Adapting Signal Timings to Automated Incident Alarms within a Self-organised Traffic Control System

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Abstract: Intersection management, routing, and congestion avoidance are key factors for improved mobility and better road network utilisation. Organic Traffic Control (OTC) is a self-organising traffic management system for urban road networks. Its main features are the self-adaptive traffic-responsive signalisation of intersections, the coordination of traffic light controllers, and dynamic route guidance of traffic streams. This paper aims at presenting how the automatic and fully distributed incident detection within OTC works and how OTC makes use of these incident alarms for the automated adaptation of signalisation.

1 INTRODUCTION

The increase in mobility poses several challenges for future transportation systems. Current research deals with optimisations related to mitigation of congestion, improvement of throughput or reduction of waiting times in front of red traffic lights. Traffic engineers agree that recurrent congestion due to demand exceeding capacity and poor signal timing account for about half of the total delay experienced by motorists, while non-recurrent congestion (due to road works, incidents, and weather) makes up the other half (Bertini, 2005). Especially in densely populated urban areas, traffic volume and traffic performance are raising. The inefficient use of the existing infrastructure demands for new and improved solutions. Simply expanding the capacity of the road network is seldom an option due to limited transportation funds and a lack of public acceptance because of environmental impacts. Furthermore, road safety and the crash frequency are affected by the occurrence of congestion. So far, most work has been limited to algorithms for the detection of traffic congestion. Some of the installed traffic management systems, such as SCOOT and COMPASS, include modules for the detection of incidents. However, none of them automatically adapts their traffic control strategies to the incident alarms raised. In this paper, we explore the benefits of an autonomous adaptation of the control strategy to alleviate the negative effects of congestion.

In the context of the *Organic Traffic Control* (OTC) project (Prothmann, 2011; Sommer et al., 2016), a traffic-adaptive system has been developed that utilises the existing road infrastructure. It reacts to changes in the observed traffic conditions and self-optimises its control strategies at runtime within predefined behavioural corridors. We extend OTC with a component for automated congestion detection within urban areas. This paper presents approaches to utilise the incident alarms raised by this component for the self-adaptive adaptation of signalisation. By automatically adjusting the signal settings, vehicles can be discouraged from entering the congested area and the efficiency of the road network can be improved.

The remainder of this paper is structured as follows: First, we present some installed traffic control systems and how they deal with congestion management. Afterwards, we introduce the self-organised traffic management system Organic Traffic Control (OTC). We move on, presenting our proposal for the automatic adaptation of signalisation due to incident alarms. Finally, we evaluate this approach based on a simulation study.

2 RELATED WORK

Reliable incident detection mechanisms and fast clearance are important for mitigating the negative effects of incidents and congestion. (Ozbay and Kachroo, 1999) define incident detection as “the process of identifying the spatial and temporal coordinates of an incident”. It is executed by automatic algorithms

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or by manual evaluation. Figure 1 depicts the incident management process (Deniz et al., 2012). First, data from surveillance systems (e.g. CCTV cameras or loop detectors) provide a description of the traffic condition. Second, this data is usually sent to a central control centre where it is processed. The data analysis is often executed by automated incident detection algorithms. Third, the incident alarm can be verified by an operator, e.g. via surveillance cameras. Fourth, the edited information has to be disseminated among the traffic participants. The actual congestion management is usually done by traffic experts. Its strategies range from adaptation of signal plans, to re-routing of traffic by means of route recommendations via variable message signs, and radio broadcasts. Finally, clearance procedures are initiated to restore the undisturbed conditions as before the incident.

Comprehensive reviews over incident detection algorithms and detector technology are given by (Parkany and Xie, 2005) and (Mahmassani et al., 1999). The family of point-based algorithms is usually deployed on freeways (Yang et al., 2004). Spatial measurement-based algorithms make use of CCTV cameras and image processing algorithms and are also used in urban traffic networks (Zhang and Xue, 2010). Congestion patterns are detected based on temporal and spatial differences of traffic parameters monitored by traffic sensors.

