Dynamic Platoon Formation at Urban Intersections

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Abstract—**Platooning has repeatedly been shown to have the potential to increase both the efficiency and the safety of future road traffic. Yet, while there is ample research that illustrates its potential in freeway scenarios, the biggest challenges of traffic efficiency and safety lie in urban environments, which pose unique challenges: They are characterized by the presence of tight speed limits, intersections, traffic lights, and buildings. Moreover, work that has targeted such scenarios has, so far, not considered platoon formation strategies – or only considered idealized vehicle dynamics, platooning controllers, or wireless network dynamics. We fill this gap by investigating dynamic platoon formation at urban intersections controlled by regular traffic lights. We propose a fuel-efficient strategy for platoon formation at such intersections and investigate its performance using realistic simulation models of (all of) vehicle dynamics, platooning controllers, and wireless networking. Our investigation reveals the potential of the proposed strategy to simultaneously save both 15 % of fuel and 14 % of travel time.**

I. Introduction

To address the challenges of rising traffic densities and increased pollutant emissions, current research focuses on cooperative mobile systems employing Vehicular Ad-hoc Network (VANET) technologies for Vehicle-to-Everything (V2X) communication [1]. Especially for freeways, the research community introduced the concept of *Platooning*. Here, vehicles are forming computer-controlled convoys that are driving cooperatively and in close coordination (under full lateral and longitudinal control).

Yet, while the literature has repeatedly shown the benefits of platooning in terms of road utilization, safety, and fuel savings on freeways, current research gives only little consideration to other scenarios like rural or even urban environments. According to the European Commission [2], however, the majority of all fatalities occur on exactly these rural roads (55 %) and urban roads (37 %); only a small fraction (8 %) occurs on freeways. This illustrates the need to focus research on non-freeway scenarios.

In general, urban scenarios share many characteristics with that of classical freeway scenarios, yet they are also characterized by specific challenges for platooning applications. Examples of such particularities are complex road topologies and an abundance of radio obstructions. The major difference, however, is the existence of intersections; both with and without traffic lights. Indeed, intersections controlled by traffic lights are a bottleneck of today's urban traffic – more specifically: while traffic lights improve safety, the queuing delay of traffic at intersections decreases traffic flow and thus decreases traffic efficiency [3].

Urban scenarios also require new platoon formation strategies as traffic speeds are (to a large degree) homogeneous. Thus, a change in speed for the sole reason of merging or splitting platoons often expends undue energy. Moreover, because vehicles' routes are often short and vehicles have a large choice of different routes, changes in platoon formation are common. This motivates us to investigate not just urban platooning in general, but also platoon formation specifically.

In this paper we therefore *(a)* present an approach to form and coordinate platoons of vehicles at traffic light controlled intersections of urban roads. In brief, individual vehicles form a platoon before (or while) waiting in front of a red traffic light and they exploit synchronized movement patterns to increase intersection throughput (and thus minimize the individual travel time). We also *(b)* investigate the benefit of this approach by means of simulations, providing a realistic exploration of platooning in urban environments (including realistic vehicle dynamics, platooning controllers, and network communication).

II. Related Work

The study of intersections regulated by traffic lights in urban areas (independent of platooning) has a long history. Regarding platooning and platoon formation, much work has focused on freeways. Hall and Chin [4] compare many different strategies that create vehicle platoons at freeway ramps. Heinovski and Dressler [5] handle platoon formation of driving vehicles, but also focus on freeway scenarios only. Both lines of work have been combined in approaches that investigate platooning on intersections controlled by traffic lights. Lioris et al. [6] investigate the effect of using such a system, but use both a custom-built simulator and abstract away from several key properties like vehicle acceleration characteristics and wireless networking effects. Lin-heng et al. [7] present a way of optimizing platoons crossing traffic light controlled intersections in terms of both waiting time and fuel consumption, but use a custom-built MATLAB simulation and abstract away from the acceleration or deceleration process and consider no wireless networking effects. Günther et al. [8] propose an approach for platoon formation in front of traffic lights, but consider platoon formations that are not string stable and consider no detailed controller model for Cooperative Adaptive Cruise Control (CACC).

The aforementioned publications illustrate that, while urban platooning is considered in some publications, conclusions commonly rest on considerations of only part of the relevant effects. Especially the consideration of vehicle dynamics, CACC controllers, and wireless network characteristics, however, is key to provide a realistic exploration of such a system.

In this paper, we close this gap; we investigate the field of platoon formation at traffic lights using a wide array of highly detailed computer simulation models of a popular and Open Source simulation tool, incorporating realistic V2X communication.

