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CONCEPTUAL FRAMEWORK FOR HEAVY-DUTY VEHICLE PLATOONING IN PHYSICAL INTERNET SYSTEMS

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Abstract: One of today's most significant challenges is sustainability, which is closely linked to environmentally friendly solutions and resource efficiency. As a solution to these goals, the concept of the Physical Internet emerged, defining the logistics network of the future as a global, open, and interconnected system. Concerning the conditions of vehicles based on Physical Internet-based systems, we cannot ignore the latest vehicle technology innovations that appear more and more intensively in parallel. The framework proposes planning at the strategic, tactical, and operational levels. Different levels of coordination implement different approaches to platoon coordination in line with the network architecture of PI-based logistics systems. We recommend the highest level of offline design in fixed π-hubs. The tactical level involves designing π-hubs online. We propose the implementation of speed-based solutions at the operational planning level.

1 Introduction

One of today's most significant challenges is sustainability, which is closely linked to environmentally friendly solutions and resource efficiency. As a solution to these goals, the concept of the Physical Internet (PI, π) emerged, defining the future logistics network as a global, open, and interconnected system. The most significant breakthrough comes from the new mindset that the operation of Physical Internet-based systems breaks with traditional storage, movement, and transportation solutions. The Digital Internet inspired methodological solutions based on new principles. The Physical Internet transfers the flexibility and standardization that comes from the Digital Internet to the physical world. The global vision requires functioning within a single cross-border system, the foundations, principles, and requirements that anyone can openly access [1]. By sharing resources, data, and designing centres for seamless interoperability, freight transport is optimized in cost, speed, efficiency, and sustainability. In order to achieve better logistics efficiency and sustainability, PI is evolving extraordinarily, found in all elements of technological innovation [2]. Given the growing number of PI publications and the growing global investment in PI-related projects, PI is becoming increasingly important in scientific and practical.

Concerning the conditions of vehicles in the Physical Internet systems, we cannot ignore the newer vehicle technology innovations that appear more and more intensively. Modularity and flexibility, which vehicles must also meet, will be central to the future logistics network. This article reviews the impact of autonomous-, electric-, shared-, connected-vehicles, and platooning concept on the PI system among the emerging automotive trends [3].

Based on our research, one of the promise innovation areas is platooning concept. The implementation of platoons in a natural environment is expected to get closer, so there is a growing need to define concepts for organizing platoons. There are several publications about platoon coordination. To our knowledge, this work is the first to provide a general framework for the coordination of platoons in a PI-based logistics network.

In this paper, following the introduction, we first review the impact of automotive trends on the Physical Internet, and then in Section 3 we summarize the relevant literature solutions for the coordination of platoons. Section 4 presents the conceptual framework, which is detailed in Section 5. In Section 6, we summarize the main findings of the article and also discuss future research plans.

2 Impact of automotive trends on the Physical Internet

In the history of humanity, we can say that vehicles have radically changed the earth's natural environment [4]. In recent years, the automotive industry has undergone significant transformations, which is perhaps the main reason for the rapid emergence and integration of innovative information and communications technology solutions in this area as well [5]. Physical Internet is also a paradigm shift in terms of transport, as according to the concept built on the Digital Internet metaphor, freight would be exchanged as seamlessly as data over the Internet. In examining the concept of the Physical Internet, it would be impossible to separate it from the automotive aspects of the system. By imagining an ideal system, vehicles as modular units of the PI-based logistics network operate energy-efficiently, are interconnected, and have maximum utilization while reducing noise pollution and environmental and air pollution [4].

In the automotive industry, various development guidelines can be defined entirely independently of the field of logistics, of which the most important trends for the Physical Internet will be reviewed in the following: autonomous vehicles, shared vehicles, electric vehicles, connected vehicles, and platooning systems. The increasing sharing of vehicles and the spread of emerging autonomous and electric vehicle technology can disturb the functioning of transport systems, especially when combined with platooning transport. Much of the recent research has focused on improving the quality of existing transport systems and services and designing new methodologies that offer a more sustainable ecological approach and address the challenges generated by growing demand. Cross-sectoral cooperation offers an excellent opportunity to improve the quality of transport services [6].

