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A Numerical Study on Constant Spacing Policies for Starting Platoons at Oversaturated Intersections

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ABSTRACT Cooperative Adaptive Cruise Control (CACC) is considered as a key potential enabler to improve driving safety and traffic efficiency. It allows for automated vehicle following using wireless communication in addition to onboard sensors. To achieve string stability in CACC platoons, constant time gap (CTG) spacing policies have prevailed in research; namely, vehicle interspacing grows with the speed. While constant distance gap (CDG) spacing policies provide superior potential to increase traffic capacity than CTG, their major drawbacks are a smaller safety margin at high velocities and that string stability cannot be achieved using a one-vehicle look-ahead communication. In this work, we propose to apply CDG only in a few driving situations, when traffic throughput is of highest importance and safety requirements can be met due to relatively low velocities. As the most relevant situations where CDG could be applied, we identify starting platoons at signalized intersections. With this application scenario we show that applying CDG only in a few specific and crucial situation can have a major impact on traffic efficiency. Specifically, we compare CTG with CDG regarding its potential to increase the capacity of traffic lights. Starting with the elementary situation of single traffic lights we expand our scope to whole traffic networks including several thousand vehicles in simulation. Using real world data to calibrate and validate vehicle dynamics simulation and traffic simulation, the study discusses the most relevant working parameters of CDG, CTG, and the traffic system in which both are applied.

INDEX TERMS Cooperative adaptive cruise control, constant spacing, traffic light, signalized intersection, vehicle simulation, traffic simulation, capacity, throughput.

I. INTRODUCTION

CACC is the extension of Adaptive Cruise Control (ACC), a driver assistance system which automatically adjusts the speed of a road vehicle to maintain a safe distance from vehicles ahead [1]. Today's ACC systems use radar sensors to measure this distance. CACC extends ACC by additional communication components to exchange information with preceding vehicles. This information exchange helps to increase the density of platoons of vehicles with activated ACC and to potentially tackle string instabilities occurring in such platoons. String instability in vehicle platoons is caused by radar sensor delays and the dynamics of the vehicles and their power trains. To facilitate string stable spacing policies, the constant time gap (CTG) has prevailed in research; namely, the target distance between vehicles grows with the speed. However, increasing distances entails efficiency loss. This fact is reflected by the recent decision of Daimler to cancel their truck platooning program, which aimed on a 0.68 seconds time gap (15 m at 80 Km/h [40]) and did not achieve the expected efficiency in terms of fuel saving as stated in [2].

In this work, a constant distance gap (CDG) policy for CACC is considered. Although CDG can improve traffic throughput enormously, its applicability in urban environments has been proven to be very limited, due to its demand on communication structures to achieve robust string stability [3]. This demand includes communication with more vehicles than the direct preceding vehicle. Additionally, CDG only makes sense in combination with very small gaps, which implies potential safety issues at increasing velocities. The hypothesis of this work is to apply CDG only in few

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driving situations, when the following circumstances occur at the same time:

- Traffic throughput is of crucial importance.
- Platoon sizes are short enough that string instability or communication topology complexity can be handled, e.g., employing mini-platoon control strategy [3].
- Velocities are low enough to cover safety requirements, acceleration is smooth and predictable.

In all other situations, there either is limited benefit in applying CDG or it entails too much difficulties, so that CTG should be applied. While there are several use cases in which such conditions prevail, clearly, traffic-light-controlled intersections are one of the most relevant. At intersections, the traffic flow of two crossing streets share one spot in a time-duplex manner. Thus, exhibiting the highest possible traffic density on this spot is of high importance. Intersections controlled by traffic lights in addition provide clearly regulated right-of-way, i.e., during a green light phase, a platoon can pass this spot as a whole without paying attention to the cross traffic. Moreover, starting up from a stop line when the traffic light changes to green results in a smooth and predictable acceleration maneuver. Thus, as the most relevant application scenario for the hypothesis of this work presented above, we will focus on starting platoons at oversaturated, traffic-light-controlled intersections subsequently. Further application scenarios will be investigated in future work. By oversaturated we mean the traffic demand is higher than the intersection capacity, i.e., its maximum traffic throughput [26], a situation commonly found in major cities. Accordingly, we shall assume urban speeds of up to 50 km/h and stable platoons on intersection either achieved by limited length or a capable communication topology [3]. The research questions discussed in the rest of this paper focus on capacity improvement of CDG over CTG at oversaturated, signalized intersections. Our model for car following dynamics is based on the controller design presented in [30], parameterized using real world data.

Remark: Before proceeding, some comments on string stability are in order. Although string stability is a very important aspect for realizing CDG in platoons (see related work in the next section), we do not address string stability nor related control theory in this work. Instead, we focus on assessing the traffic performance of CDG over other spacing policies. While there are many other publications dealing with string stability, the rationale for this work is the usefulness of platoons, string stability permitting, in the context of specific use-cases. Our objective here is to study one such situation in detail, and to illustrate the effectiveness of platoons in an elementary situation in which string stability is not likely to be a serious technical issue.

A. MAIN FINDINGS OF THIS WORK AND THE STRUCTURE OF THIS PAPER

The contribution of this work is to show the benefit of applying CDG at starting platoons at oversaturated, signalized intersections. Assessing related benefits and potential drawbacks requires a comprehensive and thorough consideration of the whole traffic system. This includes many microscopic and macroscopic aspects and aggregating partial results. From the authors' perspective, these should be presented as a whole and not be split apart in different papers. With this in mind, after discussing related work in the Section II, the remainder of the paper is structured as follows.

- In Section III, we define the scope of our research and assess the CDG capacity improvement at a single traffic light on a straight road. For this purpose, we parameterize a CDG policy for vehicle simulation using real world data. CDG shows a traffic throughput improvement over the CTG baseline of up to 140%.
- In Section IV, we extend our study to a whole intersection, in order to cover traffic related aspects which lower the traffic throughput, such as turning vehicles and right-of-way. Vehicle simulations, including 160 vehicles, showed that these aspects can lower the CDG throughput improvement down to 27% in worst case. We further found that CDG benefit on throughput grows superlinearly with the CDG penetration rate among vehicles.
- In Section V, we present a method to calibrate a traffic simulation model using vehicle dynamics simulation. This is a prerequisite to include consideration of vehicle dynamics in a traffic simulation with thousands of vehicles to simulate CDG in a whole traffic system.
- In Section VI we study the impact of CDG on mutually influencing intersections of a traffic system. A synthetic arterial scenario of five intersections revealed that CDG may create backlogs of adjacent intersections, which block the cross traffic. A synthetic grid scenario of 25 intersections revealed that CDG is vulnerable to create gridlocks. We show the impact of these effects on traffic throughput and how they are related to the traffic light configurations with respect to green light times and offset.
- In Section VII, we complement our findings with studying CDG in a real world road network simulation scenario including ten intersections in Berlin, Germany. CDG gains a throughput improvement of 70%, while a penetration of 50% CDG reached an improvement of 25%. To exhibit its full potential in urban traffic, CDG needs to incorporate cooperative behavior between vehicles in order to enable cutting in and to prevent junction blocking.

We conclude this paper in Section VIII. In order to help the reader to follow the main findings arising throughout the study, each section concludes with a discussion of its main findings.

II. RELATED WORK

The most relevant goals for the design of CACC systems are to create small gaps between vehicles to increase road capacity, guarantee string stability [5], while keeping the communication topology as simple as possible [1]. The latter is, in the best case, reduced to each vehicle in a platoon receiving data from its direct preceding vehicle. Further possible communication structures may include receiving data from the platoon leader, multiple predecessors, the successor, or from a fully networked platoon [25]. Each of these structures entail different advantages regarding control quality, string stability and, thus, on the minimum gap size. Further goals on control optimization are ride comfort and fuel/energy consumption, which are both dependent from acceleration profiles.

A. CONSTANT TIME GAP POLICY (CTG)

The constant time gap policy refers to maintaining a time gap between vehicles in a platoon, which means that the gap increases linearly with the velocity. This policy has received most attention in the literature as it is known to improve string stability even with the simplest communication structure [5], [6]. The policy also contributes to safety, driving comfort, and imitates human driver behavior. However, the downside of velocity dependent gaps is the platoon length growing linearly with the velocity and the associated required road space. Commonly suggested time gaps of 0.6 s [7] correspond relates to additional road space of 8 m at 50km/h compared to stand still.

B. CONSTANT DISTANCE GAP POLICY (CDG)

The constant distance gap policy refers to a fixed gap between vehicles, independent from the velocity. This policy achieves the maximum efficiency in terms of road capacity improvement [50]; however string stability cannot be achieved using the information of the preceding vehicle only. In [8] it was shown that including additional information from the platoon leader is required. In order to address string stability, further communication topologies like mini-platoons [3] or multiple vehicles look ahead are reviewed in [3] [49]. Cyclic as well as bidirectional communication architectures are discussed in [9]. These approaches require a formal platoon architecture in order to determine a leader and the order of vehicles in a platoon [1]. This is more difficult to achieve than a simple communication with the preceding vehicle, which seems to make it unattractive to employ CDG rather than CTG, even with the drawback in terms of efficiency. With our hypothesis in mind, to employ CDG in very specific situations only, for this work, we can summarize the most relevant information on the state of the art regarding CDG as follows. After very early work [8], [50] on CDG showed that overall string stable platoons cannot be established using a one-vehicle look-ahead communication, CDG received less subsequent attention in literature than CTG. Most works on CDG focused on achieving string stability for the employment of CDG at the full range of driving conditions [3], [5], [9], [45], [49], [50]. Since this goal is out of scope of this work, we omit a deeper literature review in this field. However, the interested reader is referred to the survey article [45] and [1], [49].

C. ADAPTIVE GAP POLICIES

In contrast to CTG, many more parameters than a constant time factor can be incorporated in the spacing strategy, such as the spacing strategy proposed in this work. In the following, we give an overview of different approaches of such a kind, summarized under the term adaptive gap policies. The hypothesis of this work is to apply CDG only in few driving situations, realized by a context aware switch between CTG and CDG. This switch is depending on the current importance of traffic throughput, platoon length, and velocity. To our best knowledge, switching between CDG and CTG as we propose in this work, nor solely at a certain velocity threshold, has not been presented in literature before. In fact, this switching is not exactly an adaptive gap policy but rather an exchange of the policy online. In contrary, most works in literature either aim on designing one variable time gap (VTG) policy for the full range of driving conditions or switch between different longitudinal controllers while targeting the same spacing strategy. Switching between longitudinal controllers, mostly refers to different controller parameterization, e.g., regarding the information flow topology [43], or safety measures [44], triggered by ambient traffic conditions or communication impairments. The desired inter-vehicle spacing of VTG policies, in contrast to CTG, is treated as a function that has more parameters than a constant multiplier of velocity. There are different approaches that either combine the benefits of CDG and CTG in one VTG policy in different ways, or further include different control goals by making the gap dependent from more parameters than velocity [45], e.g., to address traffic safety, stability, and efficiency [47]. The latter is mainly addressed by reducing the gap compared with CTG while keep it smaller in general, but enlarge it at higher absolute [48] and relative velocities [46]. Further work has been done to improve the traffic flow stability in comparison to CTG [10], to integrate safety aspects in the spacing, such as the constant-safety-factor criterion (CSF) [1], [47], and vehicle limitations [11], or to adapt it to human behavior [12]. These adaptive policies gain their positive effect mostly at shorter distances at lower speeds compared to CTG. More detailed information about different types of VTG and other spacing policies can be found in the survey article [45] and [47].

D. COOPERATIVE MANEUVERS REGARDING CROSS/PARALLEL TRAFFIC

Another important aspect regarding the spacing of CACC platoons, is related to cooperative maneuvering [13]. Since platoons need to allow for cut-in maneuvers of other vehicles, required gaps have to be provided on demand. For urban applications, cooperation is especially required at intersections when platoons need to be crossed by other vehicles. We do not go into further detail on the wide field of related applications and the performance of different concepts among them, since cooperative maneuvering is not the focus of this work. However, although this work does not deal with such cooperative coordination strategy explicitly, the subsequent sections reveal that under certain conditions, CDG should be complemented by them. Such applications [14] which extend CACC to accommodate cross traffic and parallel traffic are currently being researched, as an example the interested reader can refer to the German research project, IMAGinE [36]. Its applications ''cooperative lane merging'' and ''cooperative decentralized intersection'' enable cutting-in maneuvers and ensure clearing intersections for cross traffic, which is relevant for this paper.

