Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 151 (2019) 826–833

Procedia Computer Science

www.elsevier.com/locate/procedia

The 8th International Workshop on Agent-based Mobility, Traffic and Transportation Models, April 29 - May 2, 2019, Leuven, Belgium

Optimization and simulation of fixed-time traffic signal control in real-world applications

Theresa Thunig[a,*], Robert Scheffler[b], Martin Strehler[b], Kai Nagel[a]

[a]*Technische Universität Berlin, Transport Systems Planning and Transport Telematics, Salzufer 17-19, 10587 Berlin, Germany*
[b]*Brandenburg University of Technology, Institute of Mathematics, Platz der Deutschen Einheit 1, 03046 Cottbus, Germany*

Abstract

This paper contributes to the question how to optimize fixed-time traffic signal coordinations for real-world applications. Therefore, two models are combined: An analytically model that optimizes fixed-time plans based on a cyclically time-expanded network formulation, and a coevolutionary transport simulation that is able to evaluate the optimized fixed-time plans for large-scale realistic traffic situations. The coupling process of both models is discussed and applied to a real-world scenario. Steps that were necessary to align the models and improve the results are presented. The optimized fixed-time signals are compared to other signal approaches in the application. It is found, that they also help to improve the performance of actuated signal control.

Keywords: fixed-time traffic signal optimization; agent-based transport simulation; cyclically time-expanded networks

1. Introduction

All approaches that aim to model traffic have to make compromises between capturing the reality as well as possible and keeping the model complexity at a manageable level. Analytical models are often based on a rather simple model of traffic, abstracting away many details. For that reason, these models are accessible for highly efficient exact mathematical optimization methods. Proven optimal solutions, however, can usually only be determined for small instances. Many analytical models with time-dependency (for an overview see Köhler et al.[6]) are based on network flows over time or time-expanded networks[1]. In some of these models, it is possible to integrate fixed-time traffic signal optimization with the help of strict mathematical programming.[7]

On the other side, sophisticated simulations are able to represent many details of traffic in a realistic way (see e.g. the tools SUMO, MATSim, or VISSIM). Traffic simulation is able to model large-scale, real-world traffic situ-

* Corresponding author. Tel.: +49-30-31478783 ; fax: +49-30-31426269.
E-mail address: thunig@vsp.tu-berlin.de

10.1016/j.procs.2019.04.113

ations. However, the more realistic these tools are, the more complex they become. As a consequence, optimization can at best be accomplished with heuristics.

It therefore seems sensible to use models that are as simple as possible for optimizing tasks, and then to carry out an evaluation with simulation tools. This paper presents results of coupling an analytical model and a transport simulation tool to optimize fixed-time signal plans and evaluate their performance for real-world applications. The analytical model was developed by Köhler and Strehler[7, 8]. It optimizes fixed-time signal plans in a cyclically time-expanded network. It is coupled with the coevolutionary transport simulation MATSim[5]. Because the simulation covers more aspects of realistic traffic situations and is able to run large-scale scenarios, it is a suitable tool to evaluate the optimized fixed-time plans given by the analytical model. For this, the scenario is provided by the transport simulation and converted into a cyclically time-expanded network. The static model then approximates optimal fixed-time signal plans for all signalized intersections by solving a mixed integer program (MIP). These optimized signal plans are returned to the transport simulation to evaluate travel time effects. Initial results have been presented by Grether[4]; a detailed theoretical comparison of both models, but without real-world application, has been given by Thunig and Nagel[16]. The present study uses the knowledge about model differences and similarities to improve the coupling process and come up with better signal coordinations. Results for a real-world application to the City of Cottbus, Germany, are presented and compared to other signal approaches like adaptive signals.

The paper is organized as follows: A short introduction to the models used in this study is given in Sec. 2. Sec. 3 describes the coupling process and presents the real-world scenario that it is applied to, whereas Sec. 4 contains the results from this application. The findings are concluded in Sec. 5.

