A Comparison of Mechanisms for Compensating Negative Impacts of System Integration

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Abstract

The demand for passenger and freight transportation has grown sharply over the last decades and will triple by 2050. This also dramatically impacts the environment as traffic is one of the primary sources of CO2 emission. Platooning, which is defined as driving automated vehicles in convoys with minimal inter-vehicle distance enabled by vehicular communication, offers several benefits like energy savings due to slipstream effects, homogenization of traffic flows, increased capacity of streets, as well as improved safety due to communication. However, as the vehicles at inner positions of a platoon experience higher benefits than the first and last vehicle, the compensation of the effects of different positions in a platoon have to be taken into account when integrating vehicles in a platoon. In this paper, we discuss several strategies on how to incentivize vehicles to participate in platooning based on directly or indirectly compensating vehicles for fewer benefits resulting from the integration into a platooning system. Our considerations integrate ideas from research about altruism, social sciences, organ donation, task scheduling on computers, as well as 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. Additionally, we found that characteristics of the environment—e.g., the number of lanes or traffic density—impact the performance of the compensation mechanisms. We further provide a discussion of the identified challenges and on how to apply our proposed ideas to other systems which require self-integration.

Keywords: System integration, Incentives, Compensation, Platooning

1. Introduction

The Internet-of-Things (IoT) or interacting cyber-physical systems (CPSs) require the integration of many different, potentially heterogeneous, entities. This results in system-of-systems [1] or even interwoven system [2] constellations. To build those systems, integration—"the process in which several component (sub-)systems are brought together and interconnected into a unified system" [3]—is a necessity. However, integrating those large scale, heterogeneous entities for enabling cooperative behavior is a very challenging task [4]. Additional characteristics of these systems, such as mobility, influence the system performance and increases complexity, especially in dynamic environments with on-going changing conditions.

Research in the field of self-improving system integration (SISSY) [3]—also called self-integration—emerged as a response to the growing complexity of integrating resources in large-scale open constellations of systems. According to [4], typical system domains include high-performance computing, power management systems, vehicular traffic, and socio-technical systems. Especially in the context of a set of autonomous, adaptive systems working together and forming a system-of-systems, the integration is a very complex

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task due to the limited predictability of system behavior. Additionally, as those autonomous resources follow their own—potentially conflicting—objectives [5], the integration is additionally challenging. Consequently, resources that are disadvantaged by the cooperation might decide not to participate. To tackle this issue, we describe several coordination mechanisms that can help to identify a solution for cooperation that balances the disadvantages across several instances in our previous work [6]: Those coordination mechanisms can be categorized into decentralized (selfish behavior, altruistic behavior, negotiation) and (pseudo-)central approaches (enforcement of central decision making, rewards/incentives).

In this paper, we focus on an incentives-based view on system integration. We present several strategies on how to incentivize resources to integrate themselves into a large system composed of interacting, cooperative resources based on direct or indirect compensation for negative impacts, i.e., fewer benefits of some systems in comparison to the other integrated systems resulting from the system integration. In line with research in the SISSY community [4], we focus on a use case from the domain of vehicular traffic and apply those strategies for platooning. Platooning describes cooperative driving of automated vehicles driving with small inter-vehicle distances of 5–10 meters [7]. Those vehicles benefit from slipstream effects due to air drag reduction resulting in energy savings. Additionally, the global traffic flow is optimized by the homogenization of velocities as well as increased traffic throughput. However, the vehicles in such a platoon experience unequal benefits depending on their position in the platoon. Especially the lead vehicle experiences reduced fuel savings and, in some platooning approaches, its driver has to drive manually whereas other vehicles can follow in a self-driving mode; hence, those drivers do not have to control their vehicles. Consequently, the coordination of platooning, including the assignment of vehicles to platoons, is a challenging task as it represents a multi-level, multi-objective optimization problem [8]. As each of the vehicles act as a self-adaptive system [9], the coordination requires incentives and compensation to convince vehicles to participate in platooning.

The main focus of this paper is a study of compensating negative impacts or fewer benefits resulting from system integration in the domain of platooning. Here, we focus on integrating platooning with other traffic participants, i.e., the compensation mechanisms should not negatively influence other traffic participants. By negative impacts we refer to fewer benefits for some of the vehicles of a platoon compared to the other vehicles in the same platoon. Accordingly, our contributions are threefold:

- First, we propose an incentive model for improving the fairness of system integration optimized for platooning.
- Second, we propose mechanisms for indirect compensation of negative impacts resulting from system integration in a platooning case study.
- Last, we discuss the identified challenges exemplified in the context of typical SISSY systems.

Next, Section 2 describes the domain of platooning coordination in the context of system integration. Afterward, Section 3 presents an overview of incentive models for platooning as well as related work from the SISSY community. Based on this overview, we derive a taxonomy for compensation-centered incentivization for system integration and exemplify this taxonomy for platooning in Section 4. We further design different mechanisms for compensation of negative impacts for individuals resulting from system integration in Section 5 and evaluate them w.r.t. fairness and system performance. Section 6 evaluates the proposed methods and summarizes the results. Section 7 discusses those results. Finally, Section 8 concludes this paper.

2. Platooning as Example for System Integration

Platooning has many apparent positive effects on society and the environment, by saving energy through slipstream effects, optimizing the traffic flow through traffic homogenization, and improved safety through vehicular communication. All vehicles share a common understanding of the platooning procedure, i.e., those are equipped with a platooning management system for controlling the process of platooning including a communication system for inter-vehicular communication. Those systems apply rules to decide which platoon a vehicle should join. Some approaches rely on communicating with vehicles within the communication range and autonomously decide which platoon to join. We follow another approach [5, 8]: A central recommendation system supports the platooning process and provides recommendations for suitable platoons. However, we assume that vehicles reason autonomously which platoon to join or when to leave a platoon. For example, a vehicle might consider (i) the predicted stability of a platoon or its position in the platoon when joining a platoon or (ii) decide to leave a platoon and join another platoon with a higher velocity. Further, other—self-driving or human-driven—vehicles share the road with platoons. Hence, they interact implicitly with each other.

However, the effects for individual vehicles are less obvious, regardless if one speaks of commercial or private vehicles. This holds especially for the platoon leader as it experiences less fuel saving as one of the main factors determining fuel consumption of road vehicles is air drag. A single car is exposed to two resistive forces, a high-pressure zone in front of the car and a turbulent low-pressure zone behind it. Both forces cause drag and ultimately result in increased fuel consumption. Platooning slightly reduces these drag effects for the first and last vehicles and heavily reduces them for vehicles in between (cf. Figure 1). As some approaches like SARTRE [7] assume to have a human-driven leading vehicle, in those approaches, the driver must devote his full attention to the road. Additionally, he is burdened with much responsibility. This can be another reason for trying to avoid the leading position in a platoon. Accordingly, incentive models are required as it is questionable for users to follow the instructions of the platooning coordination mechanism voluntarily.

The integration of vehicles into platoons can be seen as system integration in an interwoven system [2]. Autonomous or human-driven vehicles acting as individual systems are assigned to platoons as a conglomerate. The traffic in total is composed of a set of platoons and individual vehicles. Platooning coordination, i.e., assignment of vehicles to platoons and the determination of the intra-platoon position, is a multi-level optimization problem with the levels of global traffic, platoon, and individual vehicles. The objective of the different levels might be contradicting. Accordingly, it can be necessary to compensate drivers of individual vehicles for their participation in a platoon. Furthermore, it can be necessary to punish vehicles or platoons for undesired behavior, for example, disturbing other traffic. Hence, we rely on a central instance that observes and controls the vehicles to some extent and we assume that vehicles that want to platoon obey a given set of rules. Still, within those rules, they act with some freedom and autonomy. Further, the assignment of the platoons, i.e., the integrated parts of the subsystems, is not static, but rather dynamic. Consequently, it is possible to self-improve the assignment, e.g., to reflect individual preferences or constraints better or optimize the air drag reduction [8]. Accordingly, platooning coordination represents an example for a SISSY system from the vehicular traffic domain [4].

3. Related Work

In the following, we discuss different related work in the area of compensation models for platooning and intra-platoon vehicle sequence optimization. Furthermore, we present approaches for compensation-based system integration from the SISSY research domain.

3.1. Platooning Compensation Models

Besides the technological aspects of platooning, the SARTRE project [7] also included studies on incentives and compensation models. In the *monthly subscription* model—i.e., a market compensation model—customers pay a monthly fee, which also compensates the lead driver for his effort. Similarly, in the *pay-as-you-go* model, users pay the platoon leader a fee to join the platoon over a predefined distance or pay per usage. To compensate the users of platooning for the paid fees, the SARTRE researchers recommend a *Free Sponsored Benefits* model, i.e., governments offer free services—free parking or access to car pool lanes—to make platooning more appealing. The *taking turns model* assumes a large user base: Users are incentivized to act as a platoon leader as this is the only possibility to earn the right to be in an inner-platoon position in the future. Whereas the first two models are examples for direct compensation of the platoon leaders, the last two are indirect compensations for users of platoons.

