An Overview on Approaches for Coordination of Platoons

Veronika Lesch, Martin Breitbach, Michele Segata, Christian Becker, Samuel Kounev, Christian Krupitzer

Abstract—**In the recent past, platooning evolved into an attractive cooperative driving technology, broadly discussed in research and practice. Vehicles in platoons use cooperative adaptive cruise control to drive at close distances to each other. Platooning (i) increases the capacity of the street by a factor of 2; (ii) reduces the fuel consumption and emissions by up to 20%; and (iii) has social implications as it increases driver comfort and safety. As platooning research progresses, platooning coordination becomes a major research focus. The coordination of platoons, including the assignment of vehicles to platoons, the management of inter- and intra-platoon interactions, and the coordination of interactions with other vehicles is an important step towards an effective usage of platooning in practice. Based on a literature review of 1,600 papers, this survey provides an overview of state of the art in platooning coordination research for both cars and trucks. In this paper, we present a novel taxonomy for platooning coordination and classify existing approaches. We use the results of the literature review to discuss challenges and outline avenues for future work such as multi-objectiveness and individualisation.**

Index Terms—**Platooning, Platooning Coordination, Cooperative Driving, Survey**

I. Introduction

Vast improvements in the area of computer science and camera, sensor, or car automation technology are the drivers of a rapid development towards autonomous driving. Autonomous vehicles, however, are not able to understand the environment beyond their local sensing. Extensive modelling and simulations show that cooperative driving is superior to autonomous driving as communications enhance the perspective of vehicles and inform each vehicle on the intended behaviour of others [1], [2]. One of such approaches is *platooning*: A cooperative driving technology where vehicles that are (partially) automated drive in close formation with small inter-vehicle gaps [1]. Contrary to conventional autonomous vehicles, platooning vehicles are capable of driving in close formation [3]. Therefore, even the lead vehicle profits from aerodynamic drag reduction [4]. Energy savings of up to 16% are achievable with platooning [5]. Additionally, better traffic flow and improved capacity up to 200% of existing road infrastructure reduce congestion and avoid the need to build new costly roads [6].

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The platooning technology evolved from its origins in the 1980s into complex and realistic scenarios in recent projects such as SARTRE [6], COMPANION [7], and ENSEMBLE [8]. Over time, *platooning coordination* became a major research focus in platooning projects. Platooning coordination is the assignment of vehicles to platoons—especially for sets of heterogeneous vehicles—, the coordination of intra-platoon and inter-platoon interactions, and the management of interactions between platoons and other vehicles. Effective platooning coordination is essential to implement platooning successfully in practice, where vehicles of multiple brands owned by different stakeholders need to cooperate.

This paper provides a comprehensive overview of the research landscape in the area of platooning coordination. It offers a broad perspective on the topic, covering various aspects such as objectives, planning horizon, and algorithmic details. The main objective is to provide an overview on the aspects that are addressed in research to provide a picture of the research landscape rather than a detailed, in-depth analysis of different approaches. Accordingly, we analysed over 1,600 papers with a relation to platooning coordination. Based on this literature review, we present a novel taxonomy on platooning coordination. This taxonomy captures the different aspects that are relevant for platooning coordination. Furthermore, we provide a quantitative analysis of the research landscape for platooning coordination by analysing which aspects of the taxonomy are frequently addressed in literature so far and which ones are less frequently addressed. As we are interested in providing an overview of the state-of-the-art in the platooning coordination research, we omit a qualitative discussion of a subset of approaches; rather, we use the results of the literature review to discuss the state-of-the-art of the field, derive open challenges, and outline promising avenues for future research. To the best of our knowledge, this review is the first to offer an exhaustive overview of coordination for both car and truck platooning.

In the following, we summarise the current state of platooning research in general (Section II), identify the research gap with an overview on related reviews (Section III), present our methodology (Section IV), assess the state of the art in platooning coordination with a novel taxonomy (Sections V, VI, and VII), discuss challenges and avenues for future research (Section VIII), and conclude the paper (Section IX).

II. Platooning in a Nutshell

This section introduces basic concepts for platooning. Further, we define the term *platooning coordination* and classify

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it in the context of the platooning process. Finally, we provide an overview of the platooning research landscape.

A. Platooning Basics

Realising platooning in practice requires a set of technologies, including control and communication systems. Control systems for platooning have two components: longitudinal control—accelerating and braking the vehicle to maintain a target distance to the front vehicle— and lateral control—steering the vehicle. However, both components are technically independent of each other and can be implemented individually in vehicles, depending on which functionality is desired. For example, a platooning implementation could involve only longitudinal control, while the drivers perform the lateral control. Further, communication is a fundamental component of platooning as it is (i) useful for lateral control, (ii) essential for longitudinal control, and (iii) responsible for coordinating platooning activities. In this section we provide a brief overview of some of the concepts required for realising platooning on the lowest possible level, i.e., the control of a single vehicle within a platoon. We do not review the literature in all its depth, as the paper's focus is on the higher levels. Still, this section can be useful for the reader to gain a general understanding of the application.

A fundamental part is the longitudinal control, which is realised through a control system computing acceleration commands to maintain a desired inter-vehicle gap. This control system is named Cooperative Adaptive Cruise Control (CACC), which derives from standard Adaptive Cruise Control (ACC) [19]. The term *cooperative* indicates that vehicles, together with data coming from radars, lidars, and cameras [20], [21], exchange state information used to compute the control action by means of communication, differently from ACCs where the decision is taken only upon locally sensed data. The introduction of communication brings several benefits, including reduced inter-vehicle spacing and faster reaction to changes in dynamics [19]. There is a vast literature of approaches to design a CACC system, which differ by control technique and assumptions on input data.

Regardless of the technique, all control algorithms must ensure a fundamental property called *string stability*, meaning that errors occurring at the head of the platoon must not be amplified but be dampened towards the tail. More formally, let δ_i be the spacing error (i.e., the difference between the target distance and the actual one) between vehicle i and its predecessor and let $H(s) = \frac{\delta_i}{\delta_{i-1}}$ be the transfer function relating spacing errors between consecutive vehicles. A CACC is said to be string-stable [19] if the following conditions hold:

$$||H(s)||_\infty \leq 1 \qquad h(t) > 0, \forall t \geq 0. \tag{1}$$

The left condition ensures that the magnitude of the errors is attenuated towards the tail, while the second ($h(t)$ is the impulse response of $H(s)$) ensures that the errors must have the same sign. It is not sufficient to dampen the magnitude towards the tail, but we must also avoid a vehicle being too close to its predecessor (negative error) and its follower being too far (positive error) and vice versa. This is one of the possible definitions of string-stability as it might need to be adapted to the control system being proposed [22], [23], [24]. As we will describe, different CACCs have different string-stability properties depending on the inputs they consider.

As an example, in the 00s the PATH project [25] defined a CACC still commonly considered by researchers in the field. The control formula for the vehicle in position i is defined as

$$\begin{aligned} u_i = {} & (1 - C_1)a_{i-1} + C_1 a_0 \\ & - \left(\left(2\xi - C_1\left(\xi + \sqrt{\xi^2 - 1}\right)\right)\omega_n\right)(v_i - v_{i-1}) \\ & - \left(C_1\left(\xi + \sqrt{\xi^2 - 1}\right)\omega_n\right)(v_i - v_0) \\ & - \omega_n^2(x_i - x_{i-1} + l_{i-1} + d_d) \end{aligned} \tag{2}$$

In Equation (2), u_i indicates the control input (i.e., the desired acceleration that should be sent to engine/brakes for actuation), a_i, v_i, x_i, l_i indicates the acceleration, the speed, the position, and the length of vehicle i, respectively, while d_d indicates the desired inter-vehicle gap. C_1, ξ, and ω_n are control parameters regulating the weight between leading and preceding vehicle accelerations, the damping ratio, and controller bandwidth, respectively. The control algorithm considers data received from the leader and the preceding vehicle in the platoon, plus the gap to the preceding vehicle measured by the radar. This particular type of algorithms is defined as leader- and predecessor-following CACCs and is proven to be string-stable under a *constant spacing* policy, which means that the inter-vehicle distance is fixed regardless of the cruising speed.