E. COOPERATIVE START-UP AT TRAFFIC LIGHTS

In the field of combining CACC with traffic-light control, most research is aimed at synchronization of platoons and green lights phases, so that stop and go can be prevented, such as [15]. Very few works focus on start-up control coordinating vehicles and traffic lights, so that as many vehicles as possible can pass an intersection after stand still. [16] studies platoons of vehicles waiting in front of a traffic-light regulated intersection, using SUMO [34]. A coordinated start-up initiated by a V2X message SPAT (SAE 2735) of the traffic light is proposed and the underlying algorithm also addresses the problem of low market penetrations. [17] considers a cooperative start-up of real world platoons at traffic lights. Findings indicate that a constant and preferably small gap is essential for increasing the throughput at traffic light regulated intersections. [18] presents an automatic start-up control to start up vehicles with less delay (47.2%) to improve traffic throughput, while [19] addresses an optimized acceleration profile to reduce fuel consumption.

F. PLATOONS IN SIGNALIZED NETWORKS

One important aspect of our study is the impact of CDG on mutually influencing intersections in a traffic system. In order to assess the impact of CACC on whole traffic systems, it is not sufficient to consider isolated intersections. In fact, multiple mutually influencing intersections such as signalized arterials need to be considered. This becomes especially relevant for dense platoons of vehicles, as shown in the subsequent sections.

Most research in this field focus on the control of traffic lights. In [20] and [51], the authors present algorithms to optimize signals at arterials, based on real-time platoon information. Different penetration rates are evaluated on an eight-intersection arterial using the VISSIM simulator, achieving a throughput improvement around 10% at 100% penetration in [20]. A travel time improvement of 70% on an arterial in a 4×4 grid network was achieved in [51] using SUMO [34].

While this shows the potential of including platoon information in the control strategies of traffic lights, in our study we focus on the benefits of optimizing platoon interspacing, rather than the signal control. Related work like [15] addresses optimization from the perspective of the vehicles in a cooperative way. Clusters of vehicles are formed that approach and depart at intersections on signalized arterials. The approach [15] requires a penetration rate of 100% and showed an increased traffic throughput of 50%, while reducing energy consumption. In [24], the authors showed, by means of a 16-intersection arterial, that without changing the signal control, throughput can be doubled if vehicles are organized to cross the intersections in platoons with 0.75 s headway, i.e., by reducing human delay and time gap only. Other works, such as [21] and [22] aim to prevent platoon stops by slowing down until the queue waiting at the intersection starts moving in order to safe energy/fuel. Penetration rates lower than 100% are considered in [21]. In [23] splitting up platoons and predicting trajectories aim on ideally passing green light phases. However, this requires a certain space while approaching the intersection and may hardly work for arterials with small intersection interspaces.

The trend of studies on platoons in signalized networks show that the most influencing factor regarding traffic throughput improvement is the fact that vehicles cross the intersections in platoons. Further, smaller enhancements can be generated by signal aware platoon control [15], [21], [22], [24] and a coordinated control strategy of the traffic lights [20], [51], which entails considerable system complexity in proportion to the achieved benefit. In this work we will show that simply applying CDG in platoons in oversaturated conditions can further increase the throughput by a similar order of magnitude as platooning itself. However, we will also give indications how CDG platooning in oversaturated grid networks could be aligned with the signal schema.

III. SINGLE TRAFFIC LIGHT PERFORMANCE

In this section we investigate the performance of CDG on a single traffic light, before considering whole intersections and traffic systems in the subsequent sections. For this purpose, we first need to define a baseline for comparison with other spacing policies and how performance can be measured.

In this regard, we define the research scope of this work, including preliminary assumptions. From this scope, we derive the working parameters for all policies; e.g., the standstill distance, as these parameters have a major influence on system performance. Once these parameters are identified, we use real world data to calibrate them. Finally, we describe the implementation of the policies that we use for simulation with the PHABMACS simulator [13] and we evaluate the results.

A. RESEARCH SCOPE

The most relevant metric to assess traffic light performance is capacity, which is defined by its maximum throughput, i.e., the maximum possible number of vehicles passing per time unit [26]. In order to measure the capacity, we consider traffic-lights in an oversaturated condition only (e.g., during rush-hour), which implies that there are always more vehicles waiting in the queue than can pass in one green phase.

The relevant relationship between throughput and platoons passing the traffic-light is the number of vehicles per platoon length. The portion of the platoon length pertaining to each vehicle in a CTG platoon is dependent upon the parameters depicted in Fig. 1. The constant portion is the vehicle length plus the standstill distance. The dynamic portion is the time gap, which grows with the platoon velocity. The dynamic

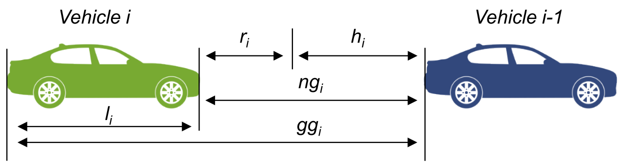

FIGURE 1. A platoon of i vehicles, where l_i is the length, r_i is the standstill distance, h_i is the time gap, ng_i is the net gap, and gg_i is the gross gap of the i^{th} vehicle in the platoon.

part is zero in CDG platoons, i.e., the CDG platoon length is always the same like in standstill, which makes the CDG so effective.

Another relevant parameter, especially for the start-up at traffic lights, is the drivers' reaction time. This time refers to the delayed start-up of a vehicle in the platoon with regard to the start-up of its preceding vehicle. In contrast to CTG, which is similar to human drivers' vehicle following behavior, CDG can hardly be realized by humans. Thus, for CDG we assume a fully automated longitudinal control with no driver in the loop. This consideration is especially relevant for the start-up at traffic lights, as human reaction time would make notable difference here. Since the objective is to compare the following behavior of CDG with other policies, we neglect the reaction time for all policies in this work.

Accordingly, in order to compare CDG with CTG, we need to parametrize the constant portion, vehicle length and the standstill distance with the same values. Furthermore, these values should be chosen as realistic as possible for comparison, as their ratio to the time gap makes a considerable difference. Finally, we also need to parameterize the time gap of CTG as realistically as possible.

Indications for all these parameters could be derived from Highway Capacity Manual (HCM) [26] and the German equivalent HBS [27]. The HCM indicates a capacity of 2400 vehicles per hour on open roadways, while the HBS indicates 2000 vehicles per hour. Besides the fact that both values differ considerably (gross gap between vehicles of 1.8 s and 1.5 s) we have no indication on how to split that time in the dynamic and the constant portion. Recent work [14], on the other hand, indicates that time gaps for CTG of below 0.6 s can be realized for string stable platoons with automated CACC, (0.25 s in [41]).

Remark: In this study we do not use the theoretical parameters used in the above reports, but rather real measurements. We assumed for this study, that future CACC distance behavior in series production will be of similar performance as skilled human drivers and with no reaction time. For this purpose, we derive our baseline (time gap and standstill distance) from real world data collected during the field trial simTD [28]. For the sake of fairness, in this section, we will also present results of using parameterization of achieved time gaps in current research. We further assume that the velocities in our study are low enough so that an automated system can keep the CDG standstill distance.

The resulting parametrization is presented in the next subsection. Recall, the hypothesis of this work is to apply CDG only in few driving situations, realized by a context aware switch between CTG and CDG. This switch is dependent from the current importance of traffic throughput, platoon length, and speed. With the focus on starting platoons at traffic-light-controlled intersections, we consider this context to be always given at all simulations presented in this work because:

- Traffic throughput is of crucial importance at intersections as they are the bottlenecks in traffic.
- The platoon length is inevitably limited due to the signal phases cutting platoons.
- Most traffic light scenarios are located in urban areas and we limit our study to velocities below 50 Km/h.

As earlier mentioned, CDG should not be applied at arbitrary high velocities due to safety aspects and stability issues arising when the one-vehicle-look-ahead communication pattern is applied. Thus, there is a speed limit at which the CDG spacing policy is required to be switched to CTG. For the threshold of this speed limit we chose 50 Km/h and 30 Km/h as parameters to be studied in simulation, due to the following considerations. While in German cities 50 Km/h is the speed limit for general safety considerations, 30 km/h is the speed limit for areas of increased safety demand. These values provide a good indication for different levels of velocity related safety in our study. Thus, we define and study two different Policies. For the 50 Km/h threshold we can apply CDG without switching in simulation of urban environments. In addition, we define another policy that switches from CDG to CTG at 30 Km/h. This policy will be referred to as SWITCH in the remainder of this work.

The specific velocity thresholds of future real world application should be derived from real world working parameters, e.g., the achieved performance of the underlying longitudinal controller and the current reliability of communication link. The same applies for the optimal standstill distance in real world, which should be chosen as small as possible in order to gain efficiency and large enough regarding the named real world parameters. Note that, keeping a standstill distance of 2.95 m, as we will use in our study, might seem challenging in terms of user experience, even below 30 Km/h. However, we assume that with the advent of automated driving, users will gain trust in that technology in the future. This also applies for CTG with very small time gaps, as [41] shows in simulation with a resulting distance of 3.25 m at 30 Km/h and 3.75 m at 50 Km/h.

As earlier stated, this study considers the one-vehicle-look-ahead communication pattern only, which does not require a formal platoon architecture and provides the best possible communication stability for high frequent real time applications like CACC. We assume this pattern to be the most suitable in oversaturated multi-intersection-scenarios with a high proportion of V2X enabled vehicles. However, in cases where one-vehicle-look-ahead communication can be employed successfully, it can reduce the time headway of CTG notably and make CDG overall string stable.

B. CALIBRATION OF SIMULATION ON REAL WORLD DATA

As motivated in the previous subsection, we employ real world data to calibrate the policy parameters for simulation, as well as the baseline for evaluation. The data we used has been captured at simTD [28], a large scale field trial for testing V2X applications conducted over a period of six month, including a test fleet of 100 controlled vehicles. For the calibration of the simulation model, we consider start-up situations at traffic lights. The relevant calibration data for parameterization includes the acceleration profile in order to model the first vehicle of a platoon, the standstill distance and the time gap. Therefore, we filtered situations from the logged test data according to the following constraints:

- start-up after standstill, preceding vehicle is present;
- vehicle accelerates, target speed 40km/h – 65 km/h;
- accelerator is not released during the situation.

The filtered data included 3,546 start-up situations from 27,642 logged trips driven by 98 different drivers (73 male, 25 female). Fig. 2 depicts the resulting data, inspired by the model matching process for acceleration maneuvers described in [13]. All situations were aligned time-wise, at the point time when the preceding vehicle starts moving. The resulting curves of velocity and distance to the preceding vehicle were averaged. The averaged time gap settles at 0.87 s and the average standstill distance is 2.95m. We used these values to feed our simulation models. The black dotted lines represent the 95% confidence intervals of distance and velocities, which mark the band for simulation model validity according to [13]. The simulation is considered as valid if it stays within the confidence band. We calibrated the acceleration profile of the platoon leader in our simulation to match the average speed trajectory of real world data. The speed profile in simulation matches the confidence band of the real world data, except for some dents in the graph during gear shifts. Thus, we consider the simulation model as valid representation of the real world data. In this way we were able to determine all relevant parameters as defined for our research scope, except for the vehicle length. For the vehicle length we assume 5.15 m due to the following considerations. According to [29] in 2011 we can assume an average length of passenger vehicles of 4.75 m. We add further 0.4 m to represent the increased length of vehicles since 2011 and some heavy duty traffic.

C. SPACING POLICIES

Using the parameters derived in the previous subsection, we can now define the following policies for studies in simulation.

1) CDG-CONSTANT DISTANCE GAP

The constant distance gap policy *CDG* is defined by the vehicle length of 5.15 m and the stand still distance of 2.95 m determined in the previous subsection.