The TNO project [11] differs substantially from SARTRE as it only targets trucks and as it does not allow a platoon to be longer than two vehicles. TNO considers Logistic Service Providers (LSPs) and Platooning Service Providers (PSP). The *scheduled platooning* model describes the idea that LSPs (forwarder, shipper, haulers) use platooning whenever two trucks of the own company at least partially travel together. The *on-the-fly platooning* model describes dynamic inter-company platooning. This requires compensation mechanisms; however, TNO does not further specify them. A third model integrates PSPs as instances that coordinate platooning, handle administrative issues, and transfer compensation payments.

Peloton uses a direct compensation model that offers platooning as a usage-based service [12]. The cloud-based Network Operations Centre coordinates platooning and assignments of vehicles to platoons. When situated in the fuel-saving position, a vehicle pays a per-mile fee that includes compensation payments for the platoon leader.

In Section 4, we define a taxonomy of compensation-centered incentives of platooning that integrate those

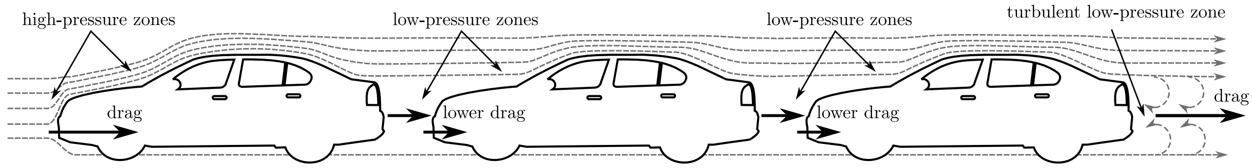

Figure 1: Aerodynamic effects of platooning visualized. Edited image, based on [10]

concepts. Further, we classify the above-mentioned approaches using our taxonomy.

3.2. Intra-Platoon Vehicle Sequence Optimization

Research on the topic of intra-platoon vehicle sequence optimization deals with finding an optimal ordering of the platooning vehicles. Depending on the exact use case, different variables can be optimized.

Hao et al. [13] investigated the optimal joining position for new vehicles in order to minimize acceleration, deceleration, and cruising maneuvers when opening/closing gaps, which leads to a more energy-efficient usage of platooning. To achieve this, they formulated a bi-level integer programming model. Similarly, Liang et al. [14] also analyzed the effects of ordering intra-platoon vehicles in different ways. They focused on the mass of heavy-duty vehicles (HDV) as an important factor which influences the driving characteristics. The results of both strategies show that the sequence of vehicles inside a platoon can have a considerable impact and can be used to achieve higher fuel efficiency. However, existing research on platoon formation so far disregards the aspect of equally sharing the benefits of platooning in terms of fuel efficiency. With this study, we contribute to this aspect.

3.3. Compensation-based Self-improving System Integration

The focus of the SISSY research lies on systems of systems, federations of systems, or interwoven systems [4]. The integration of those large scale, heterogeneous entities for enabling a cooperative behavior is a very challenging task [2]. We classified coordination mechanisms for this integration into decentralized approaches—selfish behavior, altruistic behavior, negotiation—and (pseudo-)central approaches—enforcement of central decision making, rewards/incentives [6]. First, selfish behavior might lead automatically to a coordination of the instances due to interaction awareness [15] as each entity tries to optimize its benefits through coordination with others. Information dissemination can help to lower the risk of potentially conflicting decisions. Second, to overcome the issue of conflicting adaptation plans if selfish entities are not interaction-aware, mechanisms must ensure that such entities act cooperatively [15]. Still, situations can occur where agents may disagree but still need to find a consensus. Then, negotiation techniques–such as auctions [16], or bio-inspired approaches (e.g., [17])—might support the integration of entities to a shared system. Further, there are scenarios where a central or pseudo-central instance is necessary. Approaches based on leader election for choosing one specific node that acts on behalf of the group can help to enforce a central plan. Instead of forcing the resources to obey a given plan, incentives convince the resources to choose from adaptation alternatives specifying degrees of freedom.

In emergent-based approaches, the system is fully decentralized as agents act autonomously without using explicit coordination or negotiation techniques. For coordination purposes, this generally refers to simple scheduling schemes (see [18] for an overview). Alternative solutions include concepts from Organic Computing (e.g., [19]). However, in some situations, incentives are used as a mechanism to guarantee participation. In literature, different approaches to counter the negative effects (such as decreased willingness to participate or unfairness) are known, including compensation based on (crypto-)money, trust values, scheduling priorities, or reputation. A corresponding overview can be found in [20, 21].

Another stream of research focuses on a fair distribution of benefits and resources. Pitt et al. [22] present an approach to common-pool resource management based on Rescher's theory of distributive justice [23]. Voting functions collectively determine the rank order in which resources are allocated; hence, the systems self-organize the allocation method. Similar, Garbiso et al. [24] adopt the theory of distributive justice to ensure fairness in a use case of clusters of connected vehicles.

Especially in the context of multi-agent systems, solutions for integrating a group of autonomously acting agents based on incentives and rewards in social computing, incentive-based cooperation, or compensation in contracts have been investigated (e.g., see [25] for an overview). In those settings, situations can occur where agents may disagree, but still need to find a consensus. Approaches to handle this "consensus problem" in multi-agent systems are provided by [26].

In this paper, we plan to compare several mechanisms for providing a compensation-based mechanism for system integration in the domain of platooning. In contrast to the presented works, we integrate an intermediary instance that guides the process of system integration with recommendations rather than controlling it. Similar to the above-presented research, our taxonomy relies on ideas from research about altruism, social sciences, and organ donation, while our indirect compensation mechanisms are inspired by task scheduling on computers, as well as professional cycling.

4. Taxonomy of Compensation-centered Incentives for Platooning

In our previous work [6], we review different coordination mechanisms for self-improving system integration. We classified those approaches into decentralized approaches (selfish behavior, altruistic behavior, negotiation) and (pseudo-)central approaches (enforcement of central decision making, rewards/incentives). In this paper, we focus on the category of incentives.

Kimiz Dalkir defines incentives as: "A reward for a specific behaviour, designed to encourage that behaviour" [27, p.467]. Such incentives can be classified into four types. (1) Remunerative incentives fully rely on positive reinforcement, e.g., material rewards like money. (2) Coercive incentives try to compel behavior by penalizing misconduct. (3) Moral incentives provide motivation to act in a certain way. (4) Intrinsic incentives try to amplify the natural motivation that one has to perform a specific behavior. While several incentive models are present in literature, we focus on a compensation-centered perspective of incentives.

The Webster's *New World College Dictionary* defines compensation as: "Anything given as an equivalent, or to make amends for a loss, damage, unemployment, etc". Israni *et al.* broadly classify compensation models into four different models [28]. The *No Compensation* model based on altruism does not compensate for the disadvantages at all. The *Cost Reimbursement* model provides the acting person with tangible compensation for the disadvantages. In contrast, the *Market Compensation* model and the *Fixed Compensation* model do not just compensate for the difficulties and drawbacks but allow to make a profit. In the first model, the paid-out compensation is determined by market forces (such as supply and demand); in the latter, the compensation is a fixed amount just above cost reimbursement.

Since system integration often comes along with advantages that are not necessarily evenly distributed over all subsystems, we focus on incentives that encourage integration. This section describes a compensation-centered taxonomy for incentives for supporting system integration of autonomous system elements based on recommendations of a central entity. The taxonomy can be applied in different applications in the area of self-improving system integration. Our considerations integrate ideas from research about social sciences [27] and organ donation [28]. We focus on those areas as the participation in platooning often includes the motivation of an individual to not only participate in a cooperative process but also potentially invest one's own resources for the greater good. Accordingly, we choose those concepts due to their relation to altruistic behavior. Figure 2 provides an overview of the taxonomy. Next, we describe the categories of the taxonomy, namely, *Control Instance*, *Compensation*, and *Payment Model*. Afterward, we describe how to apply the taxonomy on the example of platooning by integrating a compensation of negative impacts resulting from the participation in platooning to maximize the benefits and equally share negative impacts.

4.1. Control instance

On the level of the control instance, we subsume the actors that drive the implementation, i.e., that are responsible for providing and controlling the incentivization. Further, this level assigns the different categories of incentives to the actors. With community-driven system integration, we refer to models based on altruistic behavior. Social rewards, as well as a collective consensus, might improve system integration. Suppose a government or another authority—e.g., an organization for standardization—chooses to enforce behavior by laws, rules, or standards. They can do so because of their executive power, which allows them to punish misconduct. Modern and democratic societies might use monetary penalties such as fines, tolls, and increased taxes to enforce innovations or setting standards/regulations. However, if policymakers let their citizens decide themselves whether they want to apply a new system (and, hence, integrate themselves), they can incentivize it by introducing rewards and benefits. Private entities, such as companies, can only utilize remunerative incentives. They lack the power and the authority to enforce behavior by using coercive incentives.

