONVOI* [17], *PATH* [18], *Chauffeur* [19], and *ENSEMBLE* [20]. Moreover, commercial solutions exist, e.g., *Peloton* [21]. The assumptions behind each project vary. Some projects only target truck platoons [14], [15], [17], [18], [19], [21] while others consider platoons with mixed vehicle types [8], [16]. Further, some projects assume all platoon members to drive fully autonomously [14], [15], [16], [17] while others assume at least the leading vehicle to be driven manually [8], [19], [21]. As we are interested in providing a holistic overview in this paper, we aim to integrate all above mentioned project foci.

Several platooning projects are sponsored by different companies of the automotive industry, such as *SARTRE* by *Volvo* [8] or *COMPANION* by *Scania* [15]. Due to the involved company interests, the respective projects do not actively aim to create brand-independent technology standards. In contrast, the *ENSEMBLE* platooning project, in which 19 different companies participate, focuses on creating standards for different aspects of platooning in order to realize multi-brand platooning including maneuvering, operational conditions, and communication protocols [20]. Consequently, we assume multi-brand platooning and ignore possible brand-specific objectives and influencing factors. Our study may therefore provide a valuable input for a standardized platoon formation as we homogenize the different views on platooning objectives.

The pursued platooning objectives vary, e.g., from global improvements in environment impacts, safety, and congestion [8] to improving fuel efficiency and safety for goods transport [22]. There are only few examples that integrate several levels of platooning objectives. For example, the architecture of *COMPANION* consists of three levels with different scopes resulting in (i) pre-trip planning from a fleet level perspective, (ii) controlling the interaction between vehicles and platoons, and (iii) control of single vehicles [22]. However, the authors mainly focus on the energy efficiency aspect. Some projects not only include technical but also economic considerations [2], [13]. Especially the SARTRE project includes possible considerations regarding compensations for benefit imbalances in a platoon and the concept of commercial platoons, in which companies send out vehicles to offer platoons based on usage fees [2].

The described influence of the position in the platoon on energy savings is also analyzed within the *SARTRE* project [2]. However, specific objectives for this imbalance are not presented.

3.2 Research on Platooning Optimization

Van Willigen *et al.* [4] propose an algorithm for platooning optimization regarding individual prioritization of user requirements, such as fuel savings, comfort, or velocity. While their algorithm is able to handle any set of objectives, they define a representative set of objectives in order to evaluate their algorithm. The objectives include velocity, fuel savings, and two comfort objectives. Our literature research yielded that their approach represents the only contribution regarding platooning algorithms which focuses on a flexible objective prioritization based on user requirements.

In their review on planning of truck platooning, Bhoopalam *et al.* [13] provide an overview of objectives, benefits, limitations, and levels of human involvement of truck platooning. These parts address directly and indirectly a broad variety of objectives and influencing factors. While they provide a valuable enterprise-driven view on platooning, they limit their analysis to commercial truck platooning.

Comparably, Tsugawa *et al.* [7] limit the scope in their review of truck platooning to energy savings. Besides listing generic objectives of automated driving, they present the reduction of energy consumption and CO_2 emissions as essential goals for platooning and mention safety improvements and congestion reduction as further objectives. Influencing factors are mentioned but not categorized.

Jia *et al.* [23] mention objectives from different angles. First, they categorize platooning applications into traffic flow optimization, traffic green and economics, and infotainment services. All of these categories represent objectives. Second, they highlight two objectives for platoon formation, i.e., maximizing platoon size and maximizing platoon lifetime. Third, they present platoon stability as goal for intra-platoon optimization. As for influencing factors, they explicitly mention vehicle parameters and spacing policy, while they implicitly refer to velocity, intra-platoon positioning, platoon size, destination, inter-platoon spacing, geographic position, road attributes, and traffic as such factors.

Maiti *et al.* [11] provide a conceptualization of vehicle platooning that includes a vehicle and a platoon model. Their models capture different factors that influence platoon formation. On the one hand, the vehicle model includes the vehicle's role (i.e., platoon leader or follower), location, velocity, speed limit, and route. On the other hand, the platoon model includes the platoon's location, size of the gap between platoon members, speed limit, size (i.e., number of platoon members), maximum size, and lane. Besides, they mention vehicle characteristics, such as remaining fuel or loading weight, as a further influencing factor. They also mention several platooning objectives, including reducing the carbon footprint, reducing traffic congestion, enhancing road safety, assessing detours, and optimizing velocity.

Bergenhem *et al.* [1] compare five platooning projects and analyze their main goals for performing platooning. The identified goals include enhanced comfort, improved safety, reduced congestion, energy savings, and increased throughput per lane. Influencing factors are not analyzed.

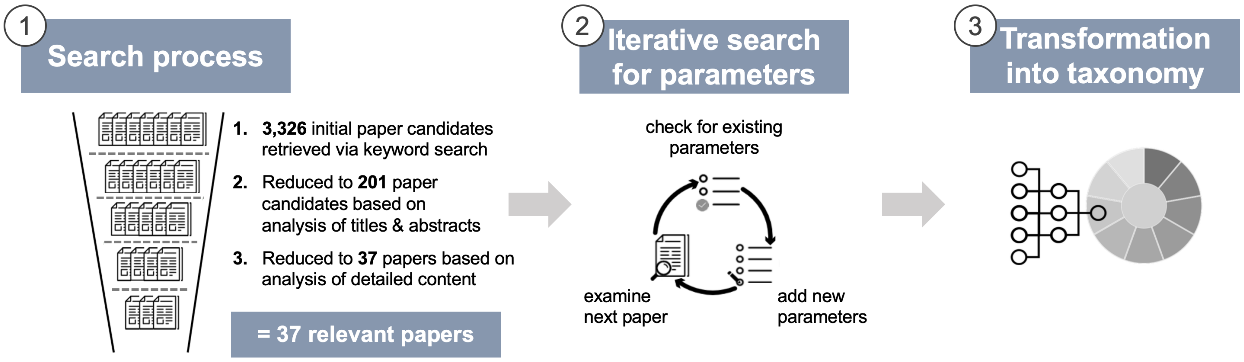

Fig. 3. The applied methodology consists of three steps. First, we searched for relevant work. Through scanning the abstract and reading the papers, we reduced the set of found papers. Second, through an iterative search in the papers, we identified parameters relevant for the taxonomy. Third, we derived a taxonomy by grouping and relating these parameters.

In [24], Axelsson discusses potential safety risks, technical issues for safety, and influences of human factors. However, he does not elaborate on how platooning performance might be affected by safety and vice versa.

3.3 Platooning Surveys

Several surveys on platooning exist which, however, do not explicitly capture related objectives and influencing factors. For the sake of completeness, we briefly discuss them in the following. Kavathekar and Chen [10] provide a categorization of platooning literature. Besides aspects like obstacle detection and collision avoidance, communication, protocols, string stability, and challenges, they also include control strategies. However, they do not provide an overview of potential objectives and influencing factors. Sawade and Radusch [25] provide an overview and classification of cooperative automated driver assistance systems. Yet, they do not focus on CACC and platooning. Sanatana *et al.* [26] provide an overview of challenges for platooning focusing on intersections, communication, and formations. Further, they mention velocity, inter-vehicle spacing, and traffic regarding influencing factors as well as safety and environmental sustainability regarding objectives. Baskar *et al.* [27] compare different traffic control systems. They provide an overview on platooning concepts and projects. However, they do not specifically highlight objectives and influencing factors for platooning. Tsugawa [28] compares different algorithms for longitudinal and lateral control for vehicles driving on automated highway systems without highlighting potential objectives and influencing factors. Shladover [29] provides an overview on different approaches of automated highway systems without referencing any platooning-related objectives and influencing factors.

3.4 Identified Research Gap

To the best of our knowledge, there is currently no contribution available that categorizes both platooning objectives and influencing factors comprehensively enough. As existent platooning research is mainly driven by implementations of specific platooning algorithms and systems, considerations of optimization factors are generally limited due to given technical capabilities. Further, while other platooning-related surveys exist, they have followed different main foci so far, only touching optimization factors marginally as part of other research subjects. While they certainly include aspects that are related to optimization factors, existent studies tend to only consider elements and relationships between them that are most evident to their specific research context. As a result, the present view on platooning optimization mainly neglects more complex considerations that comprehensively include interactions, trade-offs, and potential conflicts between different context levels, i.e., does not aim a rather holistic integration of optimization factors that focus individual vehicles, platoons, and global traffic. As we believe that the flexible optimization of a wide range of individual objectives is crucial for the success of platooning in the long run to maximize its overall value for society, users, and commercial providers, a wide-ranging view on possible optimization factors, and thus objectives and underlying influencing factors, is needed. With this paper, we aim to close this gap.

4 METHODOLOGY

We performed a structured literature review following the approach proposed by Webster and Watson [30]. We aimed to identify research that studies platooning optimization, platooning projects, or platoon formation algorithms and which likely provides possible optimization factors, related dependencies, and corresponding evaluation possibilities. Below, we explain how the review was performed.

