

Modelling and Simulation of Isolated Traffic Control Strategies in TraffSim

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Abstract - Traffic signal controls have become an integral part of urban traffic management and operations and play a crucial role in both mitigating congestion and reducing or eliminating conflicts at intersections. Starting with the installation of the first traffic signal in London in the nineteenth century, signal control technology has evolved steadily. Nowadays, traffic signal control is not only used to provide the right-of-way at intersections, but also to improve traffic efficiency by means of minimizing waiting times and optimizing traffic flow. In this paper we present recent efforts to introduce different types of both time-based and actuated traffic signal control strategies into the microscopic traffic simulator TraffSim. Furthermore, we demonstrate the applicability of selected control strategies by simulating both an isolated four-way intersection and a multi-intersection scenario under consideration of varying traffic densities. Moreover, we quantify the improvements in traffic efficiency imparted by these control strategies in terms of intersection throughput, waiting times, and network load.

Keywords - *traffic modelling and simulation; traffic lights; traffic signal control; traffic efficiency; microscopic traffic simulation.*

I. INTRODUCTION

Due to the increasing demand for mobility and recent advances in the area of Intelligent Transportation Systems (ITS), the field of traffic simulation has gained more and more importance in recent years. Simulations are a widespread and often used method to study complex transportation networks and investigate scenarios that cannot be studied in a real experiment or by any other analytical method. In recent years, a variety of simulation frameworks of different types and for diverse use cases has been proposed by researchers in the field [1-5]. Apart from models defining the longitudinal movement or lane-change behaviour of individual vehicles on the road, microscopic traffic simulators require additional components in order to control global limitations which are valid for all vehicles, e.g. speed limits, basic traffic rules and control logic for both regulated and unregulated intersections.

The simulation framework TraffSim is a microscopic traffic simulator allowing for the time-discrete and state-continuous simulation of vehicular traffic, supporting a wide range of models and parameters [5]. In such microscopic simulation scenarios, each virtual component has a corresponding equivalent in the simulation which certainly has to be modeled as close to reality as possible. Particular attention in that regard has to be paid to traffic control, as it was found to have significant influences on traffic flow and the efficiency of a transportation network in general [6,7].

Whilst a generic and accident-free intersection control logic for TraffSim has been developed recently [8], it does not allow for a more sophisticated kind of traffic control. Our work addresses this particular issue and focuses on the integration of different traffic control strategies for regulating signalized intersections. We extend the existing simulator infrastructure by a flexible data model allowing for the easy configuration of customized control logic for every individual intersection in a simulation scenario. Furthermore, the model is designed in such a way that new control strategies can be added in a straightforward manner.

The remainder of the paper is organized as follows. In Section II, different control strategies for isolated intersections developed throughout the years are elucidated. Additionally, we outline various simulation frameworks which incorporate such kind of control mechanisms. In Section III we present the developed traffic control model and how it is integrated with the TraffSim environment, comprising a detailed description of the individual model components. Section IV demonstrates the applicability of selected control strategies and quantifies their impact on traffic efficiency by simulating both a single four-way intersection as well as a multi-intersection scenario. Finally, Section V concludes the paper and gives an outlook of planned future work.

II. ISOLATED INTERSECTION CONTROL

The optimization of signal operations at intersections is an extensively studied research topic. Isolated traffic control strategies, in particular, aim to provide an optimal signaling scheme for a single intersection, whereas signal timing decisions are based solely under consideration of the subject junction, i.e. potential interactions with adjacent intersections are neglected [9]. Thus, isolated traffic control allows to determine signal timings which are most appropriate for individual junctions, but may not be efficient on a larger scale. In the following, we present various strategies designed for isolated intersection control, whereas we distinguish between time-based and vehicle-actuated approaches, respectively. Subsequently, we outline several simulation frameworks and their (in-)ability to model different types of traffic control.

