A Self-organising System Combining Self-adaptive Traffic Control and Urban Platooning: A Concept for Autonomous Driving

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Abstract: Platooning is an approach to coordinate the driving behaviour of vehicles on major roads such as motorways. The aim is to take advantage of, e.g., slipstream effects to reduce cost. We present an approach to transfer the platooning concept to urban road networks of cities. The reduced slipstream effect is compensated by integration with the signalisation infrastructure to dynamically allow for prioritisation of platoons using progressive signal systems (i.e., "green waves"). We define the scenario and derive a research road map towards fully self-organised platoon operations and integrated coordination with self-adaptive and self-organising urban traffic control systems. Starting from both directions, that is, self-organised urban platooning as well as self-organised progressive signal systems in urban road networks, we define the scenario, identify main challenges, and present first results to demonstrate the feasibility of our research agenda.

1 INTRODUCTION

The field of self-adaptive and self-organising (SASO) systems, as an umbrella for initiatives such as Autonomic Computing (Kephart and Chess, 2003), Organic Computing (Müller-Schloer and Tomforde, 2017) or Interwoven Systems (Tomforde et al., 2014), aims at developing mechanisms to counter complexity in control problems of technical systems. The vision is to distribute decision-making about appropriate behaviour to a set of autonomous entities that cooperate with each other based on current goals and demands. Compared to standard system design and operation, the advantage is a more robust and more efficient solution while simultaneously countering challenges such as single-point-of-failure, limited scalability, or decreased administrability.

Traffic operation is an ideal environment for SASO technology. Individual cars can already operate fully autonomously, the control problem of intersections has typically a limited scope, and the urban road network can be tremendously large, which turns centrally optimised dynamic planning infeasible. As a result, a variety of SASO-based traffic control and management systems have been proposed in the last decades (Rehena and Janssen, 2018). These systems mostly consider the current state-of-the-art in traffic operation and neglect trends towards green and autonomous driving. Alternatives to the combustion engine (electric, hydrogen) may pave the path towards more efficiency-focused, green solutions. However, whether our growing cities will be able to withstand and whether society will continue to tolerate individual traffic in cities is questionable. Platooning and its consideration in urban traffic control may serve as a compromise between individual and public transport with good user acceptance.

Until now, swarm behaviour (Hamann, 2018) to enable platooning and (centralised or decentralised) infrastructure-based control have been considered only in isolation. We propose a concept for an integrated solution that tightly couples self-organised platooning with maintenance and decentralised SASO-based traffic control. Such an integrated approach has to balance the potentially conflicting goals of different stakeholders. For instance, a classic urban traffic planning perspective focuses on reducing travel times, number of stops, emissions, as well as on strong capacity utilisation. On the other hand, platooning is advantageous for individual cars when being coordinated and accordingly prioritised to decrease their expected travel times. This allows, in turn, traffic authorities to increase the efficiency of public transportation through urban platooning.

Based on an initial discussion of platooning concepts in Section 2, this paper defines in Section 3 such

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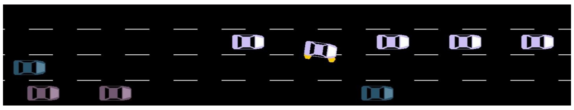

Figure 1: Example of a platoon on a highway simulated in PLEXE/SUMO.

an integrated platoon-based urban traffic control approach. We then outline a research road map in Section 4 and describe preliminary results in Section 5. Finally, in Section 6 we summarise the paper and give an outlook to our future work.

2 PLATOONING

2.1 Term Definition

Shladover (Shladover, 2007) defined platooning as "spontaneous and dynamic forming of convoys of vehicles, so-called platoons." This is based on the idea that each participating vehicle drives within short distance to its neighbours (see Fig. 1). The concept has gained increasing attraction due to the recent developments in autonomous driving since manual steering is typically not an option for optimising the benefits of platoons (Bergenhem et al., 2012). In turn, vehicles need to act autonomously or at least support the driver. Conceptually, even an individual vehicle may be considered as a platoon but the benefits (such as reduced energy consumption due to slipstream effects or better utilisation of the infrastructure due to minimised distances) increase with the platoon size.