The work in [26] instead defines a CACC that implements a predecessor-following control, meaning that a vehicle considers only information received by its predecessor. The control law, which is defined in terms of the derivative of the desired acceleration ($\dot{u}$), is the following:

$$\begin{aligned} \dot{u}_i = \frac{1}{H} & \left(-u_i + k_p\left(x_{i-1} - x_i - l_{i-1} - Hv_i\right)\right. \\ & \left. + k_d\left(v_{i-1} - v_i - Ha_i\right) + u_{i-1}\right). \end{aligned} \tag{3}$$

In Equation (3), which is defined as a Proportional Derivative (PD) controller, H indicates the time headway, while k_p and k_d are control gains for the proportional and the derivative part of the law, respectively. The control law has three components. The first one is the distance error (proportional term) and in this case, the desired distance depends on speed (Hv_i). H is indeed the amount of time elapsing between two consecutive vehicles: the higher the speed, the higher the actual distance. This spacing policy is known as *constant time headway* and it guarantees string-stability for CACCs considering the preceding vehicle information only: for these CACCs string-stability under a constant gap cannot be guaranteed [19]. The second one is the derivative of the first one (derivative term), which basically minimises the speed error between consecutive vehicles. The last one (u_{i-1}) is the desired acceleration of the preceding vehicle. For the first two components of the law, the information about distance and relative speed can be obtained through the radar. Instead, the last one can only be obtained by means of communication because the desired acceleration cannot be measured: it is an acceleration the vehicle will implement after a certain amount of delay due to actuation

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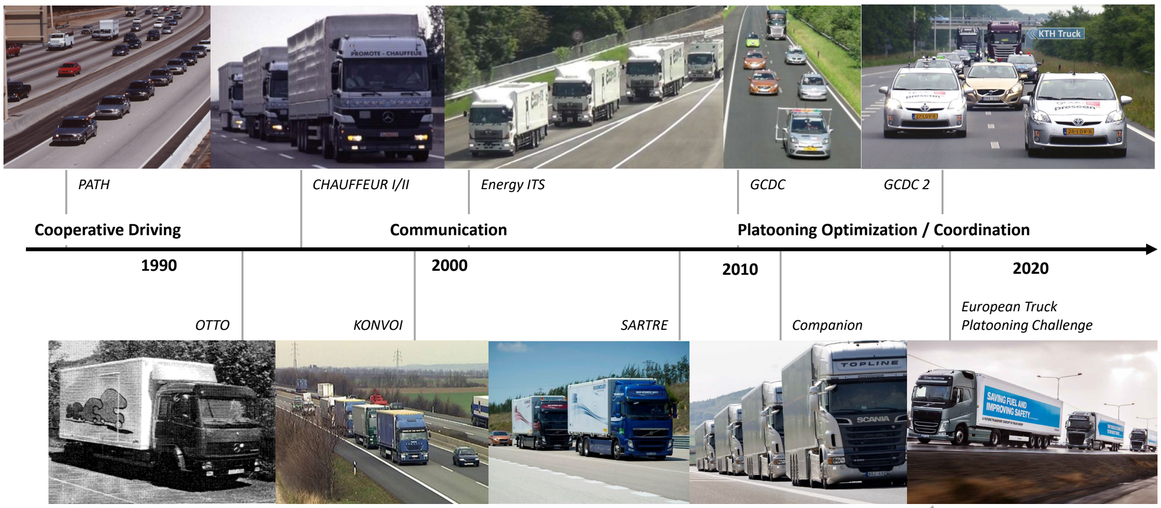

Fig. 1: Overview on the history of platooning research. Pictures from [9], [10], [11], [12], [13], [14], [15], [16], [17], [18].

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lags (engine and braking dynamics). This "knowledge of the future" enables to drastically reduce the time-headway compared to a standard ACC while guaranteeing string-stability.

In the literature, we find several other control techniques employed in the design of CACCs. One example is Model Predictive Control (MPC) [27]. This method solves an optimisation problem on a future time horizon with the aim of minimising certain quantities which include, for example, spacing and speed errors. Differently from the previous approaches, as this method relies on optimisation, it is possible to define further constraints such as maximum and minimum acceleration for passengers' comfort. Without going too much into details, a typical MPC problem is defined as

$$\min_{\dot{\boldsymbol{u}}} \boldsymbol{z}^\mathsf{T} Q \boldsymbol{z} \tag{4}$$

subject to certain constraints, which include initial state, state evolution, limits on acceleration and jerk, etc. In Equation (4), $\boldsymbol{z}$ might be defined as

$$\boldsymbol{z} = [\boldsymbol{e}, \boldsymbol{u}, \dot{\boldsymbol{u}}], \tag{5}$$

where $\boldsymbol{e}$, $\boldsymbol{u}$, and $\dot{\boldsymbol{u}}$ are the vectors of all the spacing errors, the control inputs, and the derivative of the control inputs over the prediction horizon, respectively. The matrix Q, instead, is used to weigh the minimisation terms. This problem is solved using standard mathematical solvers, with the result being a vector of jerk values (control input derivatives) $\dot{\boldsymbol{u}}$. Of this vector, the first value is the one being sent for actuation.

Other approaches take a completely different perspective. While the majority of the control systems are defined in time domain, we find some approaches defined in space domain. As an example, [28], [29] define the spacing policy to be

$$x_i(t) = x_{i-1}(t - \Delta t). \tag{6}$$

The policy indicates that a vehicle should track a delayed version of the trajectory of its predecessor. The authors prove that this can be achieved if and only if all the vehicles are capable of tracking a reference speed signal defined in the spatial domain, i.e.,

$$v_i(x) = v_{i-1}(x) = \tilde{v}(x), \tag{7}$$

which is solved by defining a control law of the form $u_i(x)$, i.e., the acceleration a vehicle should apply depending on its position rather than the current time.

The list of approaches we mentioned is a minimal subset of the vast literature on the topic which includes consensus control, event-triggered control, artificial potential field control, and many more [30], [31], [32], [33], [34], [35], [36], [37]. This also includes the issue of lateral control, i.e., how vehicles should steer in order to follow their predecessors, for which the same string-stability property of longitudinal control must be guaranteed [38], [39]. Recently, several approaches have been developed to tackle engine heterogeneity which has been addressed using robust control or adaptive control [40], [41]. Further, some research has been conducted on handling non-homogeneous platoons in terms of their dynamical capabilities, especially focusing the platoon cohesion problem [42]. The interested reader can refer to [43] for an in-depth view of CACC systems.

B. Levels of Platooning

The overview on concepts required for realising platooning on the lowest possible level already mentioned that we distinguish two levels of platooning: (i) platooning control and (ii) platooning coordination. We now define both terms, delineate them by explaining our understanding of both levels, and clarify the level on which this paper focuses.

> **Platooning Control** is the control of a single vehicle on the lowest possible level including maintaining the distance, sending braking signals, or signalling platoon members to overtake another vehicle.

> **Platooning Coordination** includes the management of (i) the composition of a platoon, (ii) inter-platoon interactions as well as (iii) interactions between other vehicles and platoons.

Hence, we refer to all actions performed by a CACC controller including longitudinal control, lateral control, or

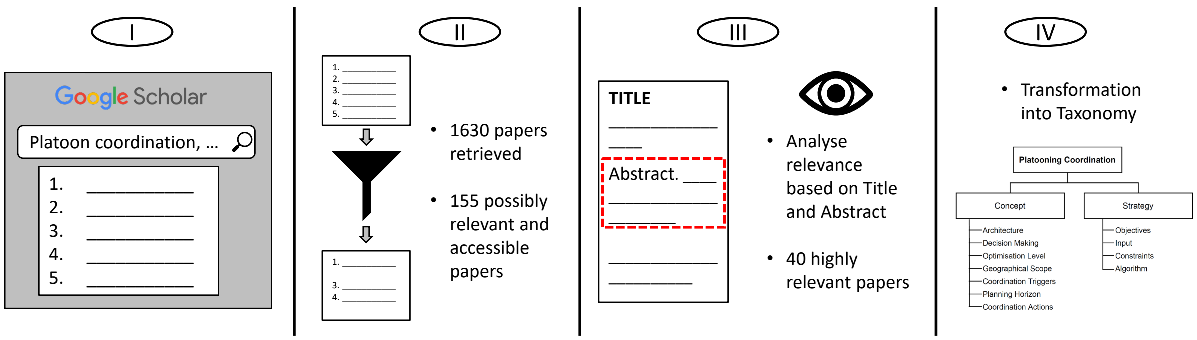

Fig. 2: Overview of the methodology for building the classifications for the survey. The initial search of relevant papers is followed by an iterative process for building the classifications.

string stability as platooning control. In contrast, platooning coordination operates at a higher level and coordinates the composition of platoons as well as intra-platoon and extra-platoon manoeuvres. Thus, coordination regarding platooning is possible on two levels: (i) between platoons and other platoons or vehicles as well as (ii) within a platoon. For both types, we assume the presence of a platooning control approach to maintain the distances between vehicles in a platoon at any time. Platooning coordination typically incorporates, for instance, (i) finding a suitable platoon for a vehicle, (ii) managing inter-platoon interactions, such as merging platoons, or (iii) routing platoons.