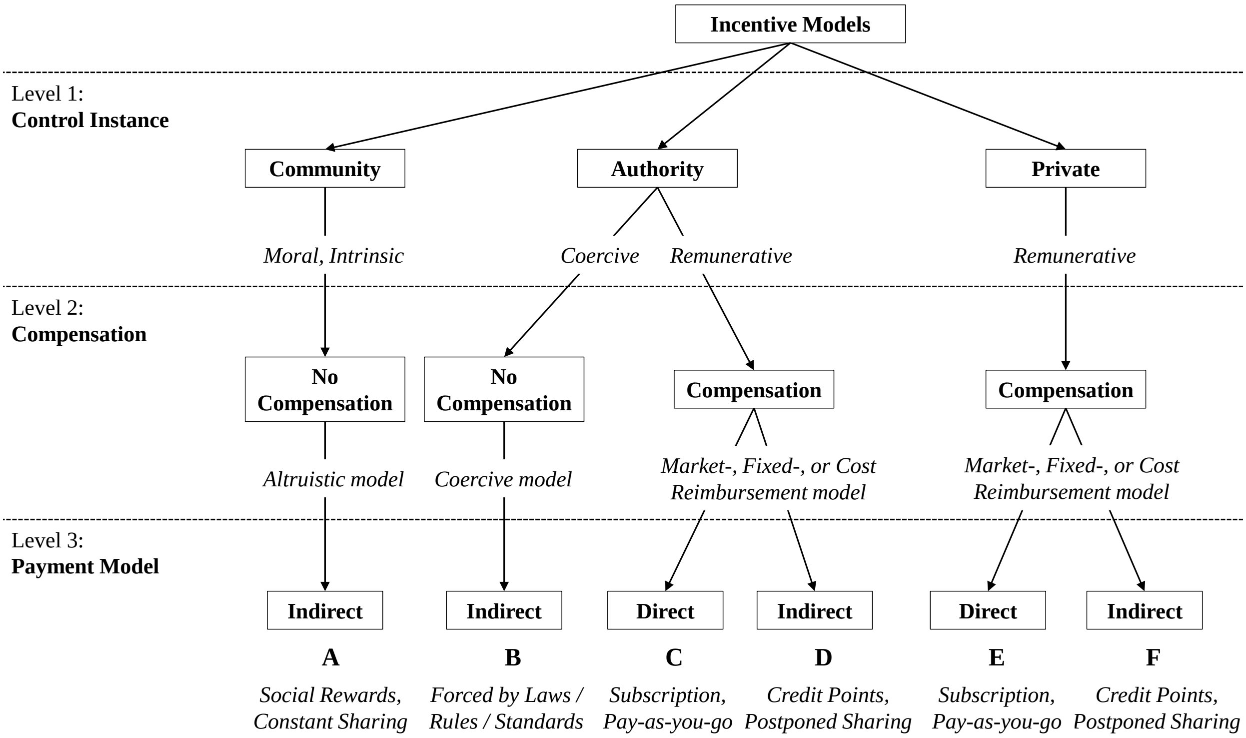

Figure 2: Classification of incentive models on three different levels: control instance, compensation, and payment model.

4.2. Compensation

Incentives might include compensation for negative impacts or not. This is primarily determined by how the incentive model is implemented. If the implementation entity chooses not to permit compensation, i.e., if there is no compensation in the form of a tangible recompense, system integration solely relies on its users' altruistic mindset. Additionally, one could think of a *No Compensation* model using coercive incentives; the specific types of incentives depend on the actor. If compensation is granted, then regardless of the exact scheme that is used, all models rely on remunerative incentives. The schemes *Market Compensation* and *Fixed Compensation* allow the generation of profit and thereby add an additional incentive for users to accept negative impacts resulting from system integration. The *Cost Reimbursement* scheme focuses on establishing equal benefits for every user.

4.3. Payment Model

Payment describes the act of transferring the incentive from one entity to another. It can be distinguished by how it is carried out -– directly or indirectly. Direct payments are characterized by transactions of currency between system elements. Indirect payments could use currency equivalents or payment means that are not at all related to money, such as credit points, tax credits, and state-issued vouchers. The altruistic nature of the *No Compensation* schemes include social effects, such as achieving equality by sharing the negative impacts or social rewards. Additionally, methods to equally share the negative impacts are indirect payment methods as well. Yet, one must differentiate between constant and postponed sharing. Constant sharing relates to sharing the negative impacts on-the-fly, i.e., at system runtime. In postponed sharing, a user earns, for example, credit points, for temporarily accepting negative impacts.

4.4. Application of the Taxonomy for the Example of Platooning

The taxonomy provides an easy-to-use approach to identify and structure possible compensation methods that can act as incentives for system integration of autonomous entities. However, the specific methods for the groups A–F shown in Figure 2 might be specific for the use case. In the following, we apply the taxonomy to structure the incentive models for platooning from related work (cf. Section 3.1). Platooning can be incentivized by the community itself, governments, and by private entities, e.g., logistics companies, platooning service providers, or Original Equipment Manufacturers from the car/truck industry. The models in a particular group (denoted from A–F) are equal to each other in terms of implementation and compensation.

The community can incentivize platooning itself using altruistic models, e.g., social rewards such as recognition of taking part in platooning and enhancing its benefits as well as a collective consensus to use a constant rotation model as payment model can help to realize platooning. Those methods belong to `Group A`. Additionally, the government can apply coercive methods, e.g., fines, tolls, additional taxes or traffic law, to force a specific behavior (see `Group B`). Instead of using compensation payments, both categories rely on measures that can be derived from moral or intrinsic incentives.

Models of `Group C` and `Group E` both use remunerative incentives to ensure compensation and do so in a direct manner; for `Group C` this is controlled by the government whereas for `Group E` this is done by private companies. Most related work can be sorted into `Group E` (private sector), e.g., SARTRE's monthly subscription and pay-as-you-go models [7], TNO's on-the-fly and PSP models [11], and Peloton's business approach [12]. Especially for `Group E`, the methods allow the generation of profit for users by driving in the first position in subscription-based approaches. As governments can utilize the same methods as implementing companies could, all models are also sorted into `Group C`.

Both, `Group D` and `Group F` use remunerative incentives to compensate users in an indirect manner. Except for SARTREs taking turns model (sorted into `Group F` as Postponed Sharing) and the Free Sponsored Benefits model (`Group D`), no project has specifically intended to use indirect payments. Nevertheless, all models that can be sorted into the `Groups C & E` can also be extended to models that fit in the `Groups D & F` by simply introducing indirect payment. However, some government methods—such as tax reliefs, state-issued vouchers, and benefits such as free parking—belong exclusively to `Group D` as those cannot be replicated by private entities.

5. Indirect Compensation Mechanisms

In this paper, we want to investigate possible negative impacts resulting from system integration in the domain of platooning, where we focus on integrating a platoon with other traffic participants. Therefore, we propose different approaches that do not require a direct compensation mechanism for transferring compensation between participants (category A in the taxonomy). Further, we evaluate whether they influence the other system elements, i.e., in the use case of platooning this relates to traffic participants that are not part of a platoon. In the following, we first name assumptions required for implementing and simulating these methods before presenting different kinds of rotation methods for platoons[1] that are based on *Round Robin Scheduling* and the *Belgian Tourniquet*. We provide abstract illustrations for all methods and numbered the participating vehicles in ascending order at the time they travel in the platoon without rotating, i.e., prior to starting the rotation.

5.1. Assumptions

The use case for the mechanisms pictures a road with at least two lanes and one-way traffic flow. On the road, only one platoon and non-platooning traffic are simulated. Even when more than two lanes are given, the mechanisms only occupy the right lane and the lane left to it at times. The latter will be referred to as the left lane even though there could be additional lanes left of it. On top of these general conditions, the following simplifying assumptions are made to keep the complexity within reasonable bounds:

Firstly, all non-platooning cars drive faster than the platoon and no overtaking of traffic cars is considered. Secondly, we assume that all vehicles inside the platoon have the same vehicle type. Otherwise, differing acceleration or braking performances would lead to delays or make adaptations of the inter-vehicle spacing inevitable. Thirdly, we dismiss all kinds of limitations stemming from currently prevailing legal norms. Not only is the concept of platooning not yet legally enforceable in most jurisdictions given the low inter-vehicle spacing required for it, but also overtaking on the right lane as utilized by some strategies is forbidden in countries such as Germany. Lastly, the vehicle to vehicle communication is assumed to work flawlessly.

5.2. Round Robin Scheduling

The following mechanisms are inspired by the CPU scheduling mechanism Round Robin where processes receive time slices in circular order.

[1] In this paper, we describe the methods in a textual representation. A formal definition using sequence diagrams can be found in [29].