A. Time-Based Control

The most basic type of control logic follows a predetermined, fixed time plan to operate traffic signals. In general, such time-based strategies are cyclic, by means that they serve each traffic phase in a certain order. Thereby, the phase length is often determined by analyzing historical flow data as well as the intersection's expected volume and turning movements. Notable efforts to find optimal phase lengths in accordance to the mentioned parameters have been proposed by Miller [10] and Webster [11]. Despite their simplicity, time-based control strategies have one major limitation, that is their inability to react to fluctuations in traffic flow.

Two well-known examples in that regard are the systems SIGCAP [12] and SIGSET [13]. Given the expected traffic passing through an intersection, SIGCAP estimates the practical capacity of the junction and calculates signal settings so as to maximize the intersection's throughput. SIGSET uses the given information to determine signal timings which minimize the estimated delay experienced by vehicles that want to pass through the intersection.

B. Vehicle-Actuated Control

Control strategies belonging to the class of vehicle-actuated (VA) traffic control make use of real-time measurements provided by inductive loop or video detectors which are located in the vicinity of the subject intersection. This information is usually used to find optimal signal settings in accordance to changes in traffic flow in the intersection's approaches [14].

One of the first VA-based intersection controls was proposed by Miller [15] already in the 1960s. His self-optimizing strategy is based on the total delay experienced by vehicles considering the impacts on traffic in all approaches to the intersection. A control function which is executed in regular intervals is used to determine whether to extend a signal phase or not. Miller's approach was further improved by

Bang [16], whose system TOL (Traffic Optimization Logic) allows for a significant reduction of waiting times and vehicle stops compared to conventional control strategies.

The regulation systems LHOVRA [17] and MOVA [18] base their signal timing decisions on measured time gaps between vehicles approaching an intersection. Although already deployed in the 1980s, both systems are still widely used, especially in the Nordic countries.

A noteworthy approach was proposed by Lämmer in [19] and [20]. His control strategy realizes a priority-based operation of traffic signals, where the priority is directly associated to the traffic flow measured in the respective approaches to the intersection. Whilst the system tries to reduce waiting times to a minimum by serving the incoming traffic as fast as possible, a stabilization mechanism ensures that the queue lengths in the intersection's approaches are kept below a certain threshold. This stabilization mechanism is required as the short-sightedness of the optimizing strategy could lead to an inefficient use of capacity, for example because of too frequent switching or too long green time extensions.

C. Intersection Control and Traffic Simulation

From the aforementioned simulation frameworks, the systems FreeSim [1] and MovSim [2] are capable of modelling highway junctions, however, they do not support signalized urban intersections nor unregulated crossings using priority rules. Also, Gora's traffic simulation framework TSF [4] does not provide any deeper insight on how traffic in intersections is managed. One of the most comprehensive traffic simulators publicly available is the framework SUMO [3], which is developed and distributed by the Institute of Transportation Systems at the German Aerospace Center. SUMO provides a road intersection model supporting signal-controlled as well as prioritized and unregulated intersections.

Apparently, commercial simulation tools such as Paramics [21] or VISSIM [22] comes with a wide range of functionality related to traffic control. The former allows to model different kinds of intersections, including but not limited to signalized or continuous flow junctions, using both time-based and actuated signal plans. The same applies for VISSIM, which also allows for modelling entire signal groups and public transport priority schemes for signalized intersections.

III. TRAFFIC CONTROL MODEL

This section introduces the developed traffic control model and its components, their responsibilities and relations to each other. Subsequently, we outline how the model is integrated with the TraffSim infrastructure.

A. TraffSim's Intersection Model

Intersections in TraffSim are modeled as separate entities, which handle all vehicles approaching the junction and those

waiting for entrance. Each junction provides an interface method which is used to determine whether or not a specific vehicle can traverse the crossing from a given lane inwards to a target lane outwards. Figure 1 depicts the graphical representation of an exemplary four-way intersection obtained from TraffSim. In the following we characterize the underlying data model and describe the particular model entities in more detail.