Figure 3 illustrates the identification of useful literature that followed a three-step approach. Step 1 consisted of a broad search for literature candidates based on defined keywords. The search was based on four search engines, i.e., *IEEE Xplore*, *Google Scholar*, *EBSCO*, and *Google Web Search*. The origins of found papers include *IEEE*, *Springer*, *ResearchGate*, *ACM*, and *EBSCO*. Additionally, websites of platooning projects were used to identify and include project-related publications. We used the following keywords to guide our search: *"platoon optimization"*, *"platoon assignment"*, *"platoon objectives"*, *"intra-platoon"*, *"intra-platoon positioning"*, *"platoon formation strategy"*, *"platooning"*, *"cooperative cruise control"*[1], *"platoon goal"*, *"platoon multi objective"*,

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[1] We used the term "cooperative cruise control" in order to ensure a broader search. This term also includes the widely used concept of "cooperative *adaptive* cruise control"

"sartre platoon", *"companion platoon"*, *"grand cooperative driving challenge"*, *"tno platoon"*, *"peloton platoon"*, *"european truck platoon challenge"*, and *"konvoi platoon"*. The term "platoon" was used instead of "platooning" to make use of fuzzy search capabilities to broaden the search. The motivation for the choice of the keywords was to focus on aspects of platooning evaluation and objectives for platooning, i.e., we aimed to identify studies related to reasons for and benefits from platooning rather than objectives that describe how to optimize specific technical aspects in the implementation of platooning. Hence, we neglected the inclusion of terms that describe specific technical aspects of platooning, e.g., *"communication"* or *"string stability"*. Yet, we acknowledge that those aspects are central for implementing a correctly running platooning system. Further, we also added specific platooning projects that integrate measurements for determining the effects of platooning or describe its objective.

While we took all search results of IEEE and EBSCO into account, we limited search results of Google and Google Scholar due to the high amount of search results. The respective result pages were analyzed until the focus of the listed results differed too much from the research objective. On average, we considered the first 80 to 100 hits for each keyword. In total, 3,326 results were gathered.

In step 2, we analyzed the literature that resulted from step 1. Based on the title and abstract, we evaluated each paper's suitability for the research topic and selected papers with high likelihood to contribute to our research objective, i.e., papers that either focus on listing/discussing platooning objectives and influencing factors directly as part of their main research question. This includes papers that (i) provide an overview on platooning research in general (and hence often focus objectives and factors indirectly), (ii) present possible platooning system architectures, or (iii) propose platoon formation algorithms using objectives as optimization goals and influencing factors as input variables. This reduced the number of literature candidates to 201.

Step 3 represented a detailed review of the remaining papers. By analyzing the content in-depth to identify contained objectives, influencing factors, and evaluation possibilities, we identified the final set of literature. It consists of 37 papers. The identified papers cover different topic objectives that include different focus and abstraction levels. Some papers refer to project reports or compare optimization approaches on top-level while others aim at low-level mathematical optimization of platoon formation.

For each paper, we determined and extracted the described platooning objectives and influencing factors. This resulted in a collection of terms and descriptions for each of the two target areas. Afterwards, we scanned each collection for reoccurring terms, respective synonyms, and overall topic areas. Based on the findings, we reorganized them into mutually exclusive clusters. As a result, we derived clusters that describe 9 objective areas and 14 influencing factors from the collections of literature.

As Figure 4 illustrates, the identified papers were published on a time span from 2003 to 2019 with increasing publication rates in the recent years. The majority of the identified papers were published in 2016, 2017, and 2019 which also account for more than half of the identified papers. Besides a single technical report, all papers represent conference or journal publications. With 15 conference and 21 journal papers in total, both publication types are well-represented in in our derived literature sample. Besides, journal papers represent the clear majority of the more recent papers that we included in our study.

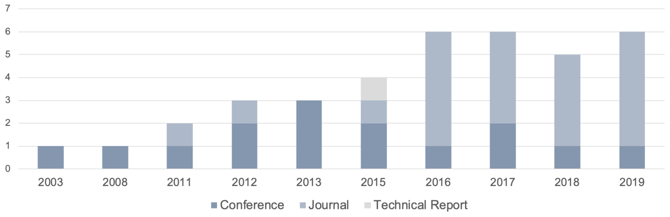

Fig. 4. Number of papers grouped per year of publication and paper type (including journal article, conference article, and technical report).

The papers were published in 20 different conference proceedings and journals. Figure 5 highlights that the papers are dominated by publications as part of one specific journal and one specific conference, i.e., the *IEEE Transactions on Intelligent Transportation Systems* journal (27.0%) and the *IEEE International Conference on Intelligent Transportation Systems* (16.2%). Otherwise, only the *International Journal of Intelligent Transportation Systems Research* (5.4%) and the *American Control Conference* (5.4%) with two contributions each are represented more than once. However, the remaining conferences and journals – including the *IEEE Transactions on Vehicular Technology* journal and *Vehicular Technology Conference* – still make up 45.9% of all papers, ensuring paper diversity on publication level.

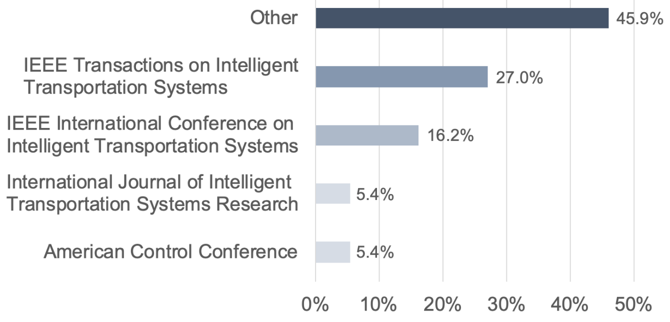

Fig. 5. Paper ratio per conference and journal.

Figure 6 shows that the identified publications originate from 12 different countries with the most contributions coming from China (21.3%), Sweden (19.1%), and USA (19.1%). Overall, the papers were created by authors from institutes of Europe (44.6%), Asia (27.7%), North America (25.5%), and Australia (2.1%). The KTH Royal Institute of Technology in Stockholm represents the institute with the highest contribution in this area by far, contributing eight papers in total. This results especially from their involvement in the COMPANION platooning project which includes research on the optimization of platooning algorithms that strongly contributes to the analysis of platooning objectives and influencing factors. 37 different institutes were involved in the creation of the identified papers.

TABLE 1
Overview of identified literature with respect to mentioned platooning objectives.
(EE = Energy Efficiency, Sa = Safety, TFRC = Traffic Flow & Road Capacity, V = Velocity, T = Time, UC = User Comfort,
DD = Destination & Distance, BIO = Balance of Individual Objectives, CB = Cost Balancing)

Identified Paper	**EE**	**Sa**	**TFRC**	**V**	**T**	**UC**	**DD**	**BIO**	**CB**	**Covered Objectives**
Bhoopalam *et al.* 2018 [13]	x	x	x	x	x	x	x	x	x	**100%**
Besselink *et al.* 2016 [3]	x	x	x	x	x	x	x	x		**89%**
Eilers *et al.* 2015 [22]	x	x	x	x	x	x	x			**78%**
Van Willigen *et al.* 2013 [4]	x	x	x	x	x	x		x		**78%**
Wu *et al.* 2019 [31]	x	x	x			x	x	x	x	**78%**
Saeednia & Menendez 2017 [32]	x	x	x	x	x			x		**67%**
Liang *et al.* 2016 [33]	x			x	x	x	x	x		**67%**
Robinson *et al.* 2010 [8]	x	x	x	x		x			x	**67%**
Dao *et al.* 2008 [34]		x	x	x	x		x	x		**67%**
Wang *et al.* 2012 [35]	x	x	x	x		x		x		**67%**
Jia *et al.* 2016 [23]	x	x	x		x	x	x			**67%**
Ma 2013 [36]	x	x	x	x	x	x				**67%**
Amoozadeh *et al.* 2015 [37]	x	x	x	x		x	x			**67%**
Larson *et al.* 2013 [38]	x		x	x	x		x			**56%**
Tsugawa *et al.* 2016 [7]	x	x	x			x	x			**56%**
Li *et al.* 2011 [39]	x	x		x	x	x				**56%**
Maiti *et al.* 2017 [11]	x	x	x	x			x			**56%**
Schaper & Bruns 2015 [40]	x		x	x	x		x			**56%**
Zhai *et al.* 2018 [41]	x	x	x			x		x		**56%**
Omae *et al.* 2012 [42]	x	x	x	x						**44%**
Németh *et al.* 2012 [43]	x			x	x		x			**44%**
Van de Hoef *et al.* 2018 [44]	x			x	x		x			**44%**
Shao & Sun 2017 [45]	x	x	x	x						**44%**
Van de Hoef *et al.* 2015 [46]	x			x	x		x			**44%**
Huppé *et al.* 2003 [47]	x	x	x			x				**44%**
Sun *et al.* 2016 [48]	x	x	x			x				**44%**
Parra Alonso *et al.* 2017 [16]		x		x	x	x				**44%**
Zhai *et al.* 2019 [49]	x	x	x			x				**44%**
Nourmohammadzadeh & Hartmann 2019 [50]	x		x		x		x			**44%**
Goli & Eskandarian 2019 [51]	x	x	x			x				**44%**
Hao *et al.* 2017 [52]	x			x			x			**33%**
Kayacan 2017 [53]		x	x	x						**33%**
Yu *et al.* 2016 [54]	x	x		x						**33%**
Heinovski & Dressler 2018 [55]	x	x			x					**33%**
Huang *et al.* 2019 [56]	x	x	x							**33%**
Feng *et al.* 2019 [57]		x	x							**22%**
Guo & Li 2018 [58]	x				x					**22%**
Ratio of Total Mentions	**89%**	**76%**	**73%**	**65%**	**51%**	**51%**	**46%**	**24%**	**8%**	

