Towards Infrastructure-Aided Self-Organized Hybrid Platooning

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***Abstract*—Nowadays, the technical feasibility of autonomous driving is out of the question. This technology opens the door for several research topics (e.g., information exchange, security of information) in the IoT domain. One such application is platooning: coordinated driving of vehicles in convoys. Therefore, such platoons set up Internet-of-Vehicles. Although platooning has been mainly researched on highways, the idea of platooning in smart cities can have several benefits, such as efficient use of roads, time-saving through route optimization, and minimizing traffic in peak times. In this position paper, we present our vision of a traffic management approach for combining platooning on highways and urban areas. We explain the idea of platooning, how to manage it efficiently, and the differences between platooning on the freeway and in smart cities.**

***Index Terms*—Internet-of-Things, Smart Traffic, Platooning, Coordination**

I. INTRODUCTION

According to the U.S. Department of Transportation, 94% of all traffic accidents are caused by human errors, accumulating an annual cost of four billion dollars. Recent technological advances in computing power, sensor technology, and wireless communication have resulted "Autonomous Vehicles" (AVs) that can sense their surroundings and make intelligent decisions by communicating with neighboring vehicles and nearby infrastructure. Today, it is not the question anymore whether autonomous driving will be technically feasible. *Waymo*'s self-driving cars have driven more than $8,000,000$ miles[1] in the last few years, even in crowded urban areas. Whereas Waymo relies on expensive state-of-the-art laser technology, car manufacturers, such as *Mercedes-Benz*, use (close to) series-technology as base for their autonomous driving initiatives. So today, the technical feasibility leads to another issue: **How can we use autonomous driving efficiently?**

Drivers of autonomous vehicles enjoy more comfort and safety as human errors – which are one of the main reasons for accidents – are eliminated. But the real strength in using autonomous driving comes into play when smart infrastructure is combined with the vehicles' autonomous capabilities through vehicle-to-infrastructure (V2I) communication. This enables efficient traffic management through dynamic routing, adaptive traffic light control (A-TLC), as well as platooning. Project studies have shown, that cooperative driving, meaning that vehicles share information, such as brake or acceleration data, via wireless communication is superior to autonomous driving based on local sensing only [1].

In this position paper, we present our vision for infrastructure-aided and self-organized platooning of vehicles. Whereas most approaches focus on platooning on highways only, the objective of our work is to provide an integrated approach for efficient urban and inner-city traffic management. Therefore, we combine platooning and smart navigation on highways with platooning enabled through dynamic navigation and A-TLC within cities. We focus on using existing infrastructure and technology combined with state-of-the-art technology in autonomous driving [2].

The remainder of the paper is structured as follows. In Section II, we define platooning and present our approach. Section III presents our research objectives and questions. In Section IV, we discuss related work in platooning and route guidance. Section V depicts our project status and future work.

II. A HYBRID APPROACH FOR PLATOONING

In this section, we present a scenario that shows efficient highway and inner-city traffic management through platooning, dynamic routing, and Adaptive Traffic Light Controller (A-TLC). The scenario is based on existing standard technologies which can be commonly found in cities and on highways, such as cameras, induction loops, or variable-message signs (VMSs) which are small matrix signs based on LED technology. This technology is combined with state-of-the-art Vehicle-to-Everything (V2X) communication technology as well as autonomous driving [3].

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[1] Announced in July 2018: https://waymo.com/ontheroad/

A. The Principle of Platooning

In accordance with literature (e.g. [4]), we define *platooning* as "*spontaneous and dynamic forming of convoys of vehicles, so called platoons*". Each vehicle drives within a short distance to the next vehicle. Vehicles need to be driven autonomously or at least support the driver in holding the distance and keeping the vehicle within the lane boundaries, which involves autonomous braking. It can be argued that a single vehicle is a platoon already. However, as we assume self-driving vehicles which can drive without support through a *Platooning Control System* (PCS), the benefits of platoons are not valid for single-vehicle platoons. Therefore, in our view, a platoon consists of at least two vehicles. Drivers do not have to control forming of platoons as this is done automatically. The responsibility for controlling a platoon can be within a specific vehicle in the platoon or infrastructure-aided [1], [4]. In our approach, a hybrid PCS manages platooning, i.e., the highway is divided in sections that are cooperatively managed in a regional planner-like approach by semi-autonomous sub-systems of the PCS. The platooning process is divided into the following activities: (i) finding/joining/creating a platoon, (ii) maintaining platoons (including lane changing), (iii) leaving a platoon, and (iv) dissolving. The control system follows the MAPE-K model known from Autonomic Computing [5]. Accordingly, it integrates (i) monitoring the vehicles and the environment, (ii) analyzing the need for adaptation actions – such as joining a vehicle to a platoon or dissolving a platoon–, (iii) planning these action, and (iv) controlling the execution of these actions. All modules share a common knowledge repository. This makes the vehicles in combination with the control system a self-organized system. Subsequently, we describe these activities in more detail.