2. Model traffic flow over time including traffic light optimization

2.1. Cyclically time-expanded network model and MIP

The model of Köhler and Strehler was developed to optimize traffic signal coordination and traffic assignment simultaneously in an urban road network.[7] It is based on a time-expanded network, which uses the periodicity of traffic signals to limit the time horizon and, therefore, restrict computation time. In the following, it is called *cyclically time-expanded network model* (CTEN). Time-expanded networks map the time dependency of traffic by introducing network copies of the static network for different time steps. As shown in Fig. 1, links connect copies of the origin and destination nodes in the expanded network in different time slices according to the constant travel time in the static network. To cope with the significantly increasing network size, CTEN limits the time horizon by taking advantage of the periodicity of traffic signals. The model considers all occurring times modulo the signal cycle time. This results in a manageable network size, but limits time dependency: Demand and link flow pattern have to be cyclically repeated.

Traffic signals in CTEN are modeled by controlling the inflow capacities of downstream links by binary variables. Waiting links, illustrated as vertical links in Fig. 1, allow flow particles to wait in front of red signals or congested links. Although link travel times are constant in this model, resulting route travel times of travelers behave not constant for increasing demand values, since more and more waiting arcs have to be used, i.e. waiting times disproportionately increase with increasing demand.[7] The multi-commodity traffic assignment problem in the cyclically time-expanded network is analytically formulated together with signal offset coordination constraints in a corresponding MIP. Recently, an extension also supporting green split and phase order optimization was presented.[8] The program has a linear objective function that minimizes total travel time and, therefore, results in a *system optimum* (SO). To solve the MIP, the high performance solver CPLEX is used. CPLEX iteratively calculates primal and dual bounds to search for a good solution of the problem and to prove its optimality by closing the gap between primal and dual solutions.

2.2. Multi-agent transport simulation

In contrast to analytical models, a coevolutionary transport simulation is not based on a closed mathematical formulation that minimizes an objective, but simulates single agents traveling through a network and selfishly minimizing their travel time. It is, therefore, able to simulate traffic demand and travel times that changes over time.

The multi-agent transport simulation MATSim [5] considered in this paper is based on a network with constant free-flow travel times for links. Outflow rates are restricted by link flow capacities. Additionally, links have storage

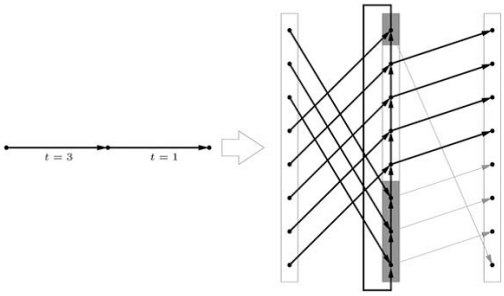

Fig. 1: Cyclically time-expanded network with waiting links and traffic-signals. [7]

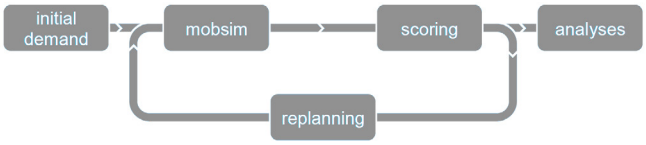

Fig. 2: Iterative cycle of the multi-agent transport simulation MATSim. [5]

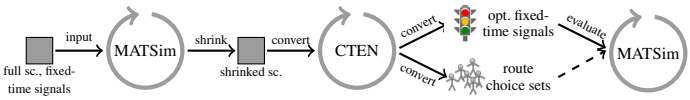

Fig. 3: Coupling of MATSim and CTEN.

capacities that restrict the number of vehicles that can queue on a link. MATSim links are modeled as queues: Vehicles that enter a link queue up and are finally allowed to exit the link when they have reached the front of the queue, their free flow link travel time is reached, and flow capacity of the current link and storage capacity of the next link are not exceeded. Traffic signals and lanes are modeled in MATSim by an extension module[3]. If a signal exists on a link, leaving the link is not possible during red phase. First studies focused on fixed-time signals[4], but also traffic-actuated[2] and traffic-adaptive[9, 15] signals have been implemented in MATSim. Agents, i.e. synthetic travelers, are modeled by daily plans. They depart and arrive on arbitrary links at arbitrary times. Plans contain a schedule of activities, including times and locations, along with the travel modes and routes.