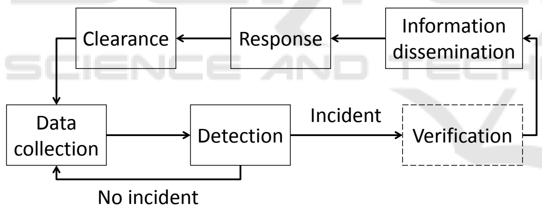

Figure 1: Typical flow chart of an AID system. The verification step is optional.

The traffic management system SCOOT raises cycle times and green times according to increased congestion (Bretherton et al., 2000). SCOOT includes modules to automatically identify critical links causing congestion, to target regularly recurring congestion, and to propose the recommended action to take. However, the actual execution is done by a traffic export. SCOOT assumes the presence of congestion when the detector related to an upstream intersection of the respective road monitors a stationary queue.

COMPASS (Masters and Wong, 1991) relies on sensor technology to monitor the traffic conditions, software to analyse these conditions, and further plans defining which actions to take. All information is gathered in a central traffic operation centre. The incident detection is executed by the all purpose incident detection (APID) algorithm which is based on a binary decision tree. Further management actions during incident situations have to be executed by humans.

SCATS (Sims and Dobinson, 1980) is equipped with a centralised *unusual congestion server* which receives updates of the monitored traffic data in real time. It generates alerts in case a road is classified as congested by its monitoring tool. Again, countermeasures have to be taken manually by traffic experts.

In contrast to these traffic control systems, we go one step further, proposing a self-adaptive traffic management process, automatically detecting and reacting to congestion. The AID component of OTC is fully distributed and completely autonomous. It is responsible for the detection of incidents and the automated incident management. At each signalised intersection, an AID component extends the standard OTC controller. The controller receives traffic data from nearby sensors describing the traffic states at nearby sections. This data is then used by an automatic incident detection algorithm to classify the current traffic conditions into incident-free or congested. In case, the selected algorithm classifies the current situation as congested, OTC will react with an adaptation of its control strategy. This adaptation can incorporate a modification of the signalisation in terms of green times and cycle time, calculating new route recommendations, or triggering the adaptive progressive signal system mechanism.

3 ORGANIC TRAFFIC CONTROL

Current traffic management systems usually rely on fixed-time signal plans. Thus, they are not able to adapt to the highly dynamic traffic patterns and to react to unforeseen situations, leading to longer travel times and higher emissions. OTC (Prothmann et al., 2011) is a self-organised intelligent traffic management system extending standard parametrisable traffic light controllers (TLC). OTC consists of several components: a) adaptive control of traffic lights, b) traffic-dependent establishment of progressive signal systems, c) dynamic route guidance, d) forecasting of traffic situations, and e) automatic incident detection.

3.1 Adaptive Control of Traffic Lights

OTC handles the adaptation of green times of traffic lights at intersections according to the present traffic conditions. The self-learning, self-optimising system follows a safety-oriented concept that allows OTC to adapt within certain controlled boundaries. Each individual instance of OTC is fully decentralised and controls one signalised intersection only. Fig. 2 depicts the multi-layered observer/controller architecture as applied to traffic control.

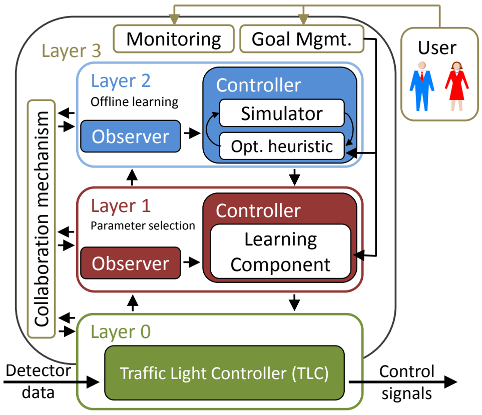

Figure 2: Multi-layered observer/controller architecture of an OTC-controlled TLC.