Traditional platooning scenarios are situated at highways and motorways: Halle and Chaibdraa define the concept of platooning as "[...] vehicles travel[ling] on highways in closely spaced groups." (Hallé and Chaib-draa, 2005). Here, dedicated access and exit roads (typically at large distances in kilometre-scale), sometimes combined with several lanes, allows for static composition of platoons. The shorter the coordination time of vehicles and the higher the fluctuation (e.g., due to reorganisation of the platoon), the lower is the possible benefit for participants (Shladover, 2007). The challenge in urban traffic would be to quickly and dynamically form and re-configure platoons while still achieving benefits in terms of reduced overall organisational effort, increased safety, and possibly saved fuel. Table 1 offers more details about theses challenges while comparing traditional highway-based platooning to novel urban platooning systems.

2.2 State of the Art in Platooning

The platooning technology dates back to the 1980s. Current approaches mainly consider the coordination of truck platooning due to, for example, the potentially longer duration of the coordination and possible savings in salaries. Additionally, researchers recently focus on the efficient assignment of vehicles to platoons, while mostly neglecting individual constraints and behaviour of participating drivers. For instance, group and individual benefits need to be balanced as a vehicle leading a platoon does not save fuel. So, from an individual perspective, drivers might try to avoid this position. Consequently, in contrast to existing approaches (see (Bhoopalam et al., 2018) for an overview), personal preferences of drivers and individual decisions about which platoon to join must be considered. To demonstrate the feasibility, a platooning coordination test environment exists (Krupitzer et al., 2019), which is based on the PLEXE platooning simulation (Segata et al., 2014). A recent overview of platooning is given by Kalbitz (Kalbitz, 2017).

One of the first platooning projects was the PATH programme (Shladover, 2007): All vehicles are self-driven and have the same role. Platoons make use of dedicated lanes and longitudinal control is achieved by following magnetic nails in the street. In contrast, the SARTRE project (Bergenhem et al., 2012) considers platooning on existing public roads without altering the infrastructure. A leading truck or bus is steered by a trained driver, which is then followed by autonomously driven vehicles. An additional remote system guides novel drivers to the nearest platoon with a suitable destination.

Another 'Intelligent Transportation System' (ITS) that forgoes a modified infrastructure is Energy ITS (Tsugawa et al., 2011). It employs on-board equipment: dedicated short-range communications between vehicles as well as lidar for gap measurement, which is also used in combination with radar for obstacle detection. Only fully automated trucks were upgraded, resulting in 14% fuel reduction.

Also focusing only on trucks, the EU project COMPANION (Eilers et al., 2015) aims at dynamic platooning. It uses on-board systems for coordinated platooning along with an off-board platform for the coordination of established platoons. The project is supported by large car manufacturers.

Heinovski and Dressler formulate platooning as an optimisation problem (Heinovski and Dressler, 2018). In simulations, the decentralised approach (with less knowledge) yields on average larger platoons (2.47 cars) than their centralised variant. How-

Table 1: Challenges in platooning; comparison between highways and cities (urban platooning).

challenge	on highways	in cities
saving gas	major advantage due to slipstream	minor influence of slipstream due to low speeds but platoon-wise synchronised traffic lights
safety	reduced lane switching	reduced dangers for non-car traffic
traffic diversity	diverse due to less significant speed limits	reduced due to strict speed limits
benefits of switching	depends on traffic diversity	more potential benefits due to waiting times at traffic lights
benefits for infrastructure	increased throughput in number of vehicles	prioritisation of throughput traffic to increase capacity utilisation

ever, both approaches need significant time to form a platoon. Concerning time-efficiency, the distributed solution is slightly worse than the centralised variant.

2.3 State of the Art in Urban Platooning

As shown by Gershenson in the context of self-organising traffic lights (SOTL) (Gershenson and Rosenblueth, 2012), platoons may emerge automatically in urban road networks. In multi-agent simulations based on a toroidal traffic grid, applying simple rules without direct communication can reduce the average waiting times at red lights and the number of stopped cars. The request control of the SOTL holds a counter for the waiting cars. When a sufficient number is reached, the lights turn green, which creates platoons of cars. However, this result is limited to toroidal traffic grids with regular topologies, such as Manhattan-style networks. A transfer to a real-world road network topology is pending. We propose to study such emerging properties as part of our research roadmap using appropriate experiment platforms.