1) Finding/Joining a platoon: Using the V2I communication infrastructure, vehicles send information that are relevant for platooning – such as desired speed and their route – to the PCS. The PCS uses this information and plans a platoon. It sends the information to the relevant vehicles. The condition that at least two vehicles should have a similar route for a threshold time T where T is an arbitrary value that can be calculated depending on the route, and time of the day. Usually, there should be platoons available if a vehicle enters the highway or city, so vehicles just join a platoon. If this is not the case, a vehicle enters the highway and drives autonomously until a platoon is available. As soon as a certain number of vehicles is available within near vicinity, the infrastructure coordinates the formation process for a new platoon. The vehicles use V2I and Vehicle-to-Vehicle (V2V) communication as well as sensors (e.g., distance sensors) for joining a platoon. Additionally, the PCS delivers information constantly via V2I communication.

2) Maintaining platoons: Vehicles driving in a platoon use V2V communication for keeping the distance to the vehicle in front of them. Through V2V and V2I communication, information is spread very fast, such that the vehicles are able to react with very small delay in dangerous situations, such as an incident or items/people on the track without crashing into each other. Further, vehicles send their positions to the PCS. By combining the information from the PCS with inter-platoon V2V communication, overtaking processes are possible. Within the PCS, a handover of a platoon's coordination is important, as one sub system of the PCS only controls a region. Further, the PCS is responsible for merging and splitting of platoons (e.g., at highway junctions).

3) Leaving a platoon: Usually, the PCS delivers the information when a vehicle leaves the platoon, (e.g., in case it has to leave the highway or join another platoon in the city due to its route). Furthermore, a vehicle can leave the platoon on its own by signaling it to the PCS, e.g., for resting purpose on highways or the driver spontaneously changes the route by taking over control manually. In both cases, the PCS has to confirm the leaving request and the vehicle or PCS has to signal it to the other vehicles within the platoon. Gaps will be closed automatically by succeeding vehicles.

4) Dissolving a platoon: Through the constant update of a platoon's position, the PCS can determine when a platoon achieve a position where it is dissolved, e.g., a highway crossing. In this case, the PCS sends messages to the vehicles for forming new platoons or signaling the end of the platooning process. A vehicle must wait for a certain time before joining another platoon.

Figure 1 shows the platooning process on a highway. In the figure, within `platoon (1)` a vehicle leaves the platoon. `Platoon (2)` overtakes another `platoon (3)` and further, an additional vehicle joins `platoon (2)`. In the following two sections, we motivate the benefits of platooning with an integrated scenario covering platooning on highways and in cities.

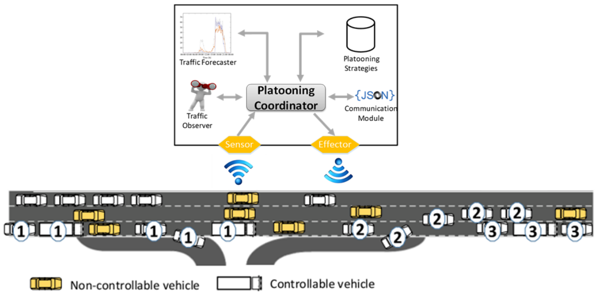

Fig. 1. The platooning process on a highway.

B. Our Approach for Platooning

State of the art platooning approaches focus on highways. In our work, we integrate platooning on highways with inner-city platooning. In this section, we describe our scenario for a hybrid approach.