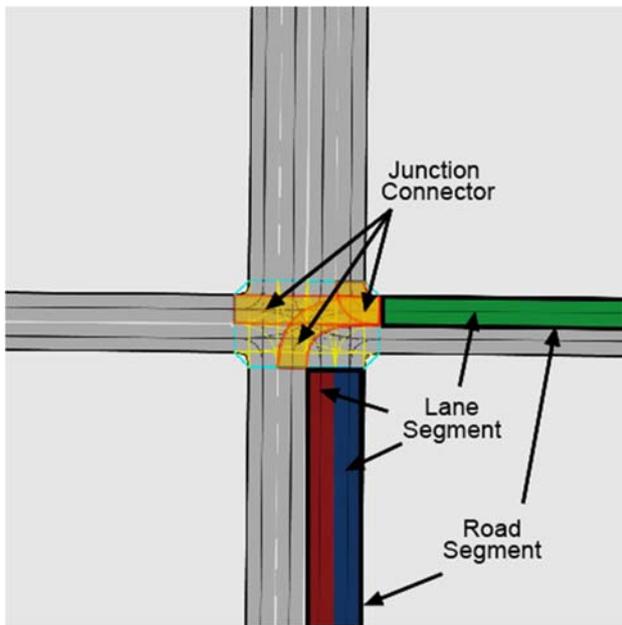


Figure 1. Simplistic model of a four-way intersection in TraffSim.

LaneSegment: A lane segment constitutes the most ordinary entity in TraffSim's road network. Throughout a simulation run vehicles move along those lane segments, which define the road's geometry as well as the connections to preceding or successive segments and potential turn restrictions.

RoadSegment: A road segment is basically a wrapper around one or multiple lane segments leading in the same direction and encapsulates logic that is applicable to all lanes in that conglomeration, e.g. speed limits.

JunctionConnector: This special type of lane segment is used to define all possible paths a vehicle can take through an intersection considering a given lane for entering the junction and a desired target lane. A junction connector is directly related to an intersection and can be managed by either a traffic light or a road sign, allowing to regulate each path through the intersection individually.

TrafficLight: TraffSim already contains a rudimentary implementation of traffic lights, which are capable of switching between phases in predefined, static intervals. To this point, each traffic light is operated independently of all other signals at an intersection according to a fixed time plan, which does not allow for any kind of sophisticated control.

RoadSign: Apart from traffic signals, road signs can be used to control traffic at non-signalized intersections.

TraffSim supports a variety of road signs such as stop signs, give way or priority road.

AbstractJunction: This entity serves as a base class encapsulating the access logic for vehicles approaching or traversing through the intersection by integrating the generic control scheme outlined in [8]. It maintains a list of road segments and junction connectors for managing inward and outward connections and is capable of obtaining general key figures such as an intersection's throughput.

B. Model Architecture

In order to allow for the integration of both time-based and vehicle-actuated traffic control strategies into TraffSim's existing intersection model, the aforementioned data structure is extended and modified considerably. Figure 2 gives an overview of the introduced components and their relations to the existing intersection model. Hereinafter, the individual components are described in more detail.

LoopDetector: As mentioned previously, actuated control strategies act upon data gathered from inductive loop or video detectors deployed along the approaches of an intersection. The loop detector entity represents the virtual counterpart to these sensor systems, providing the functionality to determine the number of vehicles passing a certain location in the road network and, by aggregating this data, to obtain macroscopic quantities such as traffic flow or average velocities. Apart from measuring the current traffic flow in the intersection's approaches, these entities are also used for presence detection, i.e. to determine whether or not a vehicle is standing e.g. at the stop line. Loop detectors are directly assigned to road segments and span over all lanes of that specific road segment.