Autonomous vehicles, especially their partially automated versions, are increasing focus in industrial and research areas [7]. Automated technology is considered an innovation to introduce eco-driving and energy-saving features, more stringent safety and security standards in the future [4]. However, despite its current popularity, there are still several unanswered questions associated with it. Fully autonomous vehicles are of enormous importance for future logistics and are expected to transform the practices known for decades.

Research on **shared mobility** is one of the automotive trends [6]. The advent of the Physical Internet will allow shared transportation by creating a dynamic and flexible network. Companies can gain a competitive advantage by not only using access to their resources efficiently. Thus, in the Physical Internet, the idea of sharing is by no means an unknown or new concept. It can be said that the idea of sharing is part of the Physical Internet [3]. Sharing maximizes resource utilization.

Research into the use of **electric vehicles** is more common within the city due to shorter distance requirements [7]. In a Physical Internet-based network, the goal is for drivers to stay as close to home as possible, so they only need to travel short distances. With this goal in mind, electric vehicles can be considered a highly relevant area, as their benefits are well integrated into the planned open, global hub-and-spoke system [3].

Nowadays, the essential feature of a **connected vehicle** is that it can communicate via the Internet and thus interact with other intelligent objects, which may extend to other vehicles, traffic signs, or other infrastructure elements [4]. Modularity and flexibility, which vehicles must also meet, will be central to the future PI-based logistics network. Development guidelines for coupled vehicles are of paramount importance in PI-based logistics networks. The PI concept embodies the idea of a global interconnected network. The innovation of connected vehicles based on a similar theory is, therefore, a well-integrated system. In such a system, the entities within it (people, machines, and even infrastructural elements) can continuously communicate. The aim is to strive for a constant optimum while resolving a current situation. Figure 1 illustrates the connection system of interconnected vehicles in a network of Physical Internet π-hubs.

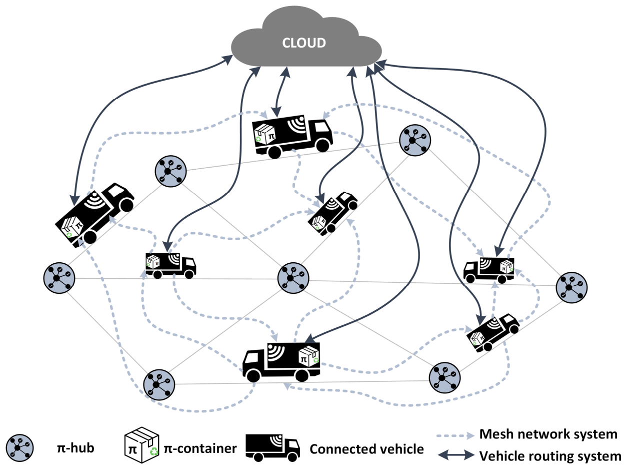

Figure 1 Cloud-based connection system of interconnected vehicles in a network of Physical Internet π-hubs based on [8]

Reducing extralogistics shipments, which has increased significantly over the past decade, has become key for environmental and economic reasons. According to studies, fuel costs account for about 30% of the life cycle costs of trucks [9]. Furthermore, a quarter of the significant 20% of CO2 emissions from vehicles can be attributed to trucks [10]. In general, 82% of roads are unoccupied due to traffic density, which is due, among other things, to compliance with the mandatory distance required by the rule [11]. A promising approach to reducing fuel consumption is to drive **vehicles in a platoon**, which is a kind of transition between autonomous and conventional transport. The essence of the technology is that the trucks move in close succession, in parallel with which they increase energy efficiency and reduce road occupancy [12]. The PI-based open, global logistics network creates the common platform needed to organize vehicles, even in cross-company collaboration.