MATSim iterates between two major components: In the mobility simulation (called *mobsim* in Fig. 2), demand is simulated on the physical network while every agent executes its selected plan. Because of congestion, travel times and activity durations of the executed activity travel pattern may differ from the plan. The second major component of the iterative process is the mental simulation: Agents evaluate their decisions (called *scoring* in Fig. 2) and possibly replan them (called *replanning* in Fig. 2). Plans are evaluated based on their performance, which is quantified by a score. Agents are allowed to select a plan for the next iteration. A certain percentage of agents is chosen to generate a new plan by modifying an existing plan. Possible modification strategies are e.g. route, time, or mode choice. The remaining agents select one of their existing plans through probabilistic selection by a multinomial logit model, where the selection probability of a plan is related to its score. The iterative process is repeated until agent scores do not vary anymore. If scores converge, the process leads to a (stochastic) *user equilibrium* (UE), i.e. no user may improve their score by unilaterally changing their strategy.

2.3. Optimization vs. simulation

The models described above both model traffic in a time dependent way with flow-independent link travel times and flow-dependent waiting times. Besides that, they differ in many aspects, see Tab. 1. This section describes the most important differences. A more detailed comparison can be found in a previous study[16].

Table 1: Overview on important similarities and differences of both models.[16]

	CTEN	MATSim
Demand	stationary	time-dependent
Link travel times	constant	constant
Waiting times	bounded (cycle time)	unbounded
Physical model	flow preservation	mass preservation
Priority	passing possible	FIFO
Optimum	SO = UE	SO $\leq$ UE

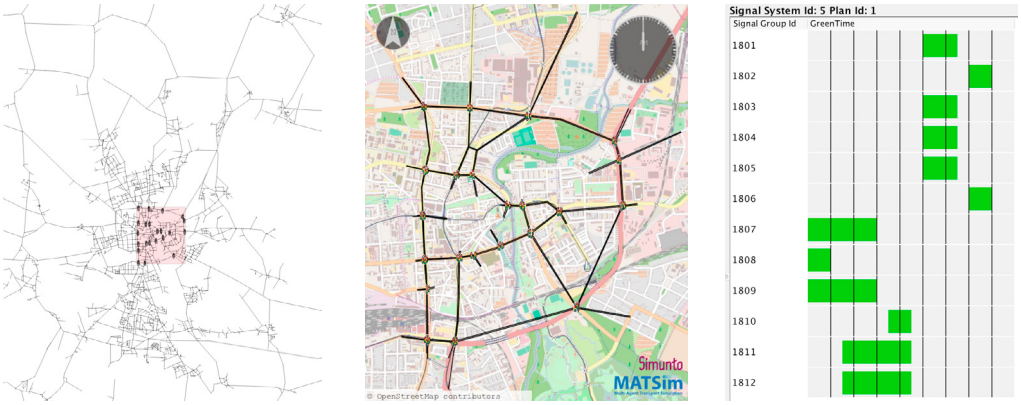

Fig. 4: Cottbus scenario. From left to right: Full network with 22 signalized intersections in the inner city; subnetwork used for optimization; examplary base case fixed-time signal plan for the east most intersection of the subnetwork.

The most important difference is related to the way of capturing time dependency: In CTEN, demand has to be the same for every cycle. During a cycle, congestion can vary but variations are the same every cycle. In MATSim, demand varies arbitrarily over the day. Another difference is related to the way traffic flow is handled physically: In CTEN, no vehicles are considered. Flow values split up in arbitrarily small flow particles to different routes. In MATSim, individual vehicles are considered which cannot split into smaller parts. Also, the objective functions of both models differ: CTEN determines a route distribution that minimizes total travel time, which means that it finds the system optimum. In the model, this route distribution constitutes a user equilibrium.[8] Other user equilibria with higher travel times may exist, however. MATSim, on the other hand, iteratively maximizes individual scores and results in a (stochastic) user equilibrium which does not necessarily minimize total travel time nor total score.