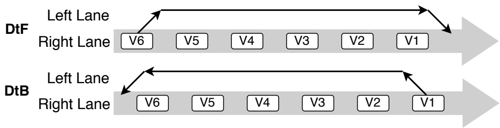

Figure 3: Drafting to Front (top) and to Back (below).

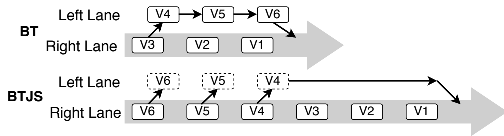

Figure 4: Belgian Tourniquet (top) and Belgian Tourniquet with Jump-start (below).

5.2.1. Drafting a Single Vehicle to the Front (DtF)

In this method, one of the following vehicles, for instance, the last vehicle (V6) of the platoon, overtakes the platoon and takes over the lead (see Figure 3). Therefore, it will temporarily leave the platoon and switch lanes once it is safe to do so. After the lateral movement is completed, the car starts overtaking and increases its desired speed. When the overtaking car is in front of the platoon, it decelerates again. Once the leader (V1) has been passed by a safe margin, the overtaking car (V6) switches back to the right lane. Finally, the overtaking car (V6) establishes itself as the new leading vehicle. With this maneuver, it is possible to either always rotate the last vehicle to the front or select a specific vehicle to become the new leader if there is a compensation model that tracks leading time over multiple platoons. The strengths of this method lay in a low disturbance of other traffic vehicles, as overtaking is performed rather quickly.

5.2.2. Drafting a Single Vehicle to the Back (DtB)

In this method, depicted in Figure 3, the leading vehicle (V1) will leave the platoon, switch lanes and then let the platoon pass before queueing up behind it as the new tail of the platoon. First, the second car (V2) in the platoon is assigned the lead role. Then, the previously leading car (V1) switches to the left lane as soon as safely feasible. Once it has completed the lane switch, it will start to fall back by reducing the desired speed. After the overtaking car (V1) has fallen behind half of the platoon, it picks up pace again to rejoin the platoon with similar speed to the rest of the platooning vehicles. This prevents the creation of a large gap at the end of the platoon. When the drafted back vehicle has the right distance behind the tail of the platoon (V6), it switches back to the right. Beneficially the singled out vehicle (V1) will not have to use more fuel by increasing its speed and overtaking; instead, it can coast until the platoon has passed. However, we expect that the utilization of a slowing car on the left lane will force traffic vehicles to brake or take evasive actions more often.

5.3. Belgian Tourniquet

The Belgian Tourniquet, mostly known from bicycle racing or motorcycle racing, inspired the following mechanisms.

5.3.1. Belgian Tourniquet (BT)

This technique originates from professional cycling, where usage of the slipstream effect is essential to save energy. The platoon is separated into two groups across two lanes and a constant rotation takes place. The method is similar to DtF; however, the next vehicle starting an overtake is always the last one of the original platoon, that is V3 in Figure 4. It starts the overtake right when there is enough space on the next lane, i.e., it does not wait until the currently overtaking vehicle (V6) is set as the new leader. The leader of the overtaking platoon (V6) is meant to overshoot the leader of the overtaken platoon (V1) and reduces its speed after it has rejoined the right lane. As soon as the switch to the right lane is finished, this car (V6) becomes the new leader as long as no other car switched to the right lane in front of it. This behavior is favorable for this approach because the following cars on the overtaking lane would be forced to brake and accelerate once again otherwise. Here, the cars on both lanes make use of platooning and because of the constant rotation, the benefits are approximately equally distributed at all times. Though, one possible drawback of this method is the starting sequence. As the initial situation includes a platoon driving on the right lane, the overtaking platoon needs to be formed from scratch. First, the last vehicle (V6) starts its overtaking maneuver before the next vehicles follow (V5) and (V4). We address this issue in the next section.

5.3.2. Belgian Tourniquet Jump-start (BTJS)

Since it takes a while to get the continuous rotation of the BT properly running, we also consider an alteration of it with a different starting procedure. In this instance, the trailing half, that is vehicles (V4) to (V6) of the platoon, switches lane synchronously once enough space is available to jump-start the rotation. Afterward, the performed actions are the same as in the normal version of the BT as long as the flow is not interrupted. If traffic interferes such that no overtaking car remains, the rotation restarts with the same multi-car switch strategy. This alternative option should allow for an accelerated start to the platooning on the faster lane since the platoon is instantly split in half with the vehicles switching lanes already having a short gap to each other. Consequently, it should also lead to more overtaking maneuvers being performed in higher traffic densities as interruptions of the procedure will not be as costly given the rotation's faster restart. On the downside, it can not be guaranteed that the benefits are always distributed equally anymore because the timing of perturbing traffic determines when the strategy switches from the last vehicle of the platoon starting the overtake to a full restart with multiple vehicles. In the second scenario, the vehicle at the back of the original platoon (e.g., (V6)) only takes the leading position after the vehicles in front of it, switching lane at the same time (e.g., (V4) and (V5)) have done so, even though those have already led.

5.3.3. Reversed Belgian Tourniquet (RBT)

Akin to the distinction made between the methods DtF and DtB, we also propose a reversed version of the BT, depicted in Figure 5. Instead of the last vehicle of the platoon being the next to start an overtake, the leading vehicle (V1) is the next to switch lanes and fall back once enough space is provided. Now, the second car in the platoon (V2) is the leader as long as it drives on this lane. If this car starts its fall back procedure and switches to the left lane, the leader role is assigned to the next car in the platoon (V3). From there on, the rotation continues as the new leader of the original platoon (V3) will also follow suit once safely possible and so on. We hope this results in a more energy-efficient procedure since acceleration actions will only be performed while driving in the slipstream of a car in front. However, this also makes the implementation a bit more complicated. A vehicle falling back will have to pick up the pace again once it is getting close to the end of the platoon in order to adapt speed and assure the maintenance of a close gap after rejoining the platoon. For this process not to impact the smooth flow, it is critical to pick the speed and the gap distance for the vehicles dropping back carefully. After all, it is a lot easier to maintain safe distances by braking of trailing vehicles rather than acceleration of preceding ones, as braking is more instant. However, suppose additional braking maneuvers have to be performed by a vehicle falling back. This vehicle cannot adapt its speed accordingly before reentering the platoon lane. Therefore, it will create a bigger gap at the end of the platoon that will also further complicate the rejoining of subsequent vehicles.

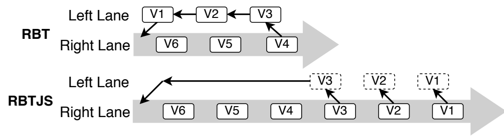

Figure 5: Reversed Belgian Tourniquet (top) and Belgian Tourniquet with Jump-start (below).

5.3.4. Reversed Belgian Tourniquet Jump-start (RBTJS)

Similar to BTJS, we also examine an alternative version to the RBT, jump-started by the preceding half of the platoon, that is vehicles (V1) to (V3), switching lane simultaneously. The switched vehicles will first take a short time to increase their inter-vehicle gaps before starting the usual procedure of the RBT. If the rotation is blocked by non-platooning traffic, and no platooning car is overtaking, the jump-start procedure re-starts.

6. Evaluation

The objective of the evaluation of this paper is a comparison of compensation mechanisms for the negative effects of system integration in settings with autonomous system elements. Hence, in the following, we study the effects of the proposed compensation mechanisms in the domain of platooning. Besides the fairness of the compensation, another essential factor is the interplay with system elements that do not participate in the system integration, i.e., that are not part of a platoon. Therefore, we implement our mechanisms using the platooning simulator Plexe [30]. In the following, we describe the metrics for the evaluation, followed by the methodology and the results of the simulations.

6.1. Evaluation Metrics and Objectives

The goal of our experiments is to show whether our mechanisms distribute the negative effects of the system integration equally among all participants of the subsystem, which is the platoon. At the same time, we evaluate whether the mechanisms have negative effects on the surrounding system by disturbing non-platooning traffic. We identified multiple metrics that can be determined using Plexe and match our requirements:

6.1.1. Fairness

Given that this work focuses on finding a solution to fairly distribute platooning benefits over all involved vehicles, the aspect of fairness is a crucial objective. Similar to Rescher, we see fairness as "dividing goods or bads on the basis of general principles that pertain to everyone alike" [23, p.13]. As the goods and bads in this platooning domain depend on slipstream effects, wind and/or vehicle model, and all these impact factors cannot be simulated within one simulation, we focus on the intra-platoon position each vehicle takes during the trip. Hence, we track the time driven at a certain position inside the platoon relative to the time overall spent in the platoon, for all cars belonging to a platoon. Ideally, to distribute goods and bads equally over the platoon members, every vehicle should have spent an equal amount of time in the leading and tail position respectively.

6.1.2. Traffic Throughput

This evaluation metric measures the average travel speed of the platooning cars and non-platooning cars, as well as the number of cars that pass predefined road indicators. The results on this metric will show how much the use of those mechanisms disturbs the enclosing traffic and vice versa. The higher the average speeds and the number of cars throughput are, the better the mechanism performs in this regard.