In this paper, we provide an overview on approaches that handle platooning coordination, i.e., that provide an approach for managing the composition of platoons as well as inter-platoon interactions and interactions between the remaining traffic and platoons. We explicitly exclude work dealing with platooning control, i.e., the control of a single vehicle, as we want to review exclusively on the higher levels of platooning. Additionally, we make several assumptions to judge the relevance of approaches in the literature for our survey and present them in Section IV.

C. Platooning Research Landscape

Research on platooning already started in the early 1970s for example in Matra's Aramis vehicles operating in platoons [44]. Since the 1980s, several projects described platooning concepts. The research focus of these platooning projects shifted over time from enabling cooperative driving capabilities and communication-supported cooperative driving behaviour towards platooning coordination and, more recently, multi-brand platooning and real-live demonstrations. This section summarises funded and well-known platooning projects. Figure 1 presents an overview of the historical development of projects and research objectives with a focus on projects that at least enable platooning coordination or in more recent projects address the coordination aspect.

First Platooning Projects. In 1986, the *Partners of Advanced Transit and Highways (PATH)* program was initiated to improve traffic flows and increase road capacity [45]. Consequently, PATH introduced the idea of an automated platoon where vehicles share information among each other and drive on a dedicated lane achieving lateral control by magnetic orientation with nails in the ground while longitudinal control was based on radar ranging and V2V communication. In the 1990s, Daimler-Benz developed solutions for platooning, leading to the *OTTO* truck, the *PROMOTE-CHAUFFEUR* project conducted by Daimler-Benz, Iveco, and multiple automotive suppliers from 1996 to 1998, and the follow-up *PROMOTE-CHAUFFEUR II* project from 2000 to 2003 [14]. The main motivation of both projects was to focus on communication within platoons of trucks.

Research on the Applicability of Platooning and its Coordination. The projects in the second phase rely on current advances of longitudinal and lateral automation of vehicles and inter-vehicular communication. Hence, the focus shifts from establishing platooning towards issues related to its applicability. From 2005 to 2009, the *KONVOI* project [15] also focused on usability and legal aspects, such as effects of platooning on traffic participants, drivers, efficiency, and infrastructure [46]. Additionally, the on-board driver information system communicates with a central server using mobile communications to find platoons, which is an early example for platooning coordination [47]. In the *Energy ITS* project, trucks use two cameras, radar, and lidar for longitudinal and lateral automation [48]. The research included different scenarios, such as trucks leaving and joining the platoon, lane changing, and vehicles cutting into platoons. The *Safe Road Trains for the Environment (SARTRE)* project (2009 to 2012) focused on platooning using existing technology without changing the roadside infrastructure [49]. Vehicles communicate via mobile communications with a remote system that guides drivers to the nearest platoon. The *Cooperative dynamic formation of platoons for safe and energy-optimized goods transportation* (COMPANION) project [7] (finished in 2016) focused on prediction of fuel consumption [50] and solutions to coordinate platoons using a real-time coordination system [17], [51].

Research towards the Practicability of Platooning. Recent projects show the practicability of platooning. The *Grand Cooperative Driving Challenge (GCDC)* was a competition of cooperative driving systems launched in 2011 [52] and 2016 [53]. In the *European Truck Platooning Challenge* [54], six truck manufacturers operated platoons cross-border to reach Rotterdam from their respective company headquarter on real highways. In the *ENSEMBLE* project, 19 different companies cooperate in multi-brand platooning scenarios. The aim

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of the project, which started in 2018, is to create standards for multi-brand platooning, including manoeuvring, operational conditions, and communication protocols [8].

III. Related Surveys

Most related to our work, [55] provide an overview of objectives, benefits, limitations, and levels of human involvement in truck platooning. This includes an overview of recent approaches for the planning of platooning, i.e., platooning coordination. However, the authors provide an enterprise-driven view and focus on commercial truck platooning while we focus on a general overview of all platooning related coordination mechanisms. [56] categorise platooning applications from a network perspective and highlight two objectives for platoon formation—maximising platoon size and platoon lifetime. However, they do not specifically analyse and compare existing approaches for platooning coordination, which is the focus of this review. [1] present a comparison of SARTRE, PATH, GCDC, SCANIA, and Energy ITS. They focus on the technical aspects of platooning and compare the approaches in the dimensions vehicle type, lateral and longitudinal control, infrastructure requirements, integration of traffic, sensors, and goals. [5] compare PATH, KONVOI, and Energy ITS focusing on their fuel saving potentials. Those two reviews, however, do not cover platooning coordination.

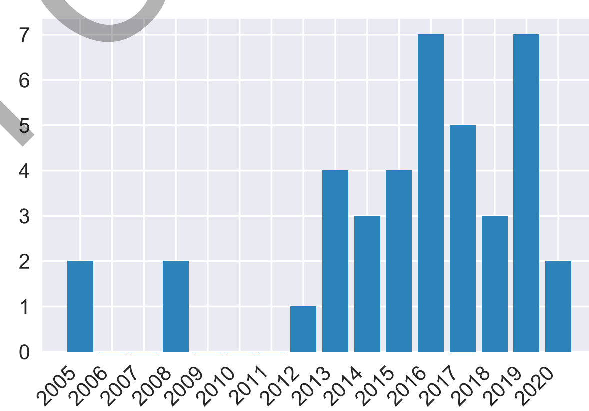
The following surveys include works that focus on single aspects rather than a holistic view. In [57], the authors present overviews of works in the areas of inter-vehicle communication, collision avoidance, obstacle detection, string stability of a platoon, and how to tackle challenges such as security and communication delays. [58] focuses on safety in platooning. [59] present challenges for platooning regarding intersections, communication, formations, and security. [60] provide an overview on applications for connected cars, but they omit platooning. [61] compare different traffic control systems. Some of these systems—PATH, Dolphin, Auto 21 CDS—take platooning into account. These systems, however, do not perform platooning coordination.

To the best of our knowledge, there is no overview that extensively reviews and compares approaches for coordination of trucks and cars in platoons. Thus, this review gives a comprehensive overview of platooning coordination approaches and presents challenges for future research.

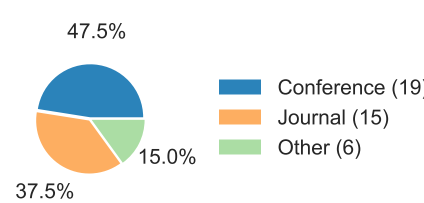
IV. Methodology for Literature Review

We apply the *systematic literature review* introduced by [62]. Figure 2 illustrates four steps to identify the relevant literature. In step 1, we use the search engine Google Scholar and predefined keywords to guide our search process. Thus, we use the following keywords for search: "platoon", "platooning", "platoon coordination", "platoon assignment", "platoon management", "platoon formation", "platoon formation strategy", "platoon algorithm", and "platoon multi objective". We consider the first 90-110 hits for each keyword, which results in a total of 1,630 papers.

In step 2, we filter the papers based on the title and the preview in Google Scholar. For this filtering process, we rely on different assumptions to guarantee a consistent choice of literature. First, we do not restrict our analysis to a specific type of vehicle. Most of the approaches in the literature target platoons of trucks, as the potential for saving fuel seems to be the highest. However, we also include platoons composed of only cars as well as mixed platoons. Second, we focus on platooning coordination rather than platooning control (see Section II-B). Hence, we excluded approaches that only target control aspects, such as communication/security mechanisms in platoons, inter-vehicular distance control, or string stability. Last, when focusing on platooning coordination, literature provides two types of approaches we include in our overview: (i) high-level approaches and (ii) focused approaches. High-level approaches mainly focus on assigning vehicles to platoons but support all phases of platooning. Focused approaches target specific aspects of platooning control, e.g., focusing on which position in a platoon a vehicle should join or the merge of platoons that drive close to each other. After this step, 155 papers are considered potentially relevant. In step 3, we perform a detailed analysis of those papers by assessing their abstract and parts of the sections that present the approach. In step 4, we extract the approaches of the remaining 40 papers. Since some of the papers propose more than one approach for platooning coordination, we analyse 43 approaches as a basis for the review and taxonomy in this paper[1].



(a) Number of papers published per year.



(b) Share of the publication type.

Fig. 3: Statistics of the relevant papers.

Figure 3a presents the number of papers published per year. We observe that 90% of the papers were published between 2012 and 2020, with an average of four publications per year. Thus, we argue that platooning coordination is currently

[1]All analysed approaches and their classification can be found at https://doi.org/10.5281/zenodo.4267685.