1) Highway: An Intelligent Transportation System acts as PCS and enables the formation of platoons. It receives information from drivers as their goal or route characteristics (e.g., if they want to go the shortest route, fastest route, or most efficient route) through the V2I interface. This information is used for finding an existing platoon or forming a new one. The PCS sends the information to the involved vehicles. Platooning is controlled by the vehicles via V2V communication. Vehicles need to provide at least automatic longitudinal control. Overtaking of platoons is coordinated with the PCS or with other platoons. Platooning on a highway offers various advantages. The use of slipstreams lowers fuel consumption and environmental pollution. Furthermore, the PCS can coordinate the platoons' actions, such as overtaking, and reducing the travel time further through coordination. Safety is increased as the likelihood of accidents due to human error is reduced. Streets are used more efficiently, as the security distance can be reduced resulting in an optimized utilization. Studies elaborated that platooning could increase the capacity of highway lanes by 100-200% in comparison to individually driven cars [4]. Further, spontaneous traffic jams can be avoided with platooning. Inhomogeneous traffic flows arise if high differences in vehicles' velocity exist. If this happens in combination with exceeding a threshold in highway density (vehicles/km) braking can lead to spontaneous traffic jams. Platooning eliminates these jams as it homogenizes and optimizes the traffic flow.

2) City: Whereas most platooning approaches focus on platooning on highways, our approach combines platooning on highways with an approach for inner-city traffic management. Within a city, we focus on vehicles that come from the highway and aim for a certain location in the city (e.g., a specific event location) or want to drive through the city (e.g., as result of a redirection due to a closed highway). As it is more complicated to establish a V2I communication infrastructure in cities, our inner-city approach does not aim at the formation of closely-driving platoons (which require strong communication) as on highways. Hence, we support formation of convoys through prioritization of specific vehicles (prioritization can be based on inner-city vs. going-through traffic or the number of people in a vehicle) by dynamic routing and A-TLC [6]. The A-TLC enables Decentralized Progressive Signal Systems (DPSS, also called "green waves") for convoys of going-through traffic with a common goal outside of the inner city, as these vehicles should pass the inner, crowded part of the city faster for lowering the traffic load there. The use of bus lanes (only for controllable units, such as autonomous vehicles) can be allowed dynamically if there is no distraction of public transportation. The A-TLC is complemented by dynamic navigation information sent to navigation systems (of non-autonomous vehicles), to VMSs, or to the control unit of an autonomous vehicle via V2I. This information can also be used for specific routing, e.g., for distributing trucks on different routes in the city, or for separating vehicles that want to drive to downtown and going-through traffic. Moreover, the combination and splitting of platoons through routing and A-TLC is an important aspect here. Whereas platooning in cities does not generate slipstream effects, it still optimizes the utilization of the streets and drivers' routes.

III. RESEARCH QUESTIONS

The main objective of our work is to enable the efficient use of autonomous driving through platooning. This objective can be split to two main research questions: (i) *How to manage platoons efficiently?* and (ii) *How efficient is our approach for platooning?* Whereas the first question covers the efficiency of platoon coordination activities as forming of platoons, the second question compares the efficiency of platooning compared to situations without platoons. Further, differences in platooning on highways and cities are in our research scope. In this section, we highlight our research questions.

A. How to Manage Platoons Efficiently?

Different factors influence the efficiency of coordinating such platoons. As vehicles in platoons are highly fluctuating and their characteristics can change, merging of platoons, rerouting of platoons, vehicles changing platoons, as well as overtaking of platoons are relevant issues. Different quality of service metrics can be used for optimizing the platooning process, e.g., put the vehicles that have to leave next at the back for avoiding acceleration to close a gap. For joining platoons, we survey factors as whether it is more beneficial to speed up for joining a platoon versus slow down to wait for platoons. For platooning on highways, we have some specific research issues. We assume, that various platoons with different objectives use the highway at the same time. Therefore, overtaking processes of platoons are important here. One important issue is the necessary degree of interaction between infrastructure and platoons (as well communication within a platoon). Therefore, we will compare the amount of messages between a platoon and the infrastructure against intra-platoon (between the vehicles of a platoon) and inter-platoon (between vehicles of different platoons) messages. Based on this, we provide efficient algorithms for platoon coordination.