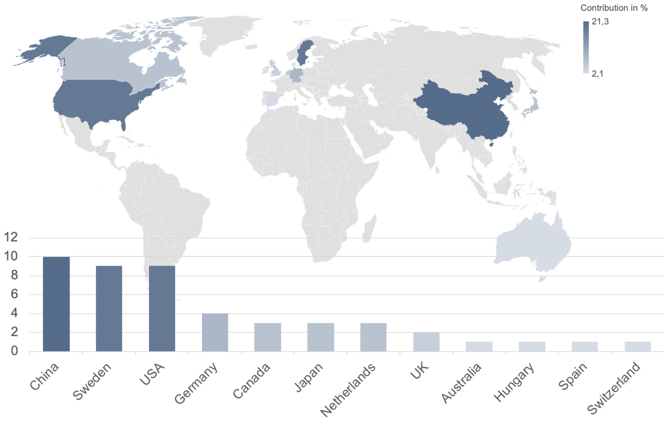

Fig. 6. Paper contributions per country.

5 PLATOONING OBJECTIVES

Platooning systems are often based on a layered architecture. For instance, Omae *et al.* propose a two-layer concept which includes a vehicle and platoon layer [42] and the concept of the COMPANION project contains an additional third fleet layer on top [22]. To control the components of the different layers, different objectives for each layer are defined. This is useful as the objectives of the layers can have a different scope of stakeholders and added value. For example, the vehicle layer ensures fuel efficiency by optimizing the inter-vehicle distance for single vehicles while the platoon layer is responsible for defining a route which suits the arrival deadlines of all platoon members. Additionally, also if no such architecture is followed, several papers mention objectives of different scope. Following such hierarchical concepts, this paper proposes a three-layered taxonomy for platooning objectives. Figure 7 illustrates the three proposed levels: the *vehicle*, *platoon*, and *global level*.

The ***vehicle level*** includes objectives that focus on optimizing the target attainment for occupants of single vehicles. Consequently, these objectives are decoupled from concerns of occupants of other vehicles. The ***platoon level*** focuses on optimizing the value of the platoon as a whole. Thus, it includes objectives which affect each platoon member and aims at obtaining a platoon-wide optimum. Finally, the ***global level*** incorporates objectives that originate from

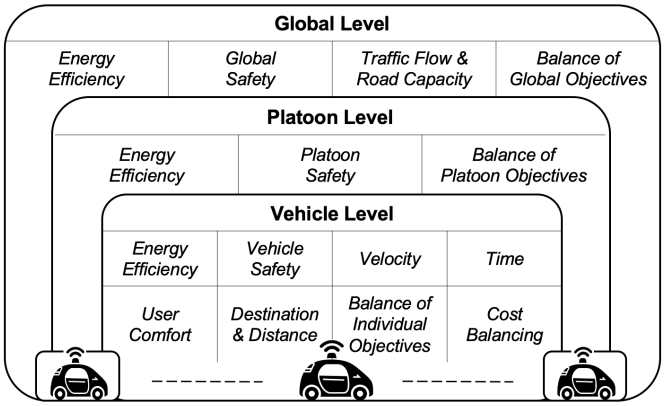

Fig. 7. Categorization of objectives, organized by the three levels of individual vehicles, platoons, and global traffic optimization.

multiple platoons, traffic, and public, and therefore aim at a global optimum. Due to the diverse research foci of the identified literature, included papers contribute from different perspectives. Consequently, as Table 1 illustrates, mentioned objectives vary widely. In this paper, we combine identified individual objectives into generalized areas.

Figure 8 illustrates the derived taxonomy of platooning objectives. Each wheel covers the objectives of one of the three objective levels. Illustrated inner circles cover the objective areas. They comprise further objective subareas which are listed in the respective outer circles. While the vehicle level exclusively covers *Time*, *Velocity*, *Destination & Distance*, *User Comfort*, and *Cost Balancing*, the global level exclusively includes *Traffic Flow* & *Road Capacity*. *Safety*, *Energy Efficiency*, and *Balance of Individual Objectives* are present on all three levels. The taxonomy distinguishes three types of objective optimization, i.e., maximization, minimization, and ensuring objectives. In Section 5.1 to Section 5.9, we describe each objective in detail. To enable the optimization of platooning systems that base on our results, evaluation factors for evaluating objective attainment are needed. We therefore also propose evaluation metrics for each objective. The metrics may be used to evaluate how well the system works or by the system to adapt itself to the given states of considered influencing factors. For the sake of clarity, no concrete literature for certain aspects is directly stated in the text. Instead, it can be referred to the papers listed in Table 1 that contain the respective areas.

5.1 Energy Efficiency

Energy efficiency fundamentally aims at decreased energy consumption and greenhouse gas emissions [7]. On the vehicle level, the focus lays on improving the energy efficiency of a single vehicle, ignoring any potential energy savings or costs of other vehicles that result from platooning [43]. On the platooning level, the focus lays on maximizing the energy efficiency of the whole platoon, i.e., balancing savings and costs of each platoon member [33]. On the global level, the energy efficiency of multiple platoons and other traffic is targeted [46]. This is relevant if the platooning is regarded from a fleet owner or from a public perspective, i.e., improving the control of multiple platoons related to the same fleet or the government aiming at reaching political environmental objectives. Moreover, concerns exist that autonomous driving in general may lead to a higher total traffic volume and, thus, may increase the total energy consumption of all road users [59]. For example, this may result from autonomous driving allowing people with mobility constraints (e.g., elderly or disabled people) to use vehicles independently or from commuters that switch from public transport to single vehicles when such vehicles allow them to use their travel time differently than having to actively drive the vehicle [60]. As platooning aims to increase the energy efficiency on vehicle and platooning level, it may even amplify this effect as people may tend to use autonomous vehicles more frequently if their energy efficiency on individual level appears to be almost as low as that of public transport. Thus, both positive and negative platooning-related effects on energy consumption and energy efficiency have to be considered as part of this objective to ensure a beneficial trade-off.

Metrics: To assess energy savings, the individual fuel or power consumption of each vehicle can be measured in liter [23]. Emissions can be analyzed regarding various produced exhaust gases, including HC, CO, NO$_x$, and CO$_2$. Energy (kJ/s) and fine dust (PM$_{2.5}$) reduction represent further metrics [52]. To also capture any negative effects on global energy efficiency, the metrics may comprise the total energy consumption of all road users on global level, including non-platooning vehicles.

5.2 Safety

The safety objective on vehicle level aims at ensuring safety of single vehicles by maintaining a reasonable safe inter-vehicle distance during platooning, especially in case of emergency situations with sudden brakes [47]. On the platooning level, ensuring the safety of the platoon as a whole is targeted. This includes internal safety, i.e., the prevention of intra-platoon collisions by, e.g., taking the individual braking performance of vehicles into account for a safe intra-platoon ordering [52]. It further includes external safety, i.e., the prevention of collisions with non-platoon vehicles, by, e.g., using a safe platoon size to reduce the amount of caused dangerous driving maneuvers. For example, a long platoon might block a highway exit leading to vehicles passing through the small safety distance between platoon members [61]. On the global level, it aims at improving the overall traffic safety, extending the safety perspective to all road users [34]. As platooning may introduce novel additional safety risks, this objective requires a special attention on all three levels to ensure that the adoption of this technology is not harmed by platooning-related safety concerns in the long-term. For example, additional risks may include human drivers trying to join the platoon [61] or platooning leaders performing dangerous driving maneuvers that jeopardize the safety of following platoon members [31].