TABLE I. DIFFERENT CONTROL STRATEGIES SUPPORTED BY TRAFFSIM

Strategy	Description
Fixed Time (FT)	Every traffic light is operated according to a pre-defined, fixed signaling scheme. This strategy does not follow a certain control mechanism, i.e. each signal is operated independently from all the others.
Mirrored (FT _M)	Opposite approaches are operated using identical phases, i.e. both driving directions are served at the same time. Applicable only to intersections with three or more approaches. Phase lengths can be defined for each pair of approaches separately.
Cyclic (FT _C)	All approaches are served individually, one after the other. This strategy follows either a clockwise or a counterclockwise scheme and uses customizable phase lengths for every single approach.
Self-optimizing (SO)	Vehicle-actuated control strategy proposed by Lämmer in [19]. Each approach is operated individually depending on the measured traffic load and the number of queued vehicles. A stabilization mechanism guarantees that all approaches are served in regular intervals.

QueueMonitor: A queue monitor is a logical unit comprising two loop detectors, one at the stop line right in front of the intersection and one mounted at a certain distance further upstream the approaching road. By repeatedly collecting data from these two detectors, the queue monitor is

capable of providing insights into the number of vehicles queued in the intersection's approaches and the presence of vehicles in the individual lanes.

Strategy: A strategy aggregates one or multiple instances of junction connectors and their associated traffic lights into one logical object. The linkage between particular junction connectors and a strategy allows for the definition of separate phases for specific lanes of an incoming road, as it may not always be desirable to have one common signal for all lanes of that road. Furthermore, a strategy provides all data which is required in order to implement a specific control scheme, e.g. phase and cycle lengths or queue lengths obtained from the associated connectors.

TrafficLightController: This entity serves as a base class for managing all signals at an intersection by continuously evaluating the data provided by all strategies associated to connectors of the subject junction. Depending on this data and the underlying strategy the controller decides which of the

incoming lanes have to be served at a given point in time. A list of currently available control strategies can be obtained from Table 1. New control logic can be integrated conveniently by simply adding new instances of traffic light controllers implementing the desired functionality.

C. Model Integration

Figure 3 gives an overview of the general architecture of TraffSim and the embedding of the developed traffic control model into the very same. It interacts with longitudinal and lane-change models of the simulation framework and the user interface for setup and supervision during a simulation run. Additionally, it is closely related to the intersection control model, which integrates the current phase of traffic signals in its decision making process in order to determine whether to grant or refuse access to the junction.

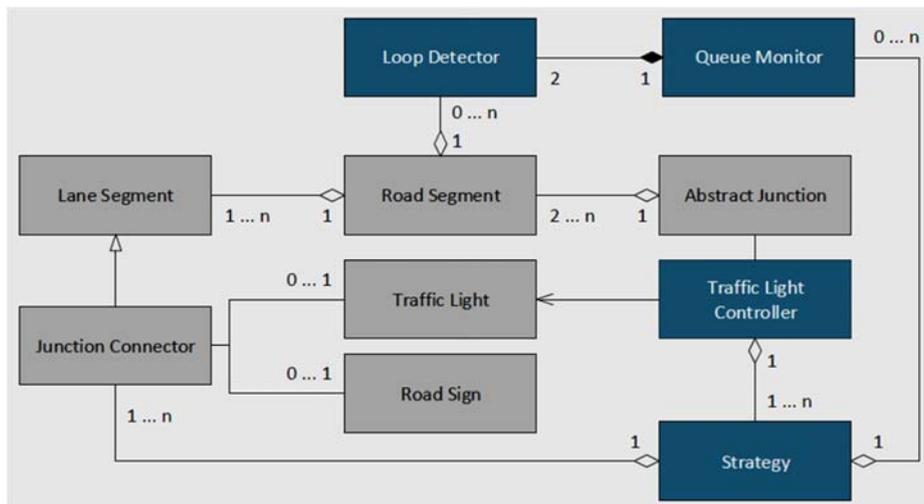


Figure 2. The traffic control model's components (blue) and their integration with the existing intersection model (gray).