3. Coupling optimization and simulation

As described in the previous section, the analytical model can optimize fixed-time plans, whereas the simulation lacks in optimization but can model large-scale, realistic scenarios. These different advantages are combined in the following (as depicted in Fig. 3): CTEN is used to optimize fixed-time signal plans which are then included into MATSim to evaluate their performance in a more realistic setup.

A real-world scenario is used to apply and evaluate the coupling of both models. The scenario is based on Grether[4]. It consists of the city of Cottbus, Germany, and its surrounding county. 22 signalized intersections in the inner city are modeled (depicted in Fig. 4). Base case fixed-time signal plans are taken from Strehler[14]. Most of the signalized intersections have separate signal timings for left or right turns, see, e.g., the east most intersection of the inner city, whose base case fixed-time plan is shown in Fig. 4. The transport demand for the MATSim scenario consists of approx. 33300 commuters traveling from home to work in the morning and back to home in the evening.

MATSim is run to get the UE route distribution of the agents in this base case setup (see left part of Fig. 3). As a next step, the network is reduced to the major roads in the inner city (depicted in Fig. 4) to keep the size of the MIP feasible for the optimizer. It consists of 65 nodes and 134 links. Also, demand is simplified: The 11534 agents traveling through the inner city in the base case in the morning peak are aggregated to commodities (agents with same origin and destination in the subnetwork). Only commodities representing at least 50 agents are considered for signal plan optimization. This results in 49 CTEN commodities representing 4445 MATSim agents in total.

To be able to optimize fixed-time signal plans in the mathematical model (center part of Fig. 3), the shrinked MATSim scenario is converted into a cyclically time-expanded network as described in Sec. 2.1. A time horizon of one cycle (i.e. 90s) and a step time of 1s is used. Agents are aggregated to commodities as described above. Agent departure times can not be transfered, because CTEN only models one cycle. Instead, all flow is sent each cycle with uniformly distributed departure times; network capacities are scaled up accordingly. Because of this, traffic patterns (and also congestion) cyclically repeat, and single flow particles can not wait longer than one cycle at an intersection. To model turn specific traffic signals in CTEN, intersection nodes are expanded and each turn gets its turn specific link

to cross the intersection (called *light* in CTEN). If two lights are controlled by the same signal in MATSim, they are defined to always indicate green together in CTEN, too. Lanes are, however, not modeled in CTEN which complicates the coupling process, see Sec. 4.1. Information about conflicting turns for the 22 signalized intersections is derived from the base case fixed-time signal plan. If, e.g., left turns are separate from oncoming straight traffic in the base case plan, the corresponding lights are defined as conflicting in CTEN. Two possible combinations remain in this case: The combination with straight traffic from the same direction, and the combination with oncoming left turns. Minimum green times are set to 6s, intergreen times to 3s for the whole scenario.

The optimization with CTEN gives signal plans with green times for all signals and an offset per intersection (to be able to model green waves between intersections). Also, travel times and links that flow particles of a commodity use in the optimal solution are given.

Optimized fixed-time signal plans can directly be transferred to the simulation to evaluate their performance under user reaction in terms of travel time, delay of agents etc. (see right part of Fig. 3). The optimized signal plans can be evaluated in MATSim in the shrinked scenario as well as in the full scenario. To also analyze the difference between UE and SO with the optimized signal plans one could think of also transferring the SO routes from CTEN to MATSim. Unfortunately, demand can not be fixed to the optimal routes that flow particles in CTEN use because agents in MATSim are, in contrast to CTEN, discrete vehicles with a specific departure time (see also Sec. 4.1). Two options are possible: 1. Agents are allowed to freely choose their route in MATSim, and, 2. each agent gets a fixed route choice set consisting of all routes that flow particles of the same commodity use in CTEN. Both options are evaluated in this study for the shrinked scenario.