Layer 0 is a parametrisable fixed-time TLC. It offers interfaces for monitoring of sensor data and adaptation of signal plans. Figure 3 depicts a exemplary signal plan with six phases (phase 3 and 5 being interphases with all signals showing red light), and three signals. Each green phase is followed by three seconds of yellow light.

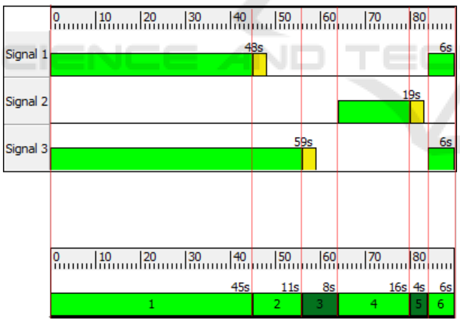

Figure 3: Example of a signal plan with a cycle time of 90 seconds and three signals. The duration of yellow light is three seconds.

The observer at Layer 1 retrieves raw data from the TLC which is processed in the following (e.g. filter noise or generate forecasts). This component provides a situation description of the traffic flow of the intersection for the corresponding controller on Layer 1. This controller is represented by a learning classifier system with a database of rules (signal plans matched to traffic conditions). Matching signal plans are selected based on the current traffic conditions at the intersection and actuated on Layer 0. Before a new signal plan is added to the rule base, it is simulated and evaluated based on an optimisation heuristic at Layer 2. The simulator is configured with the topology of the intersection and the current traffic situation. It evaluates several signalisation plans with the help of an evolutionary algorithm. The signal plan providing the lowest estimated average delay is returned to Layer 1. As these simulations tend to be time-consuming, Layer 2 acts in parallel to Layer 1. At last, Layer 3 provides interfaces for monitoring and goal management. For further details on OTC and a more detailed description of the process, the interested reader is referred to (Sommer et al., 2016; Prothmann, 2011).

3.2 Automatic Urban Incident Detection

The standard OTC is extended by an additional module for the real-time automatic incident detection, designed for application in urban areas. Based on locally monitored detector data, each TLC is enabled to detect nearby congestion. Incidents can occur due to accidents, lane closures, or long-lasting road works. Figure 4 depicts the architectural prerequisites for the installation. First, at least two detector stations are needed that monitor the upstream and downstream traffic conditions on a section (here called link). Second, these detector stations belonging to each other are logically coupled as *detector pairs*, defining a *monitoring zone*. Each zone can be assigned with a different automatic incident detection (AID) algorithm. A monitoring zone can also cover additional branching sections via *divided detector stations* which allows for the detection of more complex congestion patterns. Thereby, the complex patterns created by incoming and outgoing traffic streams are taken account of. Finally, a detection algorithm is assigned to each monitoring zone. OTC demands no specialised AID algorithm and the applied algorithm and its parametrisation can be different for each zone. The applicable algorithms can range from simple heuristics to sophisticated machine learning techniques.

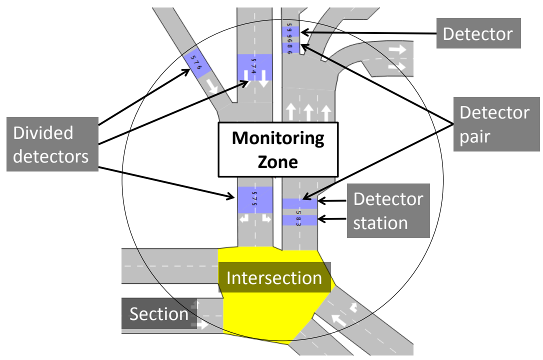

Figure 4: Architectural prerequisites for the AID framework within OTC.