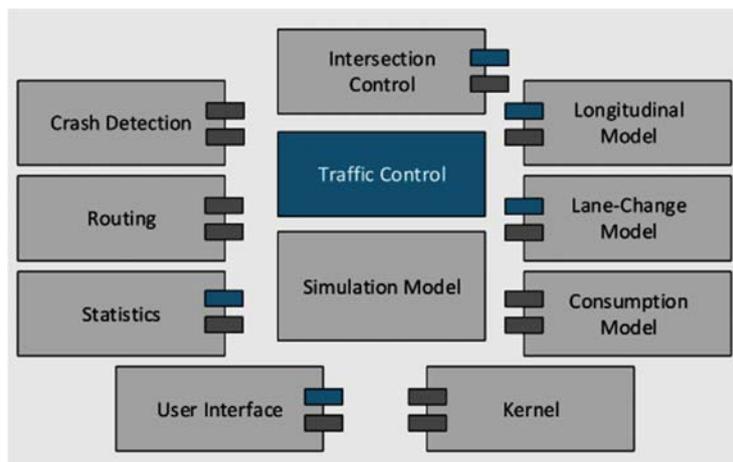


Figure 3. Integration of the traffic control model into the TraffSim environment. Relations to existing simulator components are highlighted in blue.

Furthermore, the model interacts with TraffSim's statistics module in order to provide metrics such as intersection throughput, waiting times or queue lengths for every individual intersection. The model's interfaces to other simulator components are defined as to allow for its modification or even replacement without affecting any other component.

IV. SIMULATION AND EXPERIMENTAL EVALUATION

In this section, we demonstrate the applicability of the developed traffic control model and evaluate the impact of different control strategies on traffic efficiency by means of dynamic traffic simulations. In particular, we investigate how different control strategies affect both intersection throughput and waiting times under consideration of different traffic intensities.

A. Simulation Setup

All simulations conducted in the scope of this work are carried out using the microscopic simulator TraffSim [5] and

with the aid of two exemplary scenarios, which are outlined in Figure 4. The first scenario comprises a single four-way intersection made up by an arterial road (two lanes, left and right turners) and a crossing street (single lane, no turn restrictions). The second scenario consists of an arterial road with six adjacent intersections. For both scenarios we apply the following traffic control schemes:

- Mirrored time-based control (FT_M)
- Cyclic time-based control (FT_C)
- Lämmer's self-optimizing control strategy (SO)

For every single control strategy we consider different parameter settings (e.g. phase and cycle times) and varying traffic densities. For the latter we systematically vary the traffic demand on the respective approaches to the intersections. Thereby, we assume that the demand along the arterial road Q_A is significantly higher compared to the (constant) side inflow $Q_B=180\text{veh/h}$. In particular, we vary the arterial flow Q_A from 540 up to 900veh/h.