2.4 Experimental Platforms

Many platforms for simulation aspects of platooning exist in both forms, commercial as well as open-source, and are used in the context of road traffic simulation. However, none of them currently allows for an integrated investigation of platooning and urban traffic control behaviour. A fairly recent open-source development with a scalable client-server architecture is the autonomous driving simulator CARLA.[1] It has a feature for cooperation (“co-simulations”) with the *Simulation of Urban MObility* (SUMO),[2] which is another open-source project, developed by the German Aerospace Centre. The software is well maintained as indicated by frequent updates. An active community exists, providing well-documented projects and tutorials. *Vehicles in Network Simulation (Veins)*[3] is an open-source framework for Inter-Vehicular Communication (IVC). It is composed of SUMO and the powerful event-based network simulator (OMNeT++).[4] For a realistic simulation of platooning, it can be combined with the *Platooning Extension for Veins* (PLEXE),[5] presented by Segata et al. (Segata et al., 2014). As for commercial modelling and simulation software, Simulink (The MathWorks, 2019) can also be used in conjunction with PLEXE. Finally, the commercial solution, Aimsun Next (Aimsun SLU, 2020),[6] can simulate various vehicles and pedestrians in models of varying granularity, ranging from single intersections up to entire urban regions.

3 SCENARIO AND VISION

In this section, we specify the envisioned scenario we want to study. For certain aspects (e.g., centralised vs. decentralised), we allow spectra of possibilities while we exclude other aspects (e.g., privacy) that we keep aside to focus on despite their importance.

Communication. We assume that all cars establish a car2car network with scalable local communication. A (large) fraction of autonomous vehicles is connected to the smart city’s infrastructure via communication links to receive information and commands.

Autonomy and Cooperation. Traffic light controller (TLC) determine the green-light duration at intersections and their distributed coordination. The coordination in progressive signal systems (PSS, so-called ‘green waves’) is done by identifying the

[1] http://carla.org/
[2] https://www.eclipse.org/sumo/
[3] https://veins.car2x.org/
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[5] http://plexe.car2x.org/
[6] https://www.aimsun.com/

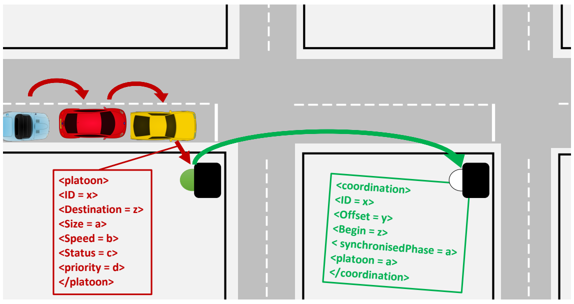

Figure 2: Platoon-responsive coordination of traffic lights to establish progressive signal systems.

strongest streams and/or platoons, followed by self-organised coordination of the underlying phases at distributed intersections (Tomforde et al., 2008). If an autonomous car (independent of whether part of a platoon) receives a command from the infrastructure (e.g., ‘use Lane A’ or ‘leave Lane B’), it directly follows these commands (see Fig. 2). So we neglect the possible intervention of users and the possibility to ignore commands at this preliminary stage of the concept. At later stages, we plan to investigate the impact of non-cooperative behaviours on system performance. Initially, all cars are considered to be fully cooperative. They voluntarily participate in the platooning system, and they compromise to optimise common benefits. However, they are individually motivated allowing them to switch between platoons or leave them if the benefit is reduced.

Control Level. The infrastructure-based traffic control is done using a centralised or a decentralised approach. We may also allow the combination of both, therefore forming a hybrid approach. Following the centralised approach, the system generates traffic organisation plans for whole sub-networks. Following the decentralised approach, the system is composed of autonomous intersection controllers. Similarly, we study a centralised and a decentralised approach to platooning.