6.1.3. Time Loss

In this metric, the influence of our mechanisms on the time wasted or saved is investigated. The travel time of each vehicle is measured and compared to the respective expected travel time to identify the time lost or gained. The lost time of a vehicle is caused by driving below the desired speed and therefore requiring more time to reach the destination. This metric is calculated to represent the percentage deviation from the expected travel time.

6.2. Evaluation Methodology

The following section summarizes the methodology of our evaluation and introduces the platooning simulator and used scenario. Further, we describe the parameter settings and a baseline mechanism for comparison.

6.2.1. Platooning Simulator

For the implementation of the different driving maneuvers, we use a Python API of Plexe, a tool developed by Segata et al. [30]. Plexe is a modification of Veins [31], a vehicle simulation framework combining a realistic simulation of wireless communication using OMNeT++ [32] with realistic vehicle physics simulation based on SUMO [33]. Plexe further adds functionality to enable platooning by providing additional driving models that disable security distances and special vehicle controllers for adaptive cruise control and cooperative adaptive cruise control [34]. The specific API we use discards the aspect of network communication simulation, as this is not the focus of this work and including it would needlessly increase complexity.

6.2.2. Simulation Scenario

All simulation runs are conducted under the following scenario: The used road is a ten kilometer long straight line with no junctions or other inferences. All simulated cars are already up to speed, inserted at the beginning of the straight and travel until the end of the road. In line with current research on platooning, the non-platooning traffic vehicles, if present, each share the same vehicle characteristics with the platooning cars. As we do not evaluate engine and model-related data such as fuel savings and slipstream effects, this assumption does not limit the significance of our results. The platoon is placed into the simulation before any traffic has been inserted and drives until the road's end. Starting at five seconds, the traffic vehicles are entered for four minutes with a given time interval between each car, depending on the desired traffic flow. The traffic behavior is configured to use the Krauss [35] car-following model. The preferred velocity of a vehicle can deviate around the speed limit by ten percent of the restriction. Meaning that if a speed limit of 130 km/h is set, the traffic vehicles have desired velocities ranging from 117 km/h to 143 km/h. If no explicit restriction is given, the cars fluctuate around an average velocity of 150 km/h with 105 km/h being the minimum and 180 km/h being the maximum possible velocity. Therefore, the unrestricted setting not only induces a higher average speed but also a more heterogeneous choice of speed for each vehicle. Furthermore, the traffic vehicles are instructed not to change lane cooperatively, i.e., vehicles do not switch lanes just to create space for another car signaling a lane change. While this setting is not realistic, it provides better comparability across our tests as differing implementations of lane changing behavior had to be utilized to coordinate a safe procedure for the multi-car switching strategies. The simulation terminates when all cars arrive at their destination.

6.2.3. Parameter Setting

In our experiments, we used the following parameters for all six compensation mechanisms plus one baseline method in every possible combination.

- traffic density (veh./h) = {500, 1000, 2000}
- platoon size = {4, 6, 8}
- speed restriction = {unrestricted, 130 km/h}

- platoon speed (km/h) = {80, 100, 120}
- number of lanes = {2, 3, 4}

The different traffic density represents different sizes of systems-of-systems, while the varying platoon sizes of four, six, and eight cars represent integrated subsystems of different sizes. The parameters speed restriction and the number of lanes represent an environmental parameter; in contrast, platoon speed is a system-related parameter. One simulation was run for a combination of all parameters and mechanisms that sums up to a total of 1512 simulation runs. For running the simulations, a Linux server was used[2]. When discussing aggregated evaluation results in the following sections, we always present a set of fixed parameters we want to compare. The other parameters are combined as explained and the measured values are aggregated over these simulations.

6.2.4. Baseline Mechanism

To help to put the obtained values into perspective, a baseline method that is tested along the six proposed fairness mechanisms is defined. In this baseline method, no intra-platoon position swaps are performed at all. Instead, the platoon persists of the same platoon leader, followed by the same platooning vehicles for the whole duration of the trip.

6.3. Evaluation Results

We already defined system integration in the context of platooning and proposed a taxonomy of compensation-centered incentives for platooning. To investigate the impact of integrating autonomous system elements into a system while compensating for this integration's negative effects, we introduced six mechanisms to compensate for the negative effects of intra-platoon positions. In the following, we analyze the effects of these mechanisms w.r.t. fairness. For this purpose, we evaluate the time spent in the relevant platoon positions such as the lead, in the middle, at the back or in transition. Afterward, we show that specific environmental characteristics require a certain mechanism to reduce the negative influences on the whole system. For doing so, we investigate the average traffic velocity and the time loss induced by each mechanism for each parameter configuration.

[2]Specification of the Linux server: HP ProLiant DL360 Gen9, Intel(R) Xeon(R) CPU E5-2640 v3 @ 2.60GHz, 8 cores, 32GB memory.

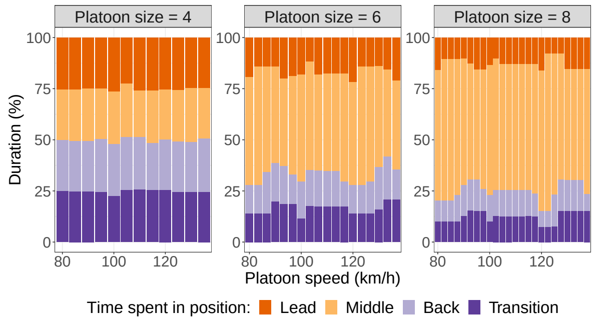

Figure 6: Time spent in different intra-platoon positions for each platooning vehicle with regards to different platoon sizes shown for DtF.

6.3.1. Fairness

First, we discuss the fairness of our proposed mechanisms, i.e., how well the compensation inside the integrated subsystem performs, by inspecting the time each platoon vehicle spends in the different intra-platoon positions. As we want to analyze the behavior of the isolated methods and do not want to measure the influence of the surrounding traffic, lane count, and speed limits have on our methods, we set these parameters accordingly: no traffic, three lanes, and no speed limit. Figures 6 and 7 depict the time spent in the according position inside the platoon for each vehicle in percent. The x-axes show the platoon speed and for each speed scenario, a vertical bar for each vehicle is depicted. The y-axes depict the duration in seconds. The colors represent the different positions inside the platoon, where orange depicts the time at the lead, yellow the time inside the platoon between the leader and back vehicle, that is presented in light blue, and the time spent for overtaking or falling back, i.e., during the transition, is depicted in dark blue.

Figure 6 compares the time spent in the different positions using the DtF mechanism for different platoon sizes, four vehicles on the left, six vehicles in the middle, and eight vehicles on the right. For all scenarios, it can be seen that all bars for each platoon speed and platoon size show similar color distributions, i.e., the time in the various intra-platoon positions is spread equally among all vehicles of the platoon. The small deviations between single vehicles inside a platoon can be explained by the timing the simulation has ended, as can be retraced due to the consistent ordering of bars. For example, for a platoon size of six and a velocity of 100 km/h, the vehicles reached the end of the road while the vehicle starting in the second position was overtaking or has only freshly taken over the lead. Thus, all vehicles have similar times in each intra-platoon position

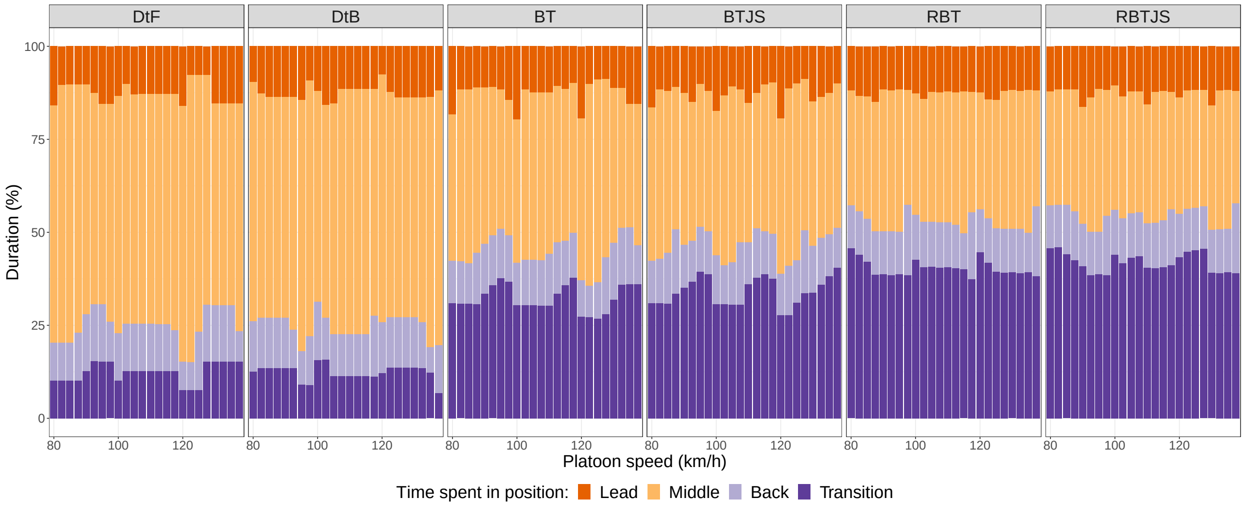

Figure 7: Time spent in different intra-platoon positions for each platooning vehicle shown for all methods and a platoon size of eight.

regardless of the initial position at platoon formation time. For a platoon size of four, it is also visible how the travel time of each vehicle splits into four equally sized portions representing the different positions. The reason for this is that a new overtaking maneuver is started when the previous ended. Therefore, one vehicle is situated in transition at all times. With increasing platoon sizes, this pattern is not present anymore because now multiple cars are positioned between the leader and tail of the platoon. Thus, the larger the platoon size, the longer the time in the favorable middle of the platoon.