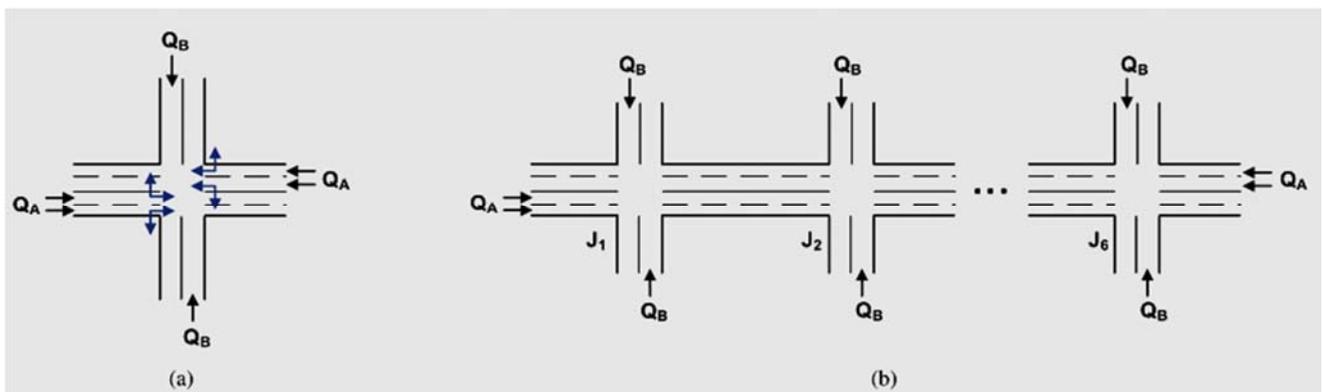


Figure 4. Scenarios used for simulation: an isolated four-way intersection (a) and an arterial road with six consecutive intersections (b). The distances between all intersections are equal to $d=500\text{m}$. Blue arrows indicate the turn restrictions for the arterial road, Q_A and Q_B denote the inflows associated with the arterial road and the side-arms, respectively.

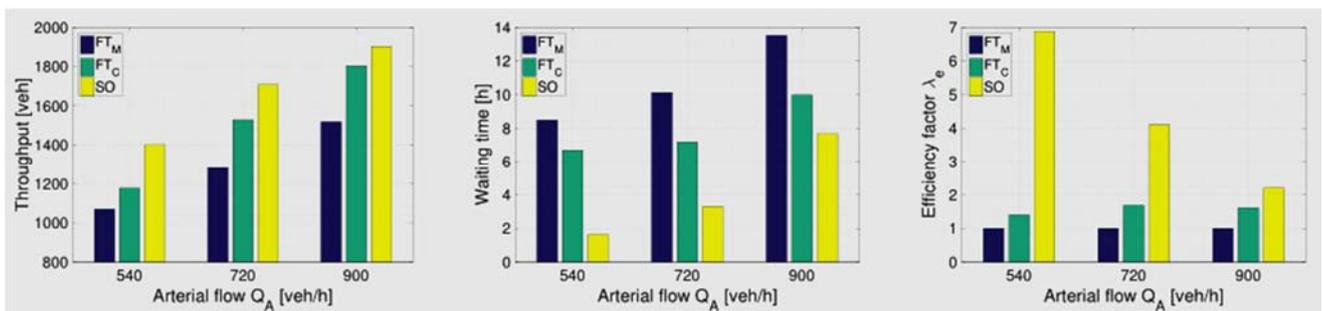


Figure 5. Performance indicators for the isolated four-way intersection scenario and three different control strategies. The horizontal axis shows the arterial flow Q_A in vehicles per hour, the vertical axis shows (a) the intersection's throughput, (b) the aggregated waiting time, and (c) the efficiency factor $\lambda_e=T/t_w$, representing a trade-off between a preferably high throughput T and a minimal waiting time t_w , respectively. Note that the efficiency factor is normalized with respect to the least efficient control strategy, i.e. it outlines the relative improvement compared to the worst case scenario.

Moreover, for every distinctive set of simulation parameters, i.e. each unique combination of control settings and traffic demand, we simulate one hour of traffic in order to obtain meaningful results. The car-following behavior of all simulated vehicles is modeled by the Intelligent Driver Model (IDM) [23], lateral movements are simulated using the lane-change model MOBIL [24] and its Cooperative Longitudinal and Lane-Change Behavior Extension (CLLxT) [25]. For further information on the applied models and their recommended parameter ranges it is referred to the literature cited. All simulations have been carried out using a simulation update interval $\Delta t = 0.1$ s.

B. Results

In the following, we present and discuss the findings obtained from simulating both scenarios outlined above.