Urban Platooning. By default, we assume that individual driving cars try to join either an existing platoon or another single car (see Fig. 3). Once a car has joined a platoon, it continues to monitor potential benefits based on current alternative platoons including the option of driving alone. Within a platoon, the participants need to negotiate the trajectory (destination and route), their preferred speed, and positions within the platoon (e.g., alternating leaders). We assume a particularly increased need to reorganise platoons dynamically due to the urban traffic environment in comparison to classical platooning on highways. Human drivers in an urban setting are more likely to switch to manual driving and to change the destination or other user-defined constraints. Furthermore, we assume an increase of diversity and uncertainties compared to platooning in highway scenarios (see Fig. 4) because of the more complex road network and the more diverse traffic (e.g., vulnerable road users).

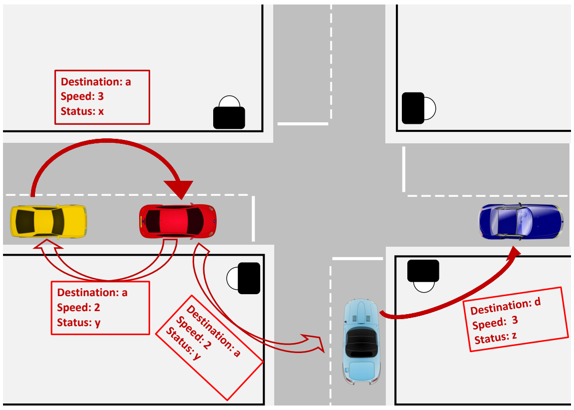

Figure 3: Possible communication of an ad-hoc network to establish urban platoons.

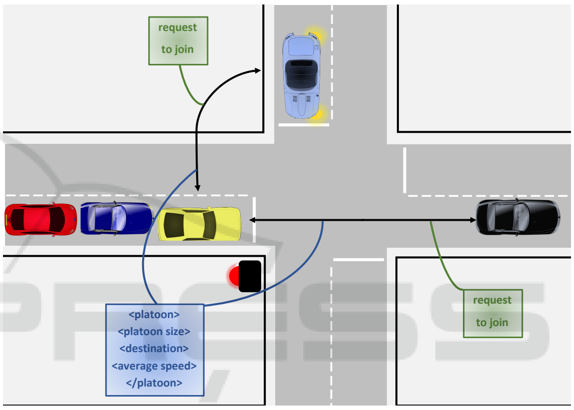

Figure 4: Display of the increased diversity of situations in urban platooning, the black car may consider to slow down or even stop to join the platoon, the left-turning light-blue car may choose to join coming from a different rout.

Prioritisation. The SOTL has awareness of the platoons and may allow them priority over other road users (i.e., synchronisation of corresponding phases using PSS). Even dedicated lanes for platoons can be considered (or shared bus lanes). Prioritisation is required in the case of conflicting platoons and/or the trajectory planning in the network with an impact on both the centralised and decentralised approach.

Traffic Generation. The destinations of cars are known to the infrastructure and other cars, and they can be modelled dynamically (i.e., as random-waypoint model for inner-city traffic) and as an origin-destination matrix for passing traffic (i.e., defined as streams). Route choice is modelled stochastically (i.e., as shortest path, fast route, main street, or individual route).

Privacy. We exclude privacy aspects and allow the sharing of information about destination, speed, etc.

4 CHALLENGES AND OBJECTIVES

The scenario specified above introduces several challenges to the operation of urban traffic systems and the coordination of autonomous vehicles. In this section, we derive the most urgent challenges from the overall problem statement to provide a basis for the subsequent investigations.

4.1 Problem Statement

We propose a research track that studies the potential benefit of urban platooning supported by and integrated with SOTL. Methods that need to be developed can be adjusted in two main qualitative dimensions: (1) Are platoons formed and coordinated by SOTL or by the cars themselves with SOTL influencing them almost only as a side effect? (2) Is the whole system organised centrally or are platooning and/or SOTL coordinated in a decentralised approach? For dimension (1), a mixture of responsibilities between individual cars and SOTL is possible, too. Similar, for dimension (2), a hybrid approach could allow some aspects being managed by a decentralised system in alternation with situation-aware, temporary interventions by centralised coordination.