Metrics: The compliance of the inter-vehicle safety distance can be measured with linear measures, e.g., in meters between a vehicle and succeeding vehicle [37]. Platoon and global safety can be measured by the total number of collisions or by the severity of the impact [61]. Even though a collision might be unavoidable, the prompt response of a cooperative and automatic driving system can mitigate

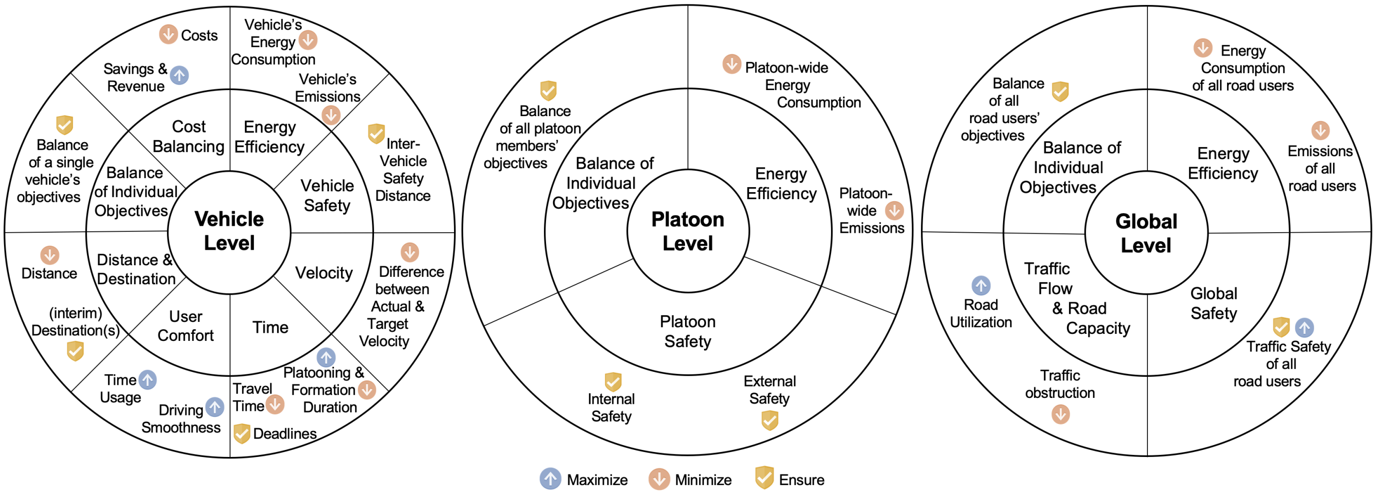

Fig. 8. Taxonomy of platooning objectives on the levels of individual vehicles, platoons, and the global traffic optimization. Inner circles describe the objectives and outer circles depict different manifestations of the objectives.

the effects. To capture the effect of any newly introduced platooning-related risk, the metrics may also cover the number of collisions and related severity of non-platooning road users through measuring, e.g., number of collisions of and related injuries and deaths to platooning and non-platooning road user per billion vehicle-kms.

5.3 Traffic Flow & Road Capacity

Improving the traffic flow and the road capacity is an exclusive global-level objective as it represents a public interest [3]. As platooning can lead to a smoothed traffic flow and an increased road capacity, it can result in a higher traffic throughput which reduces road congestion [34]. While this aims at maximizing the efficiency of road utilization, platooning can also have a negative effect: when too many trucks use the same route to form a platoon or if platoons hinder other vehicles to leave the highway by blocking exits, they cause road congestion [13]. Hence, to improve the traffic flow for all road users, platoon-related traffic obstructions are targeted to be minimized while road utilization is aimed to be maximized.

Metrics: The congestion reduction and road capacity increase can be measured based on the average travel time of all road users in some time unit, e.g., minutes or hours [34], and based on the vehicle volume on a road section in vehicle per time unit, e.g., vehicles per hour [34].

5.4 Velocity

Each vehicle aims at driving at its target velocity, i.e., its maximum possible/legal velocity or some desired velocity. The objective is therefore to minimize the deviation between the vehicle's current and target velocity [43]. As platooning might lead to a decreased velocity that results from homogenization between platoon members or from joining processes, this difference might influence platoon formation decisions negatively if it becomes too large [46].

Metrics: The deviation between the desired and current velocity can be measured in measure units for velocity, e.g., km/h or miles/h [43].

5.5 Time

Originating from trip planning and navigation problems, the travel time is always aimed to be minimized for each vehicle [43]. As platooning can lead to a higher travel time compared to the trip without platooning, e.g., due to a slower average velocity or detours, the travel time might increase. The compliance of additionally stated deadlines or desired arrival times complement the objective [44]. Additionally, the duration of being part of a platoon is aimed to be maximized as this maximizes the total platoon benefits that the driver receives [34]. The duration of forming or joining a platoon is also aimed to be minimized [33].

Metrics: Depending on the desired level of granularity, time is measured in time units, e.g., minutes, regarding additional travel time [40], platoon forming duration [37], platooning duration [34], and deviation of desired arrival times [62]. For the latter, the number of fulfilled deadlines may be used instead.

5.6 User Comfort

The user comfort objective can be split into (i) driving smoothness and (ii) time usage. Drivers aim at maximizing the driving smoothness to minimize any stress and inconvenience [35]. Driving smoothness includes, e.g., avoidance of uncomfortable aggressive acceleration and deceleration [45], many lane changes [4], unpleasantly small inter-vehicle spacing [63], and high velocity variation [4]. Time usage refers to the free time that the driver receives during platooning through the elimination of driving the vehicle due to autonomous driving [13]. This includes the maximization of this free time and the maximization of the usage quality. The latter includes the usage of resting times in the context of either private individuals, who want to rest during traveling, or professional drivers, who have to comply resting time regulations and can use platooning to avoid time-consuming stops [52]. The usage quality also includes additional service offerings that platooning infrastructure providers might offer, such as high-speed internet connections or entertainment services [2]. Therefore, drivers may want to maximize time usage quality by preferring platoon providers that offer such services.

Metrics: Driving smoothness can be measured by the number of lane changes [4] and average or peak levels of inter-vehicle distances [37] or acceleration/deceleration [4] measured in some distance and speed unit. Time usage can be measured by the resulting free time, i.e., platooning duration measured in some time unit [34]. It can be further evaluated by assessing its match with resting times, i.e., the duration devoted to resting, or the number of available additional service offerings.

5.7 Destination & Distance

Each vehicle aims at reaching some (interim) destination. The destination(s) of the vehicle must be compatible with the destinations of the other platoon members in order to limit detours [46]. In other words, the difference between the resulting distance of the route with and without platooning has to be minimized. If platooning results in some unreasonable extent of detours, a vehicle might not benefit from platooning [13].

Metrics: The distance of a trip can be evaluated based on the total length of all caused detours, e.g., in meters or kilometers [40]. Besides, the distance over which each platoon remained stable and each vehicle traveled in a platoon can also be taken into account [32].

5.8 Balance of Individual Objectives

Objectives within or across the vehicle, platoon, and global level may be conflicting [4], e.g., high velocity versus low energy consumption. As the conflicts have to be resolved by introducing trade-offs between the single objectives, not all may be fulfilled optimally [33]. Hence, an optimal consensus for the vehicle, platoon, and global level has to be found in order to maximize the respective objective attainment [35]. Therefore, the balance of individual objectives can be seen as the major underlying objective in and across all levels, aiming at providing an optimal balancing strategy. To be optimal, this strategy has not only to respect all objectives and their respective relations but also has to balance them as fair as possible between all involved parties. As a result, all objectives may be influenced by the underlying balancing strategy which has to be respected at all time.

Metrics: The quality of the balancing strategy can be measured by comparing resulting benefits of each member. If the total difference is low, it indicates high balance quality.

5.9 Cost Balancing

Making use of platooning can come with certain revenues and expenses for each driver. Through increased energy efficiency, less money has to be spent on energy while platooning. However, different platoon positions result in different amounts of energy savings [64]. To resolve this benefit imbalance, an incentive for taking a worse position may be required [2]. Different approaches exist, including member rotation, platooning fees, and governmental benefits (see Section 7.9). Platooning can also create costs. If a vehicle has to increase its velocity as part of a joining maneuver, the increased velocity leads to additional energy costs [33]. Therefore, the driver's objective is to also ensure that the platooning benefits compensate these costs. Other costs that a driver might want to minimize are route-related costs, e.g., road tolls or platooning usage fees. The latter may arise from above mentioned incentives of other members or from commercial platooning providers.

Metrics: Cost balancing can be evaluated based on the margin of caused revenues and costs that is measured in a specific currency, e.g., euro or dollar per trip or year [2].

6 INFLUENCING FACTORS

To ensure that a platooning system satisfies the established objectives optimally at all times, the system must be aware of the factors that further specify and influence objective attainment. While objectives represent adaptation goals of the platooning system, influencing factors represent conditions that the system has to adapt to. In this section, we address such influencing factors. Hereinafter, we provide an overview of the derived categorization. Then, we describe single influencing factors in Section 6.1 to Section 6.14.