B1. Four-Way Intersection: For the first scenario we investigate the impact of different control strategies on intersection throughput and waiting times for an isolated four-way intersection, i.e. we neglect any potential repercussions on adjacent road sections or other intersections. Figure 5 shows the key findings for this scenario given comparable setups for all control strategies, i.e. identical phase and cycle times, and different traffic densities. It can easily be seen that the self-optimizing control mechanism outperforms the time-based approaches significantly, both in terms of intersection throughput and waiting times, yielding also the best trade-off between the former and the latter (cf. Figure 5c). The reasons therefore are twofold: One the one hand, the self-optimizing strategy allows for a dynamic adjustment of phase lengths in accordance to the measured traffic demand in the respective approaches, which avoids unnecessary blocking of the arterial flow in case no or only very few vehicles are queued in the intersection's side approaches. On the other hand, the demand-responsive control strategy serves just a single approach during a green phase, and thus automatically resolves potential conflicts between left turners and oncoming traffic. Note that this also explains the performance improvement of the FT_C strategy compared to the FT_M approach.

These conflicts, in turn, are the leading cause for the comparatively low throughput and high waiting times attained by the FT_M strategy, as vehicles turning left may block an entire lane while waiting for the intersection to become clear.

Apparently, both intersection throughput and waiting time do not only depend on the traffic demand at the intersection, but to a large extent also on the control settings of the applied strategy. In fact, under the premise that the traffic demand in all approaches is: (i) known *a priori* and (ii) remains relatively stable, both quantities can be improved significantly simply by a proper configuration of the applied control strategy, i.e. by an appropriate choice of phase and cycle lengths, or other control settings.

Figure 6 exemplar outlines this relation for the FT_C strategy using different phase lengths for the arterial and side approaches, respectively.

For the given scenario both throughput and waiting time can be optimized by prioritizing vehicles approaching from the arterial road, i.e. by increasing the phase length for the respective approaches. This, however, may lead to disproportionate waiting times for vehicles queued in the side approaches, as the corresponding phase lengths decrease likewise, given a fixed cycle length. In practice, finding the right trade-off between both high throughput and moderate waiting times is crucial in order to provide efficient signaling operations at intersections.

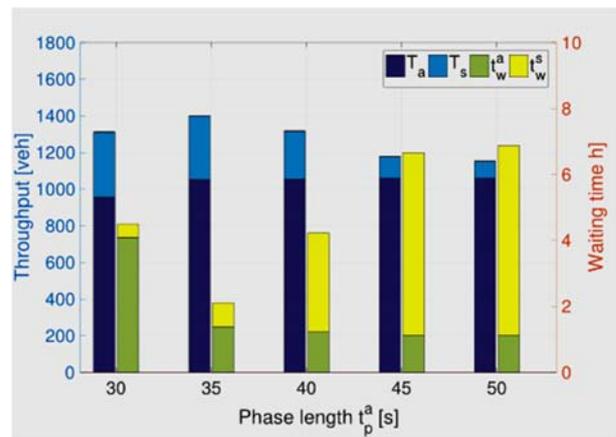


Figure 6. Intersection throughput and waiting time as a function of phase length for the arterial approaches t_p^a using a FT_C control scheme. T_a and T_s denote the throughput on the arterial and side approaches, t_w^a and t_w^s the corresponding waiting time, respectively. The total cycle length for the intersection is set to $t_c=120$ s, i.e. the phase length for the side approaches is given by $t_c/2-t_p^a$. For all simulations the arterial flow Q_A is set to a constant value of 540 veh/h.

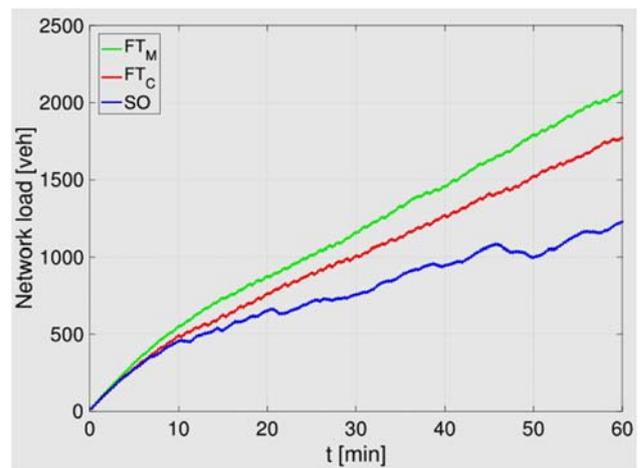


Figure 7. Network load for the arterial scenario and different traffic control strategies. The traffic demand along the arterial road is set to $Q_A=720$ veh/h.