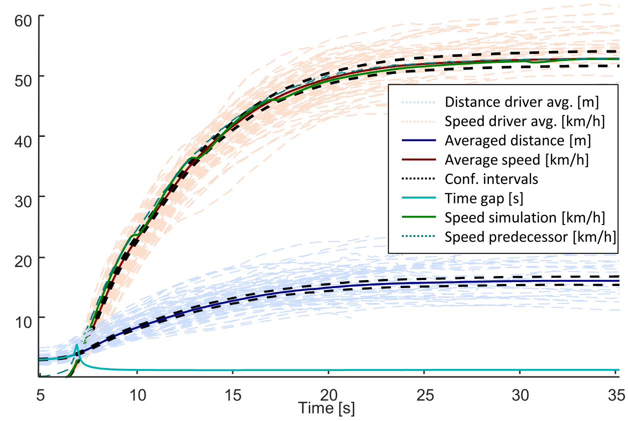

FIGURE 2. Velocities, following distances, and confidence bands processed from real world start-up situations to derive CDG and CTG controller parameters.

2) CTG-CONSTANT TIME GAP

According to the calibration with real world data we define the baseline policy for this work with 0.87 s time gap, in the following referred to as *CTG-Ref.* At 50 Km/h a gap of 15 m is reached. This is close to match the American HCM at speeds in urban areas (50 Km/h). Assuming the gross gap between vehicles of 1.5 s (HCM at 2400 vehicles per hour) together with vehicle length and standstill distance (as defined above), this results in a time gap of 0.92 s. *CTG-HBS* represents the German HBS with 2000 vehicles per hour, a time gap of 1.22 s.

3) SWITCH

Based on the parameters of *CDG* and *CTG-Ref*, we define two polices to switch between *CDG* and *CTG-Ref* at a predefined velocity of 30 Km/h. *SWITCH1* renders the time gap using the difference between the current velocity and 30 Km/h, i.e., at 50 Km/h a gap of 7.8 m is reached. *SWITCH2* increases the gap from 0 m at 30 Km/h to 15 m at 50 Km/h, so that the same distance as with *CTG-Ref* is reached.

4) MIX

In order to enable studying a certain rate of CDG penetration, we define the *Mix* policy. The penetration rate (fraction of vehicle adopting the policy) is set to 50% with a randomly alternating pattern on *CDG* and *CTG-Ref.*

D. REALIZATION

All spacing policies described above have been implemented in the PHABMACS simulator [13], for subsequent evaluation. Furthermore, all policies rely on the one-vehicle look-ahead communication pattern [25]. The evaluation scenario consists of a straight single lane road with a single traffic light, generated manually. In order to measure the maximum achievable throughput of all policies, we create the same oversaturated initial condition for each policy simulated. All vehicles are queued up to at the stop line. Once the traffic light turns green, the platoon starts accelerating up to 50 Km/h. Vehicles passing the stop line are counted for evaluation.

1) CTG

The basis controller for the vehicles is a Java implementation of the cascaded PID framework presented in [30] (see Fig. 3), integrated as longitudinal controller in the PHABMACS driving controller hierarchy (see [13] for explanation). As the controller design is discussed in detail in [30], we just briefly describe its main components. G_i represents the low-level controller LL acting on the vehicle model$i$, where i represents the i^{th} vehicle in the platoon. LL is different from the low-level controller in [5] and was initially presented in [31]. The input of LL is the control value u_i represented by the desired acceleration of the vehicle, while the output is the desired torque for the engine and the brake, which are fed directly to the vehicle model as described in [13]. $C_{i,ACC}$ is a PD-type feedback controller that acts on a locally sensed distance to the preceding vehicle with a simulated sensor delay of 150 ms. H_i implements the spacing policy. For CTG the policy H_i is defined by $1 + h_{d,i}s$ [30] (here, s is the Laplace transform variable) which is the transfer function representation of $d_{r,i} = r_i + h_{d,i}v_i$ in the time domain, where $d_{r,i}$ is the desired spacing, r_i is the standstill distance, $h_{d,i}$ is the time gap and v_i the velocity. $C_{i,CACC}$ is a feedforward filter described in [30] using the communicated information (with a simulated delay of 50 ms at 25 Hz) of the directly preceding vehicle, i.e., the current and desired acceleration a_{i-1} and u_{i-1}, as well as the current time lag of the vehicle model τ_{i-1}. In contrast to [30] we treat τ_i as a dynamic value for each vehicle, which is taken online from a calibrated map depending on the current gear, requested torque (drive/brake), and current engine rotational speed.

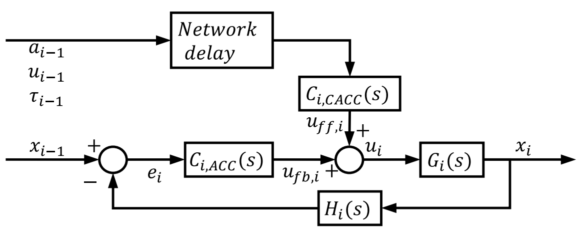

FIGURE 3. Control structure of the longitudinal model.

2) CDG

For the *CDG* policy, there are two differences from the setup described above. The spacing policy H_i is expressed by $d_{r,i} = r_i$ in the time domain and $H_i = 1$ in the frequency domain. The feedforward controller $C_{i,CACC}$ is the implementation of the system depicted in Fig. 4. An acceleration curve is predicted for the preceding vehicle, based on the received information $a_{i-1}(t)$, $u_{i-1}(t)$, and $\tau_{i-1}(t)$. Taking the latest measured communication delay into account, u_i is calculated so that a_i meets a_{i-1} in a predefined time interval in the future. This controller has been tested in real world test vehicles and will be presented in detail in future work.

3) SWITCH

By combining *CDG* and *CTG* according to the parameters described above, we realized *SWITCH1* and *SWITCH2* as

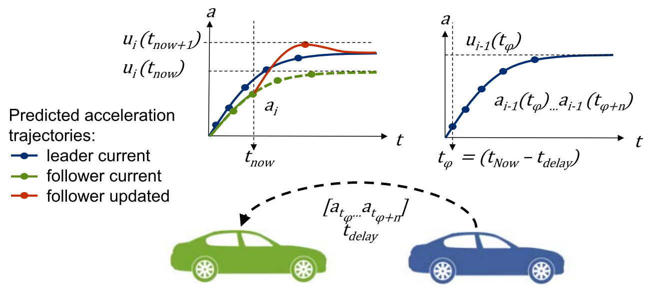

FIGURE 4. Concept of the predictive CDG feed forward controller, where t_{now} is the current point in time, t_{now+1} is the next future point in time, t_{delay} is the communication delay, n is the length of the acceleration trajectory $[a_{t_\varphi}..a_{t_{\varphi Cn}}]$.

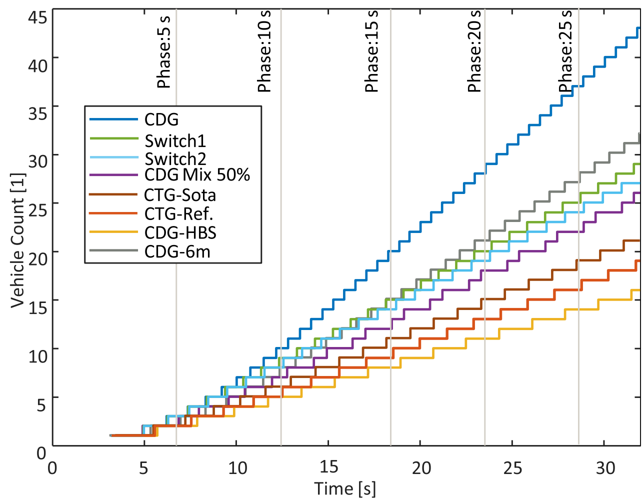

FIGURE 5. Throughput comparison for the different spacing policies.

a simple change between both policies at 30 Km/h, with accordingly defined time gaps. As stated in the research scope (section III.A), we consider the context for switching to CDG to be always given at all simulations presented in this work and the only parameter to be varied in the simulation is the velocity threshold. Consequently, we can simplify the switch by formulating it in one policy *SWITCH1* as $d_{r,i} = r_i + h_{d,i}\max(0, v_i - v_{lim})$, where v_{lim} is the threshold of 30 Km/h. For *SWITCH2* the time gap is larger with $h_{d,i} = 2.5h_{d,i}$.

E. EVALUATION

Fig. 5 depicts the results of eight simulation runs with one graph each for the eight described polices. The graphs can be interpreted as a counter of vehicles passing the traffic light stop line over time. The counter starts at time 0 when the traffic light turns green after red. The vertical lines in the figure mark the throughput at different green phase lengths. Their offset to the time scale is caused by the yellow phase of three seconds. The throughput of the alternative spacing policies for a specific green phase length can be read from the figure at the point where its vehicle counter graph crosses the vertical lines. For instance, the number of passing vehicles at a green phase of 15 s is 20 for *CDG*, 15 for

SWITCH1, 13 for *MIX*, 11 for *CTG-Sota*, 9 for *CTG-Ref.*, and 8 for *CTG-HBS*. In order to make the performance of *Mix* comparable to the other policies at each green phase in Fig. 5, we need to create the same portion of *CDG/CTG* at each point in time. Thus, we applied a deterministic alternating pattern on the *Mix* policy for this simulation, while a random pattern is applied in subsequent sections. Note that at time 15 s the platoon leader reaches maximum speed of 50 Km/h. In case of the *CDG* policy that means the whole platoon is already at maximum speed and *CDG* can fully exhibit its performance benefit. Accordingly, its throughput graph becomes linear. On the other hand, in the case of *CTG*, vehicles start moving one by one, while the *CDG* platoon is moving as a whole from the point in time when the platoon leader starts up. This is the key effect which makes *CDG* effective at traffic lights. For a more performance oriented analysis of the results, Fig. 6 compares the throughput improvement of all policies with the baseline *CTG-Ref* over time. While the throughput improvement of *SWITCH1/2* and *MIX* reach their saturation around 50% near 20 s, *CDG* approaches an improvement of about 140%. In order to illustrate the impact of different standstill distances, we ran one simulation with the double standstill distance of 6 m *(CDG-6m)*. It improved the throughput by 70%. We note that, 6 m is an (artificial) large standstill distance and more than one vehicle length so a reduction in efficiency is expected. Clearly, as one increases the gap, the steady state throughput gain decreases proportionally.

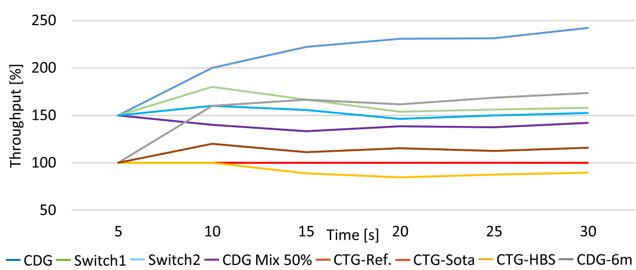

FIGURE 6. **Throughput improvement of the different spacing policies.**

F. CONCLUSION – SINGLE TRAFFIC LIGHT PERFORMANCE

Our studies of *CDG* on start-up at a single traffic light show a performance benefit over *CTG* and the other policies. This performance benefit grows with the green phase length, reaches 120% at 10 s green time and then saturates at approximately 140% for longer green phases. A penetration rate of 50% *CDG* in a mix with the baseline policy only reaches 45%, i.e., the *CDG* benefit does not scale linearly with the penetration rate. In order to provide a comparison between the policies, the baseline parameters of the policies were calibrated on real world data and human reaction time was neglected. It must be noted, that for green phases of more than 30 s, the *CDG* platoon exceeds a length of 43 vehicles, which already could give rise to string stability issues. For that reason, for a real world implementation, counter measurements such as splitting up into mini-platoons must be considered [3], which may also affect the performance. The *SWITCH1* policy, which switches from *CDG* to *CTG* at 30 Km/h reaches a performance gain of 60%.

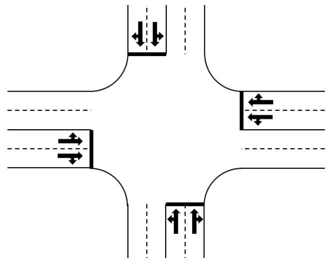

FIGURE 7. **Four way, reference intersection layout for simulation.**

IV. SINGLE INTERSECTION PERFORMANCE

In this section we expand the analysis of *CDG* from a single traffic light to a whole intersection. The very good performance of *CDG* policies, described in the previous section, is to a large extent due to the fact that the platoon could pass the traffic light in a free flow. However, at whole intersections the impact of traffic flow reducing factors needs to be taken into account for performance comparison. This includes reduced velocities while turning, stops due to giving way while turning, as well as the fact that green light phases cannot be arbitrary long as they share the full cycle time with cross traffic and turn phases. We start with the definition of an intersection layout that covers all aspects relevant for this research. Subsequently, we define further metrics to assess *CDG* performance at intersections and we finally evaluate results gained from simulating a whole intersection.