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a highly relevant topic that is attractive for future research. Figure 3b shows the share of publication types in the data set. The largest share of papers originates from conference proceedings (47.5%), followed by journals (37.5%), and other paper types (technical reports, project reports, or dissertations).

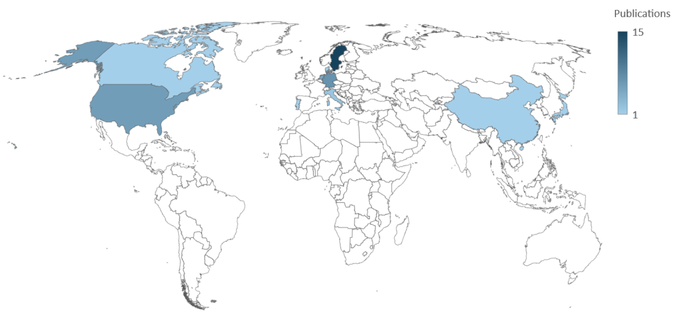

Fig. 4: Distribution of authors' countries of origin[2].

We present the geographical distribution of the authors' institutions in Figure 4. We observe that 15 of the 40 papers originate from Sweden. Germany, the USA, and the Netherlands also published several papers on platooning coordination, with seven, six, and five papers, respectively. Other papers are from Italy, Canada, China, Denmark, Japan, and Portugal.

V. Platooning Coordination Taxonomy

Although the overview in Section II-C shows an increasing importance of platooning coordination in platooning research, no comprehensive overview exists so far that compares similarities and characteristics of platooning coordination approaches. To close this gap, this section presents a taxonomy of platooning coordination composed of the two categories `concept` and `strategy`. Both categories have several dimensions with various characteristics and handle individual conceptual levels. The `concept` category describes the basic design of the coordination approach. It describes which entity performs the coordination, which actions the coordination includes, and how the coordination is triggered in time. The `strategy` category describes the strategy that is applied within the presented concept, i.e., the exact way to determine coordination actions from an algorithmic perspective. Hence, the `strategy` category describes how to formulate the research issues defined using the `concept` category. We use this distinction into `concept` and `strategy` to emphasise that—in theory—different strategies could be applied in the same concept. Figure 5 depicts the categories and their dimensions and Table I presents the characteristics for each dimension.

The `concept` category contains dimensions that describe the principle type of organisation for the coordination procedure. In total, we identify seven dimensions: architecture, decision making, optimisation level, geographical scope, coordination triggers, planning horizon, and coordination actions. First, the coordination process follows different fundamental design aspects. The `architecture` ranges from

[2]Supported by Bing, Copyright GeoNames, Microsoft, Navinfo, TomTom, and Wikipedia.

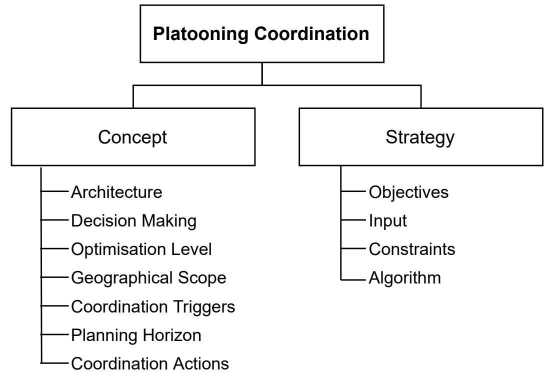

Fig. 5: The classification of platooning coordination approaches with 11 dimensions clustered into two categories.

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a central control unit for platooning coordination to decentralised coordination performed by each vehicle, including approaches in-between those extremes. The coordination processes can support different types of `decision making` w.r.t. the dimensionality of the decisions, i.e., the number of considered objectives. Further, those coordination decisions can target different `optimisation levels`; we separate here individual, platoon, and global. Additionally, platooning coordination has a spatial aspect. The coordination could be employed by a central coordination unit that performs a global optimisation. When mentioning a central coordination unit, we refer to a central authority responsible for the decisions. Nevertheless, the calculation of the decisions can be distributed to several instances that exchange all existing information to handle the number of instances. Still, the amount of required data might overwhelm the coordination process and heavily slow down the decision making. Hence, approaches may operate on different `geographical scopes`. Further, the coordination approaches differ in time aspects. The `coordination triggers` dimension refers to the triggers for the coordination process, i.e., the point in time when the coordination takes place. We distinguish pre-trip coordination (triggered by the driver before starting the journey), event-based coordination (triggered by events such as the split of a platoon during the journey), and on-going coordination triggered regularly. Related to that, we distinguish different `planning horizons`. Approaches either plan the whole journey in advance (scheduled planning), plan the rest of the journey based on real-time input (real-time planning), or spontaneously evaluate coordination actions without a particular planning horizon (opportunistic platooning). Last, coordination processes support different types of `coordination actions`, e.g., joining a platoon, merging of platoons, or adjusting parameters of a platoon (e.g., its speed).

Whereas the `concept` category depicts the general design of the coordination process, the `strategy` category focuses on how the coordination actions are determined. Hence, it describes how to formulate concrete research issues and contains the dimensions objectives, input, constraints, and algorithm. As captured in the dimension `decision making` of the `concept` category, platooning coordination follows one or

TABLE I: Overview of the taxonomy including both categories, their dimensions and possible values.

Category	Dimension	Possible Characteristics
Concept	Architecture	Control unit, individual vehicle, collective of vehicles
	Decision Making	Single-objective, multi-objective, many-objective
	Optimisation Level	Global, platoon, individual
	Geographical Scope	Global, regional, local
	Coordination Triggers	Pre-trip coordination, event-based coordination, ongoing coordination
	Planning Horizon	Scheduled planning, real-time planning, opportunistic platooning
	Coordination Actions	Join, split, route, merge, leave, platoon parameter change, lane change
Strategy	Objectives	Energy efficiency, cost minimisation, common distance, travel time, schedule miss penalties, comfort, road capacity, speed, profit, fleet utilisation, failed actions, consistency of controllers, trust in leader, departure time
	Input	Destination, location, speed, time, route, vehicle characteristics, vehicles within horizon, road network, headway to vehicles, user preferences, fuel consumption models, departure, weather, traffic situation, platoon length
	Constraints	Deadlines, speed limit, platoon size, timing, speed, max. road capacity, lanes, distance
	Algorithm	Optimisation-based, rule-based, heuristic-based, graph-based, iterative, greedy, game theory

several objectives. The dimension `objective` provides a list of possible objectives for the coordination. This list is based on [63]; however, we adjust the objectives to better reflect platooning coordination as the original publication targets platooning in general. Obviously, one important characteristic of the platooning coordination strategy is the `input`. For instance, some strategies expect the specification of the route as a given input, while others calculate the best possible route as a part of the coordination strategy. Most of the platooning coordination approaches operate within specific `constraints`. These constraints include, for example, an intended speed range or specific vehicle types. Additionally, it is possible to define constraints to improve the coordination process, i.e., to avoid having an unrealistic solution (e.g., a speed of 300 km/h) or to limit the solution space for parameters to accelerate decision making. For making a strategy usable by information and communication technology systems, we need to codify it in an `algorithm`. We identify several types of algorithms in the literature review, which use, e.g., optimisation procedures, rules, heuristics, or game theory.

VI. Concept

In this section, we provide an overview of existing literature for all dimensions of the `concept` category. We decided not to discuss the papers individually but to categorise them based on the dimensions and highlight relevant details. Figures 6 and 7 provide statistics on this classification.

A. Architecture

The majority of the approaches uses a dedicated *control unit* for platooning coordination. The control unit is able to make well-informed decisions for multiple vehicles simultaneously. Thus, this architecture is used for approaches that optimise a metric such as fuel efficiency or traffic flow on a whole highway, highway segment, or across a region. For instance, [51] propose an algorithm to find fuel-efficient routes and speeds for truck platoons before the start of their journey. A centralised control unit receives transport assignments by trucking companies and minimises the aggregated fuel consumption of the whole fleet.

In contrast, several approaches allow the *individual vehicle* to plan actions. [64] present an algorithm for platoon formation at urban intersections where vehicles communicate in a peer-to-peer fashion via beacons. Based on the transmitted positions of potential platoons, vehicles decide which platoon to join without communicating with any kind of control unit.

We observe that—even though platooning is a cooperative driving technology—only [65] introduce an approach where a *collective of several vehicles* coordinates the platooning process together. All vehicles on a particular highway segment collectively decide on platoon formation and lane assignment to maximise the distance that platoons stay intact.

B. Decision Making

We differentiate between *single-objective*, *multi-objective*, and *many-objective* decision making in platooning coordination. Single-objective approaches optimise a single parameter such as fuel efficiency or traffic flow under certain constraints. More than 60 percent of the approaches—including the large body of research on fuel-optimal route planning such as [51], [66], and [67]—apply this type of decision making.