Figure 7 shows the same kind of diagrams for all six mechanisms but a platoon size of eight only. We decided to show the results for a platoon of eight vehicles as the characteristic effects of the different intra-platoon positions become most visible there. When comparing the DtF and DtB, the figure shows that also in the DtF method, all eight bars for each platoon speed show nearly the same color distribution, i.e., all vehicles have similar times in each position regardless of the initial platoon formation. The pattern of this distribution is similar to the one for DtF and the cars are situated in the middle, i.e., the most favorable position, most of the time. The patterns of color distribution of the BT variants differ from the ones before, as the dark blue bars are significantly higher. This means that the cars spend more time in transition. As this lies in the nature of the BT, this shows that the desired effects occur and constant rotation is performed. However, when a vehicle is not in transition, it still drives most of the time in the middle of the platoon. Additionally, a notable difference can be seen for the first and the last four cars of the platoon, as the first car is the leader of the platoon for a longer time and the last vehicles have increasing time at the back and in transition. This can be explained by the characteristics of the BT as it requires some time to get the rotation going. This effect can be explained by the overtaking platoon that needs to be formed on the left lane from scratch at the beginning of the rotation. The jump-started version of this mechanism shows similar behavior. However, more vehicles have the effect of increasing time in the back and transition, as multiple cars switch to the left lane for overtaking at the same time in the beginning. In the reversed versions of the BT, the cars spend more time in transition than in all other mechanisms. Besides, the time in transition decreases with regards to the initial position in the platoon, so that the first car spends the most time in transition and the last car the least. This lies in the nature of these mechanisms as the fallback procedure requires more time for the fallback as we implemented the mechanisms to minimize the disturbance of other traffic. However, these mechanisms distribute the time as leader equally among all cars and no negative effects happen for the initial leader as in the other two BT versions. In summary, for the DtF and DtB mechanisms, the time spent in positions with negative effects is split equally among all vehicles and they drive in the middle of the platoon most of the time. The BT versions show negative effects for the initial leader and the cars drive more time in transition, while the reversed BT mechanisms do not show the negative effects for the initial leader but the cars spend the most time in transition.

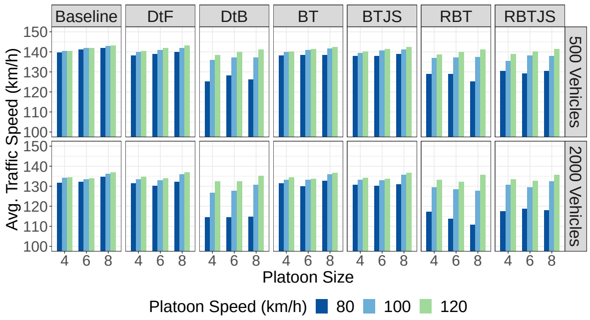

Figure 8: Traffic throughput of non-platooning traffic with two lanes for all indirect compensation mechanisms.

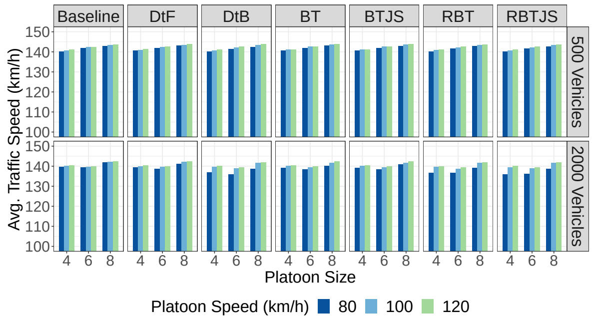

Figure 9: Traffic throughput of non-platooning traffic with three lanes for all indirect compensation mechanisms.

6.3.2. Traffic Disturbance

After we analyzed the fairness, that is the compensation of negative effects of the proposed indirect mechanisms, we now investigate the impact a platoon using these mechanisms has on the surrounding traffic.

Traffic Throughput. We first investigate the traffic throughput when using the mechanisms for a system with few resources, i.e., 500 vehicles, and a large resource amount of 2000 vehicles. We analyze the average traffic speed as a measure for the traffic throughput as this is not biased by the number of vehicles inserted into the simulation. The average traffic speed is aggregated over all non-platooning cars. In the simulation runs for all methods, no speed limit was set. Variable parameters of this evaluation are the resource amount, the platoon size, the platoon speed, and the number of lanes as depicted in the according figures. An increase in the average traffic indicates an increased traffic throughput as more vehicles can pass a certain section of the road. Furthermore, we compare the effects the mechanisms have with different environmental characteristics, namely two and three lanes depicted in Figures 8 and 9. The x-axes show the platoon size and the y-axes the average traffic speed aggregated for all non-platooning vehicles in km per hour. The plots are split vertically into the different mechanisms, and horizontally into 500 and 2000 vehicles, respectively. The different colors depict the different platoon velocity.

Figure 8 shows the average traffic speed for the scenario with two lanes. As can be seen for the baseline mechanism, i.e., a platoon without compensation, the average traffic speed for 500 vehicles is around 140 km/h and for 2000 vehicles around 130 km/h while slightly increasing with higher platoon speeds. When looking at the results for the DtF, it can be seen that the average traffic speed is nearly the same as for the baseline and the compensation mechanism has no impact on the surrounding traffic. In contrast, the DtB mechanism has a strong impact on the average traffic velocity, especially for the slowest platoon speed of 80 km/h. In this scenario, the average traffic velocity decreases significantly to 115km/h. For higher platoon speeds, the decrease is still present but not as clear as for the lowest platoon speed. This is due to the nature of this mechanism, as the fall back vehicle has to switch to the left lane (remember that this scenario only includes two lanes), decelerate and wait until the platoon overtakes on the right. During this procedure, the surrounding traffic has to brake and is blocked by the fall back vehicle. When looking at the BT and BTJS mechanisms, it becomes visible that the average traffic speed is not significantly reduced because of these mechanisms, neither in the 500 nor the 2000 vehicles scenario. The reversed mechanisms of the BT show similar behavior as the DtB mechanism, as the average traffic speed is reduced significantly. This becomes particularly clear for the scenario with eight platooning cars, a platoon speed of 80 km/h and 2000 vehicles. For the RBT mechanism, we can state that the more surrounding vehicles, the more vehicles in the platoon, and the lower the platoon speed, the stronger this effect. In the jump-started version of RBT, the number of vehicles inside a platoon seems to not influence the traffic speed. Still, the more vehicles in the surrounding and the slower the platoon drives, the stronger is the decrease in average traffic speed.

Figure 9 shows the results of the same scenario using three lanes. As can be seen, all bars show similar results for the 500 vehicles surrounding traffic. This shows that the negative influence of the drafting to back and reversed mechanisms can be reduced by increasing the lane count. This means that even the reversed mechanisms can be profitable under different environ-

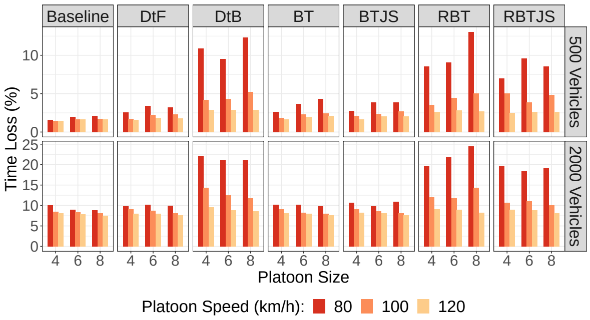

Figure 10: Time loss of non-platooning traffic with two lanes for all indirect compensation mechanisms in percent.

