International Journal of Electrical and Electronic Engineering & Telecommunications Vol. 7, No. 1, January 2018

Real-Time Microscopic Traffic Simulation and Optimization at Intersections with Video Traffic Detection

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Abstract—**In this paper, real-time vehicular data from video traffic detection (VTD) was used to minimize the travel delay at intersections and a real-time traffic optimization model—based on Simulation of Urban Mobility (SUMO) traffic simulation software—was established accordingly. The proposed model is implemented in a small industrial control computer, which serves as the communication interface between the traffic signal control system, the traffic simulation and optimization model, and the real-time VTD equipment to optimize the respective signal timing plans. The decision to shorten or extend the respective green time can be made at each second under the current development. To verify the results of the simulation study a field study was undertaken in Hefei, China. The overall intersection performances before and after the signal timing optimization were calculated and compared. The results show that the method proposed in this paper can significantly minimize the vehicle delay and the corresponding air pollution in real-time.**

***Index Terms*—-time intersection optimization, online simulation; SUMO, VITAL**

I. INTRODUCTION

Serious traffic congestion and its respective pollution problem have become one of the critical issues that worldwide governments have to face in metropolitan areas. Intersections are critical locations that affect the efficiency of traffic operation. The efficiency of traffic signal operation has therefore become one of the important indicators used to evaluate the performance of city traffic management. Diverse research on traffic signal optimization has been undertaken. Along with the innovation in technology more research studies have focused on real-time signal control optimization [1]-[4]. Different traffic control systems have also been developed and applied in practice, such as the Australian SCATS system, the British SCOOT system and the German ACTRA system [5], [6]. Moreover, microscopic traffic simulations have been extensively applied for traffic forecasting and strategy evaluation in the traffic management field. The respective application trend has obviously shifted from offline to online [7]. For example, Lin, Liu and Yao [8] proposed a method to assist decision making with use of an online traffic simulation. With this method the optimal emergency treatment plan can be promptly and quantitatively identified after a traffic incident has occurred. Wu, Shi and Xie [9] proposed a real-time calibration method for an online microscopic traffic simulation at intersections. In this method, a platoon dispersion diagram was used as the fit indicator. The calibration works by constantly adjusting the selected parameters until the difference between the simulated and the real platoon dispersions is less than the pre-defined threshold. Zhang, Zheng and Li [10] carried out the synchronization between the simulation and reality, and reproduced the traffic situation in the investigated area. They proposed the necessary interface components of the traffic data and control data so that the microscopic traffic simulation VISSIM can be connected with the real traffic data. Further, Deng and Li [11] proposed a data-driven intelligent traffic virtual simulation system architecture and the corresponding key technologies in a large data environment. Jia, Wu and Du [12] used FLOWSIM as an example to demonstrate the possible applications of microscopic traffic simulations in city traffic management.

The above-mentioned research has reached certain academic achievements. However, most of the proposed methods are still limited for practical applications. Moreover, the advantages of open source traffic simulation software, e.g., flexibly adjust/develop customized interfaces, and functions, have not been effectively utilized, especially for studying the traffic-related environmental issues at intersections in China. Therefore, this study focuses on the real-time optimization of traffic signals and the evaluation of the respective traffic emission productions with the use of microscopic traffic simulations and video traffic detection (VTD) data. The corresponding implementation and the applicability in practice are also the focus of this paper. In the following, the methodology and software used are described in Section II. Section III explains the respective

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Manuscript received October 14, 2017; revised December 11, 2017.

doi: 10.18178/ijeetc.7.1.30-37

implementation work for practical application. After that, the field study area and the current traffic situation are illustrated in Section IV. Section V shows the results from both the field study and the simulation. Finally, the corresponding conclusions and the perspectives are given in Section VI.

II. METHODOLOGY

The applied methods in the proposed model include the delay-based traffic signal optimization and the SUMO traffic simulation suite, which are explained below.