4.2 Main Research Challenges

Almost all published methods about platooning focus on the standard application of platoons on highways. Organising platoons within cities comes with different requirements, new methods need to be developed, and even more so for a decentralised approach. Similarly, SOTL is usually focused on coordinating individual cars or only loosely coupled flows of cars (see Table 1 for a comparison). Hence, also methods of SOTL require changes to operate on platoons or even on mixtures of platoons and individual cars. Therefore, the main research challenge is about adapting methods from both fields and integrating them to achieve a clear benefit in terms of reduced travel times, improved safety, and reduced emissions. We can formulate a main research question: "How to create a self-organising system that combines SOTL with the decentral organisation of platooning respecting emerging mutual effects?" Given the state of the art, we do not know all effects that SOTL has on platooning and how we could provoke constructive coordination between SOTL and platooning to gain added efficiency. This will most certainly require to adapt classical SOTL methods to appropriately deal with platoons instead of individual cars. Furthermore, aspects of privacy and user acceptance need to be considered to assess the feasibility of such an approach.

Specific for the SOTL approach is whether it can be done centralised or needs to be done decentralised. A centralised approach would require to plan (optimised) trajectories for platoons through the network and a platoon-aware progressive signal system. This may become less feasible as soon as the autonomous cars can ignore the centralised plan. A new challenge would be to integrate inner-city platoons with prioritised public transport and similarly with special-purpose infrastructure (e.g., bus lanes). A decentralised approach would require to plan trajectories of homogeneous platoons (e.g., same destination). In the case of heterogeneous platoons, the split of platoons would be required in certain situations. Overall, a key question is whether platoons can be composed dynamically by external self-organisation robustly and with a clear benefit. For the decentralised approach, a complementary cornerstone is the question of whether it requires scalability for large-scale city networks with many intersections.

Specific for the platooning approach is whether individual cars are allowed to switch between platoons dynamically and whether that is explicitly supported by SOTL. Appropriate methods need to be developed for efficient platoon organisation and re-assignments. However, we should ask whether dynamic platooning should be substituted by static platoon assignments in certain situations. We can even ask whether there are situations when urban platooning is of no good use. A unique challenge of platooning in cities could be non-trivial interplays of phases with bursts of car-to-platoon assignments, followed by periods of reduced re-assignments. Appropriate modelling techniques need to be developed to reflect such temporal asymmetries. Overall, a key question is a balanced trade-off between centralised control of all platoons with global information and scalability while achieving only sub-optimal assignments to platoons.

5 CURRENT STATE OF THE INVESTIGATIONS

Based on the overall challenges presented above, we started the investigations from both underlying perspectives: (a) the self-organised adaptation of infrastructure-based signalisation and coordination (of traffic lights) behaviour and (b) the self-organisation of platoons in heterogeneous environments. In the following sections 5.1 and 5.2, we present first results of these two directions of research.

5.1 Infrastructure-supported Urban Platooning

In (Krupitzer et al., 2018), a first vision of how to integrate urban infrastructure and platoon coordination at highways has been presented. The main focus is on the connection between a centralised highway platoon management and intelligent handling of platoons leaving the highway and entering the city. Compared to this paper, the autonomy of the individual participants is restricted, the coordination problem is handled by centralised planning, and the traffic light coordination is not fully integrated.

The *Organic Traffic Control* (OTC) system (Prothmann et al., 2011) and its extensions serve as a basis for investigations towards urban platooning. OTC is a self-organised traffic control system that decides locally at each intersection about the behaviour of the underlying intersection controller. Based on the Observer/Controller paradigm (Tomforde et al., 2011), it is able to adapt the signalisation of traffic lights to changing traffic demands, improve this adaptation over time based on reinforcement learning (Stein et al., 2016), to establish progressive signal systems in a fully self-organised manner (Tomforde et al., 2010; Tomforde et al., 2008), and to provide route recommendations to drivers which reflect the current state of the traffic network (Sommer et al., 2016a). Based on OTC, further contributions investigated are robust traffic demand prediction (Sommer et al., 2016b), integration of these predictions in the control strategies (Sommer et al., 2015), and infrastructure-based anticipatory route guidance (Sommer et al., 2016a; Sommer et al., 2016b).

