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VITAL: Traffic Signal Control Based on V2X Communication Data – Application and Results from the Field

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Abstract

The aim of the research project VITAL (Vehicle-Actuated Intelligent Traffic Signal Control) was to implement and to test two novel signal control methods in the field. The two new approaches are the delay-based control and the cooperative control which are based on vehicle-to-infrastructure (V2X) communication data. The two test intersections used for validation are located in the German cities of Halle (Saale) and Braunschweig. Before applying the controls in the field, they were benchmarked in simulation studies and prepared in the traffic signal laboratory of DLR for implementation. The test intersections had to be adapted with additional detection and controlling equipment, and the vehicle-actuated controllers were modified. After these preparations the two new VITAL control approaches were activated for test runs with durations of several weeks. The measured data showed that the two new VITAL control methods work as well or better than the existing reference controls.

Keywords: traffic signal control; new control approaches; validation in the field

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1. Introduction

Traffic signal control has a major impact on the quality, safety and environmental effects of traffic flow within urban road networks. With a view to optimize these and similar parameters, a variety of different signal control approaches are applied which differ in their structure and complexity. These approaches range from well-established fixed time controls (Webster, 1958), via classical vehicle-actuated procedures, to model-based network wide controls (Busch and Kruse, 1993), (Friedrich, 1997), (Hunt, et al. 1981) or decentralized self-organized strategies (Lämmer, 2007) to name but a few. In this context, new methods in traffic data collection based on e.g. video capturing, probe vehicle data and other wireless communication technologies open up new possibilities for traffic signal control. Especially data from the vehicle-to-infrastructure communication (V2X) seems to be of great value for an improved future signal control. In this case, vehicles are directly connected to the traffic signal control system and can exchange data in both directions: transmit information to the system as well as receive data from it. The vehicles with their trajectories and the parameters, which can be derived from them, are becoming multiple redundant detectors for the system. These derived parameters include e.g. vehicles' travel times, delay times and speeds on the approaches of an intersection. These time- and path-continuous parameters have been difficult to capture with fixed-location detection equipment so far, which is why they have hardly been applied for real-time signal control.

Based on this progress in traffic data collection and especially the upcoming vehicle-to-infrastructure communication (V2X), two new traffic signal control methods have been developed. They utilize the information which can be derived from the vehicle-to-infrastructure communication (V2X) and use it as input for their control decisions. These novel control methods and their functionality are briefly described below, before their implementation and testing in the field, as well as the obtained results are presented.

2. New signal control methods

The two novel signal control methods are the so-called delay-based control and the cooperative control. Both methods were designed with the aim to use only information from the described vehicle-to-infrastructure communication (V2X) (ETSI, 2014) as input for control decisions and no data from fixed-location detection equipment. Both novel methods are based on different philosophies and have different degrees of complexity as well as functions.

2.1. Delay-based control

The basic idea (Wagner, 2009), (Oertel and Wagner, 2011) behind the delay-based control is to use the delay times of approaching vehicles to adjust the green times of an intersection. In this context, the delay time of a vehicle is the additional travel time for passing the intersection compared to an uninterrupted flow. That means, as soon as a vehicle has to decelerate on an approach and moves below a defined speed limit, which can be e.g. the maximum permissible speed, it automatically accumulates delay time. This is usually caused by the traffic signal itself or by other interruptions in traffic flow and includes the deceleration, waiting and acceleration process, which is reflected in the vehicle's accumulated delay time. Using this information as an input and bounded by a minimum and a maximum permissible green time, the control extends a running green phase as long as all vehicles with accumulated delay time on an approach have been served. Then the current phase is changed and the described principle is applied to the next phase in the cycle. A detailed description on how the delay-based control works and how it performs in several simulation studies can be found in (Oertel and Wagner, 2010), (Oertel and Wagner, 2011), (Oertel et al., 2012).