Multi-objective approaches optimise multiple, potentially conflicting objectives simultaneously. [47]'s work from the KONVOI project is a prominent example of a multi-objective approach. They identify the savings through improved energy efficiency in platoons, the insurance savings through fewer accidents, and the wage costs for waiting times as relevant objectives. To balance these conflicting objectives, the approach combines them in a single profit function that is optimised by the coordination algorithm.

Many-objective approaches also consider multiple objectives but do not necessarily optimise all of them simultaneously. Based on user preferences or the current context, the approaches adjust the weighting of the objectives or choose, for instance, a different cost function. Many-objective optimisation is rarely applied in platooning coordination research so far. Only [68] allow individual vehicles to maximise a custom utility function that may be different for each vehicle and that may change over time.

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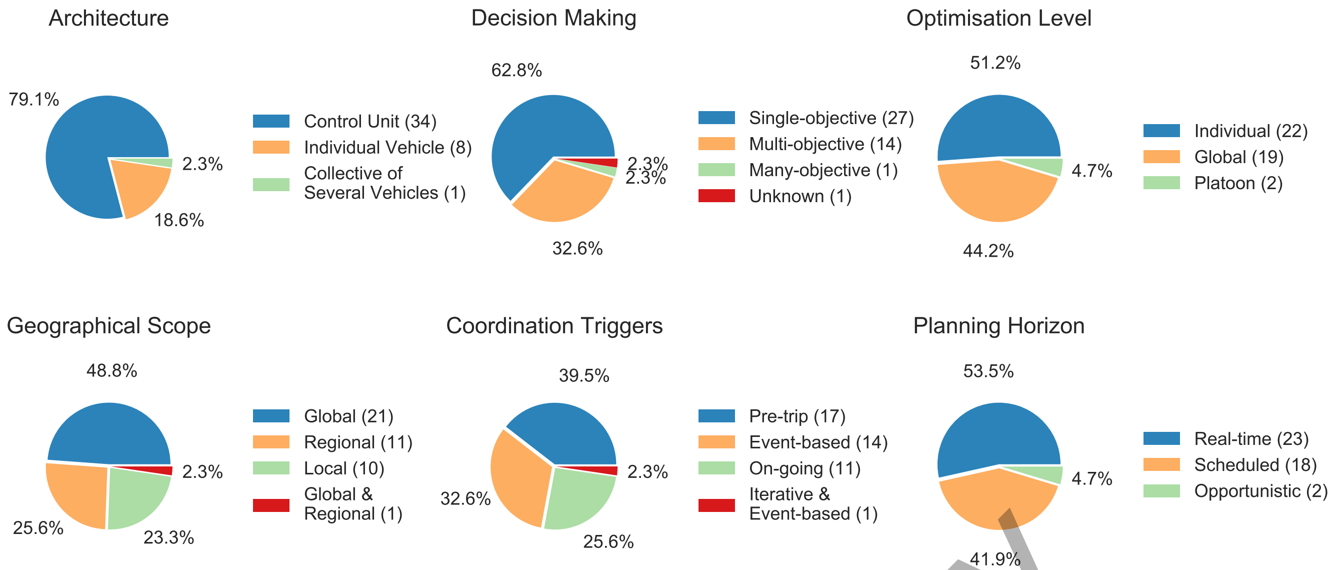

Fig. 6: Results of the literature review — Relative and absolute frequency of the different platooning coordination characteristics in the 6 dimensions of the `concept` category.

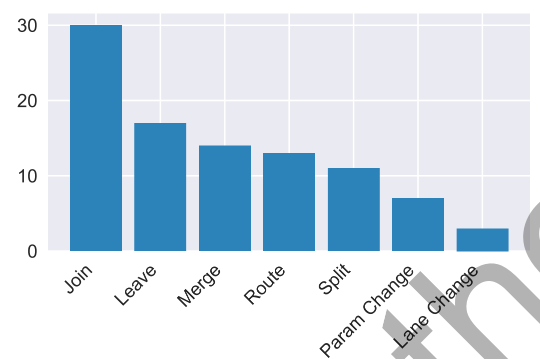

Fig. 7: Results of the literature review — Absolute frequency of different actions that approaches are able to coordinate.

C. Optimisation Level

Existing approaches either coordinate platoons to optimise their objective(s) on *global*, *platoon*, or *individual* level. Global optimisation encompasses approaches that maximise the objective for a larger group of vehicles. Thus, platooning coordination actions by these approaches may increase, e.g., the fuel consumption of one vehicle to decrease the total fuel consumption of all vehicles in a highway segment. Often, such approaches still consider individual constraints of drivers. For instance, [69] present a coordination approach that considers individual travel deadlines while minimising the total fuel consumption of all vehicles.

Only [70] and [71] describe approaches that optimise objectives on a platoon level. Much more common are approaches that choose the best action for each vehicle independently and thus optimise objectives on an individual level. [72] present a system for each vehicle that decides to create, join, or leave a platoon based on the context and user preferences.

D. Geographical Scope

As far as the geographical scope is concerned, we distinguish between *global*, *regional*, and *local* platooning coordination. Global approaches coordinate all vehicles in the area under consideration and account for 49% of all approaches. A global geographical scope is especially prominent in routing approaches for truck platooning such as [51] and [66].

Regional coordination approaches divide the area under consideration in several regions that are managed separately. The coordination approach of the COMPANION project—presented in [17]—places control units at highway intersections. These control units manage the respective surrounding area by assigning approaching vehicles to platoons. The authors state the absence of a central unit with sufficient knowledge and authority as well as the computational complexity of global optimisations as reasons for a regional approach.

Moreover, 23% of the approaches perform local coordination. These approaches coordinate vehicles in proximity without defining distinct regional borders. The majority of the local coordination approaches (nine out of ten) optimise the objective on an individual or platoon level, which shows that local coordination is particularly useful when vehicles or platoons decide on their actions by considering only the situation in their immediate vicinity. [70] propose a three-layered approach for controlling each vehicle, a platoon, or a fleet in one approach. Hereby, they perform both global and regional coordination.

E. Coordination Triggers

Platooning coordination approaches use *pre-trip coordination*, *event-based coordination*, or *on-going coordination*. Pre-trip coordination happens before the start of the journey and is applied by 40% of all approaches. Drivers or trucking companies submit plans that contain, e.g., destination, deadline,

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and speed options. These plans are then leveraged by the platooning coordination approach to determine routes (e.g., in [73], [51], [74]) or coordinate platoon formation (e.g., in [47], [75], [76]).

Event-based coordination approaches are triggered when certain events occur, for example, in [77]. The authors develop several heuristics for the formation of platoons on highway entry ramps. The coordination algorithm runs every time a new vehicle reaches the entry ramp and chooses an action such as joining a platoon, waiting for potential following vehicles, or entering the highway for this new vehicle.

On-going platooning coordination approaches apply an algorithm periodically or even continuously. [78], for instance, periodically re-plan the current routes of platoons to optimise the traffic flow. Thus, the approach takes up-to-date traffic information into account and is able to react to unforeseen changes. The planning effort, however, is considerably higher and frequent plan changes may occur. [79] propose an approach that works on-going and event-based. Monitoring and coordination run continuously while an additional event-based coordination is triggered in case of unexpected plan changes.

F. Planning Horizon

We observe different planning horizons in the platooning literature. Whereas some approaches plan the whole journey in advance, others spontaneously evaluate platooning options. We therefore distinguish *scheduled planning*, *real-time planning*, and *opportunistic platooning*. Scheduled planning takes place before the journey and plans the whole trip as used by 42% of the approaches. Scheduled planning is especially prominent in truck platooning where departure times, destinations, and deadlines are known in advance. Of the 18 approaches that apply scheduled planning, 15 work with trucks only.

Real-time planning plans the remaining journey while the vehicles are already on the road. More than half of all approaches (54%) use this type of planning horizon. The focus is on the formation of platoons on the road, with some approaches even planning routes in real-time (e.g., [78], [79]). [67] present a coordination approach that plans fuel-optimal routes for trucks. Whereas the core idea is similar to many scheduled planning approaches, the paper explicitly states that the proposed algorithm can be used during the journey if deviations occur or new information becomes available.

Only two existing approaches ([68], [80]) apply opportunistic platooning. Instead of planning the remaining journey, the opportunistic approaches spontaneously evaluate platooning options. [80], for instance, present spacing policies for platoons to maximise the road capacity. Vehicles that enter the respective road are able to spontaneously join platoons that drive in immediate vicinity.