4. Results

This section presents results of the model coupling described in Sec. 3 applied to the real-world scenario. First, the section focuses on improving the coupling process to come up with better signal coordinations. Secondly, a systematic analysis of travel times in the two models is presented to verify the evaluation process. Last but not least, the optimized fixed-time signals are compared to actuated and adaptive signals.

4.1. Greensplit optimization – closing the gap between optimization and simulation

Naively converting a complex scenario into CTEN, optimizing signal plans and evaluating them in MATSim did not work as expected. CTEN resulted in optimized fixed-time plans that promised significant travel time gains compared to the base case fixed-time plans, but not even half of these gains could be reproduced in MATSim. I.e. the same signal coordination got evaluated much worse in MATSim than in CTEN. Different steps have been made to analyze why the two models result in different travel times and how to improve the coupling process to come up with better signal plans. The most important steps are presented here. Corresponding travel time gains of optimized signals plans in CTEN vs. MATSim for all these setting are compared in Fig. 5.

As a solution of an analytical optimization formulation, the fixed-time plans CTEN comes up with, by default, give green for the minimal time that is required to handle the demand – even if no conflicts to other signals of the intersection prevent them from expanding their green phase. As a first improvement step, **green times** of the optimized fixed-time plan where expanded to efficiently fill the cycle. This was done by alternately expanding green times by one second at the beginning and the end as long as the modified signal plans did not produce conflicts. Intuitively, this increased the travel time gain measured in MATSim (see the first two blocks in Fig. 5); reproduction of travel time gains increased from 45.1% to 51.1%.

A next important step in improving the coupling process was the **adjustment of capacities**. In MATSim, different turns can be combined by one lane (as in reality) and, therefore, share a flow capacity, whereas in CTEN every turn has its own capacity. To overcome this difference, only (aggregated) link capacities where used for the conversion at the beginning. In consequence, capacities in CTEN could be arbitrary shifted between turns of the same link, which caused too low green times for turns with too high capacities. As a first improvement, turn capacities in CTEN were, therefore, bounded by the capacity of the corresponding lane in MATSim. Travel time gains in CTEN reduced a bit (see third block in Fig. 5), but the described problem could still occur when a lane combines different turns. To exclude this issue here and to further analyze and improve the rest of the coupling process, **lanes** in the MATSim scenario have

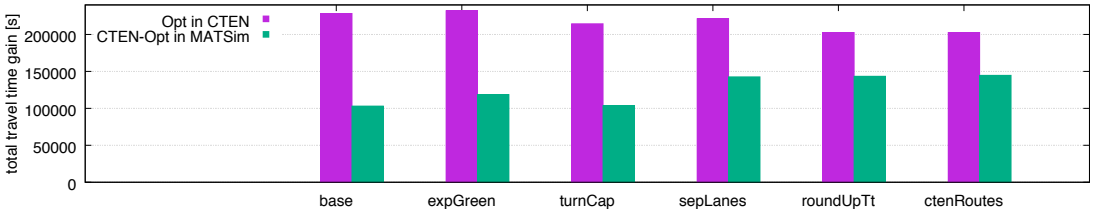

Fig. 5: Travel times in CTEN vs. MATSim of the optimized signal plans with different set ups described in Sec. 4.1.

been **simplified**. At approaches with multiple lanes they were separated such that each lane represents only one turn and lane capacities can be directly translated into turn capacities. Approaches with only one lane for all turns were not changed (only link capacities are used in this case). This significantly improved the reproduction of travel time gains between the two models from 48.8% to 64.4%, see fourth block of Fig. 5. Note, that this step modifies the scenario, and, therefore, also changes travel times for the base case signal plan, as it changes flow capacities and the interaction between different turns.