B. How does Platooning on Highways Differ from Platooning within Cities?

In urban environments, prioritization of platoons can increase the traffic conditions in situations where many drivers have to leave the city very soon, e.g., after a sports event. In our work, we model such situations and derive algorithms and rules for efficient coordination of platoons and traffic including prioritizing platoons. Within cities, we have another approach for platooning. In cities, platooning is achieved by a coordinated A-TLC, use of bus lanes, and adaptation of traffic signs through VMSs. As other vehicles should not be affected negatively, we need efficient forecast algorithms for the prioritization, e.g., dynamic use of bus lanes for platooning should not affect adversely the bus traffic. Our algorithms have to take into account the administrative effort compared against the usefulness of platoons in cities considering the length of possible platooning in cities (which is usually shorter as on highways). We will pay special attention to the handover of platoons from highway to urban environments. Vehicle control will change between different systems. Delays cannot be tolerated. Efficient algorithms for the handover process are required.

C. *How Efficient is Platooning?*

The question regarding the efficiency of platooning is two-folded. On the one hand, there is the question about how efficient platooning itself is. On the other hand, there is the question how efficiently platooning uses the infrastructure.

1) Which factors enable efficient platooning? Possible factors for measuring the efficiency of platooning such as the travel time, the achieved throughput, energy consumption, or utilization of the street influence the characteristics of platoons, e.g., platoon size, speed, or vehicle type. Further, studies can reveal factors that influence user acceptance of platooning and when it is beneficial to use platooning. Additionally, efficient forecast techniques are relevant for efficient platooning based on dynamic and robust techniques that can cope with uncertainty, e.g., arising from non-controllable vehicles. Forecasts are relevant for forming platoons and determining which vehicles should join which platoon. Further, the quality of forecast techniques determines the efficiency of prioritization of platoons in urban environments. Scalability of the platooning approach is another factor that influences the efficiency of platooning. We assume that decentralized approaches will perform better than centralized ones as they offer higher responsiveness, faster adaptation, and can easier cope with a high amount of data. However, as we want to avoid platooning with leading vehicles as coordinator, the infrastructure has central points that enable the coordination of platoons. Another issue concerns the amount of autonomous vehicles vs. normal vehicles: *Where is the threshold for the share of non-automatic vehicles such that platooning works efficiently?* As platooning is dedicated to vehicles that can be controlled by the control system, we assume that the higher the amount of such vehicles is, the better the performance of platooning will be. The ratio of autonomous (controllable) vehicles versus vehicles, that are not controllable by our system, influences the efficiency of platooning. This includes the comparison of different ratios and definition of thresholds.

2) How to use the existing infrastructure more efficiently with platooning? Further, another objective is to enable a more efficient use of the existing infrastructure. Our approach for platooning avoids the use of special leading vehicles. Instead, the infrastructure enables platooning. However, our approach should be non-intrusive to the existing infrastructure. The degree of reuse of the infrastructure is an interesting research topic within our studies. Further, the type of communication is within our research scope. *Can we use V2I communication infrastructure in cities and on highways? Do the requirements for V2I communication differ between these scenarios?* The communication analysis results are the foundation for the definition of efficient communication protocols (defining how to exchange which data) and communication mechanisms. We assume that infrastructural providers such as telecommunication companies could play a leading role in offering a platooning infrastructure. Another important infrastructural resource is the street itself: *How can platooning use streets efficiently?* This question is obviously related to the design of efficient platooning algorithms. We assume that platooning improves the utilization of streets by increasing the throughput while minimizing traffic congestion. We specially focus on the efficiency of inner-city through A-TLC.