A. Delay-Based Traffic Signal Optimization

With the innovative development in information and communication technologies (ICT) the fine data from video capturing, wireless detectors and vehicle-to-infrastructure (V2X) communication have become available in real-time. This data helps to further model traffic phenomena in detail and effectively optimize traffic control/management strategies. Thus, the way to control traffic signals can be changed from traditional static control to demand responsive control to improve the operation efficiency of traffic signals.

The main concept of the developed delay-based control method, illustrated in Fig. 1, is to adjust the green time duration in each signal timing phase in regard to the vehicles' delay times, which can be derived from the collected ICT data [13].

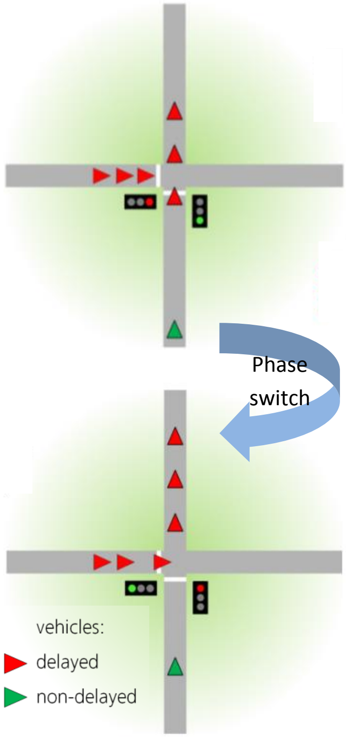


Figure 1. The concept of the delay-based method.

Given the signal timing phases, the maximum and minimum green times as boundaries allow the green time phase to be terminated either when all vehicles with delays have been served on the respective approach or the maximum green time is reached. A vehicle is considered to have a delay if its current speed on the approach is lower than the corresponding speed limit. Generally speaking, the delay time includes the initial deceleration time, queue move-up time, stopped time, and final acceleration time [14]. This method has been tested and validated with two German case studies in the VITAL (vehicle-actuated intelligent traffic signal control) project [15], [16] and is therefore also called the VITAL method.

Due to the methods characters, i.e., the phases and the respective sequence plan are fixed, the main improvement occurs during the off-peak periods. During the peak periods, there are high traffic volumes at intersections and the duration of the given maximum green time is often reached. Thus, the respective improvement is limited when comparing the traffic delay with that from the given static traffic signal control program [17].

B. SUMO traffic simulation suite

DLR's SUMO was applied for the real-time signal optimization and quantitative analysis of the influence of the VITAL method both on the environment and intersection performance in this study. SUMO is an open source, highly portable, microscopic, and continuous road traffic simulation package, which has been designed to handle large road networks. This simulation suite has been continuously developed for more than 15 years and has be extensively successfully applied in different projects related to urban traffic management, traffic emissions, V2X and other diverse traffic issues [18], [19]. Some simulation works [17], [20] with SUMO for Hefei city, China have also been conducted.

The applied emission model in SUMO is based on the emission model HABEFA 3.1 (the handbook of emission factors for road transport) [21]. The results in [17] show that the time series trend of the simulated emissions (CO, NOx) corresponds quite well with that of the respective measured emissions, especially during the daytime when most of the traffic occurs. Non-vehicle emissions cannot be simulated by SUMO.

In order to collect the simulated emissions at the subject intersection, SUMO TraCI (traffic control interface) was used so that the emissions of each simulated object can be retrieved and collected during a running the traffic simulations.

III. SYSTEM ARCHITECTURE AND IMPLEMENTATION

Instead of using loop detectors, the VTD technique was used in this study. The collected data are sent wireless to the control center. Therefore, special attention has been paid to the network latency when implementing the system. Traffic safety issues are also taken care in regard of the signal phases and vehicle clearance time.