Vehicles travelling between PI terminals can also communicate within specific scope through communication, resulting from which they can take into account each other's goals. Depending on the platoons' capacity (the number of vehicles in a platoon), it would even be possible to connect on the road. This would even admit dynamic and flexible modification of preliminary plans. By defining virtual transhipment points (virtual π-hubs) between fixed π-hubs, platoons can change their vehicles. This allows platoons to reconfigure their composition as they make their way. Recombination of platoons can further increase the flexibility of the system [13,14].

3 Literature review

The whole platoon problem consists of many different layers: global, regional, and local control. Figure 2 provides a general graphical overview of the characteristics and main properties of the layers. This figure illustrates the three main problem areas, which, although very different, are all necessary to take full advantage of the concept of teams. The local layer deals with the actual control of each vehicle. In the regional layer, we interpret the coordination of platoons by dynamic route planning or speed change. The top global layer deals with general scheduling and allocation tasks.

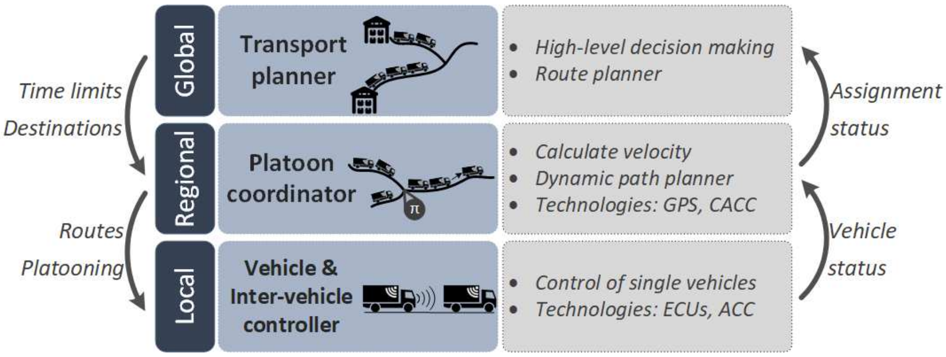

Figure 2 Layers of the control structure of platoons

There are several publications on platoon organization solutions, of which a summary table is in [15]. Among the related works presented in our article, our goal is to show the achieved results and methodologies through the diversity of solutions. It can be said that most publications deal with online organizations, and there are fewer offline operation algorithms. There are two groups of online solutions, which are hub-, and velocity-based approaches.

An example of a hub-based solution can be seen in C. Kammer publication [9], where the main idea behind the methodology is to divide the problem into several smaller sub-problems, as the original solutions have an unmanageably long runtime when handling a large number of cases. An example of the basis of their solution is shown in Figure 3, where a local controller (green dashed square) controls the arriving heavy-duty vehicles (HDVs). The local manager decides which truck to go to and where to catch another truck. There are different ways to set up a local controller problem [9].

In publication [16], the authors examined the problem of vehicles waiting at nodes in a transport network to travel with others on a platoon. They develop two models: one with deterministic and one with stochastic travel time. The simulation study showed that the uncertainty of travel times significantly impacted grouping speed and that clustering can bring notable benefits at the societal level, even if vehicles design to optimize their profits.

The other standard solution structure is to change the vehicles' speed to get close enough to each other to create a platoon. In publication [17], they present a coordinated model with multiple speed options that integrate scheduling, routing, speed selection, and section design/resolution. For problems with many vehicles, they propose a heuristic decomposition solution, in which the algorithm breaks the vehicles into a smaller set. They evaluate that if the set of the vehicle is large and the available computation time is small, the decomposed approach will find significantly better solutions [17]. In publication [18], they suggest allowing the following vehicle to drive faster to catch up with the leading vehicle. This approach can increase the frequency of creating platoons, as many HDVs do not have the exact origin and destination with the same time window. The algorithm provides the fuel recovery required to control catching up by defining a range. They define the scope derived from the route length, within which the methodology examines the connection to the platoon, as illustrated in Figure 4 [18].