The basis for platoon-responsive PSS is the decentralised PSS (DPSS) algorithm as originally proposed in (Tomforde et al., 2008). This three-step process is synchronously performed in cycles by all nodes to establish the sequence of traffic nodes for a PSS:

1. Every controller determines the pair of incoming (‘upstream”) and outgoing (“downstream”) sections that exhibit the strongest traffic flow. It then notifies the upstream node to be its desired predecessor. After this is done by all controllers, and a node is elected by its downstream node, a partnership is confirmed. All collaborating nodes know their partners and if they are head or tail in a PSS.
2. A common, *agreed cycle time (ACT)* is determined using an “echo algorithm” (Chang, 1982). Every node i has its own *desired cycle time* (DCT_i), already selected by OTC. The ACT is the longest of those, so the most heavily used node is not restricted: $ACT = \max\{DCT_i\}$

   The head node starts with its own DCT by setting $ACT := DCT_1$ and propagating it downstream. Every node i with a higher DCT updates $ACT := \max\{ACT, DCT_i\}$ until the tail node is reached. ACT is now determined and propagated back so every node can store it as $ACT_i := ACT$
3. The time offsets o_i of the nodes are calculated by using another echo algorithm: For every node, start times of the synchronised phase as well as offsets, queuing and vehicle travelling times from upstream nodes are required. When the tail is reached, every intersection controller knows when to activate a traffic light controller (TLC) setting that respects the ACT and establishes the PSS.

The last step requires synchronised clocks. Also, once-established PSS are updated.

To illustrate the effect of DPSS, we consider its integration into the OTC system and compare its performance to uncoordinated OTC nodes. The traffic in the Manhattan network in Figure 5 was simulated according to a 3 hour, two-part traffic demand: In the first half, 2900 cars are simulated with the most heavily used routes A to B and D to C, followed by a change to 3200 cars with the routes F to E, H to G, and J to I mostly being chosen by the AIMSUN simulator.

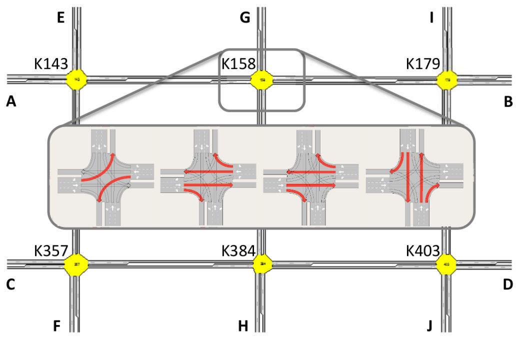

Figure 5: Manhattan network with 6 intersections, each with a 4-phased FTC (fixed-time controller) and sections of 250m length each.

Two experiments (uncoordinated OTC nodes vs. OTC-DPSS) were conducted. In the case of the OTC-

DPSS simulation, every ten minutes the PSSs were established or updated, depending on the current traffic situation. For the comparison, *average travel times* and the *average number of stops* for the complete network were taken into account (see Figure 6): The number of dropped by 7%, while the average network travel time is kept mostly constant during the simulation. For both parts of traffic demand, PPSs were established along the two or three most heavily used routes.

This preliminary experiment already shows that there is a benefit in establishing PSS in urban road networks in response to changing traffic demands. When further compared to a centralised variant as, e.g., discussed in (Tomforde et al., 2010), we emphasise the advantages of this self-organised approach: fast reaction time, robustness against individual node failures or message loss, and low complexity of the control algorithm. A drawback is that it requires synchronised clocks. The next steps in this line of research include a) the consideration of existing platoons in the simulations and to adapt the PSS strategy towards platoon-responsive behaviour, again in a fully decentralised manner, and b) to transfer the results to simulations of real-world typologies.