A. System Architecture Design and Working Principle

The whole system consists of a small industrial control computer (IPC), an intersection signal controller and the video detectors at the intersection. All these components are connected by external physical interfaces. The IPC and the video detection server are deployed in the cabinet of the respective signal controller in order to shorten the communication distance and ensure that the communication chain is stable and reliable even under the harsh environment. The system architecture design is shown in Fig. 2. The applied VITAL method is implemented in SUMO. The IPC serves as the operating carrier in the SUMO-based traffic simulation and optimization model, and is connected to the signal controller and the video detector via the external interfaces RS232 and RS485, respectively.

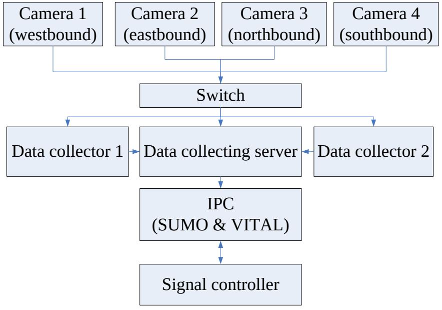


Figure 2. The system architecture design.

The working process of the system is explained as follows. The videos made by the camera in each direction are sent to the data collectors. After that, the data collecting server sends the real-time traffic flow data to the IPC as the basic input data. If a video detector is occupied, the corresponding vehicle is generated in SUMO for traffic simulation and signal optimization. Moreover, the traffic signal controller sends the current phase state to the IPC and, almost at the same time, receives and executes the signal control command from the IPC, i.e., shorten or extend the respective green time. The phase sequence plan remains the same. Only the duration of the respective green time will be adjusted according to the traffic flow data from the video detectors. If the given maximum green time is reached or there are no delayed vehicles on the respective approach, the IPC will send the phase switch command to the signal controller. The current green time phase will then be terminated and the next phase will be activated. All the actions sent by the IPC depend on the real-time intersection simulation and evaluation, executed by the embedded SUMO traffic simulation.

B. Data Communication Protocol

The way to connect the IPC and the traffic signal controller is to use a RS232 bus. The adopted communication baud rate is 57600. The data consists of one header, eight digit bits, and one end bit. No parity bit was applied. The traffic signal controller and IPC send data to each other every second to optimize the traffic control in real-time. The data length is in total eight bytes and the respective definition is shown in Table I.

Furthermore, the RS485 bus was used to connect the IPC and the video detectors for transmitting large amounts of data in real-time. The respective communication baud rate is 115200. The data includes one header, eight digit bits, and one end bit without any parity bit. The data format definition is indicated in Table II.

TABLE I: THE DATA TRANSMISSION FORMAT BETWEEN THE IPC AND THE SIGNAL CONTROLLER.

Name	Format Definition	
	From the signal controller to the IPC	From the IPC to the signal controller
Header (1 byte)	0XE5	0XE5
Signal work mode (1 byte)	0X00: Controlled by the planned signal controller 0X01: Controlled by the DLR-pc	-
Program number (1 byte)	1-32	-
Phase number (1 byte)	1-32	-
Phase state (1 byte)	0X00: Normal state 0X01: Transition state	-
Working state (1 byte)	-	0X00: Abnormal 0X01: Normal
Switch state (1 byte)	-	0X00: Keep the current phase 0X01: Begin to switch the phase
Reserved	Reserved (2 bytes)	Reserved (4 bytes)
End (1 byte)	0X5C	0X5C

TABLE II: THE DATA TRANSMISSION FORMAT BETWEEN THE IPC AND THE VIDEO TRAFFIC DETECTORS.