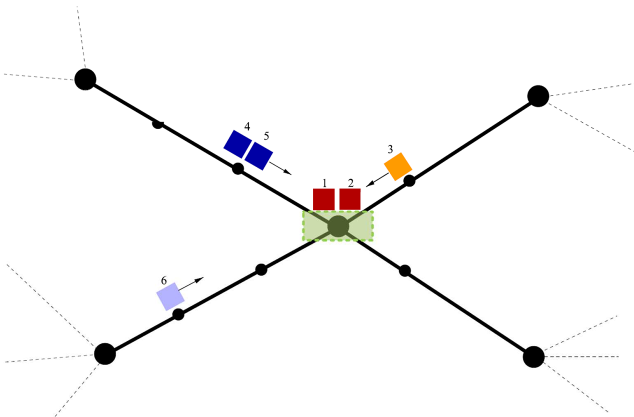

Figure 3 An example of HDVs driving towards a junction with a local controller node [9]

Figure 4 Cones (for illustrative purpose) of fuel-saving potentials if the HDV decides to catch up and form platoon [18]

Given the apparent complexity of platoon organization, it is not surprising that some artificial intelligence-based approaches have also emerged. The problem is very complex and has proven to be NP-difficult in different versions [11]. In publication [14], authors use a reinforcement learning methodology to facilitate collaboration between platoons. There is also a proposal for a local-, ant colony-based solution in the literature, where individual vehicles are independent and able to make decisions based on their speed and orientation [10].

Most publications approach the coordination of platoons with one type of solution, besides only a few papers setting up the framework for management. A framework presented in [15] consists of a platooning-enabled vehicle (operational level), a platoon manager (tactical level), a coordinator (strategic level), and a fleet management system and transport management system (service layer). The level of abstraction, geographical size, and time scale increase from bottom to top [15].

We can see several solutions for organizing platoons, which have in common that, due to the complexity of the task, they are looking for local solutions to achieve a globally sustainable system. Considering the presented solutions and the main features of the framework proposed in reference [15], a comprehensive, conceptual framework is presented in the next chapter, considering the structure of the Physical Internet-based logistics network.

4 The conceptual framework

In this chapter, we present the conceptual framework, which is detailed in Section 5. When defining the framework, we take the structure of the logistics network provided by the Physical Internet and provide a theoretical structure for the organization using the possibilities provided for the coordination of the platoons.

The Physical Internet logistics network consists of connected fixed and virtual π-hubs. For sustainability, defined as a goal in the future, the Physical Internet proposes hub-based operation to achieve a flexible and efficient operation. An essential consequence of hub-based operation is that transports by HDVs are interpreted exclusively between π-hubs. Thanks to the global cooperation available through the open and global logistics network, the sharing and interconnection of vehicles as resources can be achieved by applying the expected unified management system. The establishment of platoons contributes to resource-efficient operation, which can reduce fuel emissions and thus pollution. Virtual π-hubs that complement fixed π-hubs have no setup cost, no infrastructure, and can be interpreted dynamically on any node in the network. The Physical Internet system places particular emphasis on the alternative routing issue. Routes that exist in the world of the Digital Internet can be static or dynamic [8]. In the case of static routing, the nodes forward data through predefined nodes. Dynamic routing means that the nodes in the network are responsible for finding the best route. PI centers can be mapped as Digital Internet nodes (routers). These transit points do not necessarily have to be static. Virtual π-hubs can provide a possible design solution [8].

Platoon coordination options can be divided into two main groups: off-board and on-board. The former provides a statically defined load schedule from the platoons formed from vehicles starting from one place. There are no predefined platoons for the latter type but use real-time data to create new, unplanned platoons for a more sustainable system to operate. Based on the publications, we distinguish two main options for the on-board case: catching up with a truck or waiting for a truck [19]. In the former case, HDVs change their speed to get close enough to each other to form a platoon. In the latter case, the vehicles are waiting to form a platoon with oncoming vehicles. The advantage of this is that it is possible to form platoons more predictable and safer than the velocity-based case, where traffic disruptions can prevent the planned speed changes [20].