A. INTERSECTION LAYOUT AND SIMULATION SETUP

Intersection layouts in urban areas include many possible combinations of elements where each element might have a different impact on the performance of *CDG* [26], [32]. As we have to handle and permute many parameters apart from the layout, our objective now is to define a reference layout that covers as many layout related aspects as possible and can be a fixed parameter for further studies.

Note: A literature review failed to reveal results on the question of what are realistic portions of turning vehicles.

We, thus, decide to permute both as parameters of the simulation. Fig. 7 depicts our reference layout with two lanes in each direction. Each right lane mixes straight driving with protected right turning vehicles, as there are no pedestrians. Each left lane mixes straight driving with unprotected left turning vehicles, which always need to wait for oncoming vehicles. This is ensured as the intersection is oversaturated according to the scope defined in the previous section, i.e., there are always more vehicles waiting in front of red traffic lights from each direction than can pass it during the green phase. This oversaturation at the intersection inlets is also necessary to allow the different policies to exploit its full potential of passing vehicle per green light phase. Left turning vehicles entering the intersection consequently block their lane until the end of the green light phase. This reduces the random effects in the resulting throughput, independently from the desired parameterization of the simulation. The radius of the intersection is 20 m and turning velocity is 7 m/s which results from a maximum lateral acceleration of 2.5 m/s^2 [33]. We choose this particular intersection layout due to the following considerations. We should cover protected turning (turning signal phase - no yielding required) due to the reduced velocity while turning and unprotected turning (yielding required) due to its blocking effect on the following vehicles. We do not need to consider dedicated turning lanes, as they would just shift the blocking effect to occur at a higher portion of turning vehicles. We also do not need to consider dedicated traffic light phases for turning, as we already cover protected turning. We also decide to avoid lane changes in the whole scenario, in order to exclude the impact of lane changes on the simulation results. Lane changing is difficult to model, it depends on many parameters of random character, and we have no ground truth for calibration. Lane changing would further enlarge the parameter space for our simulation, while having a considerable random influence on the results. For the metrics discussed in the next subsection, missing lane changes are only relevant for the travel time of single vehicles on the blocked left lane when the right lane is free. However, we assume these to be averaged out by faster vehicles on the right lane. Thus, the results in real world would differ only slightly from the simulation.

B. METRICS

To compare the performance of *CDG* and *CTG* at intersections, we measure the maximum intersection capacity [27] for both. The intersection configuration parameters to be permuted are the green phase length and the ratio of left and right turns per lane. While oversaturating the intersection inlets, we choose to measure the following metrics:

- Throughput (vehicles passing per time)
- Travel time (average time vehicles need to pass)
- Density (portion of road meters occupied by vehicles)

The throughput is needed to derive the intersection capacity, while the travel time experienced is a quality of service (QoS) measure. We also measure the density to analyze the efficiency of road utilization, which is foremost relevant when whole traffic systems are considered in the following subsections.

C. EVALUATION

As earlier stated, our goal is not to find an optimization for the traffic light setup but to study the performance of *CDG* vs. *CTG* under all potentially occurring traffic conditions. In order to map this span of conditions, the simulation ran with 504 permutations of the following conditions, as motivated in the previous subsections.

- Intersection layout is fixed.
- Traffic flow at the intersection inlets is oversaturated, so that there are always more vehicles waiting at a red light than can pass during one green phase.
- Portion of right (0%, 10%, 30%) and left turns (0%, 5%, 15%, 30%) are permuted.
- Penetration rate of CDG and CTG are permuted with (0%, 10%, 25%, 37%, 50%, 75%, 100%).
- Green light phase is permuted from 5 s to 30 s. In one permutation, the green time is the same for all directions.
- Simulation time is five full traffic light cycles.

The portion are a sample of possible permutations to illustrate trends. Additional measurements can easily be incorporated. The intersection layout and the simulation setup as described in Section IV-A, as well as the policies as described in Section III-C were implemented in the PHABMACS vehicle simulator [13]. Fig. 8 depicts a view on the intersection during simulation. The colored circles represent the radius for travel time measurement (40 m) and density (20 m). The travel time of each vehicle is measured from the point in time when it enters the named radius until it leaves the radius. The density is calculated for each second of a simulation run by dividing the length of available lane meters within the named radius by the cumulated length of all vehicles currently being inside the radius. For the evaluation, the measured travel times and densities are averaged over one simulation run. Throughput is calculated from the number of vehicles leaving the 20 m radius per time. To generate randomness and equally distribute turnings and penetration ratios, PHABMACS employs the Mersenne Twister algorithm [35]. On average around 160 vehicles were in the simulation at the same time, 40 vehicles per direction.

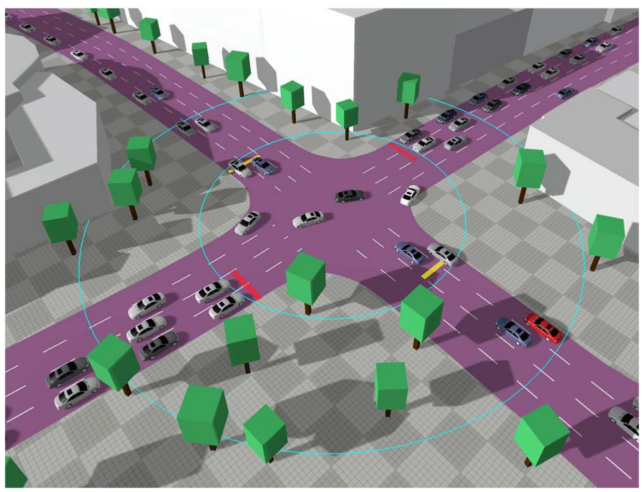

FIGURE 8. Simulation of a single intersection in PHABMACS simulator.

The results of the simulations for 15 s green phase, captured in accordance with the previous section, are depicted in Fig. 9. The throughput of different *CDG* penetration rates is depicted in vehicles per hour on the vertical axis, for each permutation of left and right turn rate on the horizontal axis. The highest throughputs were measured with no turning

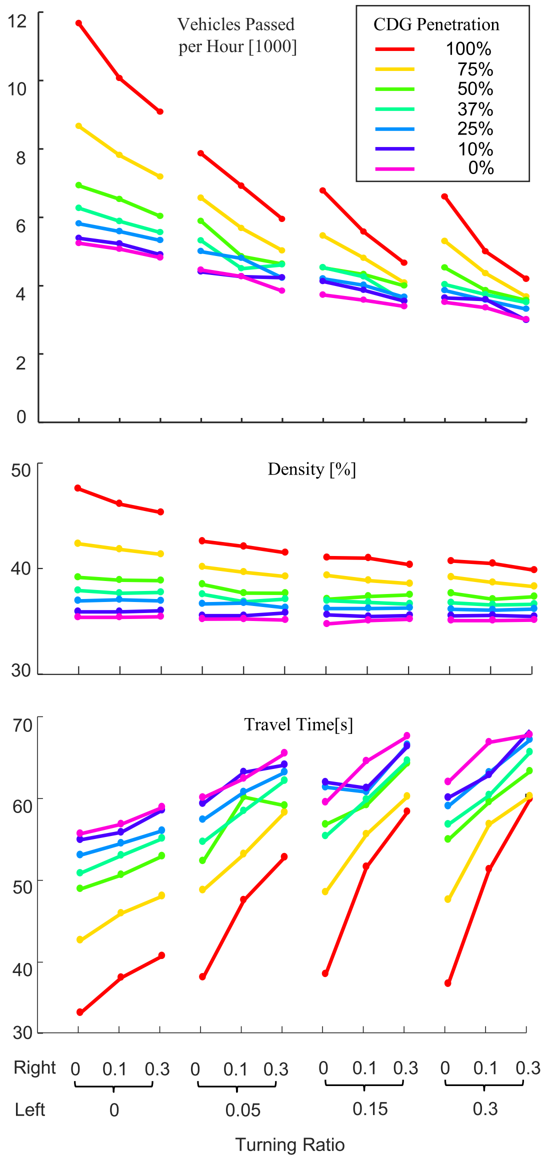

FIGURE 9. Simulation results on a single intersection CDG vs. CTG throughput, travel time, density.

TABLE 1. Throughput improvement of CDG at single intersection.

Turn ratios	Metric	Green Phase [s] 5	10	15	25	25	30
no turns	CDG [%]	50	81	120	134	140	135
	Mix [%]	21	25	33	41	42	37
	PIR	0.42	0.31	0.27	0.30	0.30	0.27
right turns 30 %	CDG [%]	50	64	85	91	94	107
	Mix [%]	21	19	25	28	29	28
	PIR	0.42	0.31	0.30	0.31	0.31	0.26
left turns 30 %	CDG [%]	45	64	94	92	112	109
	Mix [%]	19	26	17	21	29	30
	PIR	0.43	0.42	0.18	0.23	0.26	0.28
left + right turns 30 %	CDG [%]	59	27	42	50	45	46
	Mix [%]	28	10	23	21	16	19
	PIR	0.47	0.39	0.55	0.42	0.35	0.41

vehicles, at 11,550 *CDG* and 5,254 *CTG-Ref*, an improvement of 120%. The lowest throughput at 30% right turns and 30% left turns is at 4,281 *CDG* and 3,016 *CTG-Ref*, an improvement of 42%.

The improvement without turning is similar to the improvement measured at a single traffic light in the previous section. With a ratio of 30% right turns on the right lane, the improvement falls to 88% due to the reduced velocity while turning. An additional 30% left turns on the left lane almost stops the throughput on the left lane, i.e., all vehicle passing the intersection are affected by the reduced speed of the right turns, which results in a drop of the improvement to 42%.

The travel time drops from 55 s (*CTG-Ref*) to 34 s (*CDG*), which corresponds to a travel time reduction of 38%. The lowest time reduction of 12% results with 30% left turns and 30% right turns. Throughput improvement and travel time reduction correlate with an increased density on the intersection. While the average density of *CTG-Ref* is around 35% for all permutations, the density of *CDG* depends visibly on the turning ratios. With no turns, the density for *CDG* peaks at 47%. For different *CDG* penetration rates, the same superlinear effect becomes apparent on throughput, travel time and density. At the first glance all graphs seem to follow an approximately uniform course. However, there are some irregularities recognizable in the pattern due to the randomness in the simulation. For instance, at 5% left turns, 10% right turns and 50% penetration, the throughput is the same as with 25% penetration. Moreover, although the travel time falls with an increasing *CDG* penetration, the travel time gain is of less magnitude as the throughput improvement. This is due to the fact that during the red signal for all directions portion of the traffic light cycle, no time benefit can be achieved by *CDG*. Discretization effects of the traffic light queue, become apparent at 15% left turns and 25% penetration with a higher throughput than *CTG-Ref*, yet with a higher travel time.

Table 1 summarizes the throughput improvement over *CTG-Ref* (throughput of the considered policy divided by throughput of *CTG-Ref*) at all green light phases simulated. All values are rounded to the depicted number of digits. For the sake of simplicity, the table only lists the extreme values of 100% (*CDG*) and 50% (*Mix*) penetration. The penetration dependent improvement ratio (PIR) on the throughput is calculated by $\frac{Mix}{CDG}$ to compare the improvement of *CDG* and *Mix*. Accordingly, the PIR is an indicator for the relative benefit of CDG, i.e., the benefit of each single CDG vehicle among CTG vehicles in relation to absolute benefit. At 15 s green phase length with left and right turns, the PIR peaks at 0.55, i.e., 50% CDG penetration were able to gain 55% of the improvement of 100% CDG penetration. With no turns and 30 s green time, only 27% percent were gained. While the absolute improvement of CDG falls with falling green phase and increasing turning rates, the PIR grows for short green phases and high turn rate.