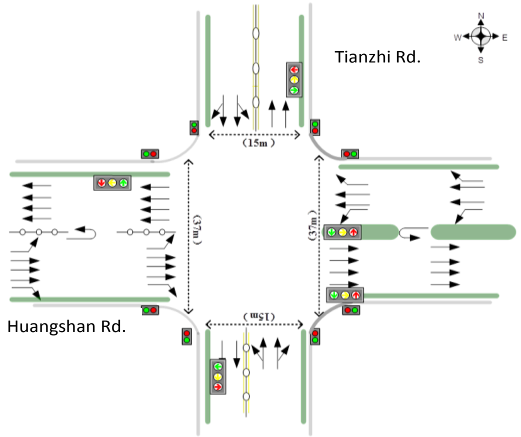
Name	Format definition	
	When a vehicle enters a detector	When a vehicle leaves a detector
Header (1 byte)	0XF0	0XF1
Detector number (1 byte)	1-39	1-39
Occupancy time (2 bytes)	-	Integer
End (1 byte)	0X5C	0X5C

IV. FIELD STUDY

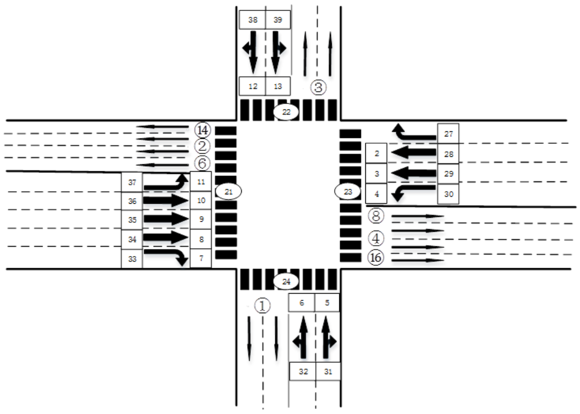
To examine the proposed system and model mentioned in Sections II and III, the intersection at Huangshan Rd. and Tianzhi Rd. in Hefei city, China was selected for the field study. This intersection is equipped with different types of sensors and communication devices used for different research studies on ICT-device testing and validation as well as intelligent traffic management. The collected data are also the important data source used to understand the local driving behavior, such as car following and lane changing. In the following, the executed field study is explained in five parts: The current infrastructure, the applied video detection, the existing traffic situation, the designed traffic signal plans, and the traffic simulation establishment.

A. Infrastructure

The subject intersection is equipped different types of sensors and communication devices used for different research studies on the intelligent traffic management system. Huangshan Rd. is the main arterial with four lanes in each direction and serves the east- and westbound traffic. Tianzhi Rd. is a minor street with two lanes in each direction. The intersection layout and sensor allocation are depicted in Fig. 3 (a) and (b), respectively. The detectors, indicated with numbers in the squares are vehicle detectors, where 1-13 and 27-29 represent the detectors at the road sections and at the intersection, respectively. The traffic signals, indicated with numbers from 1 to 15 in the circles are for vehicles and those with numbers from 21 to 24 in the ovals are for pedestrians.



(a) Intersection layout.



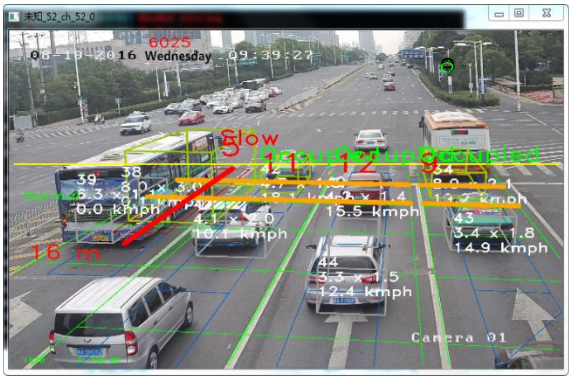
(b) Sensor allocation.

Figure 3. An illustration of the infrastructure at the subject intersection.