For the defined platoon organization solutions, we represent the road network as a directed graph $R = (i, \varepsilon)$ where i represents the nodes and $\varepsilon \in i \times i$ corresponds to the edges. The graph's nodes represent the intersections or endpoints of the road network, and the edges represent the road sections connecting these points. The function $L(e)$ maps the lengths of all edges ε. The location of the vehicles is determined by the pair $(e, x) \in \varepsilon \times [0, L(e)]$, where e is the current road section and x is the distance the vehicle has already travelled within the given segment. The set of vehicles is denoted by N, in which the index n illustrates the parameters for each vehicle. The graph representation is illustrated in Figure 5 [15].

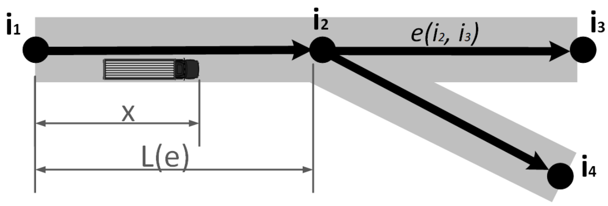

Figure 5 The road network represented as a directed graph [15]

The amount of weight assigned to the graph's edges represents the objective function. For each of the platoon coordination solutions, we want to achieve a minimum of the objective function, which is formulated as follows based on the [14] publication:

$$\min \mathrm{C}(\theta) = \mathrm{C_f}(\theta) + \mathrm{C_t}(\theta) + \mathrm{C_p}(\theta) \qquad (1)$$

where $\mathrm{C_f}(\theta)$represents the fuel cost, $\mathrm{C_t}(\theta)$ is the cost of the waiting, and $\mathrm{C_p}(\theta)$ represents the driver labour cost of the platoon leader and θ represents a set of decision variables. Taking into account the formulated coordination grouping and objective function, Figure 6 illustrates the framework for the coordination of platoons in the Physical Internet-based logistics network.

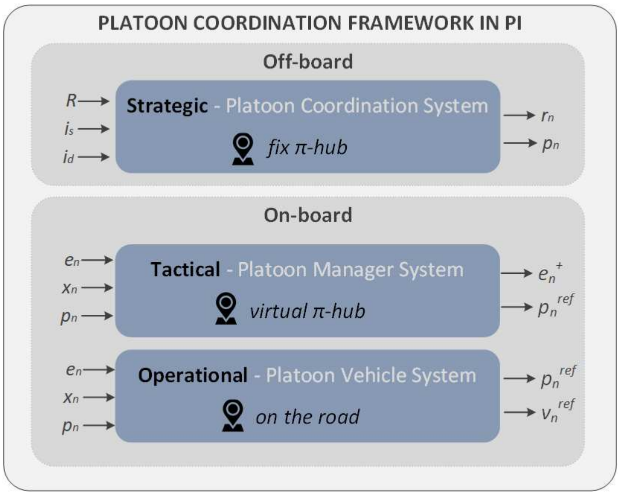

Figure 6 Platoon coordination framework in Physical Internet system

The framework divides the coordination of platoons into two main groups: off-board and on-board. In the case of off-board, we interpret the strategic-level planning performed by the Platoon Coordination System in fixed π-hubs. Graph R representing the network, and the starting stations i_s and end stations i_d belonging to the vehicles are the inputs for control. From these data, the system creates a static plan for the vehicles departing from the fixed π-hub. The solution consists of a p_n platoon plan and a r_n planned route $r_n \in R(i, \varepsilon)$. This planned route is an introductory guide to the vehicles with the expected arrival times, which can be modified later to minimize the target defined in the objective function.