A platooning system can consider a wide range of factors to reach objective achievement as each objective depends on a different set of factors. Figure 9 illustrates identified influencing factors. As with the objective levels in Section 5, three main areas can be distinguished: vehicle-dependent, platoon-dependent, and external factors.

Vehicle-dependent factors are specific for single vehicles, including *Velocity & Speed Limits*, *Vehicle Characteristics*, *Inter-Vehicle Distance*, *Duration & Time Constraints*, *Destination & Route Preferences*, and *User Preferences*. ***Platoon-dependent*** factors originate from platoons as a whole and include *Platoon Size* and *Inter-Platoon Spacing*. ***External*** factors originate from the respective environment and involves *Road Attributes*, *Traffic*, and *Weather*. While all of these factors are exclusive for their respective area, several factors refer to multiple areas. *Geographic Position* and *Intra-Platoon Positioning* may be both vehicle- and platoon-dependent. *Safety Constraints* may arise from all three areas.

Each influencing factor can affect the adaptation of a platooning system in a different way. Some factors act as constraints while others simply characterize the context. The occurrence of each factor in the identified papers is illustrated by Table 2. In the following, each factor is described. Again, for the sake of clarity, no concrete literature for certain aspects is directly stated in the text. Instead, it can be referred to the identified papers listed in Table 2 that contain the respective factor areas.

6.1 Velocity & Speed Limits

The velocity of a vehicle varies with conducted acceleration and deceleration maneuvers [43]. Legal speed limits on road segments, operational speed limits [11], and user desired velocity levels [35] limit the vehicle's maximum and minimum velocity. This defines the platoon's total speed limit which has to respect the limits of each member. It also affects joining maneuvers as a join is not possible if any velocity constraints have to be violated in order to join [42].

TABLE 2
Overview of identified literature with respect to mentioned influencing factors.
(VSL = Velocity & Speed Limits, VC = Vehicle Characteristics, GP = Geographic Position, IPP = Intra-Platoon Positioning,
SC = Safety Constraints, IVD = Inter-Vehicle Distance, RA = Road Attributes, Tr = Traffic, DTC = Duration & Time Constraints,
DRP = Destination & Route Preferences, PS = Platoon Size, W = Weather, UP = User Preference, IPS = Inter-Platoon Spacing)

Identified Papers	**VSL**	**VC**	**GP**	**IPP**	**SC**	**IVD**	**RA**	**Tr**	**DTC**	**DRP**	**PS**	**W**	**UP**	**IPS**	**Covered Factors**
Maiti *et al.* 2017 [11]	x	x	x	x	x	x	x	x	x	x	x			x	**86%**
Amoozadeh *et al.* 2015 [37]	x	x	x	x	x	x	x	x		x	x	x		x	**86%**
Eilers *et al.* 2015 [22]	x	x	x	x	x	x	x	x	x	x		x			**79%**
Bhoopalam *et al.* 2018 [13]	x	x	x	x	x			x	x	x	x	x	x		**79%**
Jia *et al.* 2016 [23]	x	x	x	x	x	x	x	x		x	x			x	**79%**
Tsugawa *et al.* 2016 [7]	x	x	x	x	x	x	x	x	x	x		x			**79%**
Saeednia & Menendez 2017 [32]	x	x	x	x	x	x	x	x	x		x				**71%**
Besselink *et al.* 2016 [3]	x	x	x		x	x	x	x	x	x		x			**71%**
Dao *et al.* 2008 [34]	x		x	x	x	x	x	x	x	x	x				**71%**
Yu *et al.* 2016 [54]	x	x	x	x	x	x	x	x			x	x			**71%**
Liang *et al.* 2016 [33]	x	x	x	x		x	x	x	x	x					**64%**
Hao *et al.* 2017 [52]	x	x	x	x		x	x		x	x	x				**64%**
Van de Hoef *et al.* 2018 [44]	x	x	x	x			x	x	x	x	x				**64%**
Sun *et al.* 2016 [48]	x	x	x		x	x	x	x				x	x		**64%**
Huang *et al.* 2019 [56]	x		x	x	x	x	x	x		x	x				**64%**
Omae *et al.* 2012 [42]	x	x	x	x	x	x	x				x				**57%**
Huppe *et al.* 2013 [47]	x	x	x	x	x	x	x					x			**57%**
Schaper & Bruns 2015 [40]	x	x	x				x	x	x	x		x			**57%**
Zhai *et al.* 2018 [41]	x	x		x	x	x	x	x			x				**57%**
Heinovski & Dressler 2018 [55]	x	x	x		x	x			x	x			x		**57%**
Wu *et al.* 2019 [31]			x	x	x		x	x		x	x		x		**57%**
Van Willigen *et al.* 2013 [4]	x	x	x		x	x			x				x		**50%**
Robinson *et al.* 2010 [8]	x	x		x	x	x		x			x				**50%**
Németh *et al.* 2012 [43]	x	x	x	x			x	x	x						**50%**
Larson *et al.* 2013 [38]	x		x	x			x	x	x	x					**50%**
Shao & Sun 2017 [45]	x	x		x	x	x	x	x							**50%**
Kayacan 2017 [53]	x	x	x	x	x	x							x		**50%**
Wang *et al.* 2012 [35]	x	x	x	x	x	x							x		**50%**
Li *et al.* 2011 [39]	x	x			x	x	x		x		x				**50%**
Parra Alonso *et al.* 2017 [16]	x	x	x	x	x		x		x						**50%**
Guo & Li 2018 [58]	x	x	x	x	x	x	x								**50%**
Nourmohammadzadeh & Hartmann 2019 [50]	x		x	x				x	x	x	x				**50%**
Goli & Eskandarian 2019 [51]	x	x		x	x	x		x			x				**50%**
Ma 2013 [36]	x	x	x					x	x	x					**43%**
Zhai *et al.* 2019 [49]	x	x		x	x	x	x								**43%**
Van de Hoef *et al.* 2015 [46]	x			x				x	x	x					**36%**
Feng *et al.* 2019 [57]	x	x			x	x									**29%**
Ratio Total Mentions	**97%**	**84%**	**78%**	**78%**	**76%**	**73%**	**70%**	**68%**	**54%**	**51%**	**46%**	**24%**	**19%**	**8%**	

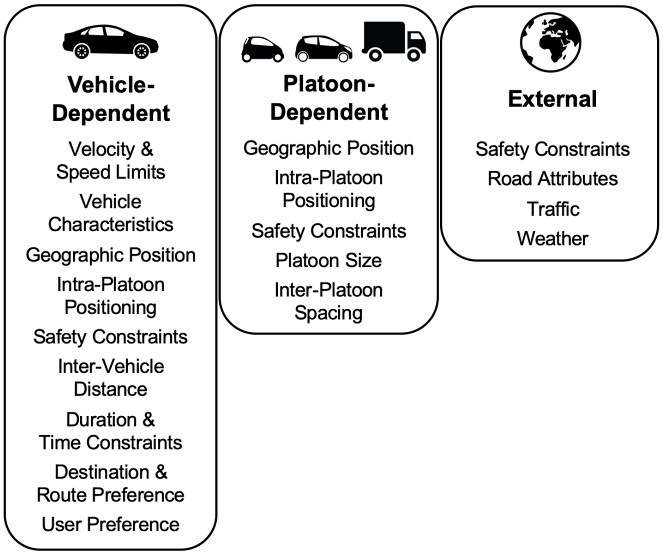

Fig. 9. Categorization of influencing factors, organized by vehicle-dependent, platoon-dependent, and external factors.

6.2 Vehicle Characteristics

Vehicle characteristics represent all physical properties of a vehicle. This includes functional properties (e.g., engines, brakes, wheels, or batteries) and non-functional properties (e.g., mass, size, frontal area, or load weight). The amount of included information in proposed models varies widely. It ranges from advanced models including numerous properties [33] to simplified models only distinguishing generic vehicle types, e.g., car and bus [8]. Vehicle characteristics have an impact on what a platoon can do, how it can be composed, and its performance. When considering homogeneous vehicles (similar physical properties), the formation can be arbitrarily chosen as they all behave in a similar manner. In this case, the impact on the overall platoon is independent of the formation. In contrast, when non-homogeneous vehicles are present, their characteristics need to be considered during the formation process. For example, it might be undesirable to have a large truck in the middle of a platoon of passenger cars, both from a safety and efficiency point of view. To mitigate this problem, it is possible to have better-performing vehicles to behave like less-performing ones [65], but this clearly needs to be negotiated and considered when computing the benefits/costs trade-off. Control theory-wise, heterogeneity can be formally taken into account [66]. Yet, it represents a key factor to be considered for its impact on objectives when forming platoons.

6.3 Geographic Position

The geographic position of a vehicle and other platoon participants determines the distance from the vehicle to platoons and to its destination [11]. In combination with a map and further external information, it defines the static environment of the vehicle, such as road attributes, traffic, and weather [16].