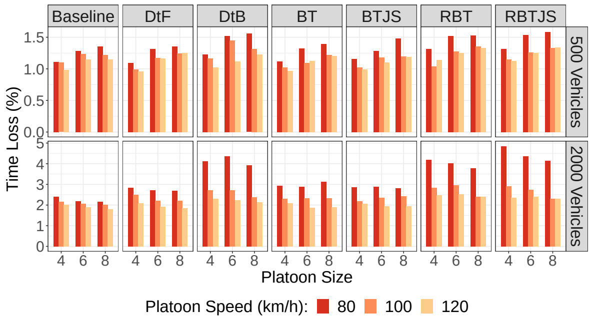

Figure 11: Time loss of non-platooning traffic with three lanes for all indirect compensation mechanisms in percent.

mental characteristics. However, for the scenario with 2000 vehicles, the negative effects can be seen but are not as strong as before. These insights also indicate the consequences when multiple backward rotating platoons drive on one road, namely that at least four lanes are required to ensure smooth traffic in such situations.

Time Loss. In the second part of evaluating traffic disturbance, we analyze the average time loss aggregated for all non-platooning vehicles induced by the compensation mechanisms. In the simulation runs for all methods, no speed limit was set. Variable parameters of this evaluation are the resource amount, the platoon size, the platoon speed, and the number of lanes. We again compare scenarios with 500 and 2000 vehicles, as well as two and three lanes depicted in Figure 10 and 11. The x-axes show the platoon sizes, the y-axes the time loss in percent, note that the y-axes limits differ from each other. The plots are split vertically into the different mechanisms and horizontally into 500 and 2000 vehicles, respectively. Different colors represent different platoon speeds in km per hour.

Figure 10 shows the results for all mechanisms in the scenario using two lanes. When looking at the baseline, where no compensation mechanism is used, the time lost in a surrounding with 500 vehicles is between one and three percent, and in a surrounding with 2000 vehicles, the time loss is between seven and ten percent. This is due to the increased traffic and required overtake maneuvers as the platoon drives slower than most of the vehicles. One trend that can be seen is the decreasing time loss with increasing platoon speed. As the platoon drives faster, fewer cars need to overtake to drive with their desired speed. For different platoon sizes, no significant distinction can be seen. When comparing the DtF mechanism to the baseline, a slight increase in time loss can be seen for the 500 vehicles scenario. However, in the surrounding with 2000 vehicles, no increase becomes visible. Here, high traffic has a stronger impact on time loss than the compensation mechanism. A clearly differing pattern can be seen for the DtB mechanism, where the time loss increases to more than nine percent for every platoon size and a platoon speed of 80 km/h in the 500 vehicles surrounding, and to more than 20 percent with 2000 vehicles. This can be explained by the slower vehicle on the left lane that decelerates to fall back behind the platoon. This forces the following vehicles to brake and, therefore, is inducing significant delays. The higher platoon speeds as well induce higher time loss but not as strong as with the slowest platoon speed. The mechanisms based on the BT show similar behavior as the DtF with slightly increased time loss and a decreasing trend with higher platoon speed. The jump-started version seems to have little to no impact on the time lost. Similar to DtB, the reversed mechanisms of the BT show a significant increase in time loss compared to the forward mechanisms, especially for a platoon speed of 80 km/h. Besides, the RBT shows that the larger a platoon, the higher the time loss for the surrounding traffic for the slowest platoon speed. The jump-started version seems to reduce this effect, i.e., this might be due to the starting maneuver until the rotation mechanism is running.

Comparing these results to Figure 11 depicting the scenarios using three lanes, it becomes visible, that the time loss is more evenly distributed among all mechanisms. Note, that the y-axes are now limited to 1.5 and 5 percent for 500 vehicles and 2000 vehicles, respectively. When comparing the mechanisms to the baseline for the scenario with 500 vehicles, the time loss lies in the same range of values of around 1.0 to 1.5 percent. Additionally, with increasing platoon speed, the induced time loss slightly decreases. In the scenario with 2000 vehicles, a similar pattern as with two lanes can be seen and the reversed methods induce a significantly higher percentage time loss of around four to five percent in comparison to two and three percent for baseline and forward mechanisms, especially for the slowest platoon speed. The results for higher platoon speeds are comparable for all mechanisms. This shows us that some mechanisms only work when at least one additional lane is present that allows non-platooning vehicles to overtake the platoon. However, in scenarios with a high traffic amount, the same patterns as for two lanes can be detected. Additionally, the scenario with 500 vehicles indicates that larger platoons have more impact on time loss than smaller ones. In contrast, when simulating 2000 vehicles, a larger number of platooning vehicles seem to reduce the time loss. This effect can be seen mostly for the Baseline, DtF, and RBTJS mechanisms. An explanation for this effect could be that the more vehicles are present and the larger the platoon size, the clearer the platooning induced advantages become visible. The advantage relevant for this effect is that platooning-vehicles drive with a smaller inter-vehicle gap than regular vehicles and require less space on the road and therefore, there is more space for non-platooning vehicles.

7. Discussion

In this section, we first discuss the results of our case study in which we analyzed the fairness of our proposed methods for compensation-based incentivation of system integration. Second, we mention threats to validity for our results. Lastly, we derive from our case study challenges relevant for the SISSY community.

7.1. Case Study Evaluation Results

In our case study, we analyzed the suitability of our proposed mechanisms for compensation-centered incentivation for platooning of autonomous vehicles w.r.t. (i) the fairness of the mechanisms and (ii) the impact on the traffic throughput and travel time. Table 1 summarizes all results of our evaluation. In the following, we discuss them in detail.

With respect to the fairness of the compensation, we found that all methods distribute negative effects equally among all vehicles of a platoon, whereat the initial leader has slight negative effects in the BT and BTJS methods. Additionally, we found that with increasing platoon size, the time spent in the most favorable position, that is the middle of the platoon, increases for the DtF and DtB methods. In contrast, the methods based on the Belgian Tourniquet as used in professional cycling (BT and BTJS) show negative effects for the initial leader and the cars drive more time in transition, while the reversed Belgian Tourniquet mechanisms (RBT and RBTJS) do not show the negative effects for the initial leader but the cars spend the most time in transition.

Additionally, we studied the influences of the compensation mechanisms on the system performance w.r.t. traffic throughput and lost time. We found that the characteristics of the environment (number of lanes, platoon velocity, traffic density) are related to the impacts resulting from the compensation mechanisms. The throughput of the traffic decreases for the back and reversed mechanisms in scenarios with two lanes. The effects vary with the number of vehicles: a larger number of vehicles lead to decreased velocities; a slower platoon velocity decreases the average traffic speed more. The front and BT mechanisms have only slight impacts on traffic throughput. In scenarios with three lanes, the negative effects on the traffic throughput of reversed methods are diminished. Concerning the loss of travel time, the reversed mechanisms induce significantly increased time loss for two lanes. Further, increased velocity of the platoon leads to decreased loss of travel time whereas an increase in the number of vehicles increases the time loss. In scenarios with three lanes, reversed methods work well for low traffic volumes but block other traffic for high traffic volumes.

7.2. Challenges

In Section 4, we present a generic applicable taxonomy for compensation-centered incentivation for system integration of autonomous system elements. Additionally, we proposed specific mechanisms for indirect compensation of negative impacts in platooning (an example for the typical SISSY domain vehicular traffic [4]) which we analyzed in a case study (see Section 6). Whereas the mechanisms are optimized for platooning, the taxonomy can be applied in several other use cases, such as the examples like high-performance computing, power management systems, and socio-technical systems in [4]. Based on the discussion of the results of our case study (see Section 7.1), we formulate in this section several challenges for improving the transferability of the taxonomy across several domains. Solving those challenges can help researchers within the SISSY domain to apply a compensation-centered incentivation for system integration, hence, to solve one of the most significant issues for SISSY systems [2, 3]. In the following, we elaborate on those challenges and integrate them into existing research in the SISSY and

Table 1: Summary of evaluation results regarding fairness, traffic throughput, and time loss. Results of traffic throughput and time loss are compared to the Baseline method.

<table>
<tr><th>Method</th><th>Fairness (Figures 6 and 7)</th><th>Traffic Throughput (Figures 8 and 9)</th><th>Time Loss (Figures 10 and 11)</th></tr>
<tr><td>DtF</td><td rowspan="2">- Negative effects split equally among all vehicles
- Time in favorable positions increase with platoon size</td><td>- Slight impact on traffic speed</td><td>- Slight increase for two lanes</td></tr>
<tr><td>DtB</td><td>- Slight decrease of traffic speed for two lanes
- Low impact on traffic speed for three lanes</td><td>- Significant increase for two and three lanes with low traffic
- High traffic intensifies this effect</td></tr>
<tr><td>BT</td><td rowspan="2">- Negative effects for initial leader
- More time in transition compared to DtF and DtB</td><td rowspan="2">- Slight impact of traffic speed</td><td rowspan="2">- Slight impact on time loss</td></tr>
<tr><td>BTJS</td></tr>
<tr><td>RBT</td><td rowspan="2">- No negative effects for initial leader compared to BT and BTJS
- Most time in transition compared to all other mechanisms</td><td rowspan="2">- Decreased speed for two lanes
- Low impact on traffic speed for three lanes</td><td>- Strong increase for two and three lanes</td></tr>
<tr><td>RBTJS</td><td>- Slight increase for two lanes
- Less increased time loss compared to RBT with two lanes</td></tr>
<tr><td>All</td><td>- All methods distribute negative effects among all vehicles in a platoon</td><td>- Higher traffic decreases traffic speed</td><td>- Increased platoon speed decreases time loss
- Higher traffic increases time</td></tr>
</table>

SASO[3] communities.