This modify is conceivable by the on-board options defined in the framework. In the case of on-board, we distinguish two levels. On-board coordination requires a continuous, real-time data service provided by a cloud-based data service in the Physical Internet system. The information required for control comes from the connected vehicles in the system. If the vehicle does not have such a connection, the driver sitting in it can easily connect to the Internet on his personal mobile device. In this way, vehicles on the road play a role in decentralized, real-time decision-making. Based on the result of the paper [8], the most appropriate solution may be the information provided by the vehicles, as the vehicles already have a primary on-board computer. The data collected is beneficial to programmers if it is in one place where a cloud-based solution seems appropriate. This would create a virtual marketplace for PI users.

The length of the platoon defines how many vehicles connect in a group. If the platoon value is 1, the vehicle is moving independently. If the platoon value is greater than 1, then in the case of on-board coordination, the lead vehicle decides on the rest, taking into account the other vehicles' goals in the group.

The first on-board case is the tactical planning that the Platoon Manager System performs on virtual π-hubs. To do this, the Platoon Manager System uses vehicle information, which is the edge represented by $e_n$where the vehicle is travelling, the distance x_n travelled on the road section, and the platoon p_n that contains the vehicle. Based on the input information, a modified path segment (e_n^+) and the new platoon ID (p_n^{ref}) are determined if there is cooperation with another platoon in the virtual π-hub.

The other on-board option is a platoon merger on the road accessible by speed change by the Platoon Vehicle System at the operational level. Its input parameters are the same as those of the Platoon Manager System at the tactical planning level. On the other hand, its output is a modified speed (v_n^{ref}) due to the possibility of changing the speed, which is necessary to connect to the other platoon and the new platoon ID (p_n^{ref}). The strategic, tactical, and operational levels are described in more detail in the following section.

5 Discussion

5.1 Platoon coordination system

Fixed π-centres organize platoons solely by considering the vehicles arriving there. The goal is to create an optimal platoon design that considers the objective function defined in Equation (1). It means it deals with the amount of detour required by the platoon members, the waiting times, and the platoon lengths as well. The platoon lengths impact the driver labour cost because if the platoon is longer, then it needs fewer drivers.

The control panels detect approaching vehicles through the flow of cloud-based information, which allows vehicles that are not yet physically in the center but already have a predictable arrival time with less uncertainty to be considered in the design. Accordingly, as part of strategic-level planning, platoon plans are prepared in a time zone per shift or day. The information used as input to the system is the graph representing the road network and the vehicles' locations of departure and destination. The algorithm required for platoon coordination is a future research direction, which determines the maximum waiting time and the amount of detour in each vehicle, keeping in mind the objective function.

The benefit available depends on the platoon leader or follower status. In the case of a follower vehicle, we can expect savings of 5-15%, and in the case of a leader, it is not so recommended to calculate savings [11]. Building on cooperation and trust, PI's system creates an organization independent of the manufacturer and owner of the vehicles arriving at the center, which, according to the publication [20], can even double the benefits of the platooning concept. An example of a platoon organization between fixed π-hubs is illustrated in Figure 7 [21].

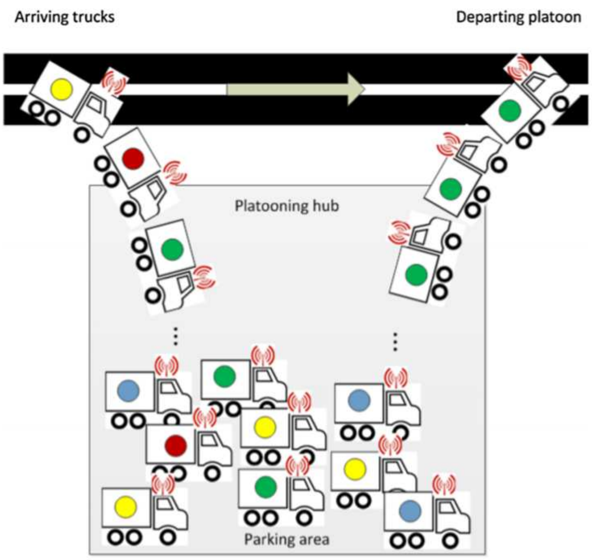

Figure 7 Fix π-hub based platoon coordination [21]

The independent operation of fixed π-centers, i.e., the absence of cooperation with other centers, is due mainly to the complexity of the task with a high degree of uncertainty induced by congestion, weather conditions, and other factors [11]. It has been investigated in several publications that the runtime of the constructed algorithm extends beyond the manageable extent, increasing the complexity of the task. Therefore, considering the results summarized based on publication [9], we propose local optimization to achieve the global goals in the operation of this framework.