6.4 Intra-Platoon Positioning

The intra-platoon position indicates the position of a vehicle within a platoon. It can range from distinguishing a specific role, e.g., follower or leader [46], to differentiating specific positions, e.g., first, second, or last position [52]. The assignment results from the overall pursued platoon ordering [52]. In Section 7, we present different strategies for this purpose.

6.5 Safety Constraints

Due to safety concerns, various constraints arise that must be considered. Resulting from the importance of safety, these constraints always represent mandatory boundaries which may not be bypassed. Safety constraints are present in almost every mentioned dimension, e.g., legal speed limits [38], minimal inter-vehicle distances [47], platoon size limits [34], compliance of legal resting times [33], or transport prohibitions of dangerous goods in platoons [67].

6.6 Inter-Vehicle Distance

The inter-vehicle distance represents the spacing between two consecutive platoon members. Essentially, it is attempted to keep it as small as possible to maximize resulting benefits, e.g., energy savings, while a safety minimum distance must be guaranteed [11]. However, due to the continuously changing context of vehicles, this minimum distance is designed flexible to capture both aspects. Huppe *et al.* conceptualize it as a dynamic "safety bubble surrounding each vehicle" [47]. The actual distance that can be safely maintained depends on the chosen control algorithm[2], but we can distinguish two spacing policies in general, namely constant gap and constant time headway. In a constant gap spacing policy, the distance is fixed and it is independent of the cruising velocity [68], [69]. In a constant time headway policy, vehicles need to keep a fixed time distance, i.e., the actual spacing must increase with increasing velocity [65], [70]. From an aerodynamic point of view, a constant spacing policy is more beneficial, but it also has higher requirements in terms of communication, i.e., every vehicle in the platoon needs to receive information from the leader. In contrast, when using time headway policies, each vehicle needs front vehicle information only. In the platooning nomenclature, the way information is exchanged between vehicles in a platoon defines the *information flow topology* or the *control topology*. In general, the approach is to define the information flow topology a priori and then design the controller based on it [65], [68], [69], [70]. However, we also find control systems where the flow topology can be dynamically adapted depending on the network performance [71].

An additional indirect factor influencing the inter-vehicle distance is the reliability of the input data, which includes the precision of sensors as well as the quality of the communication network. Sensors are usually considered as perfect, but, in reality, they have errors like any measurement device [72]. Yet, their performance is known a priori and this can be directly taken into account in the design of the control system which, in turn, affects the target inter-vehicle distance. With respect to communication, instead, the network performance cannot be pre-established as the communication mean is time- and space-dependent. The network performance clearly impacts the inter-vehicle distance [69], [73], but such performance can only be evaluated at "runtime". It is not possible to know beforehand (i.e., during the evaluation of the objectives) what the network load will be throughout the journey of the platoon (and thus the achievable inter-vehicle distance).

6.7 Road Attributes

Road attributes represent any properties that describe a specific road segment, including (but not limited to) inclination [43], number of lanes [16], lane capacities [34], road topography [3], or authorization restrictions [40].

6.8 Traffic

Current and predicted traffic information can provide valuable insights into congestion. Both may include on-site and long-distance information [40]. Traffic information can be used to ensure an optimal navigation and to reasonably assess on whether platooning is beneficial [22].

6.9 Duration & Time Constraints

Duration as a factor can appear in various forms. The duration to reach a platoon for joining, platooning duration, and traveling time delays can be derived as essential time factors [33]. Furthermore, desired arrival times and fixed deadlines represent soft and hard timing constraints on delays. Especially in the commercial application of platooning, deadlines and schedules with small time windows lead to a high relevance of meeting timing constraints [44].

6.10 Destination & Route Preferences

Platooning is meant to be used in the course of a trip of a vehicle. Hence, it aims at grouping vehicles with overlapping (sub-)routes [46]. These routes depend on the destination and route preferences of each vehicle. Although the latter is not prominently stated in platooning literature, it is usually part of state-of-the-art navigation systems within platooning systems, e.g., *COMPANION* [40]. These route preferences usually represent route constraints, such as avoidance of highways, ferries, or tolls, and are set by the user (e.g., [74]).

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[2] Hence, control algorithms can be seen as "indirect" factors. A control algorithm is tight to a spacing policy, which is the real factor. A thorough discussion of control algorithms is therefore out of the scope of this paper.

6.11 Platoon Size

The platoon size dynamically changes as vehicles join and leave the platoon [37]. A minimal platoon consists of one leading and one following vehicle [8]. Although a maximum size gets mentioned in literature [37], no general consensus on a limit exists. However, large platoons may hinder the traffic by, e.g., blocking exits, and can cause an increased wear and tear of roads and bridges since such infrastructure has not been designed for dense truck platoons [61]. Hence, it is reasonable to limit the size to reduce such effects [13]. It is also likely that governments will implement legal limitations on the number of vehicles [61]. In addition, the chosen platoon size can have an impact on the performance of the control system. As an example, Giordano *et al.* [69] compute a lower bound on the intra-platoon distance depending on different factors, including the size of the platoon (i.e., the larger the platoon gets, the greater the distance becomes). It is also well-known that long platoons might have communication issues and that dedicated communication protocols should be designed to cope with this issue [75].

6.12 Weather

Weather conditions, e.g., rain, snow, or fog, may worsen driving conditions by causing aquaplaning, slipperiness, a limited view, or other similar drawbacks [40]. Consequently, current weather information and forecasts represent valuable information for platooning control as they provide insights into current and future driving conditions [3].

6.13 User Preference

Current platooning approaches widely focus on trucks that are used for commercial purposes. Hence, included preferences of drivers are generally assumed to be similar and simplified to “ensuring in-time delivery”. However, integrating individual transportation requires an approach to balance individual, diverse preferences. User-driven objective prioritization should be considered to correctly optimize a driver’s objectives. As user preferences may change with the circumstances, the platooning systems should be able to adapt to changing priorities or user-defined constraints during runtime [4]. Further, user-defined constraints can enable the user to personalize constraints of objectives. In the commercial context, fleet owner companies may be able to indicate that they only want to form platoons with their own fleets or within a restricted coalition of fleets [13]. Especially in the private context, users could limit platoon selection to, e.g., a desired velocity [35], arrival time [46], intra-platoon position [11], usage of only commercial or non-commercial platoons, or additional service offerings [2]. User preferences have the potential to affect all platooning objectives, representing user-specific needs.

6.14 Inter-Platoon Spacing

Inter-platoon spacing describes the distance between platoons. Usually, this distance is rather large and, in that case, does not influence objective attainment substantially. However, with decreasing inter-platoon distance and platoons being in close proximity, the importance of the factor increases as it may become relevant to calculate inter-platoon interactions to ensure objective attainment, e.g., avoid a blocking of the street by platoons that overtake each other with similar velocities [37].

7 DISCUSSION

In Section 5, we presented an overview of objectives that can be considered for platooning. Table 1 subsumes objectives contained in the identified literature. It shows that 19 out of the 37 papers cover more than half of the identified platooning objectives and that the papers with the smallest ratio still cover 22% of the objectives. Only Bhoopalam *et al.* [13] cover all identified platooning objectives. However, they discuss the objectives less comprehensively than this paper as they miss certain aspects that are related to the objectives and mention various objectives only indirectly without explicitly highlighting them as such. As the measures in the ratio of total mentions indicate, the objectives *Energy Efficiency* (89%), *Safety* (76%), *Traffic Flow & Road Capacity* (73%), and *Velocity* (65%) clearly represent the most prominent platooning objectives. However, this is not surprising as they capture, among other things, essential platooning benefits and optimization goals, i.e., fuel savings, road safety, congestion reduction, and travel speed. The *Balance of Individual Objectives* (24%) and, especially, *Cost Balancing* (8%) represent the least mentioned objectives. Figure 10 provides on overview on the coverage of objectives in literature.

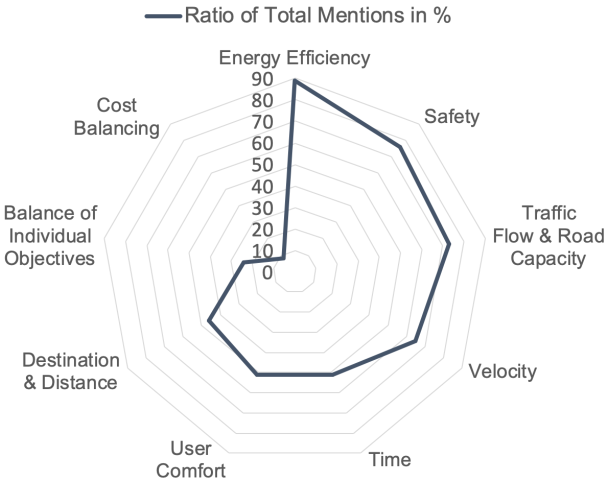

Fig. 10. Ratio of total mentions for each platooning objective in the identified literature.