7.2.1. Generic Applicable Mechanisms for Compensation

We provide in this paper a generic taxonomy for compensation-centered incentivization based on implementation instance, compensation, and payment model. However, the compensation methods are use case specific. As one contribution, we proposed and analyzed specific mechanisms for the use case of platooning. The challenge is to identify generic mechanisms that can be easily customized for further use cases, e.g., SISSY related domains as high-performance computing, power management systems, or socio-technical systems [4]. Further, in this paper, we focused on indirect compensation. A generic applicable approach also has to include direct compensation mechanisms. Whereas for the platooning use case, this can be monetary compensation, this might be hardly feasible for other use cases with mainly machine-to-machine interaction or interaction between software agents.

This requires an abstract description of the compensation mechanisms, e.g., in the form of a modeling syntax. Such a syntax enables to exchange the specific mechanisms for the relevant, specific groups of compensation. Further, a mapping of specific factors to mechanisms, comparable to the design space for self-adaptive systems from [36], can help to decide between several mechanisms. However, the gap between design and runtime of SISSY systems [4] as well as the effects resulting from emergence, complicate the integration of the compensation mechanisms; hence, this requires exchangeability at runtime of those mechanisms.

7.2.2. Generic Metrics for Fairness

The most important reason for compensation is to provide fairness. In platooning, we define fairness as equally distributing the negative impacts among the system elements, i.e., among the vehicles of the platoons while reducing negative impacts on the surrounding traffic. In our study, we focus on platoon-specific metrics for measuring fairness.

[3]With SASO, we refer to research in self-adaptive and self-organizing systems.

The challenges are to abstract from such use case specific metrics to generic applicable metrics for measuring the fairness and combine those with use case specific measurements in a comparable approach. Additionally, the concept of fairness might be different depending on the use case. For example, in volunteer computing (a class of high-performance computing), fairness might not necessarily be defined as equally contributing resources but as enabling a fair sharing of the resources of one specific system between the local applications. Accordingly, a thorough analysis of what should be compensated is required for each use case.

7.2.3. Modeling of Environmental Factors

Self-integrating systems are adaptive and act in dynamic environments. Our study reveals that the environment of the system influences the impact of the compensation mechanisms on system performance. As one example for smart grid systems, depending on the daylight, weather forecasts, utilization of the power grid, etc. it might be necessary to adjust the compensation for feeding the grid with energy or even to punish it (and hence compensate the storing of energy).

Accordingly, the choice of compensation mechanisms should be context-aware [37]. In Pervasive Computing, the context is defined as "information that can be used to characterize the situation of an entity" [38, p. 5]. Researchers in the SASO domain often distinguishes context-awareness—the operational environment of the system—from self-awareness, i.e., information of the system resources [9]).

Addressing those issues raises several challenges. First, it is important to understand the actual context of the system. The gap between design and runtime can again complicate this. Second, context-awareness introduces monitoring efforts. This involves the need to model the context for representing the required information. Lastly, the reasoning or identification of a suitable compensation mechanism for a specific context comes with a higher complexity. This is related to the first challenge, as the modeling procedure must be compatible with the modeling of the context.

7.2.4. Dynamic Choice of Incentive Model

Resulting from our observations, different incentive models and different compensation mechanisms comply with different system and environment situations as well as different global system objectives. Hence, this should be integrated into the reasoning mechanism, which is part of the adaptation process of resources and determines the process of system integration.

Accordingly, we propose to integrate meta-adaptation of this reasoning approach to change the incentive model and the compensation based on the current system decision or environmental parameters. This is in line with other works from the self-adaptive systems community, which proposed meta-adaptation for the planning functionality based on optimization functions [39], the MAPE-K functionality [40] or the structure of the adaptation logic [41] (please refer to [42] for an overview on such approaches).

Such an approach requires a generic concept for integrating the incentive model into the reasoning process for system integration to enable its exchangeability. The meta-adaptation can also support the self-improvement of system integration.

7.2.5. Multiple Incentive Schemes

A platoon is composed of several autonomous vehicles with potentially differing or even conflicting objectives. Accordingly, it might be necessary to not only integrate a situation-aware, dynamic choice of the incentivation scheme but also to provide a multi-scheme incentive approach that integrates different incentive schemes for confirming the objectives of different actors.

This introduces additional challenges, comparable to Pareto optimal solution sets for multi-objective optimization. Solving such situations require additional knowledge for deciding on how to combine the incentivation schemes.

7.3. Threats to Validity

We have identified the following threats to validity of the evaluation results. First, we focus on the specific domain of platooning. To counter that issue, we rely on a generic applicable taxonomy on compensation-centered incentives. Further, we derived challenges and discussed them in the broader context of SISSY related research. However, we have to prove the transferability of our approaches to other use cases.

Second, the proposed compensation mechanisms are specific to platooning. However, as all methods are based on generic concepts from scheduling and cycling sports, we assume that those are transferable with some customization. Still, we are required to integrate a modeling approach to generically model the system and the compensation mechanisms for supporting the transferability across systems.

Third, we measure fairness w.r.t. the time in a leading position within a platoon. Interesting further measurements would be the fuel consumption or acceleration/deceleration activities. Unfortunately, our setup with the SUMO traffic simulation did not provide reliable results for fuel consumption and CO2 emissions. We detected inconsistencies in these measurements where the baseline achieved worse results than any of the proposed mechanisms. In a detailed investigation of the root causes, we found that the inconsistencies stem from calculation flaws in SUMO as the fuel consumption and CO2 emission values are set to 0 ml/s and 0 mg/s per default whenever a vehicle decelerates. Therefore, we omitted these measurements and did not report the results. An adaptation of the calculation regarding these values could help to provide meaningful measurements in the future.

Fourth, we investigated our mechanisms using only one type of vehicles. Having heterogeneous platoons composed of vehicles with individually different characteristics—like different acceleration/brake coefficients, size, weight, or drag coefficients—establish additional constraints. The same applies for individual preferences of drivers as well as heterogeneous goals, as often present in SISSY systems [2]. Integrating those perspectives requires more flexibility in the compensation mechanisms and is part of our future work.

Lastly, we acknowledge that the taxonomy could be changed or extended. In this paper, we present our taxonomy mainly motivated by considering ideas from research about social sciences [27] and organ donation [28]. The taxonomy supports researchers in the platooning area in designing their approaches by tackling one of the main issues: the unbalanced distribution of the advantages of platooning. Moreover, we discussed how to apply the taxonomy in other SISSY use cases; however, we miss a proof of concepts in those other domains so far. As this requires customization of the implementation actions of the taxonomy for the specific implementation for each application domain, this is part of our future work. The application in other SISSY systems can trigger a revision of the taxonomy for a better generalization of our claims. Still, we believe that in the current state, the taxonomy can provide guidelines for balancing the benefits in SISSY systems to support system designers and application developers.

8. Conclusion

Integrating autonomous resources into interacting systems can be challenging, especially in scenarios in which some participants might experience negative impacts due to the integration [2, 4]. In previous work [6], we categorize coordination mechanisms for this integration into (i) selfish behavior, (ii) altruistic behavior, (iii) negotiation, (iv) enforcement of central decision making, and (v) rewards/incentives. In this paper, we derived a taxonomy of compensation-centered incentive models. In a case study in the platooning domain, we analyzed the fairness of several compensation methods as well as the impact of the performance of system elements that are not integrated into different traffic situations using simulations. The evaluation of our proposed compensation mechanisms has shown that all mechanisms distribute negative effects—in the platooning case-study fewer benefits—equally among all vehicles in a platoon. However, depending on the scenario, the mechanisms might disturb other traffic participants. Further, we investigated that increasing surrounding traffic decreases the overall traffic speed as well as introduces additional time loss. Finally, an increased platoon speed can counter this effect by decreasing the time loss. Based on the study, we propose several challenges related to the applicability of the mechanisms for compensation, the definition of fairness metrics, integration of the environment, the dynamic choice of the incentive model, and how to integrate multiple incentive schemes simultaneously.

Currently, we performed a case study with a homogeneous set of vehicles. Introducing heterogeneous platoons composed of vehicles with individually different characteristics as well as individual preferences of drivers with heterogeneous goals will require more flexibility in the compensation mechanisms. This is part of our future work in the platooning scenario. As additional future work, we plan to apply our taxonomy in further use case domains to show its transferability. Using those experiences, we then formulate generic compensation-based approaches for integrating the aspect of incentivization into the reasoning process for system integration. This also results in a "toolset" of such mechanisms that can be used in several domains. We plan to complement this by an approach for modeling incentives and compensation.

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