B2. Arterial Road: While throughput and waiting times are adequate measures to assess the functionality of different

traffic control strategies for an isolated intersection, they do not describe the performance of such strategies sufficiently on a larger scale, i.e. when considering multiple intersections or entire road networks. To this end, we introduce the *network load* as a performance indicator, which corresponds to the total number of vehicles in the network at a given point in time. The network load constitutes a simple, yet intuitive measure to determine whether or not a specific traffic control scheme is capable of handling the prevalent traffic demand. Figure 7 shows the network load for the second scenario considering different control schemes with comparable control settings. As one might expect, the self-optimizing strategy again outperforms both time-based control schemes markedly, especially when the number of vehicles queued in the approaches to the individual intersections increases over time. While the network load rises almost linearly for both the FT_C and the FT_M scheme after an initial setup phase (approximately after minute 10), the vehicle-actuated control strategy leads to stronger fluctuations in the number of vehicles, which can solely be attributed to the dynamic adjustment of phase and cycle lengths. In that manner, the self-optimizing strategy is not only able to provide comparably efficient signaling operations for every single intersection, but at the same time avoids the emergence of tailbacks to adjacent intersections, which can be observed when using static time-based control schemes.

V. CONCLUSIONS AND FUTURE WORK

In this paper we presented a flexible and extendable traffic control model allowing for the straightforward configuration of customized control strategies for isolated intersections, supporting both time-based and vehicle-actuated control logic. We integrated the developed model with the microscopic traffic simulation framework TraffSim [5] and demonstrated the applicability of selected control strategies using two exemplary scenarios and under consideration of different traffic conditions. Investigating the effects of particular control strategies for different intersection types or their influence on the performance of an entire road network are beyond the scope of this work and will be topic of a forthcoming paper. Furthermore, future work is also planned in the following directions.

A. Coordinated Traffic Control

Apart from control strategies for isolated intersections, which aim to provide optimal signaling for individual junctions, coordinated traffic control approaches are used to provide efficient traffic operations for multiple adjacent intersections or even entire road networks. A common example for the latter are phased traffic lights, which provide progression through multiple crossings along a corridor for vehicles or even platoons of vehicles traveling at a designated speed in either one or both directions [26]. Such kind of coordination between individual regulation systems allows to

increase the traffic handling capacity of the road network significantly and at the same time reduces travel and waiting times and unnecessary stops [27, 28].

B. Autonomous Intersection Management

The development of autonomous vehicles has picked up pace in recent years, and experts in the field expect that self-driving cars make up for 75% of road traffic by 2040 [29]. Advanced sensor and communication technology enable a wide range of applications related to traffic safety, infotainment and traffic efficiency. Exchanging information between vehicles and infrastructure allows for even more sophisticated intersection control strategies, which have the potential to be safer and more efficient than regulation systems for conventional vehicles, without even relying on additional infrastructure such as actuators or traffic signals.

C. Mixed Traffic

Beyond doubt, the continual introduction of partially and highly automated vehicles on our roads will bring substantial changes to the driving environment. Although it is widely accepted that vehicle automation has the potential to improve both traffic safety and efficiency significantly, there will be a long gradual transition from manual to automated driving. In fact, it is expected that there will be years to decades where both conventional, human-driven and automated vehicles share the same roads [30, 31]. Especially in view of this gradual deployment there is a strong need for developing intelligent traffic management solutions that aim for optimizing traffic not only at intersections, but also on a network-wide scale, by at the same time providing safe operations for both human-driven and automated vehicles.

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