5.2 Platoon manager system

In addition to the fixed π-hubs, the PI system consists of a system of virtual π-hubs, which can be defined, for example, at road junctions. This makes the logistics network a more flexible system, as it can increase the number of nodes, allowing for reorganization to reduce costs and achieve a more sustainable system.

Thus, virtual π-hubs provide an opportunity to connect platoons and reduce the detour by reconfiguring the vehicles [13,14]. In the case of virtual π-hubs, waiting is required for platoons to connect and reconfigure. With a continuous navigation system, the vehicles follow a constantly updated route plan. The basic algorithms used for route planning are time-consuming, so we propose the Dijkstra algorithm for this based on the publication [22]. Using the Dijkstra algorithm, we propose to design the dynamic route of the platoons. The objective function at the edges considers the cost reduction induced by the possibility of connection with the existence of the platoons on it. To this end, by [18], vehicles would consider other platoons within a predetermined radius only to avoid excessive waiting times.

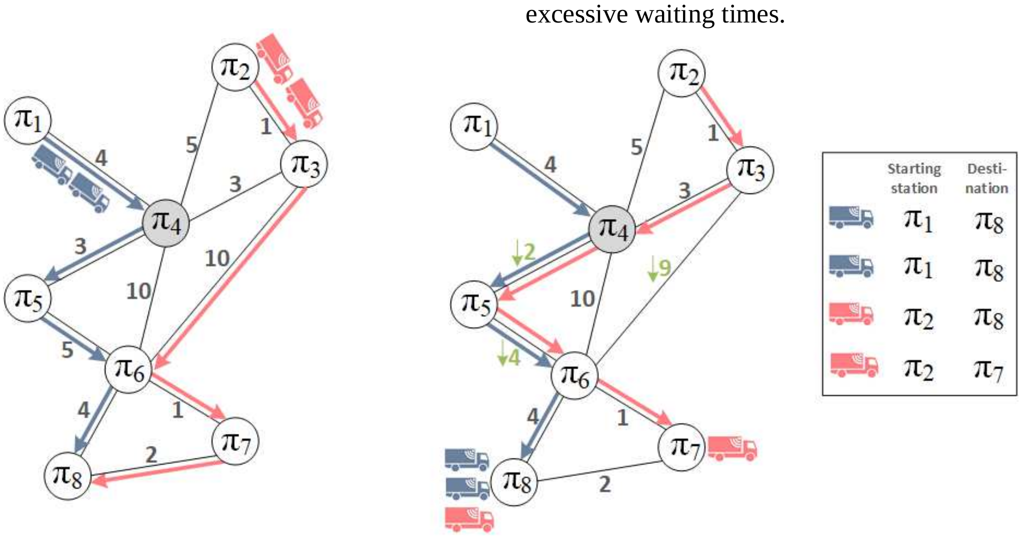

Figure 8 Platoon manager system at virtual π-hub using Dijkstra algorithm

Figure 8 shows an example using the Dijkstra algorithm. The figure's left is a separate strategic plan for the two platoons (blue and red) based on the Platoon Coordination System. The destination of the vehicles of the blue platoon is center π8, while the red platoon must also visit two destinations, which are nodes π7 and π8. The weights on the graph's edges on the right show the modified weights in green, which already considers that another platoon is moving on it. The value of the modified weights in the sample example decreased by 1 unit, indicating a decrease in the value of the objective function by the platoon merger. Modifications to the Platooning Manager System shown on the right relative to the Platooning Coordination System plan are as follows:

- the red platoon merges with the blue platoon in virtual π-hub π_4 and then continues on its blue route,
- in the π_4 virtual π-hub, the platoons are also reconfigured. One of the vehicles in the red platoon continues its route with the blue platoon (which has the same destination), so the red platoon does not have to continue its journey to π_7.