Figure 5 depicts the standard process in case of an incident alarm. First, an alarm is raised by an AID algorithm responsible for the according monitoring zone. Next, the alarm is passed-on to the *disturbance manager*. A disturbance is defined by the corresponding incident causing the disturbance, its start time, its end time, its severity, and its exact location. The disturbance manager automatically estimates the severity of the incident by using sensor data from traffic detectors and approximation heuristics. Here, we use the average speed sp and the average detector occupancy occ as measures for the congestion level of the section. Based on these two characteristics the severity of a section can be estimated by

$$severity = sev_{sp} * sev_{occ} \quad (1)$$

with

$$sev_{sp} = 1 - min(1, \frac{\sum^{d_i} v_i}{d_i} / v_{max}) \quad (2)$$

and

$$sev_{occ} = min(1, max(occ_i)/100) \quad (3)$$

where v_{max} is the speed limit, d_i denotes the detector station on the section, where v_i resembles the speed monitored by d_i, respectively occ_i the occupancy of d_i over a certain time span. Therefore, this factor lies between 0 and 1 whereas 1 denotes the highest severity. The severity factor then serves as additional parameter for the adaptation of green times at the signalised intersection and as a penalty factor within the travel time estimation on the congested section. An AID algorithm can take several states:

- Incident free: traffic is free flowing.
- Tentative incident: congestion is assumed, but no incident alarm is raised yet.
- Incident confirmed: The tentative incident was confirmed by a subsequent test. An incident alarm is raised.
- Incident continuing: the detected congestion is still present.

Depending on the chosen AID algorithm, there can be additional states. To reduce the number of false alarms, an additional verification step by a traffic engineer can be executed (i.e. by examining live feeds from CCTV cameras).

4 AUTOMATIC ADAPTATION OF SIGNAL PLANS BASED ON INCIDENT ALARMS

To alleviate the negative effect of congestion, traffic streams have to be relocated to other streets, decreasing the traffic flow near the problematic area. This

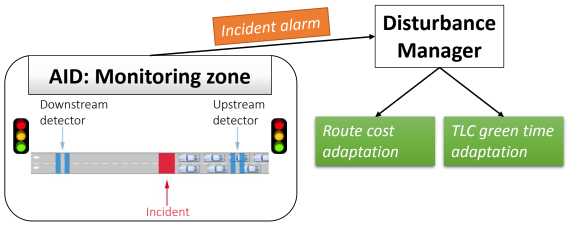

Figure 5: Automatic reaction process to a detected incident within OTC.

can be achieved by reducing the green times of traffic lights entering the congested road or by increasing green times at outgoing sections. The automatic adaptation of green times involves the following steps:

1. Localize the exact location of the incident.
2. Determine the signal groups $\{sg\}$ of the incoming turnings affecting the congested road. The green time of the phases in $\{sg\}$ will be reduced in the following. Mark all other phases $\{p\}$ for extension of their green times.
3. Filter out interphases and phases in $\{sg\}$ with green times below the minimal green period.
4. Calculate the available amount of green time reduction of the phases left in $\{sg\}$.
5. Shorten the green times of the phases in $\{sg\}$.
6. Equally increase the green time of the signal phases in $\{p\}$.

Note, that this algorithm ensures that the signal plans cycle time stays the same as before. However, it can be easily adjusted to extend the cycle time, e.g. by giving more green time to signal groups not belonging to the congested road. The phase lengths are always in whole numbers. Furthermore, no conflicts between different signal phases are created, since the relationship between phases and signal groups stays unchanged. The interphases stay the same in terms of their duration, and in terms of their position within the signal plan. According to the German handbook for traffic control (RILSA) (Forschungsgesellschaft für Strassen- und Verkehrswesen, 2010), the minimal duration for phases is five seconds. Therefore, phases with green times less or equal to this duration are not further shortened.