D. CONCLUSION–SINGLE INTERSECTION PERFORMANCE

In this section we broaden the study of *CDG* from a single traffic light to a whole intersection, including different rates of protected and unprotected turning. As expected, the presence of turnings at the intersection reduced the benefit of *CDG* compared with a single traffic light. The lowest benefit was measured at 10 s green phase length, where the throughput improvement shrank from 81% without turning to 27% with turnings. The specific impact of turnings depends on presence and length of turning lanes. In our studies we omit such lanes in order to reduce parameter space. Thus, in our studies, one turning vehicle already blocks a complete lane.

Summary of Section IV: Vehicle simulations, including of up to 160 vehicles, showed that the presence of turnings at the intersection can lower the CDG throughput improvement to 27% in worst case, compared with 140% at a single intersection. The CDG penetration rate among CTG has a superlinear effect on its absolute benefit. This fact is a potential hurdle for market-introduction. However, with falling absolute benefit of CDG, due to high turning rates and short green phases, the relative benefit of CDG penetration rate increases. Relative benefit means the benefit of each single CDG vehicle among CTG vehicles in relation to absolute benefit.

V. MODEL CALIBRATION FOR MACROSCOPIC SIMULATION

The next step for our studies on CDG is to evaluate its impact on whole traffic systems, i.e., on multiple mutually influencing intersections. As motivated earlier, development and evaluation of control systems like CACC in simulation requires realistic mapping of vehicle dynamics. Fine differences in mapping physics and the control system interacting with its environment may lead to considerable differences to the resulting behavior. Thus, for studying CDG at a single traffic light, the sub-microscopic vehicle simulator PHABMACS is the appropriate tool (for explanations of the terms microscopic, mesoscopic, macroscopic, and sub-microscopic simulation models, see [13] or [37]). Thanks to its ability to scale out physics and control algorithms, simulating a whole intersection including hundreds of vehicles for hundreds of simulation runs is enabled [13].

However, in order to research whole traffic systems including many thousands of vehicles, PHABMACS becomes out of scope. Mapping that many vehicles would still require considerable time and computation capacity. Furthermore, traffic systems under research observed from a macroscopic perspective may also produce realistic results, provided that an appropriate model is leveraged, which maps the microscopic behavior sufficiently in a macroscopic scale.

We use the methodology proposed in [42] to calibrate and validate a sub-microscopic simulation model against a microscopic simulation model, in order to enable macroscopic traffic analysis including several thousand vehicles. We use this methodology to match the implementation of CACC controllers in PHABMACS and its validated vehicle model to the SUMO [34] traffic simulator. Calibration and validation are essential here in order to ensure that the traffic simulation model in SUMO generates the same results regarding relevant metrics as the vehicle dynamics simulation model in PHABMACS. All simulations presented in Section V to VII were done using SUMO version 0.32.0. In order to make the results reproducible, all information about our modelling and about parametrization different from default values are given in this in this paper and its references.

VI. MULTI INTERSECTION PERFORMANCE

In this section, we use synthetic simulation scenarios to reveal traffic hindrance situations caused by CDG, which lead to a decreased performance of CDG in a traffic system, compared with the single intersection analyzed earlier. Two main factors lead to such a lowered performance. First, congested intersection outlets that lead to obstructed off-flowing traffic, and second, reduced in-flowing traffic. Thus, the main question to be discussed in this context is the impact of CDG on the traffic system, or more precisely on multiple mutually influencing intersections.

To proceed, for consistency with our previous discussion, we consider the same intersection layout. We combine this layout to two synthetic simulation scenarios, an arterial signalized corridor [38] with five intersections and a coordinated grid network [38] of 25 intersections. The intersections are aligned along the dimensions of an even grid with the distance of 276.5m NW bound and 192.5m SE bound. These dimensions originate from the area depicted in Fig. 10. These constant intersection interspaces enable isolating the impact of interspace length on the simulation results from the other simulation parameters. Although this area in real world consists of one-way streets partially, we unify the simulation scenario with two-way streets.

Including up to 5500 simultaneously, both scenarios are simulated with multiple permutations of traffic light configurations and turning ratios. With regard to simulation runtime, we can afford such a number of vehicles and this span of permutations, thanks to the calibration of the CDG and CTG model with the traffic simulator SUMO. The results are calculated counting vehicles entering/leaving the simulation 20 m far from the outer intersections, i.e., excluding the unbound queues. All trips end outside this area. Final values are captured when all metrics increased to a steady state level and keep it for five hours simulation time. For all simulation scenarios, we assume an oversaturated traffic flow at the inlets and an unobstructed outflow of the traffic system. We permute the parameters of the traffic light system in order to reveal possible drawbacks of CDG /CTG related to specific setups. Finally, we model a real world road network simulation scenario using a real world traffic layout and traffic light configurations in the following section. All information needed to reproduce these simulations done with SUMO are either standard parametrization of SUMO or provided throughout sections IV to VII.

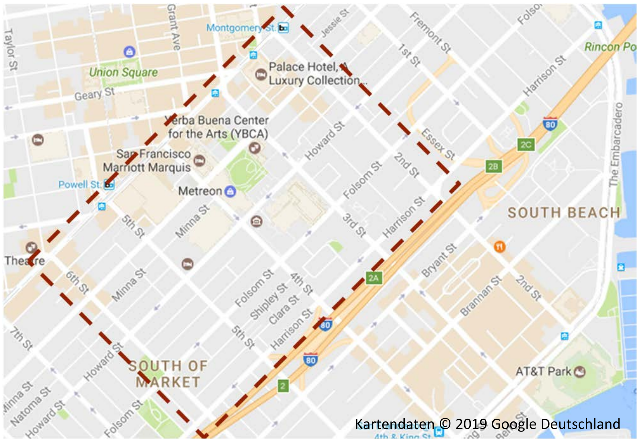

FIGURE 10. **The synthetic simulation scenarios arterial and grid combine the intersection layout of the previous sections with two way streets (one lane per direction) along the dimensions of an urban area in, San Francisco, CA.**

A. TRAFFIC HINDRANCE SITUATIONS

Applying CDG at the intersections arranged in this way, leads to three general traffic hindrance situations depicted in Fig. 11. For a better understanding of the simulation results, the disturbance effects resulting from these three situations are described in the following

1) SITUATION 1 – JUNCTION BLOCKING

We start by assuming the traffic backlog from a traffic light reaches the adjacent intersection as shown in Fig. 11 (a). Under certain circumstances vehicles come to a stop on the middle of the intersection and do not leave before the traffic light switches to the phase for the cross traffic. In this situation, the cross traffic has to wait for a full traffic light cycle until the intersection is clear again. Due to the close distances in a CDG platoon and the one-vehicle look-ahead pattern, this event occurs more often than with CTG. CTG by its very nature creates a contraction of the platoon while stopping and thereby more space on the intersection area. In order to create spaces on the intersection, CDG would require a coordination between vehicles, such as described in [36]. In SUMO there is a heuristic mechanism (*no-block-heuristic*) that helps vehicles to anticipate a possible hold at a position which blocks the cross traffic. However, as in the real world, in some specific situations, this predictive mechanism does not always work out.

2) SITUATION 2 – TURN BLOCKING

Even if vehicles stop to prevent a junction blocking, traffic backlogs might prevent vehicles from turning. In this case, as depicted in Fig. 11 (b), the cross traffic behind the turning vehicle is blocked for the current traffic light cycle. This applies for right and left turning vehicles. This event is also more likely to happen with CDG than with CTG for the aforementioned reasons.

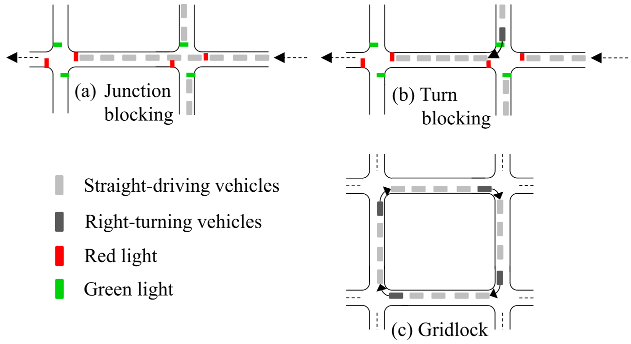

FIGURE 11. **Traffic hindrance situations.**

3) SITUATION 3 – GRIDLOCK

If situation 2 occurs at four intersections at the same time, this leads to a complete standstill beyond subsequent traffic light cycles (see Fig. 11 (c)). For such situations, SUMO offers a mechanism (*teleport* [39]) to model the real-life behavior of eventually finding a way around the blocking vehicle and so resolving the gridlock. For all experiments in this study, we set the waiting time in SUMO for each vehicle to resolve gridlocks and turn blockings to three full traffic light cycles. Solving junction blockings is set to the time of two green light phases.

B. ARTERIAL SIGNALIZED CORRIDOR – SIMULATION SCENARIO

The arterial scenario consists of five adjacent intersections of a major street with a distance of 192.5 m, as depicted in Fig. 12. The two lane layout of Section IV-A, as depicted in Fig. 7, is applied. The arrows in Fig. 12 mark the traffic inflows. As described earlier, lane changes are suppressed in order to exclude the impact of a lane change model on the simulation results. This scenario represents coordinated intersections on a major street. Thus, the green light portion of the cycle time is longer for the major street than for the minor streets. The following parameters were applied for the simulation:

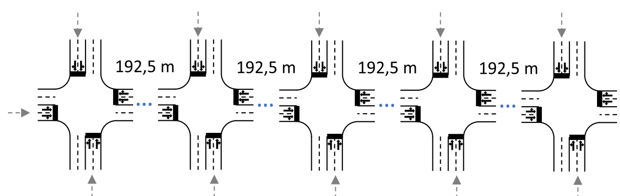

FIGURE 12. **Layout arterial signalized corridor with five intersections.**

- turning rates on minor roads: left 20%, right 40%;
- turning rates on main road is permuted with two different parameterizations: 1 (no turning), 2 (left 10%, right 20%);
- penetration rates are permuted with 0% (*CTG*), 50% (*Mix*), and 100%(*CDG*);

- green light portion for the major street is permuted with 25 s, 30 s, and 35 s with corresponding 10 s, 7 s, and 5 s for the minor streets (this also defines the traffic flow ratios);
- offset time (time shift between the traffic light cycles) between intersections is permuted with 0 s and 15 s.

1) IMPACT OF GREEN PHASE AND OFFSET TIME BETWEEN COORDINATED INTERSECTIONS FOR CDG ON ARTERIALS

For a better understanding of the arterial scenario simulation results, we present some preliminary remarks in the following. The performance of CDG in such a scenario is heavily influenced by the ratio of platoon length and intersection interspace. Assuming that there are no turnings and lane changes, the platoon length is indirectly controlled by the green light phase. Fig. 13 depicts four different situations to be distinguished regarding the named ratio:

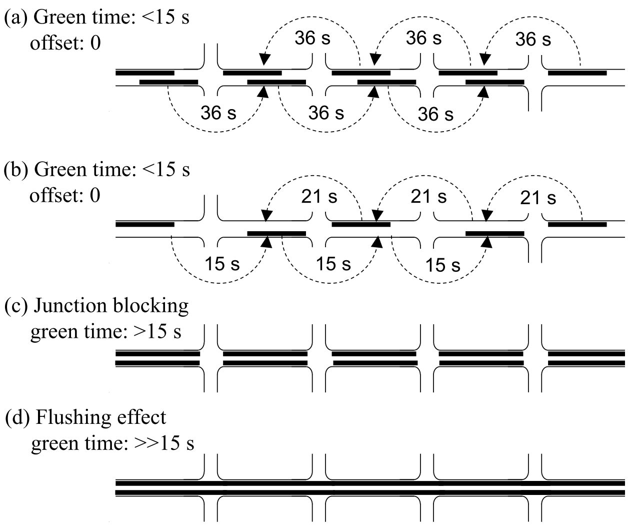

FIGURE 13. Impact of green phase and offset time between coordinated intersections for CDG on arterials.

Situation 1 – Fig. 13 (a) - Platoon length (81.5 m at 10 s green phase) is shorter than intersection interspace and traffic lights are synchronized, i.e., of same cycle time and no offset between their cycles. After starting up, the platoon needs about 15 s to travel to the next intersections at 50 Km/h. However, as the full cycle time is 36 s, additional waiting time at the next intersection results in a travel time of 36 s per intersection.