2.2. Cooperative signal control

The general approach of the cooperative control (Erdmann, 2013) is to link a vehicle-actuated control with the GLOSA (Green Light Optimal Speed Advisory) functionality (Katsaros et al., 2011). This means that this control can react to variations in traffic flow, while at the same time sending reliable speed recommendations to the approaching vehicles. For this purpose, the approaching vehicles with their current speeds and positions are detected at an early stage and their further driving trajectories are prognosticated. This can be done with a simple model or a traffic simulation. Based on these prognosticated trajectories, the vehicle arrivals at the stop lines can be predicted, too, and the green times can be adapted according to traffic. These green times are bounded by a minimum and a maximum permissible threshold for the phase duration. The green time adaption is performed by an optimization algorithm, which is based on dynamic programing and can take speed adaptations due to GLOSA into account. The aim of the algorithm is to minimize the sum of the delay time of all vehicles at an intersection.

Information then transmitted from the signal controller to the vehicles can be the optimal approaching speeds, or alternatively the calculated signal times. This allows the vehicles to adapt their own trajectories according to the prediction. The optimization process iterates influencing and predicting the green times and can be repeated for up to every second. Details on the cooperative control can be found in (Erdmann, 2012).

3. Implementation in the field

3.1. Test sites

The focus of the research project VITAL (Vehicle-Actuated Intelligent Traffic Signal Control) (Oertel et al., 2013) was to put the two novel controls (in the following also titled as the VITAL methods) into practice and to validate them in a field test. For this purpose, in a first step suitable test intersections had to be found. To simplify this selection, some requirements were defined for potential intersections. The most important requirement was that the responsible road authority was willing to support research and to provide one of their intersections for the field test. The intersection itself should not be a part of coordination and the currently applied control should be vehicle-actuated. A further desirable criterion for selection was a variable cycle time. These requirements were important, since the VITAL methods in their first development stage are only intended for usage at single intersections. In addition, the VITAL methods should have as few restrictions as possible in green time adjustment. The traffic volume at the test intersection should vary between low and high density to be able to investigate a whole range of different traffic situations. Existing public transport priority rules should not be touched. Pedestrians and cyclists should be taken into account, but they should not have an active influence on the control. Two intersections meeting these requirements were selected in the German cities of Halle (Saale) and Braunschweig. These are the intersections Dölauer Straße / Brandbergweg and Tostmannplatz, as shown in Fig. 1.

Fig. 1. Test intersections in the German cities of Halle (Saale) - Dölauer Str./Brandbergweg (left) and Braunschweig - Tostmannplatz (right).

Both intersections differ in their geometry, existing technical equipment and traffic conditions. The test intersection in Halle (Saale) has three approaches, each with one lane per direction and additional lanes for turning. The existing signal control uses induction loops and infrared sensors to capture occupancy times and time gaps for vehicle-actuated green time adjustment. Preemption for two local bus lines is applied, too. The second test intersection in Braunschweig has four approaches and is more complex. There are two lanes per direction on the main road and additional lanes for left-turning. The applied control uses a number of induction loops for vehicle-actuated green time adjustment, based on time gaps. A bus line passes through the intersection, but without preemption.

3.2. Vehicle detection

In order to be able to test the two novel VITAL control methods in the field, the test intersections had to be technically prepared. This included the traffic detection, the traffic signal controllers and some other additional components. The most important challenge was the capturing of the parameters required as input for the controls, such as the delay times, positions and speeds of the vehicles. As already described, both VITAL methods have been developed for use of data from the of vehicle-to-infrastructure communication (V2X). This should demonstrate that traffic signal control can not only work with traffic volumes and other classical parameters e.g. time gaps or occupancies. However, there is still a lack of vehicles equipped with V2X technology. The minimum required equipment rate of about 20% (Oertel and Wagner, 2011) is currently not available, which is why conventional, fixed-location sensors had to be used in the project. This made the setup for the field tests more complicated and represents a workaround for the compensation of the insufficient V2X data. In the future, where equipment rates are assumed to be higher, these sensors will not be necessary anymore.