IV. RELATED WORK

In the following, due to space limitations, we shortly summarize major platooning projects. Our technical report from [7] presents a comprehensive overview on platooning. The *PATH* program [4] is among the first projects investigating the potential of platooning. There, Platoons drive on dedicated lanes. Longitudinal control is achieved by magnetic nail following. All vehicles are fully automatically driven. Similar to PATH, all vehicles have equal roles in our approach. However, we aim at minimal intrusion. A dedicated lane for platooning is not in our scope. A focus of the *SARTRE* project [1] was to enable platooning on existing public roads without changing the roadside infrastructure. A truck or a bus as leading vehicle, driven by a trained driver is followed by autonomous driving buses, trucks, or cars. An additional remote system guides drivers which are not already part of a platoon to the nearest convoy with a suitable destination. Our approach has the same objective than SARTRE in using the existing infrastructure. However, we want to avoid the need of specific leading vehicles as in our opinion this decreases scalability, availability of platooning, as well as safety. *Energy ITS* started in 2008 [8]. As Energy ITS platoons only require on-board equipment, Energy ITS does not need infrastructural changes. Vehicles have radar and a 2-dimensional lidar for obstacle detection and gap measurement as well as DSRC for V2V communication. However, Energy ITS covers platooning with trucks only. Contrary to Energy ITS, our approach includes all types of vehicles. The EU project *COMPANION* [9] aims at dynamic forming of platoons and is supported by Volkswagen and Scania. However, the scope is limited to trucks as in Energy ITS. All of these approaches are limited to platooning on highways. None of them offers an approach for cities. Gershenson [6] studied self-organizing traffic lights in a multi-agent simulation based on a toroidal traffic grid. He showed that with simple rules and without direct communication, he could reduce the average waiting times at red lights and the number of stopped cars. The Sotl-request control holds a counter for the number of waiting cars. With a sufficient number of cars, the red lights will turn green, creating platoons of cars. However, this solution is limited to toroidal traffic grids and limited to inner-city traffic.

In contrast to fixed-time controlled traffic lights, traffic-actuated controls adapt their signalization to the monitored traffic situation. This can result in a green time adaptation, switching to on-demand phases, a phase sequence adaptation, or a cycle time adaptation. Claes et al. [10] demonstrated in a real-world traffic scenario how their delegate multi-agent system reduces congestion and the average travel times for traffic participants. Their decentralized approach mimics ant behavior, using real time traffic information from probe vehicles. Research by Pan et al. [11] showed that re-routing strategies based on real-time traffic data from vehicles lowers the average travel time with less re-routing frequency. They present three novel algorithms and evaluate them in a simulation-based study.

V. PROJECT STATUS

So far, this paper presented the vision of an integrated approach to coordination of platooning. The project contains two elements: (i) the PCS for coordination of platoons on highways [12] and (ii) the *Organic Traffic Control* (OTC) system [13], [14]. For both elements, prototype systems exist. Currently, we are working on the integration of these system. This section presents these systems as well as the challenges for the connection of both systems into an integrated testbed.

A. Adaptive Traffic Control

Earlier work applied the Observer/Controller architecture known from Organic Computing to traffic signal control resulting in the *Organic Traffic Control* (OTC) system (see Figure 2). The basic OTC system is responsible for the adaptation of the green times at traffic lights at intersections according to the present traffic conditions. The self-learning, self-optimizing system follows a safety-oriented concept that allows OTC to adapt within defined boundaries. Each individual instance of OTC is fully decentralized and controls one intersection only. Traffic light controllers (TLCs) located on nearby intersections which are directly connected via streets may communicate with each other to establish a distributed coordination of TLCs. The self-organized route guidance mechanism is able to calculate the fastest routes through the network to prominent places based on current traffic flows. Techniques from the Internet domain, such as the Distance Vector Routing (DVR) and the Link State Routing (LSR) protocols, are applied to road traffic guidance. In every time step, the monitoring component receives the current raw traffic data from sensors located at Layer 0 and processes them before the data is forwarded to other modules such as the prediction component or the situation analyzer. The latter generates a situation description of the current traffic flow for an intersection (vehicles/hour for every intersection), whereas the prediction component forecasts traffic flows for upcoming time steps. The prediction component itself consists of several prediction methods that each make forecasts. These methods range from simple smoothing algorithms that calculate a forecast based on the recent data to more sophisticated algorithms such as Kalman Filter, Artificial Neural Networks, or ARIMA [13].

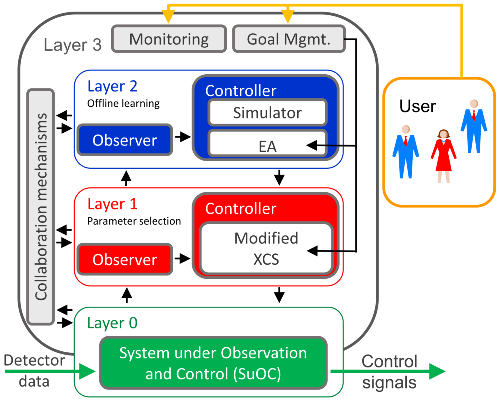

Fig. 2. Architecture of the Organic Traffic Control system.