A next improvement could be made by changing the way travel times are converted to CTEN. If the combination of link length and free flow speed resulted in a non-integer travel time, this value was rounded down in CTEN, whereas it is rounded up in MATSim, which resulted in overall lower travel times in CTEN. This has been corrected by also **rounding up** the free speed travel time in the network conversion process which further increased reproduction of travel time gains to 70.7% (see fifth block in Fig. 5).

The last step relates to the traffic assignment of both models. As described in Sec. 2.3, CTEN computes a SO, which also constitutes a UE in the model, but does not necessarily constitute a UE in MATSim. [16] Unfortunately, CTEN routes cannot directly be converted to MATSim to verify whether the remaining travel time difference is due to the difference of UE and SO, because CTEN commodities can split up in arbitrary flow particles, whereas MATSim uses discrete agents with specific departure times. Instead, all routes that flow particles of a commodity used in CTEN were assigned as **route choice set** to all agents corresponding to this commodity in MATSim. Agents are then only allowed to switch between routes of this route choice set. This heuristic does not close the gap between UE and SO but slightly further improves the reproduction of travel time gains in the application to 71.3%.

All in all, the coupling process could be significantly improved by investigating into the alignment of both models. Travel time difference of MATSim compared to CTEN decreased significantly and reproduction of travel time gains could be improved from 45.1% to 71.3% in this application.

4.2. Random greensplits – quantitative comparison of travel times

After aligning both models (see previous section), a travel time difference of around 10% remaines for the optimized fixed-time plans. To clarify whether this correlates with the optimization process or whether the cyclically time-expanded network model itself consequently results in lower travel times than the simulation, this section systematically compares the travel times in both models of 50 fixed-time signal plans with random greensplits.

To generate the 50 random signal coordinations, disjunct signal groups were chosen based on the base case fixed-time plan (analogously as described by Thunig et al.[15]). For these signal groups random greentimes have been assigned based on the following criteria. (1.) Each signal group indicates green for at least 6s, (2.) the intergreen time between all green phases constitutes 3s, (3.) green- and intergreen times per intersection sum up to a cycle time of 90s, (4.) the so constructed scenario based on network, signal plans and demand is still feasible in CTEN. Fortunately, this feasibility can be checked very fast on the static network.[12]

A comparison of the travel times of these 50 random signal coordinations in both models can be found in Fig. 6, where each dot represents one of the random coordinations with its travel time in CTEN on the x-axis and its travel time in MATSim on the y-axis. One can see that MATSim travel times are higher than CTEN travel times for all random coordinations (with an average deviation of 15.6%). There is one coordination with a travel time of almost 1.8×10^6s in MATSim which is twice as much as in CTEN, and seven coordinations which cause a travel time difference of approx. 30 to 40%. All other dots cluster parallel to the bisecting line with a deviation of around 11.1%

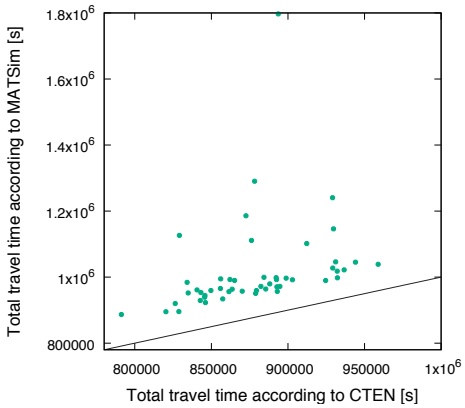

Fig. 6: Travel time comparison for 50 random coordinations in the two models (see Sec. 4.2).

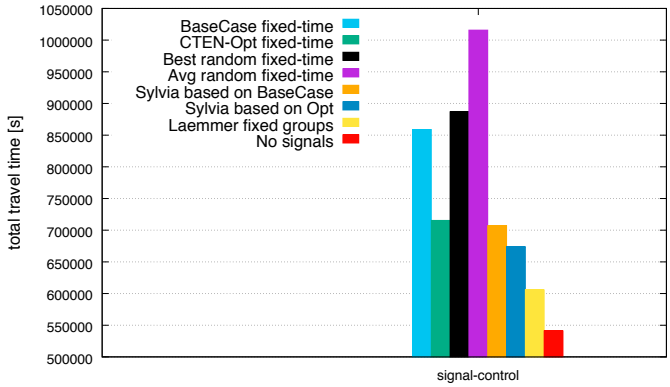

Fig. 7: Travel times for fixed-time signals, actuated signals, and adaptive signals in MATSim (see Sec. 4.3).