III. Platoon Formation

In this work, we assume that the frontmost vehicle of any platoon, the *Leader*, is driven by a human. All other vehicles, the *Followers*, are driven by a CACC controller. The converse is equally true: any vehicle that is driven by a human acts as a Leader of a platoon (of size 1). We do not assume that any information about road traffic is known in advance, nor do we assume that vehicles have already formed platoons. The basic idea of our approach, then, is to exploit the red phase of traffic light regulated intersections to form platoons from vehicles that are queueing. In more detail, the approach considered in this paper is as follows.

To be able to form platoons, all cars are transmitting *beacons* (periodic wireless broadcasts) containing their current position and their planned route (of which only a short section is relevant to the methodology described here). In addition to this, any platoon Leader is also transmitting beacons advertising its current platoon. These contain the current position, speed, and length of the platoon as well as its planned route (of which, again, only a short section is relevant to the methodology described here).

A. Join platoon

Each platoon Leader evaluates the contents of its neighbor table periodically to be able to find another platoon to join: Within 100 m of the intersection, we do not consider platoons eligible that take a different route. Overall, no platoons are eligible that are already on another lane or more than 50 m away. Among all remaining platoons the closest one is selected for joining. If a vehicle found a potential platoon to join, it contacts the platoon Leader in order to start the maneuver. Here, any join request that is not from a car on the same lane (with no other cars in-between) is rejected. After the maneuver was started, the joining vehicle continues to transmit beacons, but it rejects all incoming maneuver requests from other vehicles (except from the Leader of the desired platoon). If a join is permitted by the Leader, the actual join maneuver can be started. This maneuver is cancelled after 1 s of inactivity. The maneuver consists of the following steps.

First, the *Leader* sends general information about the platoon including *platoon formation* metadata (i.e., information about which car is driving at which position in the platoon) to the Joiner. This information includes the position which the Joiner is requested to take in the platoon. Next, the *Joiner* tries to close the gap to the desired platoon by increasing its speed until it reaches the speed limit. However, after the join maneuver started the Joiner is not allowed to change its lane anymore. In order to check the distance to the platoon, the Joiner is processing the platoon beacons of the desired platoon to be able to calculate the remaining distance. If the distance is close enough the Joiner sends an acknowledgement to the platoon Leader. Next, since the Joiner is close enough to participate in the platoon, the *Leader* updates its platoon formation metadata and forwards the update to all its Followers. Next, every *Follower* updates its platoon formation metadata. After the *Joiner* has been added to the platoon, it updates its platoon formation metadata and hands over control of the vehicle to the CACC controller. If the Joiner used to be a Leader of a platoon (with Followers of its own) before the join maneuver, it extends its platoon formation metadata by all vehicles of its previous platoon. The new platoon formation metadata is then sent to the platoon Leader. Next, the *Leader* applies the platoon formation metadata and forwards the update to all Followers. This step merges two platoons. Finally, every *Follower* applies the new platoon formation metadata.

B. Traffic light handling of platoons

We assume that traffic lights periodically announce scheduling information (current phase and remaining time until next planned switch) as beacons, transmitted at an interval of 1 s. Each vehicle stores received information in a neighbor table. This information is used by Leaders to avoid a red light violation of their platoon. This is necessary since Followers are driven by the CACC (that is, their behavior is dictated by the Leader) and while the Leader might be able to cross the intersection during a green phase of the traffic light, not all its Followers might.

If a Leader detects that its platoon is too long to cross the intersection during the green time as a whole, it requests a split maneuver. For this, it calculates the separation point of a platoon based on the current speed of its platoon and the contents of its neighbor tables as follows.

As the red phase is used for platoon formation, there is a high probability that the platoon is not driving at all when the green phase starts. Due to this, the check for red light violation needs to consider the acceleration process as well and cannot assume a constant speed. We calculate the required distance d_{req} to pass the intersection with the complete platoon as

$$d_{req} = d_{tl} + l_p + l_{tl}, \tag{1}$$

where d_{tl} is the distance to the traffic light, l_p is the length of the platoon and l_{tl} is the length of the conflict area of the intersection. In order to check if the platoon can cross the intersection as a whole, we need to calculate the distance it can travel during the current green phase d_{green}. Since the value for the acceleration $\ddot{x}_{platoon}$ can be measured by the car and since the desired speed $\dot{x}_d$ as well as the current speed $\dot{x}_{platoon}$ are known, we can calculate a bound for the required time t_{accel} to reach the desired speed as

$$t_{accel} = \frac{\dot{x}_d - \dot{x}_{platoon}}{\ddot{x}_{platoon}}. \tag{2}$$