G. Coordination Actions

The broad range of platooning coordination algorithms in the literature is also reflected in the variety of actions that the individual approaches plan and coordinate. Figure 7 depicts the number of existing approaches that cover certain actions. Most platooning coordination approaches coordinate the platoon formation process by suggesting a suitable platoon for a new vehicle. About half of these approaches also coordinate the process of leaving the platoon. The others do not explicitly advise vehicles to leave a platoon, but, e.g., assume that vehicles stay in the platoon until they reach their destination [77].

Apart from coordinating single vehicles to join or leave a platoon, several approaches are able to merge two or more platoons or split a platoon. A considerable body of research also proposes routing algorithms for platoons, which is especially attractive for trucking companies with fixed deadlines.

Platoon parameter changes or lane changes are only coordinated by a small subset of existing approaches. We observe that platooning coordination mostly happens on a high level of abstraction, leaving the execution of the suggested actions to a platooning control approach. Platoon parameter changes encompass the adjustment of a platoon's speed (coordinated by five approaches), inter-platoon positioning (two approaches), and inter- or intra-platoon spacing (two approaches).

VII. Strategy

Similar to the previous section, this section provides a broad overview of existing literature for all dimensions of the `strategy` category and highlight relevant details of the approaches. Figure 8 provides statistics on this classification.

A. Objectives

Our literature review reveals that energy efficiency is the dominating objective in platooning coordination. Closely related to this, five approaches minimise the overall cost of a journey which may—in addition to fuel costs—include wages [47] or monetary penalties for missed deadlines [81]. Further objectives are only considered by three or fewer approaches.

Several approaches define custom objectives that are only applicable to the respective approach. [82], for instance, minimise failed actions. A feedback loop in the algorithm monitors which actions were successful. This metric is then used to evaluate different controllers that coordinate the driving process. The high consistency of these controllers is another objective mentioned in this work. The authors use different controllers in simulations, compare their consistency across several simulation runs, and prefer more consistent controllers.

B. Input

The input factors for a coordination strategy can be categorised in characteristics of the:

- drive (e.g., destination, current location, or time deadline),
- user preferences (e.g., speed, route, or optimisation goals),
- vehicle characteristics (e.g., braking/acceleration coefficient, vehicle shape, or fuel consumption model),
- platooning factors (intra-platoon position, time as leader, or platoon size),
- traffic situation (e.g., traffic flow, headway to platoons, or vehicles within horizon), and
- environment characteristics (e.g., road network, topography, weather, or street condition).

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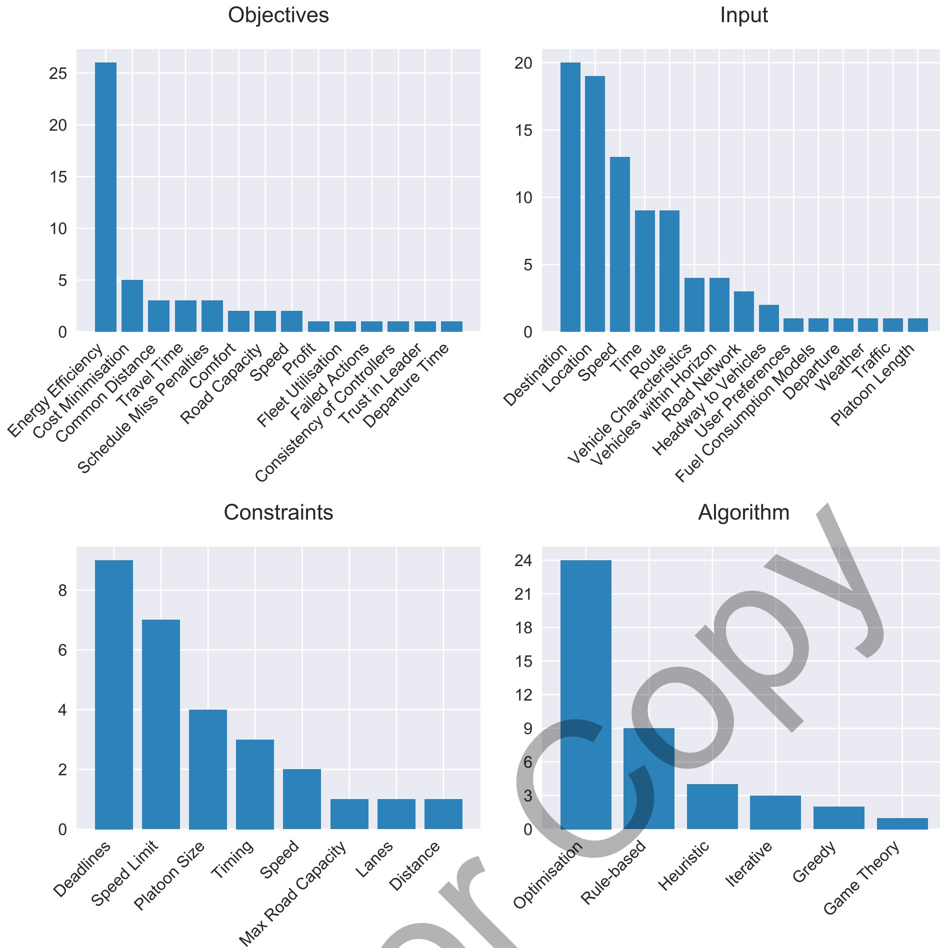

Fig. 8: Results of the literature review — Overview of the `strategy` category with the objectives, inputs, algorithms, and constraints found in platooning coordination literature.

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We observe that information about the destination of a vehicle and its current location are the most frequent inputs for platooning coordination in the literature. This geographical information is not only relevant for routing approaches but also for a well-informed platoon formation decision that allows vehicles to stay in a certain platoon for as long as possible. Many approaches also require the speed of a vehicle, the time, and the route as an input.

Surprisingly, we observe that information about the individual vehicle, such as the vehicle characteristics (considered in four approaches) and the user preferences (one approach), are only used by a small subset of approaches. The same applies to context information about weather and traffic situation that are both considered by only one approach.

C. Constraints

Platooning coordination strategies have to take constraints into account. The choice set of the algorithms is limited by, e.g., the maximum size of a platoon or the maximum road capacity. In truck platooning, deadlines of transport assignments are frequently used as constraints. This ensures that, e.g., fuel-optimal routing does not lead to detours that prolong the journey excessively. In some approaches [83], [84], this is extended to more sophisticated constraints, which may include departure times, intermediate stops, or rest periods.

Several approaches limit the possible coordination actions by considering a speed limit. [83] and [85] go beyond this and consider general speed constraints, for instance, in the form of multiple, predefined speed options for each vehicle. [64] formulate the constraint that the coordination algorithm only considers vehicles driving on the same lane as potential platooning partners.

D. Algorithm

The algorithm is the core of the coordination approach. It selects platooning actions such as joining or leaving based on the input information to achieve a certain objective under the specified constraints. Most approaches use optimisation algorithms to evaluate different options. Here, (non-)linear programming (e.g., in [78], [66], [51]) is frequently applied to optimise an objective function. In addition, several approaches perform optimisation with bio-inspired algorithms such as genetic algorithms (e.g., in [74]), ant colony optimisation (e.g., in [86]), or grey wolf optimisation (e.g., in [87], [88]).

The computational complexity of the optimisation algorithms may render them infeasible for an application in practice. Fuel-optimal routing of vehicles, for instance, is proven to be NP-hard [66]. Thus, several approaches work rule-based or develop heuristics to eliminate the need for an exact optimisation. Less common are iterative algorithms (all three approaches in [89]) or the greedy choice of coordination actions [70], [71]. [90] apply a game-theoretic approach that models the strategic interactions between vehicles owned by different companies. This coordination approach assigns trucks with different departure times to platoons and shows that this cooperative behaviour has its benefits.

VIII. Research Challenges

In this section, we interpret the results of our literature review, discuss research challenges, and analyse important aspects for a real-world transfer. Table II summarises the discussed challenges.

A. Concept

First, we discuss the challenges resulting from research gaps in the concept category. We analyse each dimension, present limitations, and show potential avenues for future work.

Architecture. Most of the platooning coordination approaches use a central control unit. This architecture is well-applicable for a limited number of vehicles, e.g., a company's fleet. We observe three significant challenges for centralised coordination approaches: i) scalability, ii) public acceptance, and iii) reliability. First, a centralised architecture will be challenging when envisioning global platoon coordination with millions of vehicles due to the increasing complexity of decision making. Second, such approaches require the broad public acceptance of a central decision maker. The central authority gathers comprehensive information about vehicle characteristics, objectives, or destinations, which may raise privacy concerns. Third, the central instance needs to ensure reliability since it represents a single point of failure. For the less commonly used decentralised architecture, we identify the collection of adequate information and the handling of limited knowledge as the two major challenges.