5.2 Platooning with Increased Uncertainties

As a first step towards the self-organisation of platoons in heterogeneous urban environments, we studied the challenges of platooning with increased uncertainties. Cars not part of platoons or cars that consider switching platoons may only have unreliable information about other platoons. In an urban setting, it may be profitable for cars to voluntarily stay halted or to slow down considerably and wait until a desired platoon passes by. However, the relevant properties of the platoon may change within timescales of a few minutes. Even on shorter timescales of a few seconds, arrival times of platoons may change considerably due to, e.g., uncertainties in traffic lights. We expect a much more dynamic assignment of cars to platoons followed by continuous platoon switching. As an overview, we give a state machine in Fig. 7 that indicates the complexity of dynamic platooning with respect to, e.g., join-leave-join sequences and aborted join processes.

We tested four dynamic platoon switching strategies inspired by methods to solve the multi-armed bandit problem. The assumption is that cars need to monitor a platoon for a short duration of time before committing to join it. Relevant features of a platoon (e.g., velocity, size, distance) may change dynamically, especially during an initial transient phase. We assume that querying features of a platoon can be modelled by sampling from a fixed probability density. The decision to whether to join a platoon and, if so, which on, can be seen as a multi-armed bandit problem paired with an exploitation-exploration trade-off (when to commit). Each car stores features of surrounding platoons in an LRU cache. The most basic method is the ε-*greedy* algorithm, which selects the best candidate with a fixed probability of $1-\varepsilon$. As a second method, we test *Upper confidence bounds (UCB)*, which uses a heuristic value to estimate the true feature value. Third, we test *Bayes UCB* that assumes Gaussian distributions for the platoon features. Forth, we test Thompson Sampling operating on α-β-distributions. As a baseline, we compare with the decentralised static approach of Heinovski and Dressler (Heinovski and Dressler, 2018), which assigns cars to platoons once and does not implement platoon switching. In a conservative ‘start-to-end’ 10-minute scenario we study how platoons form initially with all cars started as individual cars and how switching platoons can be beneficial as all cars have the same (far away) destination. As simulation frameworks we use PLEXE, VEINS, and SUMO.

The dynamic methods have an advantage at later stages of a run, as they form bigger and thus potentially more efficient platoons. For example, see Fig. 8 that shows the platoon size averaged over all platoons for a single simulation run. The give-and-take side of dynamic platooning is shown in Fig. 9 where we compare the benefits for the switching individual car and the compromise for the target platoon in terms of ‘happiness’ (e.g., the sum of different individual-vs.-platoon features, such as common destination, desired speed, platoon size). Here, we assume that platoons cannot reject a car that wants to join. Bayes UCB (in the tested parameterisation) turned out to be conservative and rarely switched platoons. All three other methods are more active and have a non-zero probability that even for the switching car the situation may worsen (upper panel in Fig. 9 for < 0). However, considerable improvements can be achieved, too. As seen in the lower panel of Fig. 9, platoons almost never improve by allowing other cars to join for the tested scenario. Whether platoon switching is profitable depends considerably on the scenario and in particular the diversity of the traffic (e.g., different speeds, destinations) and the density of the traffic (number of neighbouring platoons that can be joined). In summary, an intermediate result is that dynamic platooning is challenging and its benefit is sensitive to many aspects of the traffic situation.

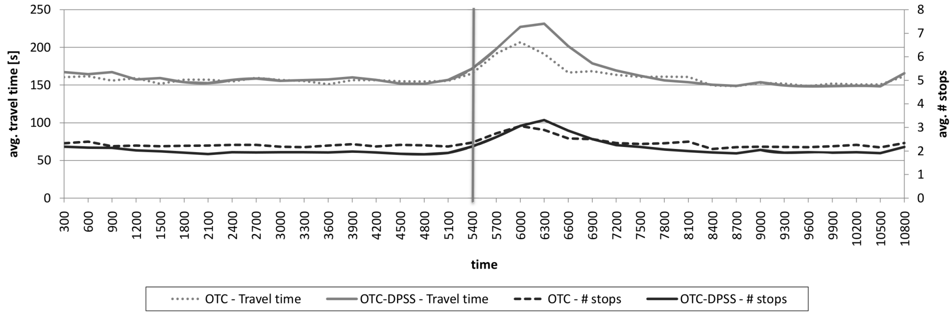

Figure 6: Average travel time and number of stops for uncoordinated OTC nodes and OTC-DPSS.