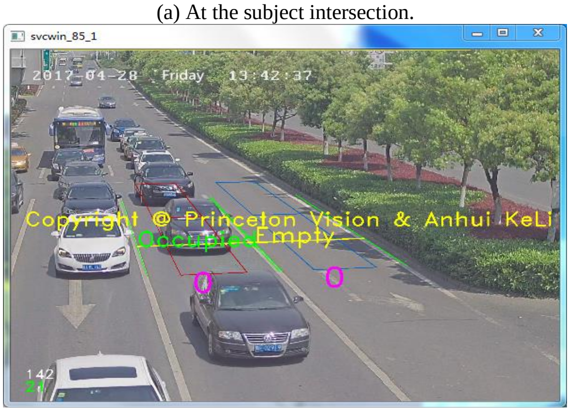
B. Video Traffic Detection(VTD)

An improved Kalman filter detection algorithm was adopted in the VTD process to overcome the intensive computation of vehicle tracing and the issue that vehicles can be obscured by other subjects. Through the prediction of the characteristics of a vehicle, such as vehicle position and vehicle edge, the moving target can be found and then matched with the current frame to find the corresponding relation in the image sequence and ensure the respective trajectory. When a vehicle is hidden, the matching template is updated with the use of the vehicle body edges before and after the occlusion in order to improve the matching accuracy.

The experimental results show that this method can accurately detect the moving objects in the given video images and can also perform well when there are changes in the brightness and background of the scene in real-time. Fig. 4 shows two screenshots of the applied video detectors.



(a) At the subject intersection.



(b) At a road section closed to the subject intersection.

Figure 4. The screenshots obtained from the deployed video detectors.

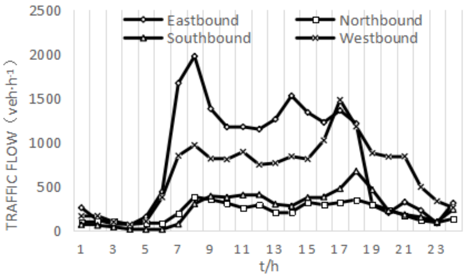


Figure 5. The traffic flow time series on a normal workday.

C. Current Traffic Situation

The traffic flow time series on a normal workday is illustrated in Fig. 5. Passenger cars are the main traffic. Some buses also exist, but mainly during the peak-hour periods. Trucks and large delivery vehicles are not allowed during the daytime. The morning and evening peak periods are between 0700 and 0900 and between 1700 and 1900, respectively. After 1900, the traffic in the eastbound direction is still quite high in comparison to that in the other directions.

Furthermore, the saturation headways and flows were collected and calculated, respectively (see Table III). It is obvious that the saturation headways in the east- and westbound directions are less than those in the south- and northbound directions. This is mainly since the lane use groups are separated, i.e., each traffic movement has its own lane(s), and the signal phases are protected for each traffic movement. Due to the shared lanes and signal phases the south- and northbound traffic has larger headways to ensure traffic safety. Such higher headways result in lower saturation flow rates, especially for the left-turn traffic.

TABLE III: THE SATURATION FLOW RATE AT THE INTERSECTION.

Direction***		Parameters		
		Saturation headway	Number of lanes	Saturation flow (pcu/h)
Eastbound	Left	2.05	1	1756
	Through	2.03	3	5320
Westbound	Left	2.31	1	1558
	Through	2.2	2	3272
Southbound	Left*	2.91	0.5	619
	Through**	2.51	1	1434
Northbound	Left*	2.65	0.5	679
	Through**	2.48	1	1452

* The lane is shared by the left-turn and through traffic. Thus, the respective number of lanes was set as 0.5.

** The lane is shared by the through and right-turn traffic. Since the right-turn traffic is not controlled, the number of lanes was set as 1.

*** The right-turning traffic is not controlled and thus not collected.

TABLE IV: THE AVERAGE HOURLY FLOW RATE AT THE INTERSECTION DURING THE OFF-PEAK PERIOD (1100-1600).