Decision Making. Since car passengers are human beings with complex goals and desires, we argue that it is not sufficient to apply single-objective decision making. Therefore, future research should focus on many- and multi-objectiveness, which is rarely covered in the literature.

Optimisation Level. In the analysed literature, individual and global optimisation are predominant, both with benefits and drawbacks. Individual optimisation often neglects the impact of decisions on the traffic, which may in turn influence the objectives of the individual vehicle. Global optimisation, however, may lead to unfavourable decisions for certain vehicles. Future research should resolve this tension by finding a compromise, e.g., by integrating bonus payments for unfavourable coordination decisions for individuals.

Geographical Scope. In practice, a global analysis represents a massive challenge due to the large number of vehicles. Therefore, we propose to focus on scalability and reliability in future research on platooning coordination. In general, we emphasise the importance of feasibility. As platooning approaches a market introduction in the mid-term future, coordination approaches should be applicable in realistic scenarios.

Coordination Triggers and Timing. Our literature review reveals that the platooning coordination literature is highly diverse in terms of coordination triggers and planning horizon. Pre-trip coordination that plans the whole journey is applicable for a large number of vehicles, as all calculations can be made in advance. In contrast, event-based and on-going approaches react to the current traffic situation, but the computational complexity may prevent effective coordination during the journey. Future research should close the gap between both designs and strive for high quality decisions during the journey.

Coordination Actions. Platooning coordination algorithms proposed in the literature only concentrate on a limited subset of all possible actions of the platooning process. This narrow scope leads to reduced benefits compared to a holistic solution that is capable of supporting all manoeuvres and behaviour changes. Further, algorithms presented in the literature are often inflexible with regard to the execution of a specific action. Even if they are able to coordinate an action, they do not provide the necessary flexibility for a real-world deployment.

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B. Strategy

In this section, we discuss challenges resulting from the strategy category of our taxonomy.

Objectives. The objectives of drivers and/or associated companies, as well as governments, are diverse. In line with that, the analysed literature covers a wide variety of objectives for platooning coordination. The main focus lies on the participating vehicles' energy efficiency, i.e., the aim is to save fuel by joining a suitable platoon and taking advantage of the slipstream effect. Besides, most approaches in the literature use only one or at most a few of the possible objectives. Public acceptance is a central challenge for platooning in general. Therefore, a promising approach for usage in real-world scenarios should include as many objectives as possible and integrate the driver to select the most important ones.

Input. The essential input features covered in the literature are the destination, current location, speed, time, and planned route. Only few approaches consider vehicle and context factors, like the acceleration/braking coefficients of a vehicle or the joining sequence. However, those factors are highly important as vehicles need compatible characteristics for acceleration and braking for operational efficiency and safety. Further, the mass of a vehicle is another important factor, as the coordination algorithm requires this information to arrange the position of vehicles for optimised fuel-efficiency [91]. Even if energy efficiency is a focus of many approaches, a real fuel consumption model (cf. [33]) is rarely used. To gain a more accurate coordination decision concerning the fuel consumption, models of the environment and vehicle characteristics, should be integrated. All in all, vehicle and context factors are crucial aspects but are often not taken into account by existing approaches.

Constraints. The overview paper of [63] mentioned *traffic law* and *topography* as possible constraints; however, we did not identify those constraints in the reviewed works of platooning coordination. Nevertheless, the legal conformity of the approaches is a basic prerequisite for implementing platooning and platooning coordination in reality. For example, a platooning coordination approach could reroute a platoon to avoid driving in prohibited platooning areas, or the platooning approach should be aware of mandatory following distances. Additionally, missing to integrate the topography might result in sub-optimal coordination. For instance, Alam et al. studied the effects of grade variations on the platoon dynamic response and energy saving potentials [92]. They revealed significant challenges in implementing energy efficient driving strategies when vehicles at different positions in the platoon are simultaneously on positive and negative grades in hilly terrain. For a more detailed study on these effect, we refer the interested reader to [92]. Further, the positioning of vehicles inside the platoon is an important aspect, such as placing the most agile vehicles at the back of the platoon and the least agile vehicle at the front to maintain overall safety of the platoon. Another example of environmental impacts on a platoon could be trucks that might slow down cars in a heterogeneous platoon on roads with many inclines.

Algorithm. Due to a large number of vehicles, the branched road network, and numerous input parameters, platooning coordination is often of high computational complexity. Therefore, most of the identified approaches in the literature provide approximate solutions to ensure that the coordination algorithm solves the problem in reasonable time. A combination with clustering or other data mining techniques plays a vital role in dividing the overall optimisation problem into manageable sub-problems. However, the complexity of models will increase further in a real-world setting as a consequence of even higher numbers of vehicles or more sophisticated input parameters. Thus, complexity remains a challenge. Additionally, many algorithms rely on simplistic assumptions, which may have a negative influence in practice. Common assumptions are low traffic density or the absence of rest times. On the way towards application in practice, approaches need to reduce these and cope with a more challenging environment.

C. Real-world Transfer

In addition to the aforementioned challenges that are directly related to our novel taxonomy on platooning coordination, we identify three broader challenges for future work. These challenges arise when transferring the concept of platooning and platooning coordination to the real world.

Fairness. A major challenge is the creation of an incentive system to compensate the leader or last vehicles of the platoon for their lowered fuel savings resulted from air drag [3]. Sturm et al. capture those aspects of fairness as the objectives *balance of individual objectives* and *cost balancing* [63]. It might be beneficial to offer monetary benefits or a virtual currency that can be used for future platooning activities to "buy" positions in the middle of a platoon. So far, none of the coordination approaches integrates a compensation mechanism. In a recent publication, we study different mechanisms based on ideas from research about altruism, social sciences, organ donation, task scheduling on computers, and professional cycling sports. Our experiments show that the time spent in a position with negative effects is split equally among all vehicles when using our mechanisms [93]. The incorporation of compensation mechanisms is an open challenge for platooning coordination.

Mapping objectives to actions. The coordination approaches often only transmit high-level data, such as speed, route, and meeting points, to vehicles. This does, however, not enable the vehicles to conduct the actions (overtaking, joining a platoon, communicating) in practice. To achieve this, it is necessary to translate the high-level actions into detailed low-level commands for the vehicle's actuators. Current solutions neglect this. One challenge in this regard is that vehicles can have their own decision making with individual goals, which might conflict with the global goals for platooning coordination [63]. The integration of mechanisms into platooning coordination approaches to harmonise those conflicting objectives is to the best of the authors knowledge not addressed in literature so far. Additionally, it might be possible that the approach proposes a coordination action not feasible for the vehicles at the moment, e.g., to catch up while a human-driven car behind the platoon is impeding the manoeuvre. In general, the issue of mixed traffic is emerging rapidly and a good example of a challenging practical problem that real-world implementations already address. However, not enough attention is paid to this topic in research and more scientific papers should be published such as in [94], [95], [96].

Communication. Cooperation through communication is a fundamental component of platooning, supporting coordination/manoeuvring and distributed control. Concerning coordination, communication is essential to enable management. The large majority of the literature considers IEEE 802.11p [97] as the lead technology for Vehicle-to-vehicle (V2V) communication within platoons, but other works consider Visible Light Communication (VLC) [98], Infrared (IR) [99], or Long Term Evolution (LTE) cellular [100]. Recent advances in 5G technology also raises the question if 5G might be a feasible option for establishing the communication for platooning coordination. Further, the question arises whether an explicit communication layer or communication structure besides the existing technologies is meaningful for platooning coordination. However, we assume the presence of a working communication in this work.

D. Threats to Validity

A common issue with systematic literature reviews based on the technique by [62] is the choice of the relevant search terms. While we also consider modifications of the terms, it cannot be guaranteed that the set of terms covers all relevant publications. Similarly, the choice of the sources is highly relevant. We cover the most relevant databases and Google Scholar, however, it is still possible that a relevant publication is not listed in the searched sources. Further, the results may be slightly biased due to the manual steps of our methodology. For example, as far as the optimisation approaches are concerned, several classifications exist, which could be applied. However, we try to minimise the risk of such effects as several researchers confirmed each step. Additionally, given

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TABLE II: Overview of the research challenges regarding the taxonomy including all categories and dimensions.