B. Platooning Coordination System

In the *iCOD* project[2], we implement a system for self-organized infrastructure-aided cooperative driving through coordination of platoons on highways. In [12], we describe the implementation of a demonstrator[3] of the PCS with LEGO Mindstorms robots. LEGO robots drive autonomously (following a colored lane) and drive in platoons (using the distance sensor). Forming a platoon is supported by the PCS. The PCS is designed as a self-adaptive system and implemented using the FESAS framework [15]. It assigns vehicles to platoons based on individual preferences of the driver, vehicle factors, context factors as well as the integration of a compensation system. V2I communication is WiFi-based. Based on the demonstrator, we recently built a testbed which integrates the PCS with the platooning

[2] iCOD project website: http://icod.bwl.uni-mannheim.de/

[3] A video showing the platooning demonstrator can be found at: https://www.youtube.com/watch?v=Nnrbq-4Dn24

simulator *PLEXE* [16] for evaluating various coordination strategies. The usage of a large-scale simulator allows a detailed quantitative analysis of the approach. Additionally, it is possible to compare different coordination algorithms and to evaluate their performance with realistically simulated vehicles. Therefore, algorithms for coordination can easily be plugged into the system and the system chooses at runtime the algorithm that corresponds to the driver's preferences. Figure 3 depicts the architecture of the simulation testbed. The left hand side shows the real world system; right hand side shows the testbed with PLEXE that integrates SUMO for traffic simulation and the *OMNeT++* and *VEINS* for V2I simulation.

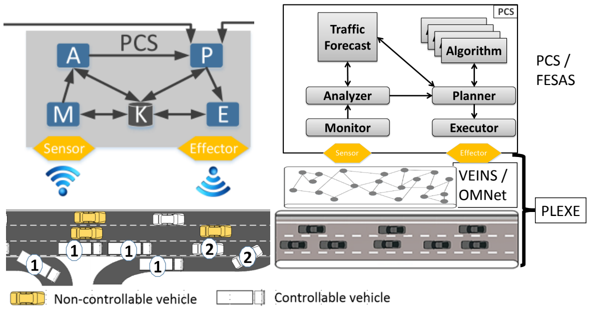

Fig. 3. The simulation testbed for the Platooning Coordination System.

C. Open Challenges

For future work, we have to link the OTC with the PCS for designing an integrated test bed. This raises several challenges, which can be categorized into (i) implementation challenges and (ii) research challenges. In the following, we present these challenges.

The existing OTC approach supports dynamic routing through A-TLC. Currently, we extend the system by an approach for dynamic, temporary assignment of bus lanes to normal vehicles. Further, we survey methods how to establish inner-city platooning through traffic light control for DPSS creation and intelligent navigation of traffic. Additionally, we increase the usability of the existing PCS testbed for avoiding the need to handle all the necessary tools and to offer an out-of-the-box approach for testing coordination algorithms. Last, the integration of both testbeds might raise implementation challenges, e.g., the integration of the AIMSUN simulation used in the OTC system with the SUMO simulation from the PCS testbed.

For profound analysis of the coordination performance, we need to define suitable metrics and objectives. However, as platooning is a multi-dimensional optimization problem, this is challenging. Possible objectives, that might conflict each other, are the optimization of the traveling time, fuel consumption / environmental pollution, or traffic throughput. Objectives of individual drivers might conflict with global optimal objectives, e.g., travel as fast as possible vs. reducing environmental pollution. In contrast to existing solutions, a platoon might be composed integrating different driver preferences. Hence, objectives need to be balanced and suitable metrics to measure them needs to be defined. Especially a reward / compensation system must be defined for two reasons. First, the position in the platoon influences the slipstream effects and the benefits in terms of fuel saving. Second, for inner-city platooning, the system might redirect individuals to longer routes for the sake of global optimization.

Our approach also takes inter-platoon interactions into account. This is not integrated in current platooning approaches so far. Additionally, we assume that not all vehicles are able to platoon, hence, interactions with normal traffic are necessary. However, this makes the solution ready for use when the very first platooning vehicles are on the streets.

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