Direction		Road Parameters		
		Flow rate (pcu/h)	Ratio/ Movement	Ratio/ Direction
Eastbound	Left	30	0.04	0.48
	Through	700	0.96	
Westbound	Left	330	0.29	0.31
	Through	800	0.71	
Southbound	Left	130	0.65	0.12
	Through	70	0.35	
Northbound	Left	80	0.29	0.09
	Through	200	0.71	

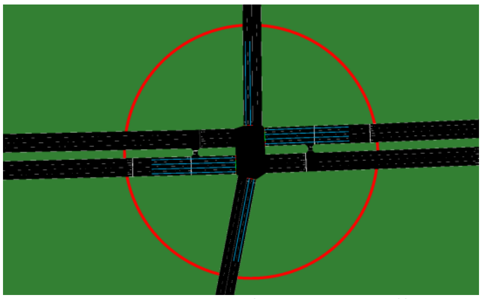
With the consideration of the characters of the VITAL method, mentioned in Section II, the field test focuses on the off-peak period from 1100 to 1600. Table IV shows the average traffic flows during the off-peak period. The through traffic is the main traffic in the east- and westbound directions, where 29% of the westbound traffic is left-turn traffic. This indicates that the current protected left-turn phase corresponds to the left-turn traffic demand. On the other hand, there are also higher left-turn ratios in the south- and northbound direction (65% and 30%, respectively). Due to the lower through traffic demand the left-turn traffic can find an appropriate gap to go through the intersection. Thus, there is no need to set a protected left-turn phase, which also corresponds to the current signal program.

D. Signal Timing Plans

The current traffic signal program used for the analysis period has three signal phases. The first and the second phase are for the west- and eastbound traffic, respectively. The south- and northbound traffic share the third phase together. All right-turning traffic is not controlled by the traffic signal. According to the observed traffic situations, the current signal phases correspond to the existing traffic demand. Thus, only the green time duration will be adjusted in the field study. The designed timing plans are shown in Table V.

TABLE V: THE PROPOSED GREEN TIME DURATIONS.

Direction	Green time (s)	
	Minimum duration	Maximum duration
Eastbound	10	31
Westbound	12	37
South- and Northbound	18	33



* The red circle is with a radius of 90 m. The traffic emissions are collected within the circle.

** The blue lines represent the detectors deployed in the field study.

Figure 6. The layout of the simulative intersection.

E. Traffic optimization and simulation model

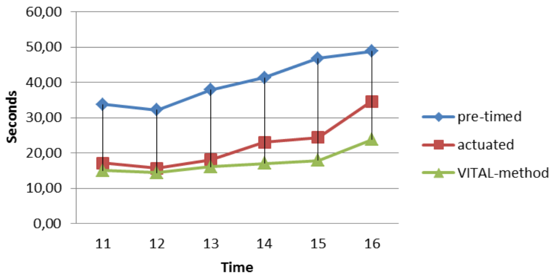
According to the traffic data, detector allocation, traffic signal phases, and designed signal timing plans, the traffic simulation at the subject intersection was established. The simulation layout is shown in Fig. 6. The real-time data will be directly sent to SUMO and the VITAL method for traffic simulation and traffic signal optimization. The simulated traffic emissions at the intersection with a radius of 90 m were also collected to analyze the environmental influence of the VITAL method. Furthermore a gap-based actuated control method [22], which is often applied in Germany, was adopted as a reference control method. The main idea of the gap-based actuated control is to switch the signal phase after detecting a sufficient time gap between successive vehicles. This method aims at forming a better distribution of green time among the phases and affecting the respective cycle duration in response to dynamic traffic conditions.

V. RESULTS

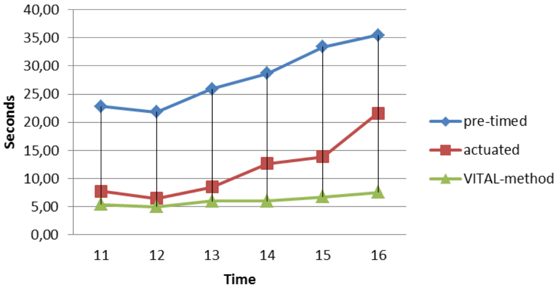
The simulation study was initially carried out to compare the VITAL method with the current pre-timed and the gap-based actuated control methods. Both the intersection operation efficiency and the environmental impact were investigated. Further, the average vehicular delay and the number of vehicular stops before and after the application of the VITAL method in the field study were compared to understand the affect that the applied online traffic simulation and optimization model has brought in practice.