Situation 2 – Fig. 13 (b) - The parameters are the same as in Situation 1 with an additional offset between the traffic light cycles of 15 s (from left to right in Fig. 13). This offset reduces the travel time to 15s per intersection in one direction, as the platoon does not need to stop. In the opposite direction, the platoon still needs to stop, however, the waiting time is reduced by 15 s to 21 s. This results in an average travel time for both directions of 18 s per intersection. This shows that synchronized traffic lights are always the worst case in terms of travel time. Any offset has a positive impact.

Situation 3 – Fig. 13 (c) - Platoon length is longer than the intersection interspaces (in our case for green times longer than 15 s). The platoons stopping at a traffic light protrude into the adjacent intersection, which leads to the traffic hindrance situations of junction blocking and turn blocking (see previous subsection). This leads to a falling traffic throughput and an increased travel time compared with Situation 1 and 2.

Situation 4 – Fig. 13 (d) - Relatively long green times on the major road lead to a platoon length which spans multiple intersections and result in a flushing effect. While junction blocking still occurs, its negative effect on throughput and average travel time is compensated by the flushing of traffic. The throughput increases due to the short red time (long green time) portion on the major road and the travel time falls as vehicles do not need to stop at each intersection.

2) RESULTS

Fig. 14 depicts the simulation results without turnings on the major road. Fig. 15 depicts the simulation results done with 10% left turnings and 20% right turnings on the major road. In both figures, sub-figures a, b, c depict the throughput, travel time and density measured for *CDG*, *CTG*, and *Mix*. Sub-figures d, e, f depict the improvement of *CDG* and *Mix* over *CTG*. In each sub-figure the relevant metric is plotted at the vertical axis on a ground plane which represents the permutation of green time and offset. The calculation of the metrics is done in accordance with Section IV using the boundaries for counting as described at the beginning of this section. In the following, we present a brief discussion of the main findings while a more detailed discussion is presented in [42], Sec.VI.B.2)].

a: RESULTS WITHOUT TURNINGS

CTG and *CDG* throughput in Fig. 14 (a) and (d) both increase with green time length, while an offset has a slightly negative effect on both above 30 s green time. *CDG* shows an improvement of around 50% in average, while *Mix* is around 35%. This means that in contrast to a single traffic light scenario, the *CDG* improvement for this scenario scales better than linear with the penetration rate. However, the overall improvement is lower, since all green times simulated are above 15 s, which means in all cases the disturbance effects of junction blocking and turn blocking occur.

A separate simulation without turnings on the minor streets, not depicted in the figures, resulted with a *CDG* throughput improvement of 65% at 25 s green time and 85% at 35 s green time. We measured the same throughput with and without offset for each green time length. This simulation revealed that without turnings, the positive offset impact on the junction blocking could completely compensate the negative offset impact on flushing.

While the travel time (see Fig. 14 (b) and (e)) of *CTG* is approximately equal for all green times and offsets, *CDG* travel time notably benefits from offset. The travel time improvement of *CDG* and *Mix* over *CTG* are both

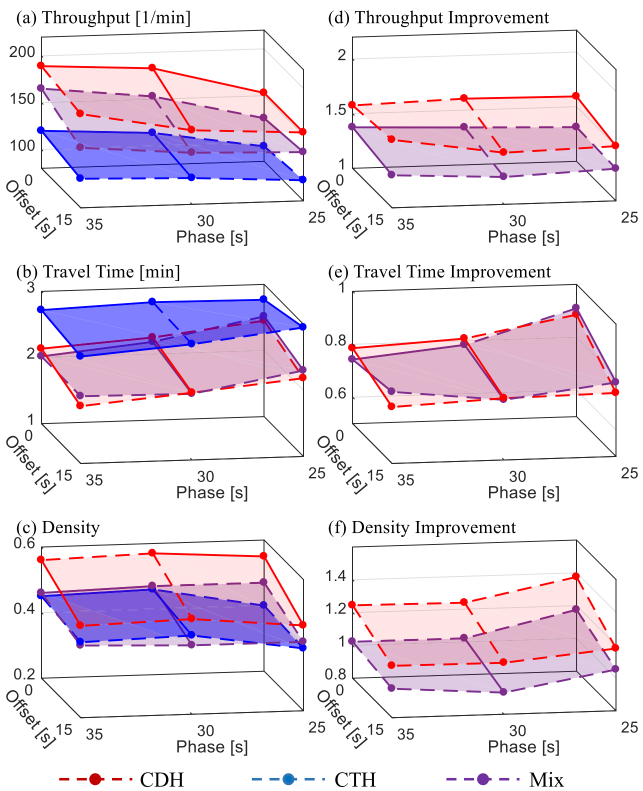

FIGURE 14. **Arterial scenario simulation results without turnings.**

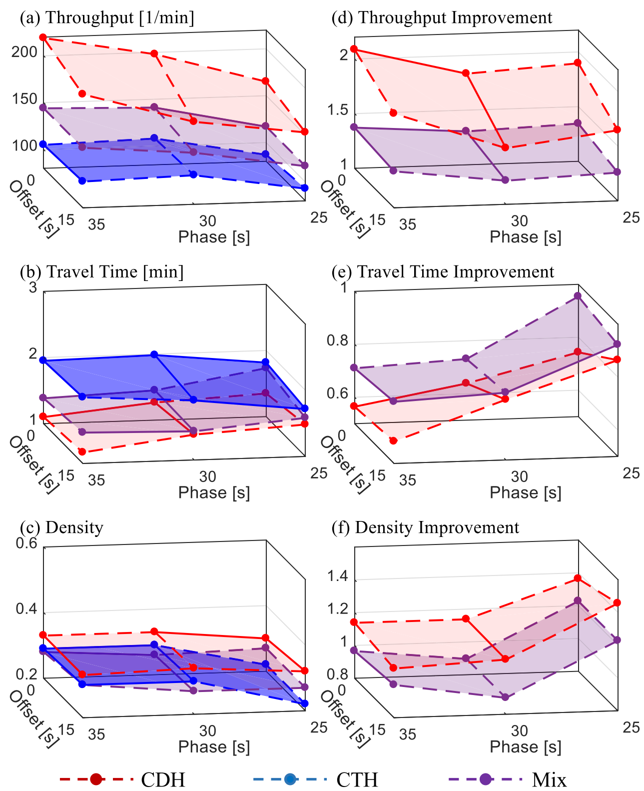

FIGURE 15. **Arterial scenario simulation results with turnings.**

around 20% without offset and around 30% with offset. In general, high green times have a positive impact for both. Here, *CDG* increases the throughput at the expense of density and travel time. Another indicator for this relationship is shown by the fact that throughput of *CDG* is higher than *Mix*, while their travel times are almost equal. The most remarkable permutation regarding travel time is at 25 s green time without offset. This permutation results in the highest travel time for *CDG*, mainly caused by the turn blocking problem. Turnings from the minor streets cannot enter the main street, which is mitigated when offset is present and compensated in average by the flushing effect at higher green times.

b: RESULTS WITH TURNINGS

An increased throughput (Fig. 15 (a) and (d)) for *CDG* can be seen in the results with additional turnings present on the main street. While the *CTG* throughput is in saturation at 30 s green time, the *CDG* throughput increases linearly with the green time length. Its improvement over *CTG* peaks at 110% at 35 s green time. The difference to the case without turnings is caused by vehicles leaving gaps on the main street platoons when turning. In this way the platoons can contract at red lights, which mitigates the junction blocking and turn blocking effect. *CTG* on the other hand is negatively influenced by the turnings, especially at longer green times. The offset shows the earlier explained influence on the flushing effect for *CDG*. Its positive impact on blocked turnings at minor streets does not come into effect, as the gaps on the major street already mitigate turn blocking.

Introducing turnings on the major street results in halving of the density in simulation for all policies. This leads to an overall reduced travel time in Fig. 15 (b) and (e). The travel time improvement of *CDG* ranges from 20% to 45%, while *Mix* goes in saturation around 30% at 30 s green time. Here, *CDG* travel time is not affected by the offset, while there is a slightly negative impact on *CTG*.

3) ARTERIAL SIGNALIZED CORRIDOR SIMULATION RESULTS SUMMARY

From the simulation results we observe the following facts about *CDG* applied in traffic system (specifically at adjacent and mutually influencing intersection on arterial streets).

- In contrast to single (or isolated) intersections, the high traffic density caused by the *CDG* platoons may lead to the disturbance effects, junction blocking and turn blocking.
- These effects lower the room for improvement of *CDG* over *CTG*. Lower penetration rates (*Mix*) are less vulnerable to these effects, which increases their relative benefit.

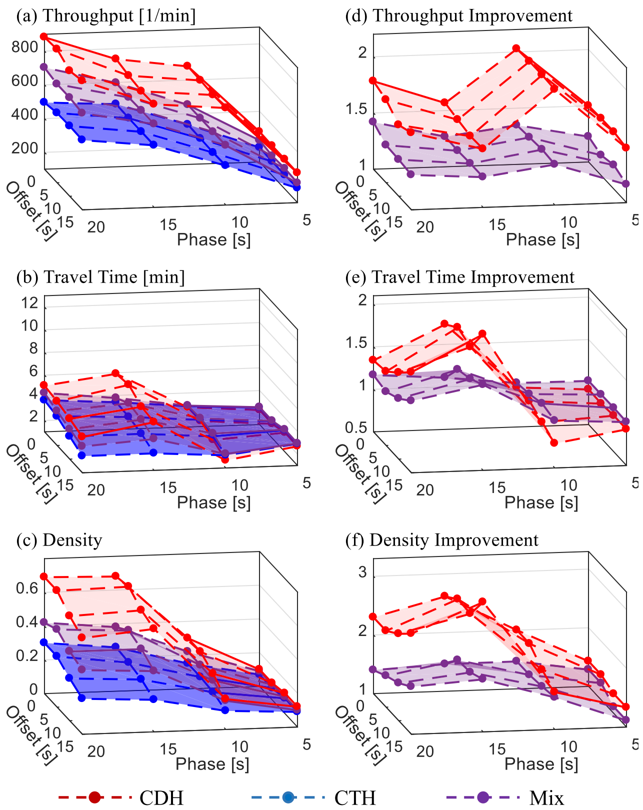

FIGURE 16. Grid scenario simulation results without turnings.

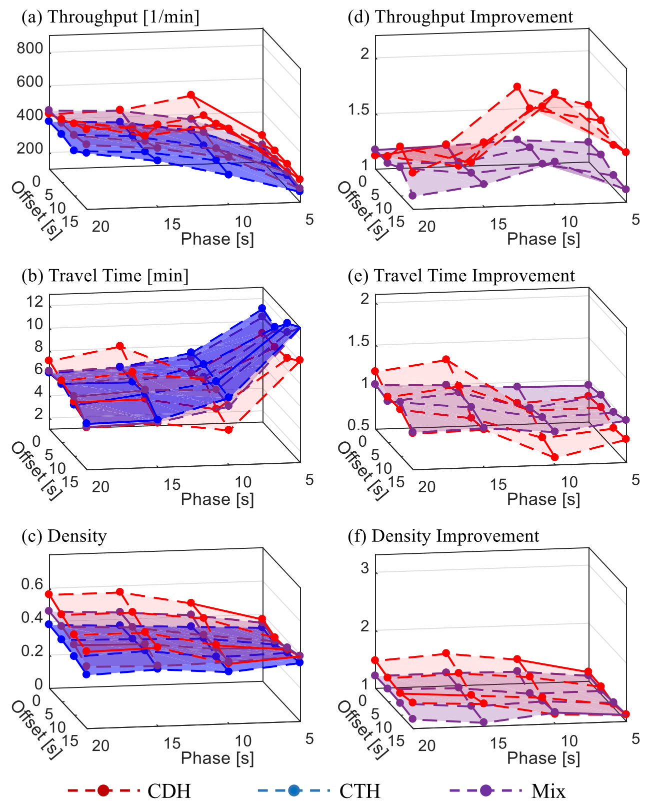

FIGURE 17. Grid scenario simulation results with turnings.

- The overall high density on the major street is usually mitigated by turnings leaving gaps in the platoons on the major street.
- The traffic density is lower in the presence of offsets or green times which create platoons that are shorter than intersection interspaces.
- Long green times that entail platoons spanning multiple intersections cause a flushing effect in the major street that improves throughput and travel time. Despite that, vehicles on minor streets still suffer from disturbance effects.
- Offsets, in general, reduce travel time for CDG and can reduce disturbance effects in one direction, however they reduce the flushing effect.