For n phases p (excluding interphases), the maximal amount of green time reduction is calculated as

$$t_{change} = \lfloor \lambda * \sum_{i=1}^{n} t_{shorten}[i] \rfloor \quad (4)$$

where $t_{shorten}[i]$ is calculated as

$$t_{shorten}[i] = \begin{cases} p_{GT}[i] - t_{red} & \text{if p can be shortened} \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

To control the extend of the algorithm, a green time reduction factor λ defines how much green time can be transferred from the shortened phases to other phases. Additionally, an adaptation threshold t_{red} can define the maximal absolute allowed change of green time (e.g. 5 seconds). In case that $t_{change} = 0$ (no green time reduction possible) or that the number of phases that can be extended is zero, the algorithms terminates and the active signal plan stays unchanged. Of course, this procedure can also applied in case there is more than one congested section. The adapted signal plan stays active as long as the applied AID algorithm confirms that the congestion is still ongoing. Afterwards, the signal plan which was active before the change, is restored.

5 EVALUATION

In the following, the evaluation scenario and the experimental results based on a real-world road network are presented. We compare the results of a simulation scenario with and without the adaptation of the signalisation based on incident alarms.

5.1 Simulation Study: Road Network

For further evaluation, we developed a simulation model in Aimsun of a real-world network with eleven intersections located in Hamburg, Germany (Figure 6). The evaluation was done with Aimsun 8 (Barcelo and Casas, 2002), a professional traffic modelling and simulation software widely used by traffic experts. The simulation duration is two hours. Figure 7 depicts the total number of trips throughout the simulation period.

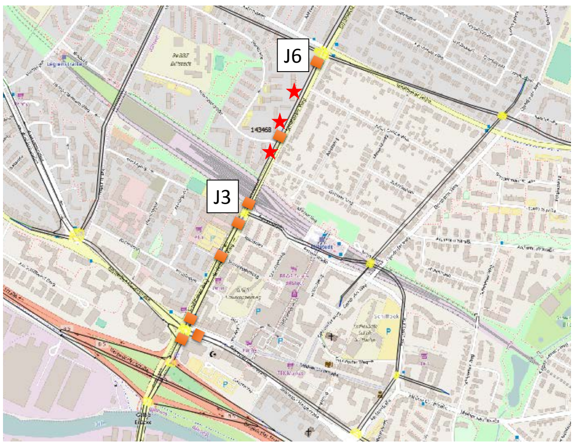

Figure 6: Aimsun simulation model of Billstedt at Hamburg, Germany. Stars highlight locations where incidents are created, rectangles mark locations of detector stations.

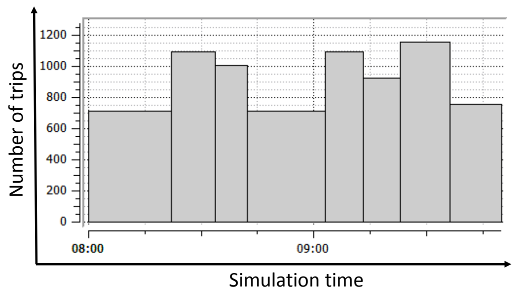

Figure 7: The absolute number of trips throughout the simulation period.

After 25, 55, and 85 minutes, an incident is created on the section going from intersection J6 to J3. Therefore, during incidents the signal plan at J6 (Figure 8) is changed in the way that less green time is given to turnings going towards J3.

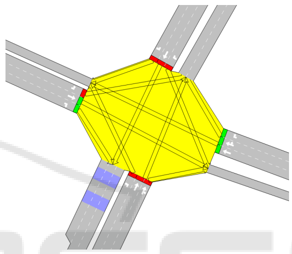

Figure 8: Simulation model of intersection J6.

As mentioned by (Deniz et al., 2012), the location of the incident can influence the detection rate. Thus, the incidents are located at three different locations within this monitoring zone. The incidents block both lanes and last for fifteen minutes. Detector stations are installed approximately 10 meters from the beginning, before the end, and in the middle of this section. The signal changes and phase durations simulated within Aimsun are controlled externally by OTC. For the eleven signalised intersections, the fixed-time signal plans have a common cycle time of 90 seconds with two to four phases. The duration for yellow light is two to three seconds. The simulations were executed on an Intel Core i7 quad-core CPU with 2.6 GHz and 8 GB RAM.