For this workaround two detectors should be used per lane, located about 100m upstream and directly behind the stop line. Together they form an intermediate measuring section, in which the delay time information and the arrival times of the approaching vehicles can be determined for the control (Oertel et al., 2012). Each vehicle is detected when passing the detectors at the entrance and exit area; vehicle recognition is not necessary. Communication from the signal controller to the approaching vehicles for speed recommendations is, of course, not possible in this setup.

Since the existing induction loops at the intersections in Halle (Saale) and Braunschweig did not cover this required combination to form the measuring section, additional detectors were applied. Magnetic field sensors were used for installation in the roadway surface. They have the advantage that a cabling over long distances could be avoided, because their information transmission to the signal controller is wireless. The setup of these magnetic field sensors is shown in Fig. 2 for the two test intersections. In some approaching lanes additional sensors were installed in order to better handle effects such as e.g. cutting the curve when turning.

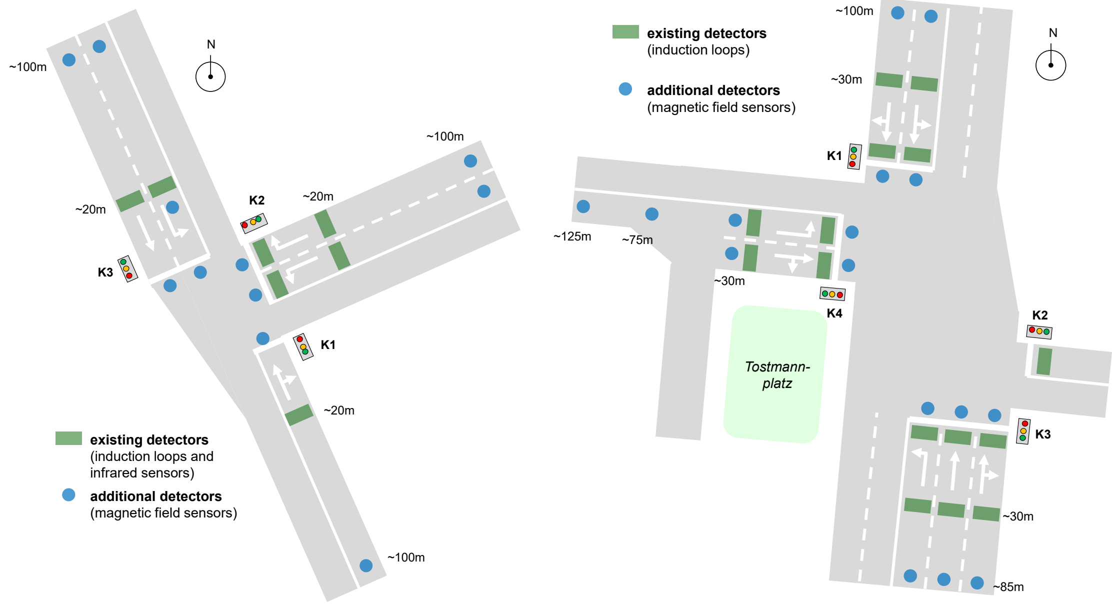

Fig. 2. Setup of detectors at the test intersections in Halle (Saale) (left) and Braunschweig (right).

In addition to the magnetic field sensors, the test intersection in Braunschweig was equipped with a roadside unit (RSU) (see Fig. 3). The RSU contains a V2X unit, which enables direct communication with equipped vehicles. Even if this RSU has not yet been applied in the field test, it has already been tested for the delay-based control method on the DLR site (Oertel et al., 2013). Since the Tostmannplatz is an intersection within the AIM network (Application Platform Intelligent Mobility) (Schnieder, 2012), the RSU is basic technical equipment.