C. GRID SCENARIO

The grid scenario includes all 25 intersections marked in Fig. 10. Again, the two-lane layout of Section IV-A, as depicted in Fig. 7, is applied and lane changes are suppressed. Oversaturated traffic inflows are specified at the 20 inlets. This scenario represents a coordinated grid network [38] of intersections that connect major streets. Thus, the green light portion of the cycle time is equal for both directions. The following parameters were applied for the simulation:

- Turning rates are permuted with two parameterizations: 1 (no turnings), 2 (left 5%, right 10%).
- Penetration rates are permuted with 0% (*CTG*), 50% (*Mix*), and 100% (*CDG*).
- Green light portion permuted with 5 s, 10 s, 15 s, 20 s.
- Offset time between intersections is permuted with 0 s, 5 s, 10 s, and 15 s.

1) RESULTS

Fig. 16 depicts the grid simulation results done without turnings and Fig. 17 with 5% left turnings and 10% right turnings. The sub-figure structure and the method of calculating the presented metrics is similar to Fig. 14/Fig. 15.

a: RESULTS WITHOUT TURNINGS

CTG and *CDG* throughput both increase with green time length (see Fig. 16 (a) and (d)). While *CTG* goes in saturation at 15 s green time, *CDG* shows a kink at 15 s, which is caused by the junction blocking beginning on the shorter axis of the grid. Along the longer axis, junction blocking occurs from 20 s green time onwards. However, we see a further increase in the throughput. The improvement of *CDG* has its maximum of 100% at 10 s green time and approaches 70% above 20 s. This value matches the results of the arterial scenario without turnings on the minor streets (not depicted in the figures). The offset has no notable influence on all policies.

The travel time (see Fig. 16 (b) and (e)) increases for *CTG* from 2.5 min at 5 s green time to 3.3 min at 20 s green time, due to the increased cycle times. Up to 10 s green time *CDG* saves travel time as expected, while above 15 s green time, the junction blocking lead to a considerably increase in traffic density and, thus, to an increased travel time. Here, throughput is increased to the expense of travel time again. In contrast to the arterial scenario, junction blocking effects both directions. Thus, the average travel time is affected in both directions by many vehicles which need to wait two cycles at the same intersection. *Mix* has no significant travel time improvement, and the offset has a positive impact in all policies.

b: RESULTS WITH TURNINGS

CTG shows similar characteristics to the case without turnings but with approximately 20% lower throughput (see Fig. 17 (a) and (d)). For *CDG* the throughput drops significantly at 15 s green time. This drop results from gridlocks occurring in addition to the junction blocking and turn blocking as discussed earlier. While *Mix* shows an average throughput improvement to about 20%, *CDG* drops from 60% to 20% at this significant threshold. Without an offset between the traffic light phases, *Mix* even generates a higher throughput than *CDG* at 20 s green time. An offset between the traffic light phases shows an overall positive impact on *CDG* as it creates free spaces and so counteracts gridlocks. In contrast to the arterial scenario, longer green times do not lead to platoons spanning multiple intersections, i.e., intersections are not cleared which in turn contributes to the emergence of gridlocks. Rather, gridlocks are a local. This becomes apparent by observing the traffic density, which is even lower on average than in the case without turnings. *CTG* and *Mix* do not suffer from gridlocks in this scenario.

At short green times the travel time (see Fig. 17 (b) and (e)) is for all policies higher than without turnings. This is explained by the fact, that without turnings, the vehicles need to stop once at each intersection. Vehicles turning inward from cross traffic enlarge the platoons, so that the whole platoon cannot pass in one traffic light cycle. The travel time improvement of *CDG* and *Mix*, as well as the impact of the offset show similar characteristics to the case without turnings.

2) GRID SCENARIO SIMULATION RESULTS SUMMARY

The following points summarize the findings of our simulation on mutually influencing intersection in a grid.

- In contrast to arterial scenarios, gridlocks may occur when *CDG* platoons are longer than intersection interspaces arise.
- Gridlocks drastically reduce the benefit of *CDG* (in our scenario down to 15%) with a simultaneous increase in travel time.
- Gridlocks do not occur in the presence of short green times when platoons are shorter than intersection interspaces. The same effect could be achieved by limiting the platoon length accordingly as part of the CDG controller.
- Offsets can mitigate gridlocks for one travelling direction.
- At very short green times, travelling times increase considerably, which is the case for all policies studied.
- Lower CDG penetration rates (Mix) are less vulnerable to gridlocks and of little potential for improvement in grids.

D. VULNERABILITY OF CTG AND CDG WITH RESPECT TO GRIDLOCKS

From the grid layout simulation we observed that likelihood of gridlock of the traffic flow increases with longer green times, high inflow rates (maximum possible in our case) and turn rates. This applies for *CDG* as well as for *CTG* and *Mix*. However, *CDG* is more sensitive in this regard. The high traffic density caused by the dense *CDG* platoons provides no buffer space like the *CTG* platoons which contract while slowing down. Hence, with *CTG* the traffic flow is stable, in the sense that gridlocks do not occur, for higher turn rates at oversaturated inflow rates than with *CDG*. For limited inflows, the traffic flow is more stable regarding gridlocks with *CDG* than with *CTG*. Offsets appear to have a negative influence on traffic flow stability with *CTG*. We further explored this relationship in [42], Sec. IV.D.

E. CONCLUSION – MULTI INTERSECTION PERFORMANCE

Fig. 18 compares the throughput improvement of the grid scenario (Fig. 16 / Fig. 17) with single intersection (Fig. 9) and the arterial scenario (Fig. 14 /Fig. 15) with the single traffic light (Fig. 5). Min and max refer to the offset with the best and the worst improvement, respectively.

The performance of *CDG* in the grid without turnings is approximately the same as for a single traffic light up to 10 s green times. Above 10 s, the disturbance effects (see Section VI-A) result in a considerable performance drop. A similar picture can be observed with turnings, with an additional performance drop when no offset is present. Additionally, the gridlock impact is higher with turnings at longer green times. The performance drop of *Mix* is less for all cases. An exceptional case is 5 s green time where we have a very high performance at the single traffic light. This is due to discretization effects in the green times and the small number of vehicles passing per green phase. Note that 5 s is a very short value used for minor streets in real world. We included it to address a range of different ratios of green times and intersection interspaces in the grid. Green times above 20 s in the grid resulted with the simulation full of gridlocks and gave no further insight.

In the arterial scenario with 25 s to 35 s green time, disturbance effects are present for all *CDG* permutations. As *CTG* is less affected by them, we see an overall worse throughput improvement of *CDG* here. Additionally, *CTG* shows comparably high throughput in absolute numbers at long green times, which makes the impact of disturbance effects on the performance comparison with *CDG* grow. Thus, the arterial chart without turnings apparently is an extension of

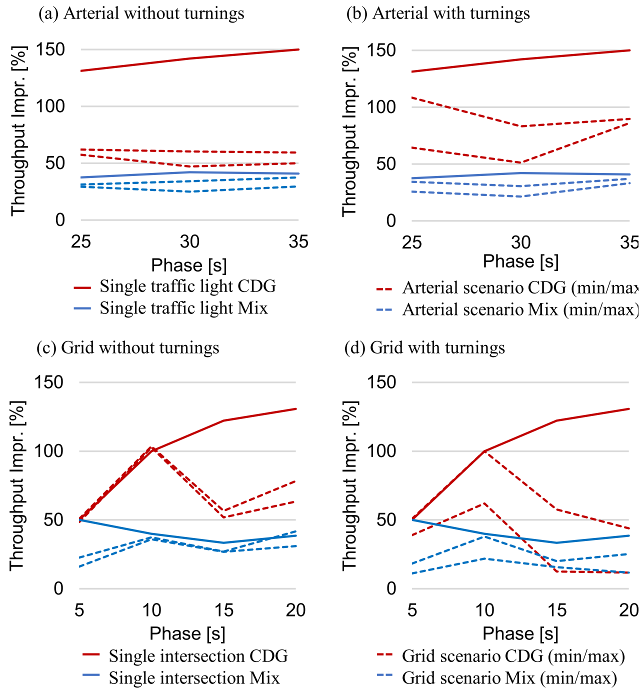

FIGURE 18. Results of arterial and grid scenario simulation.

the grid chart. With turnings, the *CDG* benefit comes to the fore notably, as the flushing effect (see Section VI-B) gets interrupted more often by the turning vehicles and *CDG* can reap the benefits of more start-ups similar to shorter green times.

In conclusion we found that *CDG* and *CTG* performance in multi intersection scenarios is influenced by many different effects. Their impact can be observed as a superposition in the measured metrics. In addition to the results presented in this work, the authors conducted further studies on each effect in order to explain them correctly. However, isolating each effect requires many more simulation scenarios, chart analytics and visual observation of simulations, which is beyond the scope of this work.

Remark: For some cases in both scenarios, grid and arterial, we observed that an improved throughput of CDG over CTG, comes with a smaller improvement in travel time. Actually one would assume intuitively that travel time and throughput should be improved approximately proportionally. However, this is not the case when different inter-vehicle distances are considered in signalized networks. If e.g., for situation 1 and 2 in Section VI-B1 the distances are halved, the throughput is approximately doubled, while traveling through the intersections takes the same time for each vehicle, except for a little less waiting time at the first queue.

Our objective in this section was to present the overall benefit of one-vehicle look-ahead *CDG* in oversaturated multi-intersection-scenarios. Our most relevant findings are summed up as follows.

- If the ratio of intersection interspaces and green time length is too high, *CDG* leads to disturbance effects in the traffic flow in the form of junction and turn blocking.

FIGURE 19. Real world scenario: arterial road with nine intersections in Berlin.

- In oversaturated grid scenarios these disturbances create gridlocks, with a probability that is more likely than with CTG. For limited inflows, *CDG* is less sensitive for gridlocks than *CTG*.
- Offset positively counteracts such disturbance effects
- *CDG* penetration rates below 100% are less sensitive to the disturbances. This improves the ratio between penetration rate and performance benefit of *CDG* considerably over single intersection scenarios. For some edge cases, a penetration of 50% *CDG* even outperforms 100% of *CDG* penetration.
- For all scenarios and parameter permutation tested, *CDG* improves traffic throughput. However for some situations, this improvement of *CDG* is bought by higher travel times due to its vulnerability to disturbance effects.

Summary of Section VI: The performance of CDG in grids and arterial scenarios is sensitive to the traffic light configuration in relation to intersection interspaces. Green times above a certain threshold may lead to disturbance effects (junction blocking and turn blocking). An offset positively counteracts such disturbance effects. CDG showed an improvement over the CTG baseline, in all cases. Finally, we emphasi ze that discussed disturbance effects could be prevented by adding a cooperative aspect to CDG. If CDG limited the platoon length to be shorter than intersection interspaces or the vehicles in a platoon could anticipate an unintended stop within the intersection area, the general performance of CDG could be improved considerably and grid locks could be prevented.

VII. REAL WORLD ROAD NETWORK

In order to confirm the results observed in Section IV to VI using synthetic simulation scenarios, we now attempt to assess the real world performance of *CDG*. For this purpose, we model a simulation scenario covering a heavily frequented arterial road in Berlin, Germany, as depicted in Fig. 19. This includes the Bismarckstraße between Theodor-Heuß-Platz and Ernst-Reuter-Platz with ten traffic light coordinated intersections with interspaces between 160 m and 500 m (266 m on average). The main difference to the synthetic scenarios in the previous section is the real world intersection layout, interspaces, and traffic light program including offset.

TABLE 2. Berlin simulation scenario configuration.