5.2 Experimental Results

The following section presents the results of the evaluation executed as described before. For the incident detection part, we select the all purpose incident detection algorithm (APID) (Masters and Wong, 1991), a well-established algorithm. We follow the algorithm configurations given by (Deniz et al., 2012) (see Table 1). Every second, APID receives its input from traffic detectors simulated by Aimsun. The traffic data (speed and occupancy values) is then averaged over a period equal to the execution interval.

Table 1: Parameters settings of the APID algorithm.

Control parameter	**Value**
Compression wave test	enabled
Persistence test	enabled
Medium traffic incident detection	enabled
Compression wave test period	300 sec.
Persistence test period	300 sec.
Medium traffic flow threshold	60
Incident clearance threshold	-0.4
Persistence test threshold	0.1
Compression wave test threshold 1	-1.3
Compression wave test threshold 2	-1.5
Incident detection threshold 1	10.2
Incident detection threshold 2	0
Incident detection threshold 3	20.8
Medium traffic incident threshold 1	0.4
Medium traffic incident threshold 2	0.1

Initially, we evaluate different execution intervals of 30, 60, and 120 seconds. The according results are given in Table 2. Interestingly, an execution interval of 120 seconds results in a low ATTD, however APID did not recognize the second congestion. As an execution interval of 30 seconds results in the lowest ATTD, we use this value for our next experiments.

Table 2: Average time to detection (ATTD) in seconds for execution intervals of 30, 60, and 120 seconds.

Start - End	**30**	**60**	**120**
25 - 40	32m 40s	33m 20s	32m 0s
55 - 75	63m 20s	62m 40s	not detected
85 - 100	91m 20s	96m 0s	93m 20s
ATTD	7m 27s	9m 0s	-

To evaluate the adaptation strategy of OTC considering congestion alarms, we took a deeper look into the signal plans created. Table 3 summarises the adapted green times for different values of λ. Again, $\lambda = 0$ displays the standard OTC strategy. For $\lambda = 1$, the cycle time is slightly increased by three seconds as the reduction of phase 7 would have resulted in a value below the minimal allowed green time. Therefore, it was set to the minimal duration of five seconds.

In the following, we compare our adaptation strategy of the signal timings against the standard OTC system running a fixed-time signalisation plan as introduced in Section 3. Each approach is evaluated based on following performance criteria:

- The total travel times for the complete network in seconds per kilometre,
- the average delay times (e.g. due to red traffic lights) in seconds per kilometre,
- the average stop time for the complete network in seconds per kilometre,
- and the vehicle's emissions: carbon dioxide (CO_2) and fuel consumption.

Table 3: Intersection's J6 adapted green times in seconds for $\lambda = \{0, 0.25, 0.5, 0.75, 1\}$. Interphases are highlighted in grey, shortened phases in red, extended phases in green. The duration of yellow light is three seconds.

λ	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
0	10	4	30	4	10	4	24	4
0.25	15	4	25	4	15	4	19	4
0.5	21	4	19	4	21	4	13	4
0.75	26	4	14	4	26	4	8	4
1	32	4	8	4	32	4	5 (2)	4

The emission of these pollutants has been estimated with the help of Aimsun's internal microscopic pollution emission model which is based on (Panis et al., 2006). The final results of the simulation runs are given in Table 4. A value of $\lambda = 0$ resembles the standard OTC behaviour. Compared to the standard OTC, the incident-adaptive OTC-control significantly reduces the evaluated traffic performance measures. Reacting to automatic incident alarms has the potential to reduce important traffic parameters, such as the average delay time and the average stop time at red lights. Independent of the value of λ, the results of the evaluated measure showed an improvement. On the one hand, the average stop time and the average travel time is reduced more for a smaller λ. On the other hand, the pollution emissions due to CO2 and the fuel consumption can be reduced more for higher values of λ.