Category	Dimension	Research Challenge
Concept	Architecture	Scalability, public acceptance, and reliability in centralised approaches; handling of limited knowledge in decentralised approaches
	Decision Making	Integration of more than one objective (many- and multi-objectiveness) and also individual preferences/constraints
	Optimisation Level	Finding a compromise between individual and global optimisation (e.g., incentives for disadvantageous actions)
	Geographical Scope	Scalability and reliability of global analysis approaches
	Coordination Triggers and Timing	Hybrid coordination triggers (pre-calculated plans with online adaptation w.r.t. dynamic traffic situations)
	Coordination Actions	Holistic solution integrating all coordination actions in one approach; advanced flexibility for real-world deployment
Strategy	Objectives	Increase public acceptance by integrating multiple and diverse objectives into one approach
	Input	Integration of vehicle and context factors (e.g., fuel consumption model, vehicle characteristic model, environment model)
	Constraints	Consideration of legal constraints and the topography of platoons as well as their dynamics
	Algorithm	Design of efficient algorithms to cope with complexity of real-world application without restricting assumptions (e.g., low traffic density, absence of rest times)
Real-world Transfer	Fairness	Incorporation of mechanisms to compensate negative effects such as driving in front or at the back of a platoon
	Mapping Objectives to Actions	Automatic translation of high-level actions to low-level commands for vehicle's actuators; develop mechanisms to meet global goals when individual goals and actions conflict
	Communication	Feasibility of existing communication techniques (e.g., 5G), meaningfulness of separate communication layer or structure for platooning coordination

that similar concepts might be named differently in papers, or vice versa, slightly different concepts might be captured under the same name in the taxonomy, some uncertainty might be left when using the taxonomy for evaluation of the platooning coordination approaches. Finally, we provide figures depicting the numbers of papers per category and dimension and base our discussion on the significance of different kinds of coordination approaches on them. We acknowledge that the number of approaches per dimension does not necessarily reflect the importance and feasibility of the approaches. Therefore, we use these proportions as an entry point into the analysis and discuss why these proportions appear as they do and their implications. Furthermore, all graphs must be seen as a whole picture and the interpretation of these numbers in an isolated view of a single dimension is not meaningful. Additionally, the distribution of publications is related to the topic areas that are deemed as relevant within the academic research community and their funding sources or by industry. This bears little relationship to which topics are most important in order to facilitate real-world implementation of platooning. Those important topics are often less valuable from the perspective of academic publications and reviewers, and less likely to be published, so they are less represented in the paper count. However, as this paper fully focuses the academic literature, this seems to be a systematic issue for a structured review of academic literature.

IX. Conclusion

A large variety of platooning coordination approaches, which differ in terms of architecture, timing, or objectives, emerged in the recent past. This paper reviews and classifies literature on platooning coordination. The comparison of existing approaches in this work proved that no dominant design evolved so far. Especially, state-of-the-art approaches miss individualisation, i.e., the integration of individual preferences as well as constraints. Further, the coordination schemes do not integrate vehicular characteristics, environmental aspects, or realistic fuel consumption models. Moreover, these solutions ignore external factors which influence deployment such as the prevailing multi-vendor setting or data security.

Future work should address a more in-depth analysis of the relevant papers in a paper-by-paper literature review to identify conceptual differences of the approaches. Further, a comparative evaluation of existing approaches in realistic simulators is future work for the community. Additionally, the formulation of an individualised platooning coordination approach—integrating individual goals but also specific vehicular characteristics and individual constraints—constitutes an additional future research direction. We previously discussed the concept of such an approach (cf. [101]).

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Appendix

TABLE III: List of relevant platooning coordination papers identified during the literature review.

Author	Title	Venue
[78]	Optimal routing for automated highway systems	Transportation Research Part C: Emerging Technologies
[70]	Cyber–Physical Control of Road Freight Transport	Proceedings of the IEEE
[65]	Distributed Platoon Assignment and Lane Selection for Traffic Flow Optimization	IEEE Intelligent Vehicles Symposium
[87]	Bio inspired strategy for improving platoon management in the future autonomous electrical VANET environment	International Conference on Computer Communication and Networks
[88]	Grey Wolf Optimization in VANET to manage Platooning of Future Autonomous Electrical Vehicles	IEEE Annual Consumer Communications & Networking Conference
[102]	COMPANION - Towards Co-operative Platoon Management of Heavy-Duty Vehicles	IEEE International Conference on Intelligent Transportation Systems
[80]	Multiplatooning Leaders Positioning and Cooperative Behavior Algorithms of Communicant Automated Vehicles for High Traffic Capacity	IEEE Transactions on Intelligent Transportation Systems
[103]	An Agent-based Simulation Model for Truck Platoon Matching	Procedia Computer Science
[77]	Vehicle Sorting for Platoon Formation: Impacts on Highway Entry and Throughput	Transportation Research Part C: Emerging Technologies
[64]	Dynamic Platoon Formation at Urban Intersections	IEEE Conference on Local Computer Networks
[104]	Platoon Formation: Optimized Car to Platoon Assignment Strategies and Protocols	IEEE Vehicular Networking Conference
[90]	Multi-Fleet Platoon Matching: A Game-Theoretic Approach	International Conference on Intelligent Transportation Systems
[68]	Convoy driving through ad-hoc coalition formation	IEEE Real-Time and Embedded Technology and Applications Symposium
[105]	Coordinated Route Optimization for Heavy-duty Vehicle Platoons	International IEEE Conference on Intelligent Transportation Systems
[17]	A Distributed Framework for Coordinated Heavy-Duty Vehicle Platooning	IEEE Transactions on Intelligent Transportation Systems
[69]	Coordinated Platoon Routing in a Metropolitan Network	Proceedings of the Seventh SIAM Workshop on Combinatorial Scientific Computing
[66]	The Vehicle Platooning Problem: Computational Complexity and Heuristics	Transportation Research Part C: Emerging Technologies
[89]	Coordination and Routing for Fuel-Efficient Heavy-Duty Vehicle Platoon Formation	PhD Thesis KTH Royal Institute of Technology
[106]	Fuel-Saving Potentials of Platooning Evaluated Through Sparse Heavy-Duty Vehicle Position Data	IEEE Intelligent Vehicles Symposium Proceedings
[107]	Heavy-Duty Vehicle Platoon Formation for Fuel Efficiency	IEEE Transactions on Intelligent Transportation Systems
[47]	A data-mining technique for the planning and organization of truck platoons	Proceedings of the International Conference on Heavy Vehicles
[74]	The Fuel-Efficient Platooning of Heavy Duty Vehicles by Mathematical Programming and Genetic Algorithm	International Conference on Theory and Practice of Natural Computing
[86]	Fuel-efficient truck platooning by a novel meta-heuristic inspired from ant colony optimisation	Soft Computing
[108]	Flexible and Energy-Saving Platooning Control Using a Two-Layer Controller	International Journal of Intelligent Transportation Systems Research
[71]	Intelligent truck platooning: how to make it work	ITS World Congress
[76]	Platoon formation maximization through centralized routing and departure time coordination	arXiv
[73]	A Fast Heuristic for Finding Near-Optimal Groups for Vehicle Platooning in Road Networks	International Conference on Database and Expert Systems Applications
[109]	Platoon forming algorithms for intelligent street intersections	Transportmetrica A: Transport Science

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[51]	Fuel-Optimal Centralized Coordination of Truck Platooning Based on Shortest Paths	American Control Conference (ACC)
[110]	Computing Feasible Vehicle Platooning Opportunities for Transport Assignments	IFAC-papersonline
[111]	Fuel-Efficient Centralized Coordination of Truck Platooning	PhD Thesis KTH Royal Institute of Technology
[67]	Fuel-Efficient En Route Formation of Truck Platoons	IEEE Transactions on Intelligent Transportation Systems
[79]	A Predictive Framework for Dynamic Heavy-Duty Vehicle Platoon Coordination	ACM Transactions on Cyber-Physical Systems
[82]	Fast, Comfortable or Economical: Evolving Platooning Strategies with Many Objectives	IEEE International Conference on Intelligent Transportation Systems
[72]	A Multi-Objective Approach to Evolving Platooning Strategies in Intelligent Transportation Systems	Proceedings of the 15th Annual Conference on Genetic and Evolutionary Computation
[112]	An Energy-efficient and Trust-based Formation Algorithm for Cooperative Vehicle Platooning	International Conference on Computing, Networking and Communications
[85]	Optimizing Coordinated Vehicle Platooning: An Analytical Approach Based on Stochastic Dynamic Programming	arXiv preprint
[75]	Planning of heavy-duty vehicle platoon formulation: basic scheduling problem considering travel time variance	Transportation Research Board 95th Annual Meeting
[113]	Freight transport platoon coordination and departure time scheduling under travel time uncertainty	Transportation Research Part E: Logistics and Transportation Review
[81]	Platoon coordination with time windows: an operational perspective	Transportation Research Procedia

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