Minor street name	Traffic light program	Offset, Distance	Turnings major	Turnings minor
Königin-Elisabeth-Str.	22/3/8/3/11/3/10	54, 500	.8/.12/.08	.4/.3/.3
Sophie-Charlotte-Str.	24/3/9/0/12/3/9	19, 160	.8/.12/.08	.5/.3/.2
Witzlebenplatz	27/3/9/0/9/3/9	31, 390	.88/.12/0	0/1/0
Suarezstr	24/3/9//012/3/9	55, 290	.8/.12/.08	.75/.16/.09
Kaiser-Friedrich-Str.	28/3/9/0/8/3/9	32, 250	.8/.12/.08	.75/.13/.12
Wilmersdorfer Str.	23/3/9/0/13/3/9	46, 280	.8/.12/.08	.75/.16/.09
Krumme Str.	24/3/9/0/12/3/9	31, 160	.8/.12/.08	.75/.16/.09
Pedestrian Lights	29/3/9/0/7/3/9	42, 210	1/0/0	0/0/0
Leibnitzstr.	22/3/9/0/14/3/9	5, 160	.8/.12/.08	.5/.3/.2
Am Schillertheater	27/3/9/0/9/3/9	0, 0	.88/.12/0	0/1/0

While the road layout and the traffic light configuration are captured from real data, we again assume a maximum possible traffic inflow and an unobstructed outflow. In accordance with Section VI, the simulation results are calculated by counting vehicles entering/leaving an area that encloses all intersections together with an outer margin of 20 m, i.e., excluding the unbound queues of vehicles entering the area. All trips end outside this area. Furthermore, we assume the following:

- No pedestrians are blocking vehicles while turning.
- While assuming a capable cooperation concept to enable negotiation of lane changes between vehicles at high penetration rates of *CDG*, we excluded lane changing by respective route design in the previous sections. We now employ the SUMO lane changing model [34] without validating it analogous to Section V. As this model does not support opening gaps for merging parallel traffic, we accept a performance drop of *CDG*.
- Due to traffic backlog and quite large intersection interspaces, platoons of very large size appear, which in reality needs to be split to achieve platoon stability (see Section II-B for explanation). This splitting would slightly lower the performance of *CDG*.

A. SIMULATION SETUP

The traffic light program was observed on week-days between 10 am and 12 am. Public authorities indicated a fixed schedule for this period (dynamic priority phases e.g., for buses neglected). Table 2 lists the phase times of the program for each intersection in the following order: 1) green on major road, 2) yellow, 3) clearance interval, 4) protected left turning major road, 5) green on minor road, 6) yellow, 7) clearance interval. The base ratio for turning was estimated by observation at 80%, 12%, 8% (straight, right, left) on average on the major roads and 75% / 16% / 9% on the minor roads. The final turning configuration was adjusted based on the number of lanes per direction at each intersection, as listed in Table 2 using JTRRouter [39]. Combining the real world traffic light program with this setup leads to a

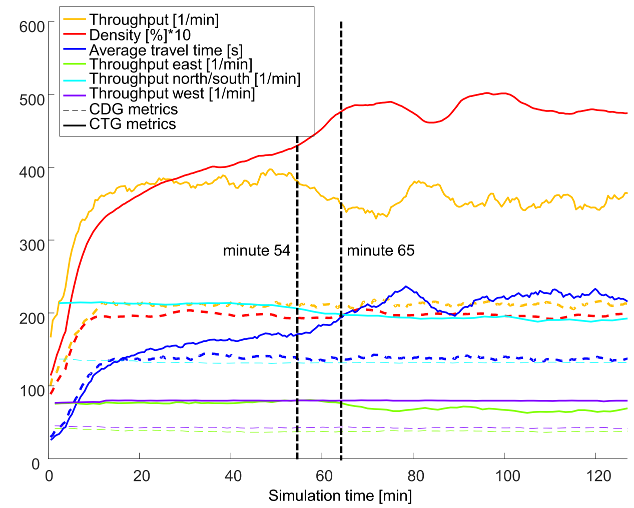

FIGURE 20. Simulation results real world scenario Berlin CDG / CTGS.

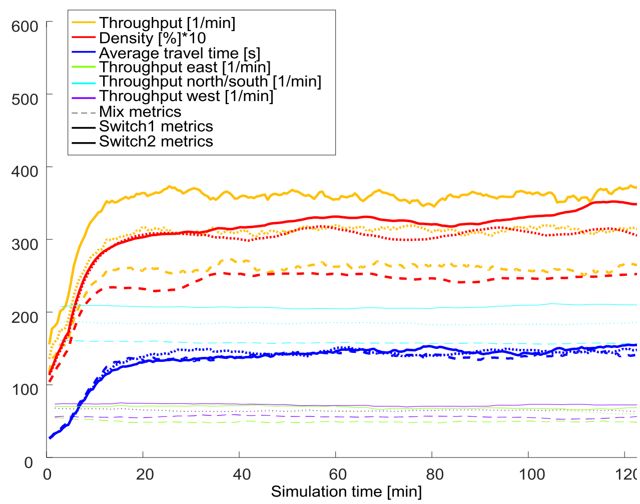

FIGURE 21. Simulation results real world scenario Mix / Switch1 / Switch2.

simulation setup using SUMO's default driver model, with all lanes evenly occupied and without traffic jams. All other parameters were left at default values.

B. EVALUATION

Fig. 20 compares the results of two simulation runs with *CDG* and *CTG* for the first two hours simulation time. In addition to the metrics used before, the figure also separately indicates the ingoing traffic flow from east, west, and from the minor roads (north and south). *CTG* reaches a steady state level for all metrics after 15 minutes simulation time, with a throughput of around 210 vehicles per minute. *CDG* reaches around 380 vehicle per minute, however the density and the travel time keep rising slightly. After minute 65 the metrics begin to stabilize while the throughput drops slightly to around 355 vehicle per minute. This behavior is the result of an east bound traffic backlog at Suarezstr. The traffic light there shows a slightly lower capacity than Kaiser-Friedrich-Str. in the simulation scenario. As *CDG* leverages the longer green times better than *CTG*, assuming a maximum possible traffic inflow, this leads to a larger capacity difference and, thus, to a rising backlog. The backlog reaches Am Schillertheater at minute 54 and finally reaches the east traffic inflow at minute 65. This becomes apparent with the declined inflow rate east. Once the traffic jam emerges, vehicles have difficulties finding gaps for lane changes, due to the close vehicle interspaces of *CDG* and missing cooperative behavior. Thus, some vehicles reach the intersection in the wrong lane and block that lane for a whole cycle. This further reduces the intersection capacity and the traffic jam cannot be dissolved. However, even with the named drawbacks, in terms of throughput, *CDG* still outperforms *CTG*. Applying, a switch to *CTG* at 30 Km/h solves this problem completely. As shown in Fig. 21, *SWITCH1* reaches the same throughput on average as *CDG*.

C. CONCLUSION – REAL WORLD ROAD NETWORK

In the previous section, we used synthetic simulation scenarios to reveal the relationship of specific constellations of road topology and traffic light configuration. This real world road network scenario in contrary shows the performance of *CDG* in a real world traffic system that mixes a plethora of such constellations at the same time. Moreover, in the previous section we neglected the impact of lane changes by route design, as we assume a cooperative merging feature coming with 100% penetration of *CDG*. In this section we included uncoordinated lane changing which led to a jammed condition for *CDG*. However, we showed that this effect would not necessarily occur in real world, as it is due to the non-cooperative character of merging in the simulation models of SUMO combined with small gaps. Besides that, even with a part of the scenario in a jammed condition, *CDG* still outperforms *CTG* in terms of traffic throughput. While the travel time raises by 60%, the *CDG* throughput is 70% higher than *CTG*. The following considerations pertain to the performance of *CDG* before the jamming occurred. Regarding throughput improvement of *CDG*, the real world road network scenario matches the results of the arterial scenario in Section VI-B, for the configuration of 25 s green time and no offset. The throughput improvement of *MIX* is slightly lower. We observe no negative impact by the presence of offset and no considerable disturbance effects (see Section VI-A) before minute 65. This becomes apparent in particular by the steady inflow from the minor roads. The absence of disturbance effects is a result of the very well balancing of traffic light configuration to the intersection interspaces done by the Berlin traffic management. Given the assumption that we usually find such well balancing in traffic management, *CDG* can exploit much of its potential in traffic systems, not only at single intersections. Surprisingly, the travel time is almost equal for all policies. Even by visual inspection of the simulation, we could not find a clear cause for this effect. The most reasonable explanation here is the following. As we learned from the previous section, *CDG* can buy throughput by travel time. Therefore, the specific configuration of the scenario might lead to levelling out the travel time by different throughputs and densities for each policy.

Summary of Section VII: In a real world network with a well-balanced traffic light configuration, CDG can exploit much of its potential in traffic systems, not only at single intersections. Comparing the performance of SWITCH1 and CDG in this scenario and in Section III, we could deduce the following finding. In dense, urban traffic systems a switch from CDG to CTG at 30km/h is recommended in order to create gaps for lane changes. At single intersections, for example, on crossing rural roads, this is not required and CDG without switching results with a considerably better performance.

VIII. CONCLUSION AND FUTURE WORK

In this paper, we comprehensively investigated the impact of applying a constant distance gap (CDG) policy for starting platoons at traffic lights. The applicability of CDG in real traffic is limited, due to its demand on communication topologies in order to achieve string stability. However, we were able to show its capability to increase the capacity of signalized intersections.

As a baseline for comparison, we calibrated a constant time gap (CTG) policy in the vehicle dynamics simulation PHABMACS using real word driving data. Compared with this baseline, CDG increased the capacity of a single intersection by up to 140%, depending on the green light time and the ratio of turning vehicles. The penetration rate of CDG in mixtures with CTG does not have a linear impact on the capacity enhancement on single intersections, which is a clear downside. A penetration of 50% still peaked with a capacity enhancement of 40%.

For large scale analysis of CDG performance on multiple adjacent intersections in traffic systems, we employed traffic simulation with several thousand vehicles. To achieve this scaling, we proposed a method for calibrating and validating traffic simulation against vehicle dynamics simulation. This calibration enables traffic simulation to render the same results as vehicle dynamics simulation regarding the relevant metrics. This study and its references provide all information needed to reproduce the simulations done with SUMO.

The large scale analysis yielded the following conclusions:

- Compared to single intersections, a full penetration of CDG reaches a lower performance at arterial roads and grids with multiple intersections due to occurring disturbance effects. This performance drop is less pronounced at lower CDG penetration rates.
- CDG outperformed CTG regarding throughput in all cases observed in this work. Although, a 50% penetration rate of CDG has less potential for improvement, it is less vulnerable to disturbance effects and appears as stable as CTG in traffic systems.

- While CDG is more prone to gridlocks in traffic grids at maximum traffic inflow, it is less prone to gridlocks than CTG if the inflow is limited. Thus, CDG should either limit the platoon length to be shorter than intersection interspaces or the vehicles in a platoon should be enabled to anticipate an unintended stop within the intersection area.
- CDG gains a considerable travel time improvement on arterial roads. However, the increased throughput of CDG comes with a higher density in traffic grids, which may lead to an increased average travel time.

After exposing some edge cases using synthetic scenarios with uniform parameterization, we finally modeled a real world road network scenario which includes a mixture of parameterizations. This mixture originates from the heterogeneous road geometry in Berlin, Germany and its well calibrated traffic light configuration. CDG improved the traffic throughput by 80% at the same average travel time as CTG. Given the average green light time and turning rates, this improvement confirms the results of a single intersection.

The simulation results revealed a potential performance drop of CDG originating from prevented lane changing and blocked intersections due to missing coordination and small gaps. Both problems could be tackled by a close range coordination between vehicles [36], to create gaps for merging and prevent entering intersections when a stop within the intersection area is likely. Given such coordination, the potential of performance improvement for CDG in a traffic system seems similar to the single intersections. Finally, it should be noted, that the CDG performance is largely dependent on the distance between vehicles. The steady state throughput gain decreases proportionally with increasing gaps, as shown in Section III.

Our future work includes implementing a coordination strategy as described above and a real world road network scenario for traffic grids. Replacing the maximum traffic inflow by real world traffic flows at rush hours will reveal information about the benefit of CDG by a market introduction in today's traffic. As a countermeasure to potentially arising string stability issues, CDG platoons should be split up into mini-platoons [3]. Future studies on switching between CDG and CTG should incorporate this splitting as an additional parameter to find the optimal platoon lengths. While in this paper we focus on platoons of homogenous vehicle dynamics, dynamics heterogeneity has a relevant impact on inter vehicle distances in real world applications. In future work, we will show the ability of the predictive controller, presented in Section III, to handle such heterogeneity.

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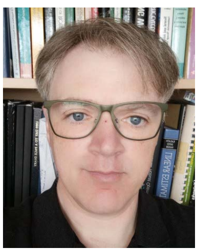

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