(which is the median). All outliers correspond to coordinations where green time for at least one mayor road is very low and high flow rates in CTEN are sent on detours. In MATSim agents tend to queue or squeeze in at this bottlenecks, which is a classical UE vs. SO difference.

To summarize this experiment, coordinations that are considered good in CTEN are in general also evaluated positive in MATSim and vice versa for bad coordinations. Exceptions can be explained by the difference in traffic assignment of both models (UE vs. SO), which seems to be the most important reason for travel time differences.

4.3. Optimized fixed-time signals vs. traffic-responsive signals

In contrast to traffic-adaptive signals, fixed-time signals are not able to react to fluctuations in traffic pattern. Because of this, traffic-adaptive signals usually result in lower travel times for real-world applications compared to fixed-time signals. Still, good fixed-time signals are needed as a basis for many traffic-responsive signals. This section, therefore, compares travel times for the optimized fixed-time signals with adaptive and actuated signals and studies whether actuated signals can improve by using the optimized fixed-time signal plans as basis.

As adaptive signals, the algorithm proposed by Lämmer[10] is used. It was implemented in MATSim and extended to cope with more realistic traffic situations in previous studies[9, 15]. The algorithm is based on an a priori assignment of signals into disjunct signal groups (the same signal groups are taken as in Sec. 4.2). It selects the next signal group to indicate green only based on local sensor data of approaching vehicles. Thereby, it minimizes waiting times while also ensuring stability (i.e. preventing spill backs). In contrast, the actuated control considered here is based on a fixed-time signal plan, shortens each green stage to 5s and only extends it if vehicles are approaching, up to a maximal extension of 1.5 times the green time of the fixed-time plan. The control was implemented in MATSim by Grether et al.[2] and is based on the approach SILVIA by Schlothauer & Wauer[13].

Travel times that result in MATSim when agents react to the different signal control methods by route choice are presented in Fig. 7. The optimized fixed-time signal plans (shown in green in the figure) improve travel times by 16.8% compared to the base case fixed-time plans (in light blue). This corresponds to an improvement of approx. 18s per trip. Compared to the average travel time of the random coordinations from Sec. 4.2 (see violet bar in Fig. 7), the optimized signals by CTEN even result in an improvement of 38s per trip. I.e. the base case fixed-time plans are already quite good; they even beat the best random signal coordination (black bar) by 4s per trip. All traffic-responsive signal approaches result in lower travel times than the optimized fixed-time plan, though. In this simplified scenario, they mostly benefit from the possibility to shorten the cycle time, because this highly reduces average waiting times in uncongested situations. The lowest travel time is reached by the adaptive signal control based on Lämmer (shown in yellow). It differs from the (unrealistic) situation without traffic signals where agents travel through each other in the simulation (red bar), which can be seen as a lower bound, by only 8s per trip and improves the travel time compared to the base case signal plans by 32s per trip. The actuated control SYLVIA (based on the base case fixed-time plans; orange bar in Fig. 7) results in similar travel times compared to the optimized fixed-time control. Interestingly, an

improvement can be observed when the optimized fixed-time signal plans are used as basis (see dark blue bar). This shows that optimization of fixed-time plans can also be used to improve traffic-actuated signals. Note, that the improvement in travel time by the adaptive signals and their higher flexibility also comes with the need of more infrastructure. Lämmers signals, e.g., need a control unit per intersection, two sensors per link to make predictions about arriving vehicles, and information about average arrival rates and saturation flow rates. SYLVIA only needs one sensor per link and no complex computation is necessary.