In Section 6, we described influencing factors that are considered in existent literature and that may influence the attainment of the mentioned objectives. Table 2 illustrates that 33 out of the 37 papers cover at least 50% of the identified influencing factors. Further, the paper with the smallest ratio covers 29% of all identified influencing factors. *Velocity & Speed Limits* (97%) represents the only influencing factor that is mentioned in all but one of the identified papers. Besides, the *Vehicle Characteristics* (84%), *Geographic Position* (78%), and the *Intra-Platoon Positioning* (78%) represent the most frequently mentioned factors. *User Preference* (19%) and *Inter-Platoon Spacing* (8%) represent the least included influencing factors. Figure 11 shows the distribution of the influencing factors in the identified literature.

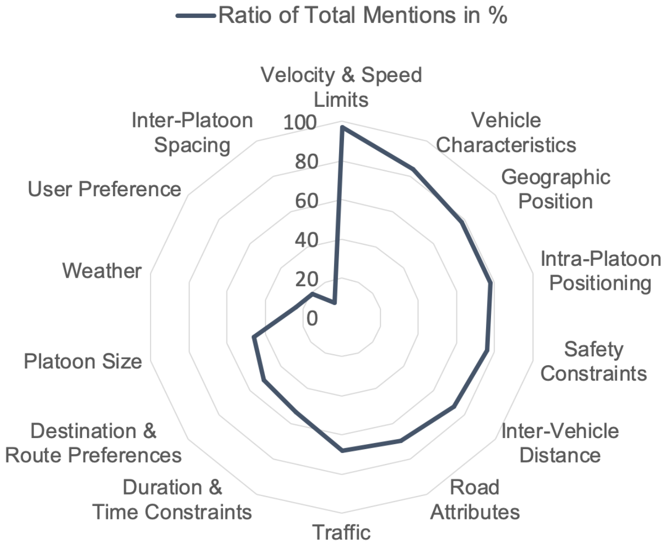

Fig. 11. Ratio of total mentions for each influencing factor in the identified literature.

Our analysis shows that, although certain objectives and influencing factors are clearly included more often than others, almost every paper focuses on a different subset of objectives and influencing factors. The identified papers therefore ensure a diverse view on both topics and thus contribute to capturing a wide-ranging foundation for the derived taxonomy.

Based on the categorizations of objectives and influencing factors in the previous sections, we discuss dependencies between both areas in Section 7.1 to Section 7.9, i.e., we highlight how each objective is influenced by underlying influencing factors. Table 3 provides a respective overview. We also discuss design possibilities for some objectives. Important to note for the discussion is that we made several underlying assumptions. First, we did not include the discussion of technical issues in platooning, such as autonomic driving capabilities, reliability of data, or availability of communication. Second, security issues are not discussed. Obviously, both topics might influence the achievement of objectives. However, in line with other research, we assume that these issues are handled and can be therefore abstracted.

7.1 Energy Efficiency

Potential energy savings through platooning depend on aerodynamic effects and reduced acceleration and deceleration due to a smoother traffic flow. With respect to aerodynamics, when a vehicle drives closely to another vehicle, it can make use of the slipstream of the preceding vehicle. As the use of the slipstream reduces the aerodynamic drag, the following vehicle has to spend less engine power and thus consumes less energy, i.e., gasoline, diesel, electricity, or comparable energy sources. In addition, due to the presence of the following vehicle in the preceding vehicle's wake, the preceding vehicle also consumes less energy as a result of pressure changes regarding the drag at the rear of the vehicle [6]. However, this benefit is smaller than the slipstream benefit of the follower [13]. Further, a decreased energy consumption generally implies decreased greenhouse gas emissions [7]. Hence, the intra-platoon position influences the energy efficiency of a vehicle. Based on the aerodynamic advantages, vehicles on intermediate, last, and first position, respectively, have the highest, second highest, and lowest energy efficiency [76]. The further back a vehicle is positioned in the platoon, the more it is affected by joining and leaving maneuvers of vehicles on intermediate positions. This results in additional energy-consuming acceleration and deceleration operations [43].

Vehicle characteristics (such as the engine or aerodynamic geometry [3]), weather (in particular wind coming from front [40]), and inclinations [43] further affect energy consumption and produced emissions. As vehicles have to adapt their velocity to the platoon's velocity, a higher energy consumption may also result from a higher average velocity of single vehicles [46]. A reduced energy efficiency through slipstreams may result from a safety-related increase of inter-vehicle spacing [42].

Furthermore, the total energy efficiency depends on the overall platooning duration and the platoon size as a respective increase implicates a longer time period of energy savings and more vehicles saving energy due to platooning [13], [33]. Therefore, both is aimed to be maximized to increase resulting energy savings. As the geographic position determines possible routes, it thereby affects the platooning duration and joining efforts [35]. Traffic information can be used to improve energy efficiency by avoiding high velocity variations through anticipatory driving [40].

Energy efficiency of the whole platoon can be further optimized by adapting the inter-platoon order to vehicle characteristics. As proposed by Robinson *et al.*, a possibility represents the use of rules, such as "buses or trucks are not allowed to follow a car" [8]. Besides, Hao *et al.* propose to order the vehicles in such a way that acceleration and deceleration actions when vehicles leave or join the platoon are minimized, i.e., by positioning vehicles which will leave the platoon earliest at the end [52]. As discussed by Bhoopalam *et al.*, position assignment could also be based on conducted joining efforts, i.e., assigning more beneficial positions to members which had to invest more energy to join [13].

7.2 Safety

An increased potential risk exists on the vehicle level: by reducing the safety distance between the single vehicles at a high velocity, the risk of collisions increases if the distance is defined too small to react to sudden brakes. Due to this, the inter-vehicle distance in the platoon must be increased with the velocity [39] and worsening road and weather conditions [47] to ensure safety. Although this can decrease the aerodynamic benefits of "tailgating", platooning can still reduce fuel consumption due to smoother traffic and increase safety by eliminating human errors, which are the cause of more than 90% of all road accidents [77][3]. The distance further depends on vehicle characteristics as they determine

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[3] The use of autonomous vehicles might also introduce new risks through, e.g., hardware and software failures, malicious hacking threats, offsetting behavior of drivers, and risks due to interaction with non-auto travelers. However, in this paper, we do not focus on such issues as they are not directly related to platooning.

TABLE 3
Overview of dependencies between influencing factors and platooning objectives.
(EE = Energy Efficiency, Sa = Safety, TFRC = Traffic Flow & Road Capacity, V = Velocity, T = Time, UC = User Comfort, DD = Destination & Distance, BIO = Balance of Individual Objectives, CB = Cost Balancing)

	EE	Sa	TFRC	V	T	UC	DD	BIO	CB
Velocity & Speed Limits	x	x	x	x	x	x		x	
Vehicle Characteristics	x	x		x	x	x	x	x	
Geographic Position	x				x		x	x	x
Intra-Platoon Position	x			x		x		x	x
Safety Constraints	x	x	x	x	x	x		x	
Inter-Vehicle Distance	x	x						x	
Road Attributes	x	x		x	x		x	x	
Traffic	x		x	x	x	x	x	x	
Duration & Time Constraints	x			x	x	x	x	x	x
Destination & Route Preferences	x				x		x	x	x
Platoon Size	x		x					x	x
Weather	x	x		x	x			x	
User Preference	x	x	x	x	x	x	x	x	x
Inter-Platoon Spacing		x	x					x	

braking capabilities and must be adapted accordingly [47]. Safety can be further ensured by considering the nature of the load of trucks. If a truck transports dangerous goods, it may be precluded from joining the platoon [67]. If platoons are near to each other, i.e., a small inter-platoon distance is present, the risk of a collision between the platoons arises [37]. In the worst case, this may result in a massive pile-up of numerous vehicles. However, as platooning implies mature self-driving capabilities of at least all following platoon members and inter-vehicle communication between all members, platooning is expected to reduce the overall number of accidents due to a faster reaction time and less velocity variation [2]. Robinson *et al.* anticipate that it can reduce the total amount of highway fatalities by 10% [8]. However, these numbers are predictions and might be speculative. Close driving as implemented by platooning control systems might increase the chances of having large chain collisions. Whether these will still be much lower than current traffic accidents or whether these will be new sources of collisions in traffic needs to be carefully evaluated. This is one of the long-term goals of this work, namely to foster the realistic simulative analysis of platooning systems with the aim of more precisely assessing the impact on future transportation systems.

7.3 Traffic Flow & Road Capacity

The reduction of inter-vehicle distance helps to improve the capacity of the road as more vehicles can be present on a certain part of the track than would be possible without coordination through communication. Further, through a homogenization of the vehicles' velocity, the traffic flow is improved, leading to a higher traffic throughput [42]. The larger the platoon size, the higher this positive effect on road capacity and traffic throughput becomes in total [13]. However, a larger platoon size may also negatively affect platoon flexibility [37] and disturb traffic flow by making it difficult for other vehicles to merge onto highways [34]. Therefore, a "reasonable" platoon size is targeted by balancing two opposite targets, namely increasing the platoon size in order to maximize the platoon-wide benefit (i.e., platooning-related traffic flow improvements and energy savings), while reducing the platoon size to minimize the negative effect on traffic flow [13]. Additional congestion may also result from joining maneuvers if a preceding vehicle or platoon slows down, hindering traffic behind it [32]. Further, platoons may create congestion behind them during an overtaking process [37].