A. Simulated Results

The collected data are limited in the field study due to some technical reasons. The vehicle data collected in June 2017 were thus used in the analysis. Fig. 7 (a) shows the average delays per vehicle from 1100 to 1600 with three different traffic control methods. Both the actuated and the VITAL method can substantially reduce the delay time in comparison to the pre-timed method. The reduction ratio over 6 h was 45% and 57%, respectively. The VITAL method can reduce the delay time more than the actuated method, especially in the period between 1500 and 1600 close to the traffic peak period (1700-1900). A similar result can also be found when observing the stopping duration (see Fig. 7 (b)). The average stopping duration remains quite constant, between 5 and 8 s, when applying the VITAL method. In comparison to that, the actuated method is more dependent on the amount of traffic and the stopping duration varies between 6 and 22 s.

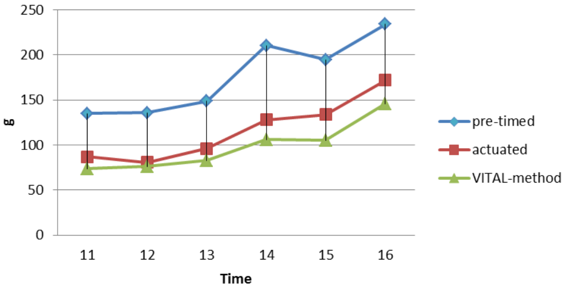


(a) The average delay observed for the three different control methods.

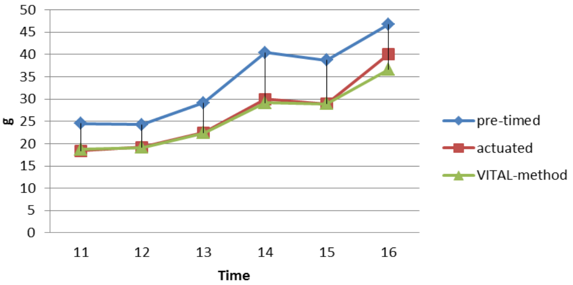


(b) The average waiting time observed for the three different control methods.

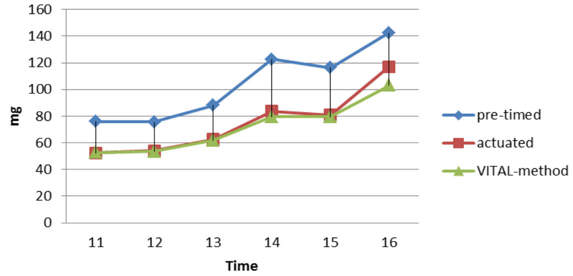
Figure 7. The layout of the simulative intersection.



(a) The hourly CO production observed for the three different control methods.



(b) The hourly NO_x production observed for the three different control methods.



(c) The hourly PM_x production observed for the three different control methods.

Figure 8. A comparison of the simulated emissions.

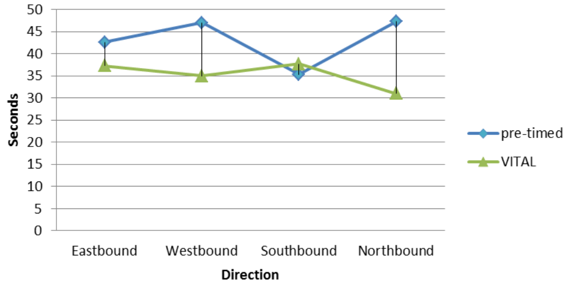
In regard to the environmental influence, the VITAL method results in the least amount of produced emissions among the three applied control methods. Fig. 8 indicates that the application of the VITAL and actuated methods have a significant reduction in the CO emissions when compared with the pre-timed method. The total reduction ratio in the overall observation period was 44% and 34%, respectively. The reduction ratio in NO_x was 22% with the actuated method and 24% with the VITAL method. The reduction ratio in PM_x was 27% and 31% for the VITAL and actuated method, respectively. The results also indicate that both traffic dependent control methods result in a similar reduction in the NO_x and PM_x emissions when the traffic flow is quite low, e.g., between 1100 and 1500. When the traffic flow increases and approaches the amount of traffic during the peak-hour period, the VITAL method performs better than the actuated method.