Based on this, the value for d_{green} can be calculated as

$$d_{green} = \dot{x}_{platoon} t_{green} + \frac{1}{2} \ddot{x}_{platoon} t_{accel}^2, \tag{3}$$

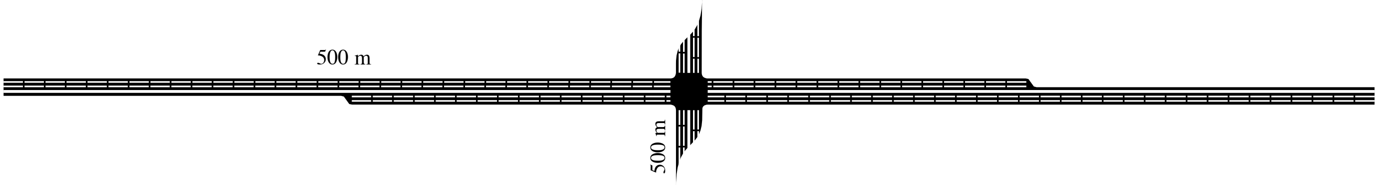

Figure 1. We are using a four leg intersection with a length of 500 meters for each leg. Vehicles are spawning at the outer end of the network on a single lane. After 250 meters, the number of lanes changes to three. Buildings (not shown) cover the free space, spaced 5 meters to the road.

where t_{green} is the remaining green time of the current phase. If the inequality

$$d_{req} \leq d_{green} \tag{4}$$

does not hold, the current green time is too short to let the complete platoon pass. In this case the Leader calculates the separation point as the longest l_p for which Equation (4) holds, then initiates a split maneuver for all vehicles behind this separation point.

After a Follower receives the order to get decoupled from the platoon, it reverts back to acting as an individual vehicle. This implies that it is the Leader of a (single vehicle) platoon again and thus starts to advertise this fact. Since the first vehicle behind the separation point will stop at the red traffic light, a new platoon will immediately start forming with it as Leader – ready to start driving at the beginning of the next green phase.

IV. Evaluation

We implemented the approach presented in this paper using the popular simulation tool Plexe [9] (version 2.1). It extends the Veins [10] open source vehicular network simulation framework by simulation models for platooning. Beside the proposed approach for platoon formation and management we also added a baseline scenario without any V2X communication or platooning mechanisms.

We consider a single symmetric intersection (illustrated in Figure 1) with four legs, each allowing vehicles to turn left, turn right, or go straight (for a total of twelve links) and each controlled by a static traffic light. Each leg of the intersection has a length of 500 m. The first half of each road leading towards the intersection is a single-lane road; the second half offers three lanes (one for each turning direction). All vehicles are entering and leaving the road network at its outer ends. Thus, each vehicle is travelling the full length of 1000 m.

Following recommendations by Koonce et al. [11], we are using a green time of 8 s and an additional 3 s for each yellow phase. For simplicity, we configure the traffic light to four phases, ensuring that there are no competing phases. This results in a total cycle length of 44 s for all traffic light phases. Beside the intersection, the network also contains buildings, located next to each leg of the intersection and fully opaque to radio transmissions. The distance between road and buildings is set to 5 meters. We are using the CACC Path controller by Shladover et al. [12] as recent research [5], [13] is focusing on this as a baseline. We employ common baseline parameters and note that investigating the behavior or properties of CACC controllers is out of the scope of this paper. Vehicles spawn uniformly random distributed at the start of a leg, at a rate of $0.48\,\mathrm{veh/s}$. Their position is simulated at 0.01 s time steps. Turn directions at the intersection are chosen with weights of 1:4:1 (left:straight:right). The Car Following (CF) model is set to Krauss and CACC, depending on whether the vehicle has joined a platoon. We configure CF parameters to a vehicle length of 4 m, desired speed v_d of 13.9 m/s (approx. 50 km/h), min speed v_{min} of 0 km/h, max speed v_{max} of 13.9 m/s (approx. 50 km/h), max acceleration of 2.5 m/s^2, and max deceleration of 9.0 m/s^2. For the Krauss model, we employ a driver imperfection σ of 0.5 and a desired headway of 0.5 s with 5 m minimum. For the CACC model, we configure a California PATH controller [12] with desired gap d_d of 5 m, bandwidth ω_n of 0.2 Hz, damping ratio ξ of 1, weighting factor C_1 of 0.5, and maneuver timeout of 1 s.

For statistical significance, we conduct 50 independent replications of 2000 s long simulations and discard any results recorded during the transient phase at the beginning (and a concluding phase at the end) of each simulation run.