For all of these considerations, we assume that platooning vehicles and human-driven vehicles share the road. We neglect the view of research projects that use dedicated lanes for platooning (e.g., [5]). One interesting aspect for analysis might be whether objectives regarding traffic flow improvements can be achieved when having roads shared by platoons and conventional vehicles. Such a mixture of vehicles certainly influences other objectives, such as safety.

7.4 Velocity

Vehicle characteristics, especially aerodynamic geometry as well as weight, brake, and engine properties, influence the acceleration and deceleration performance and thus generate operational speed constraints [32]. These further depend on road attributes and weather, which affect the driving conditions of vehicles as they may impair braking capabilities [33], [40]. The velocity further depends on other platoon members as constraints of all members have to be considered. The consideration may be forced by the platoon ordering. For instance, Hao *et al.* propose to arrange a platoon of trucks in ascending order of their engine power to mass ratio to ensure that trucks in front of the platoon do not pull away from the others on uphill terrain [52]. Timing constraints and the minimization of traveling time can result in a higher velocity to meet time-related objectives [43]. Legal speed limits further restrict velocity [38].

7.5 Time

Lower average velocity in the platoon [33], time-consuming joining maneuvers [33], and potential detours [34] may increase travel time significantly. As the route of a vehicle's trip might change due to platooning [78], an increase may also result from route-dependent traffic, weather, or road attributes [40]. Especially the latter two factors may cause time-consuming velocity reduction due to safety concerns. The overall time objective may also be affected by possible intermediate stops at gas or power stations which depend on the vehicle's fuel level or state of charge.

7.6 User Comfort

Additional service offerings may vary widely. They can range from more fundamental services (e.g., internet access) to more specific offerings (e.g., video or music streaming) [2]. Such services can result from cooperative approaches, like vehicle-platoon-aware data delivery among vehicles [79] or platoon-based drive-through internet access [80]. Service offerings of commercial platoon providers, in which the leading commercial vehicle offers fee-based services, are also possible [2]. The availability of additional services depends on the technical properties of the vehicle which essentially enable such services. Platoons may be rendered as infeasible if they do not offer the desired services [2] or are incompatible with a resting time schedule [13]. Furthermore, resting and the use of additional services during platooning is only possible if the vehicle drives autonomously in the platoon. Hence, as some platooning concepts assume the leading vehicle to be driven manually, the intra-platoon position may crucially affect the user experience when a driver wants to make use of the potentially free time but cannot do so if she/he has to manually lead the platoon. Driving smoothness depends on speed variation as it is negatively affected if extreme acceleration is involved in some driving maneuver [45]. Driving smoothness can be further improved by using traffic information to avoid high velocity variations through anticipatory driving [40].

7.7 Destination & Distance

Possible routes of a vehicle essentially depend on the destination, route preferences, traffic, and its geographic position [40]. If the routes of the platooning participants do not comply well enough with each other, platooning results in detours [34]. The allowed extent of such detours is limited by timing constraints and time minimization as detours increase travel time [33]. Detours also depend on the vehicle's fuel level or state of charge as they may lead to intermediate stops at gas or power stations. Detours may also arise if a driver decides to accept a detour in order to be able to rest while traveling only in the rough direction of the driver's destination [52]. Road authorization restrictions indicate whether (certain) vehicles are not allowed to pass a road segment [40]. This may also lead to detours for all platoon members if the platoon is restricted to pass a segment due to some member(s) not being allowed to pass.

7.8 Balance of Individual Objectives

The balance of individual objectives has to include all given objectives to derive a fair trade-off between them. This balance is transposed by focusing on the total objective attainment in and across all levels. By implication, it is therefore affected by all underlying factors which influence the attainment of each single objective included in the balancing. As a simplified example, one can assume that, e.g., the objectives velocity and energy efficiency are aimed to be balanced. In this case, the balancing itself depends on all respective influencing factors of both velocity and energy efficiency as they are required to allow an evaluation and control of the total objective attainment. Hence, the balance of individual objectives primarily depends on the selected set of included objectives while it is secondarily affected by the respective underlying influencing factors of each of these objectives. Thus, objective balancing may be influenced by any of the identified influencing factors.

7.9 Cost Balancing

Incentives for compensating less beneficial intra-platoon positions can be designed in various ways, resulting in different returns for the drivers. Brännström [2] proposes different business strategies that can be used and are described in the following. In the case of member rotation, platoon members rotate over time in such a way that every vehicle takes a worse position for the same amount of time as the others. With this, every driver would maintain a time account to collect time in which the driver took a worse position to be able to trade this time for driving at a better position in the future. Considering that the leading vehicle may not drive autonomously, the drivers might want to maximize their collected time to make use of it in the future, e.g., to minimize the time devoted to driving on a long trip.

Another possibility represents platooning fees. Here, platoon members that drive on a more beneficial position must pay a fee to platoon members that drive on a worse position. Hence, drivers could decide whether they want to make some profit through platooning by trading their energy savings for receiving fees. Instead of compensation processes between platoon users, governmental incentives represent a further approach. As a government might be interested in supporting platooning due to its environmental and traffic benefits, it could subsidize the initial spreading of platooning or provide governmental incentives (e.g., free parking) to platoon members on less beneficial positions. Certain drivers might be more interested in such incentives and aim at maximizing those. Comparable to the Uber fare system [81], the amount of incentives or fees may be designed flexible, depending on, e.g., location, duration, distance, or platoon size. Hence, drivers might prefer platooning under certain settings to optimally balance their costs.

8 CONCLUSION AND FUTURE DIRECTIONS

Based on a structured literature review, we proposed a taxonomy for platooning optimization. We derived several objectives on the vehicle, platoon, and global level and provided evaluation metrics. Further, we categorized influencing factors and discussed how these factors influence objective attainment.

Our results show that many diverse areas can be considered in each of the three covered fields. Due to the high diversity of this problem, the proposed taxonomy should not be seen as a complete list but rather as a reflection of the most relevant areas and dependencies that are addressed in related research. Especially more complex dependencies among objectives and between objectives and influencing factors can be explored. Many simplifying assumptions in related papers originate from technical limitations. With a rising number of considered objectives or factors, the complexity of the problem grows rapidly. As many decisions during platooning have to be taken quickly in order to react to changing conditions, an excessive complexity may result in infeasibility of the system if it consumes too much time. Thus, depending on available computing power, it is questionable whether a consideration of all presented aspects is useful and should be evaluated in the future. We also assume a perfectly working platooning system. As a consequence, any technical issues which could arise are abstracted. However, technical issues (e.g., communication errors) or resulting effects (e.g., string instabilities) as discussed by Axelsson [24] may influence platooning control. They might be included as additional influencing factors or as additional objective areas which address technical issues. Although Section 6.13 shows that platooning has many possibilities to include user context, such context is widely ignored in related research. Overall, most literature includes destinations or desired arrival times as the only user-related information. More advanced aspects remain widely ignored, probably due to complexity reasons. However, this shows that platooning is currently missing a fundamental context area that should be further analyzed. Including user context enables the personalization of platooning experiences that may eventually increase user acceptance of platooning.

Based on our study, we foresee future research directions in terms of platooning optimization. The organization of vehicles within platoons is still an open topic. How to properly manage platoons depending on drivers' goals and/or to maximize the overall gain in terms of fuel savings and smoother traffic flow is a fundamental challenge of platooning, and its success depends on whether the research community will be able to find convincing solutions. So far, the problem has been investigated in the context of truck platooning, e.g., within the COMPANION project [15]. However, commercial traffic is completely different. While the main goal in truck platooning is to minimize fuel consumption to decrease shipping costs, civilian drivers might have different and diverging goals. In addition, platooning for commercial vehicles does not only concern the single citizen, but rather the commons, as pollution and congestion affect the society as a whole. In [12], we propose a concept for a self-organized approach for platooning coordination that takes a balancing of objectives on the three levels – vehicle, platoon, and global – into account and tries to achieve this by relying on the principles of self-adaptive systems [82]. Our study poses the basis for research in this direction by reviewing the literature on objectives and influencing factors which must be taken into account in the design of coordination algorithms for efficient assignment of vehicles to platoons; hopefully making the initial design phase simpler.

ACKNOWLEDGMENT

This work has been funded by the German Research Foundation (DFG) within project A4 of the Collaborative Research Center 1053–MAKI.
Dr. Segata was partially supported by the University of Trento within the framework of young researcher support (Bando Giovani Ricercatori 2018).

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