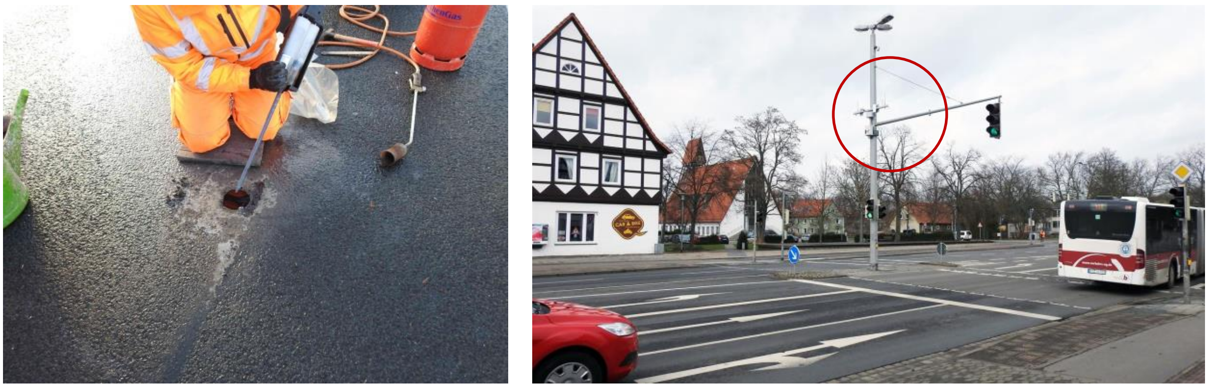

Fig. 3. Installation of magnetic field sensors (left) und roadside unit (right) at the VITAL test intersection in Braunschweig.

3.3. Control integration

The next step was to prepare the two VITAL control methods for the integration into the local signal controllers. For the delay-based control this means it had first to be adapted to the local conditions of the test intersections and a control logic had to be defined. The basic idea was to keep the existing vehicle-actuated controls completely unchanged; only the criteria for the decision making when to terminate a running green phase should be replaced. Parameters such as cycle times, phase sequences, minimum and maximum signal times, public transport preemption, etc. were not touched. The new criteria for green time termination is now the clearance of all delayed vehicles on an approach, instead of using the time gap (currently measured time gap is greater than the maximum permissible time gap). The idea for the cooperative control method was different; instead of using time gaps, an optimized switching sequence was computed anew each second and the first part of that sequence was used to determine whether a phase should be prolonged or terminated.

For the implementation of the delay-based control method according to this description, the existing control logics of the two test intersections were modified at different points and extended by several new modules. The modules contain all the functions of the delay-based control and were simply added to the existing logics. This procedure ensures that the delay-based control can be implemented on any signal controller. It only requires functions from the standard library that each signal controller supports and is independent from a special manufacturer. The delay-based control method requires no additional computing unit and is only executed on the signal controller itself.

A comparable approach has been adopted for the implementation of the cooperative control method. However, certain components of this method have not been able to be implemented on a common signal controller. They have been transferred to an external industrial mini-PC as depicted in Fig. 4, left. These components are a SUMO simulation (Krajzewicz et al. 2012) in the background, as well as the optimization algorithm. The task of the simulation is to predict the further trajectories of the vehicles on their way from the upstream detectors to the stop lines, which is the input for the optimization algorithm. The existing control logics had to be modified to transmit the detections of the magnetic field sensors and the current signal states via digital outputs from the signal controller to the external industrial mini-PC. In turn, the existing control logics had to be adapted to receive and process phase switching commands via the digital inputs from the external mini-PC. The logic on the signal control has only a dummy function: it forwards the phase switching commands of the cooperative control from the external mini-PC and monitors the compliance with the basic conditions e.g. intergreen times.