B. Actual Results

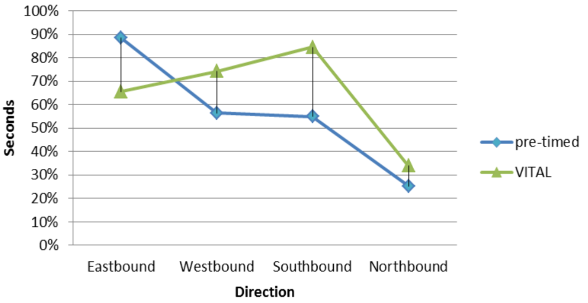
A survey of the intersection operation efficiency was conducted during the field test. The average delay and the vehicle stopping rate at the subject intersection were 45 s and 64%, respectively before the proposed model was applied. After the model was applied the values become 35 s and 66%, respectively. The reduction in the traffic delay was 21%. However, the vehicle stopping rate slightly increased by 3% after the model was applied. This was attributed to the signal phases being switched more often to better allocate the available green times. More vehicles may therefore need to stop, but for a short period of time.

Fig. 9 shows a comparison of the results for each driving direction. The proposed model reduced the average delay in most of the directions except the southbound direction (35 s with the pre-timed control and

38 s with the VITAL method). This is mainly due to the simulated objects and real vehicles do not perfectly synchronize with each other. Sometimes, some simulated vehicles have already left the intersection and the signal phase is then switched to red. However, the respective vehicles in practice are still in front of the intersection and therefore need to wait for the green phase. Fig. 9 (b) indicates that the eastbound traffic has around a 20% lower vehicle stopping rate after applying the proposed model. There are higher vehicle stopping rates in the other three directions, especially in the southbound direction. Such a result is also due to the frequent phase switching. Moreover, the left turning traffic in the southbound direction was higher than the through traffic, and needs more time to cross the intersection in practice than in the simulation. Thus, less left turning traffic can pass the intersection and more stops need to be made.



(a) The average delays.



(b) The vehicle stopping rate.

Figure 9. The intersection performance before and after applying the online traffic simulation and optimization model.

VI. CONCLUSIONS

In this study, a real-time traffic simulation and signal optimization model have been proposed and implemented on a small IPC with high applicability and practicability. Further, it is demonstrated that with the use of the ICT data, the varied traffic states can be easily captured in real-time and the intersection's operation efficiency significantly improved with the proposed model in practice.

Due to the illegal crossing behavior by pedestrians and some "imperfect" driving behavior in practice the achieved improvement in the real field test is less than that in the simulation study. However, the overall performance of the proposed model is still better than the other methods. Further enhancements in the synchronization of the simulated and the real objects, and the adjustment of the crossing time for left turning traffic need to be undertaken in order to improve the models performance. It is also planned to extend the field test area to a road corridor with several intersections and then to a complete traffic network.

ACKNOWLEDGMENTS

This work was carried out within the Optimization of Urban Traffic Management towards Environment-Friendly and Safe Mobility (OptimUM) project, which is financially supported by the Helmholtz CAS joint research groups (HCJRG) of the Helmholtz association of German Research Centers. This support is gratefully acknowledged.

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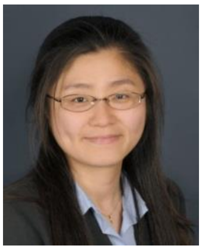

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