5. Conclusion

Simulation is a powerful tool to model large-scale, real-world transport situations and to evaluate case studies or predict user behavior. But because of its complexity, simulation lacks in optimization possibilities. In contrast, mathematical models like the cyclically time-expanded network model described in this study can be used to optimize fixed-time signal plans. Because of model simplifications, an application to real-world scenarios does not work out of the box, though. This paper presented steps that were done to align both models and to improve the optimization process. It was shown that, despite all model differences, the coupling of simulation and optimization can be used to come up with better fixed-time signal plans for real-world applications. Additionally, the paper presents a comparison of optimized fixed-time signals and responsive signals in the application. It could be shown that the optimized fixed-time plans improve travel times, when used as basis for the actuated signal control SYLVIA.

The presented results consider every day traffic. An interesting further research question is, whether they can be extended to special traffic situations such as mega events, e.g., football matches or concerts. Since such mega events were already studied in both models[2, 11], a combined approach seems to be reasonable.

Acknowledgements

This work is part of the project *Optimization and network wide analysis of traffic signal control* funded by Deutsche Forschungsgemeinschaft (DFG).

References

[1] Ford, L., Fulkerson, D., 1962. Flows in Networks. Princeton University Press.
[2] Grether, D., Bischoff, J., Nagel, K., 2011. Traffic-actuated signal control: Simulation of the user benefits in a big event real-world scenario. In: 2nd International Conference on Models and Technologies for ITS, Leuven, Belgium.
[3] Grether, D., Thunig, T., 2016. Traffic signals and lanes. In: Horni et al.[5], Ch. 12.
[4] Grether, D. S., 2014. Extension of a multi-agent transport simulation for traffic signal control and air transport systems. Ph.D. thesis, TU Berlin, Berlin.
[5] Horni, A., Nagel, K., Axhausen, K. W. (Eds.), 2016. The Multi-Agent Transport Simulation MATSim. Ubiquity, London.
[6] Köhler, E., Möhring, R., Skutella, M., 2009. Traffic Networks and Flows over Time. Vol. 5515. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 166–196.
[7] Köhler, E., Strehler, M., 2015. Traffic signal optimization using cyclically expanded networks. Networks 65 (3), 244–261.
[8] Köhler, E., Strehler, M., 2018. Traffic Signal Optimization: Combining Static and Dynamic Models. Transportation Science, to appear.
[9] Kühnel, N., Thunig, T., Nagel, K., 2018. Implementing an adaptive traffic signal control algorithm in an agent-based transport simulation. Procedia Computer Science 130, 894–899.
[10] Lämmer, S., Helbing, D., 2008. Self-control of traffic lights and vehicle flows in urban road networks. Journal of Statistical Mechanics: Theory and Experiment 4, 04–019.
[11] Scheffler, R., Strehler, M., 2016. Optimizing Traffic Signal Timings for Mega Events. In: 16th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems (ATMOS 2016), 8:1–8:16.
[12] Scheffler, R., Strehler, M., 2017. Optimizing Traffic Signal Settings for Public Transport Priority. In: 17th Workshop on Algorithmic Approaches for Transportation Modelling, Optimization, and Systems (ATMOS 2017), 9:1–9:15.
[13] Schlothauer & Wauer Ingenieurgesellschaft für Straßenverkehr mbH & Co. KG, 2011. SYLVIA+ short description. https://www.schlothauer.de/en/software-systems/sylvia/, website version: 29-12-2018.
[14] Strehler, M., 2012. Signalized flows – optimizing traffic signals and guideposts and related network flow problems. Ph.D. thesis, BTU Cottbus.
[15] Thunig, T., Kühnel, N., Nagel, K., 2018. Adaptive traffic signal control for real-world scenarios in agent-based transport simulations. Transportation Research Procedia.
[16] Thunig, T., Nagel, K., 2017. The structure of user equilibria: Dynamic coevolutionary simulations vs. cyclically expanded networks. Procedia Computer Science 109, 648–655.