First, we evaluate the performance of our platooning approach wrt. core metrics of road traffic efficiency. Related work by Lioris et al. [6] and Lin-heng et al. [7] suggests that platooning can have a positive impact in terms of travel time. We set out to validate this under realistic assumptions for both vehicle dynamics and wireless communication. We calculate the average travel time of a simulation run from the time each vehicle spent in the respective simulation.

Figure 2 illustrates the results for both the platooning and the baseline scenario. Error bars show the 95 % confidence interval. The data shows an improvement of 14 % in terms of total travel time. This difference is primarily attributable to the fact that CACC allows queueing platoon members to react almost simultaneously to a green light. In contrast, human driven cars start driving one by one; this has a pronounced negative impact on the traffic flow and leads to an accordion effect that is cumulative with the number of cars queuing at the traffic light: Even though the first human driven car starts to accelerate soon after the traffic light turns green, the second car is doing so only with a delay, thus needlessly increasing the distance to the preceding vehicle. These large gaps decrease road utilization and less vehicles are able to cross the intersection during a green phase.

As a second metric, as earlier work [14] suggests that reducing travel time can have a downside in terms of increased

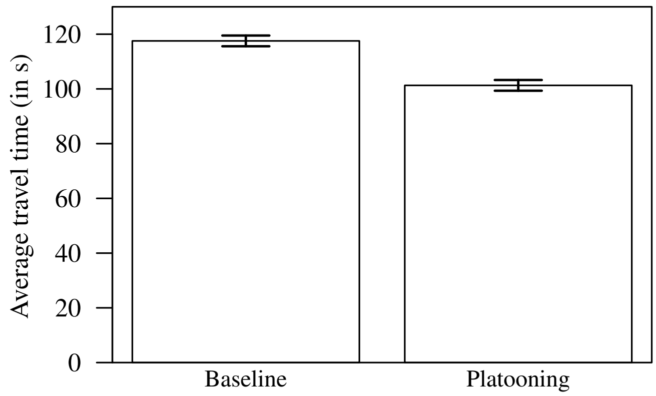

Figure 2. Average travel time of vehicles. Shown is the mean of all simulation runs and the 95 % confidence interval.

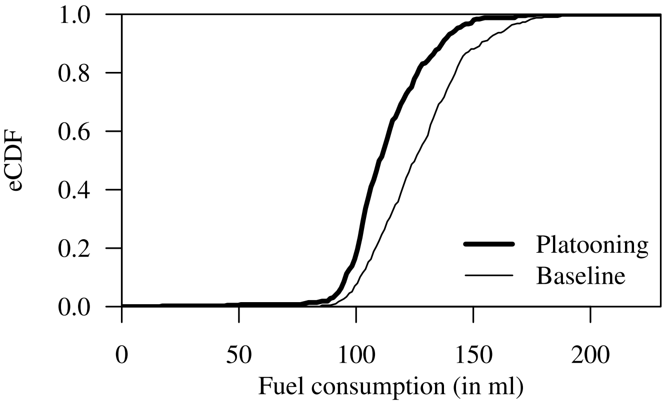

Figure 3. eCDF showing the fuel consumption of cars in the simulations. The amount of fuel is measured in ml.

fuel consumption, we investigate this metric using the models presented therein. This allows us to reason about a potential trade-off between travel time and fuel consumption. We calculate the fuel consumption of a vehicle by using the *HBEFAv3* model implemented in SUMO.

Figure 3 shows an empirical cumulative density function (eCDF) of vehicles' fuel consumption during the trip for all simulations. Here, results show an improvement of approximately 15 % when our platoon formation strategy gets applied. When investigating the reason, we find that, since the throughput of the intersection is increased by our approach, there are vehicles in the platooning scenario that only have to stop once (in front of a red traffic light). Idling in front of a red traffic light only uses little fuel, but in the baseline scenario, vehicles sometimes have to brake and accelerate more than once when queueing at the traffic light. As our platoon formation strategy is designed to be fuel efficient, these savings can carry over to the overall results.

V. Conclusion

We presented a realistic exploration of platooning in urban environments, in particular discussing the feasibility of platoon formation strategies in urban areas. We presented a strategy for the formation of platoons and compared this approach with a baseline scenario where all vehicles are human driven. Using extensive simulations based on realistic models of (all of) vehicle dynamics, platooning controllers, and wireless networking, we showed that driving in a platoon allows vehicles to save both 15 % of fuel and 14 % of travel time. In future work we will evaluate particularities of the wireless channel in urban platooning.

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