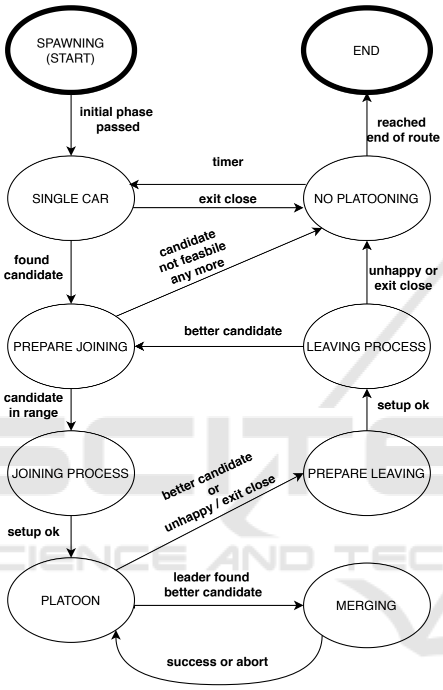

Figure 7: States in dynamic platooning with decentralised autonomous reassignment by individual cars.

6 CONCLUSION

Urban road networks are characterised by increasing traffic loads worldwide, rendering the available capacity of handling traffic volumes increasingly inappropriate. As an alternative to extending the infrastructure, we presented a concept for improving the efficiency of utilising the existing capacity of such networks by introducing an integrated approach of decentralised dynamic platoon formation and maintenance inspired by swarm robotics (Hamann, 2018), on the one hand, as well as self-organised and platoon-responsive coordination of traffic lights to establish 'green waves,' on the other hand. Based on the definition of the scenario and the underlying assumptions, we described a research road map towards fully operable self-organised urban platooning, which respects the autonomy of individual drivers and the overall service goals of the infrastructure.

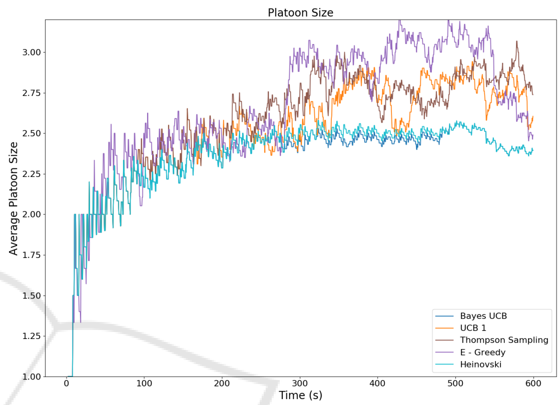

Figure 8: Dynamic decentralised platooning in an increased uncertainty scenario comparing five algorithms (four dynamic platooning algorithms and one static platoon assignment algorithm: 'Heinvoski'), average platoon size over a period of 10 minutes for different platoon switching strategies based on multi-armed bandit methods.

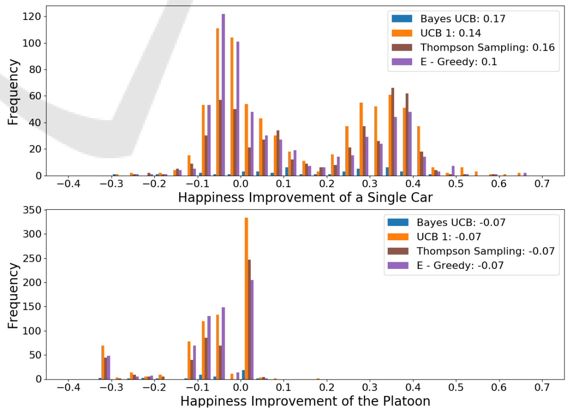

Figure 9: Dynamic decentralised platooning in an increased uncertainty scenario comparing four algorithms, average happiness improvements for a switching individual car and its target platoon (numbers in the legend give the average improvement for each method).

We presented two case studies of preliminary work on integrated urban platooning with two different perspectives: On the one hand, we performed an analysis of self-organised 'green waves' in simulations of real-world traffic network topology with actual traffic demands. On the other hand, we presented preliminary results of comparing dynamic platoon formation algorithms under increased uncertainty. Our future work investigates possibilities to close the gap between these two research directions.

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