With this, the Platooning Manager System reduces the total cost per platoon and detours the configuration.

5.3 Platoon vehicle system

Online options for organizing platoons include connecting on the road accessible by changing the speed of vehicles. It can be seen in the previous chapter that in the case of virtual π-hubs, the vehicles only detect the platoons around them in a predetermined radius. As a result, they may not have been close to each other in the case of a virtual π-hub taken into account in tactical planning due to traffic uncertainties (weather, congestion) or other reasons, but they become close to each other along the way. The proposed platoon control framework will allow connection on the road by changing the speed of vehicles at the operational level.

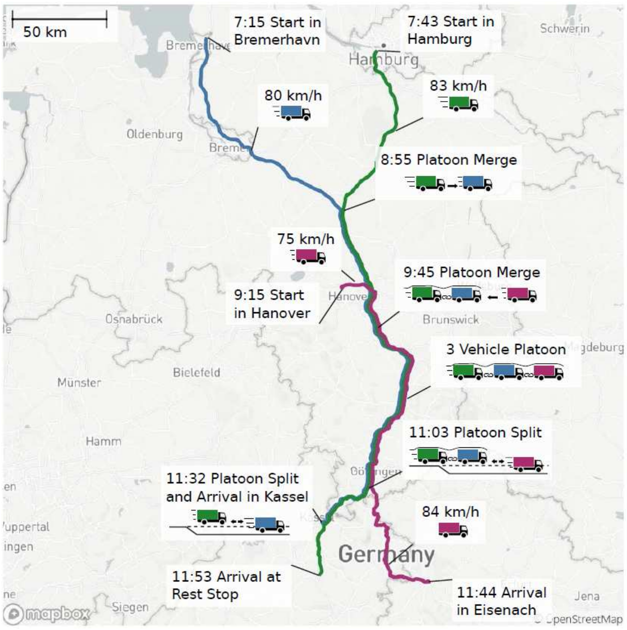

Figure 9 Three vehicles form a by small speed adaptions [15]

There are many examples of this type of opportunistic connection in the literature that provides different solutions for implementing a connection that can be achieved by changing speed profiles. Figure 9 illustrates an example of realizing progress in a platoon for three vehicles by changing speed profiles. The authors have shown that platoon creating can be implemented by the Platoon Vehicle System for more than 40% of the journey, resulting in a high platoon ratio. In states where the speed limit is higher (e.g., the US), even higher benefits can be achieved. In addition to the environmental impact of fuel reduction, there is an additional benefit to the platoon. This may be the case, for example, that future legislation may consider that the following position in the platoon may be equivalent to rest time [17,18].

6 Conclusion

In response to the goals of social, economic, and environmental sustainability globally, the concept of the Physical Internet has emerged, defining the logistics network of the future as a global, open, and interconnected system. In our opinion, one of the most defining concepts of the constantly evolving vehicle technology innovations is platoon-based transport. There are several solutions to the issue of coordinating platoons.

We propose a conceptual framework in Physical Internet-based logistics networks that can be defined as a research gap based on literature review. The concept organizes the off-board and on-board management structures into three layers. Strategic, tactical, and operational-level planning was placed in the Physical Internet network. We recommend the highest level of offline design in fixed π-hubs. The tactical level includes online-based design by PI hubs, while road-based implementation of speed-based solutions as an operational plan. We propose local optimization to achieve the global goals in the operation of this framework.

In conclusion, platooning transportation planning requires further research. Our conceptual framework is also a kind of guide, which requires specific solution proposals and algorithms in the future. In order to help practical applications, detailed algorithms are needed to achieve greater efficiency through platoon collaboration. At the same time, there is a need to increase cooperation between companies for a more sustainable future logistics system to work.

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Review process

Single-blind peer review process.