Tentative Incident Alarms

APID only raises an incident alarm in case two successive executions result in congested classifications (so-called persistence check). An incident which is not yet confirmed is called tentative incident (TI). On the one hand, this additional confirmation lowers the number of false alarm. On the other hand, the ATTD is increased. In case the AID algorithm is executed every 30 seconds, the adaptation of the signal plan can be executed 30 seconds earlier when also considering TIs. In the following, we evaluate to what extend the consideration of TIs affects the experimental results.

In contrast to what we expected, the reaction to TIs does not necessarily improve the overall perfor-

Table 4: Experimental results for different values of λ with a execution interval of 30 seconds. $\lambda = 0$ resembles the standard OTC behaviour. Best results highlighted in bold.

λ	**0**	**0.25**	**0.5**	**0.75**	**1.0**
Total CO2 emissions [kg]	4875	4798	4820	4821	**4753**
Total fuel consumption [l]	1930	1931	1923	1923	**1906**
Avg. stop time [sec/km]	88.2	**85.0**	87.1	87.2	92.2
Total travel time [h]	701.3	**694.9**	698.9	699.1	700.5

Table 5: Experimental results using an execution interval of 30 seconds, also considering tentative incidents (TI).

λ	**0.75**	**0.25**
Total CO2 emissions [kg]	4860	4824
Total fuel consumption [l]	1940	1937
Avg. stop time [sec/km]	90.9	84.8
Total travel time [h]	718.3	693.9

mance. For $\lambda = 0.25$, the results were actually better than without TIs. However, for $\lambda = 0.75$, the experiment showed that the evaluated measures were worse than before. This effect is caused by the high number of TIs which are raised without leading to actual congestion alarms. These false tentative alarms during uncongested conditions can lead to a suboptimal signalisation.

Increasing the Cycle Time

Next, we evaluate the effect when we additionally allow OTC to extend the cycle time (without considering TIs). This can be done by extending the previous cycle time by a fixed offset. However, we want to evaluate the performance when we allow OTC to dynamically extend the cycle time in dependence of the severity of the disturbance as estimated by Equation 1:

$$t_{new} = t_{old} + 10s * severity \quad (6)$$

Therefore, the maximal cycle time extension is 10 seconds. Table 6 presents the according results. The increased cycle time resulted for all values of λ in a reduction of the average stop time. However, for extreme values, such $\lambda = 0.25$ and $\lambda = 1$, the evaluation showed no improvement or slightly worse results. However, for $\lambda = 0.5$ and $\lambda = 0.75$, this approach also reduced CO2 emissions and the total travel time.

6 CONCLUSION

In terms of congested conditions, real-world traffic control systems only propose which actions to take, but do not take countermeasures by themselves. Within this paper, we extend the self-organised traffic management system Organic Traffic Control (OTC) by means of congestion detection within urban networks. Based on this architecture, we proposed a method for the automatic detection of congestion and the automatic adaptation of signal plans due to incident alarms. Compared to the standard OTC system, the automatic adaptation of signal plans can mitigate the negative effect of congestion. Based on the results of a simulation scenario of a real-world network, our findings show that this approach significantly lowers important traffic parameters, such as the average delay time or the average amount of pollution emission. This reduction is achieved by re-routeing vehicles over alternative routes. Usually, these alternatives are longer in distance, which consequently can result in slightly higher travel times for some motorists. Furthermore, our experiments showed that the dynamic, automatic extension of the cycle time has the potential to further reduce the total travel time and the average stop time at red lights. Even if the primary objectives are not related to energy efficiency and reducing CO2 emissions, the implemented measures still have a positive impact on pollution emissions.

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Table 6: Experimental results for different values of λ and a execution interval of 30 seconds considering cycle time extension. Best results highlighted in bold.

λ	**0**	**0.25**	**0.5**	**0.75**	**1.0**
Total CO2 emissions [kg]	4875	4792	4836	4795	4846
Total fuel consumption [l]	1930	1939	1918	1930	1961
Avg. stop time [sec/km]	88.2	84.8	86.9	85.9	89.4
Total travel time [h]	701.3	698.1	696.2	697.9	713.3

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