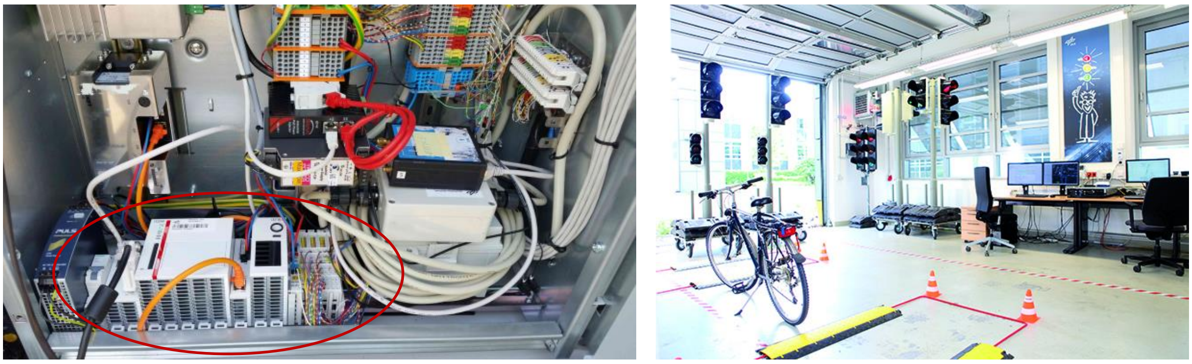

Fig. 4. Industrial mini-PC at the VITAL test intersection in Halle (Saale) (left) and traffic signal laboratory of DLR in Berlin (right).

Before these described modifications were implemented in the field, some prototypical tests were done in the traffic signal laboratory of DLR (see Fig. 4, right). This laboratory is equipped with real traffic signal controllers, detection equipment and common traffic engineering software. In addition, various simulation studies (Erdmann et al., 2015), (Oertel et al., 2016) of the VITAL control methods were performed in advance to be able to estimate traffic effects and to parameterize the new control methods. Afterwards in the field, the two new control methods were implemented as additional signal plans, which could easily be activated via a remote access from the cities' traffic management centers. This remote access was import in case of any occurring problems.

4. Field tests

4.1. Validation process

After the two test intersections were technically prepared and the two new VITAL control methods were implemented, the validation process was started in the field. First of all, the test periods for the activation of the VITAL control methods had to be defined. Special attention was paid to holiday periods and regional construction works, which had an influence on the traffic flow at the test intersections. The consideration of these boundary conditions was important in order to ensure comparable traffic volumes at the intersections during the whole validation process.

A test period should be at least three weeks, ideally even longer. Within this time period the delay-based control, followed by the cooperative control and the already existing control should be activated, each for one week. The existing control should be the reference for a later comparison. For this purpose, records from the local signal controllers were made, accessible from the cities' traffic management centers. These records contained parameters such as traffic volumes, signal times, detector occupancies, phase durations, cycle times and requests for public transport preemption. In addition, self-defined parameters from the VITAL control methods were recorded e.g. vehicles' delay times, vehicle counters and special checksums. Together with the records from the existing controls as the references, these were the data for the subsequent evaluation.

For the recording of the delay times of the vehicles, the fixed-located detectors and the measuring sections were used, which were already required for running the VITAL control methods. That means the delay times within the measurement sections were not only determined during the activation of the delay-based method for signal control, but also in the background for the other methods. These records were supplemented by manual traffic observations and counts on site at the two test intersections.

The test runs were performed during 27.06.-17.07.16 (first period) and 05.09.-02.10.16 (second period) in Halle (Saale) and during 16.09.-26.10.16 in Braunschweig. The second test period in Halle (Saale) was necessary, because the initial analysis of the recorded data showed that the VITAL control methods achieved very high gains in the average delay time per vehicle, but the existing control still had some potential for improvement. In order to achieve the most realistic results possible and to avoid any irregularities, the existing reference control was therefore slightly modified and a second test run was performed.

4.2. Results

After the completion of the test runs, the evaluation of the two VITAL control methods started, based on the previously recorded data. The records were analyzed and the results of the delay-based control and the cooperative control were compared with those of the already well-performing conventional controls at the two test intersections. In the following considerations the results from Halle (Saale) are firstly discussed, followed by the results from Braunschweig. Some of the results are broken down to individual signal groups, which were previously named in Fig. 2.

Initially, the traffic volumes at the test intersection in Halle (Saale) are examined. About 100,000 vehicles passed per week, which was approximately equal for each control method when it was activated. However, the traffic flows within the test intersection are different, depending on the time of the day. Fig 5 shows an example of daily traffic volumes for 28th of June, 2016, differentiated according to driving relations (le: left-turn, ri: right-turn). Peak hours and main directions can be recognized: in the morning with K3 and K3le as the city-bound flow and in the afternoon with K2ri and K1 in the opposite direction. This means there were some dynamics in traffic flow.

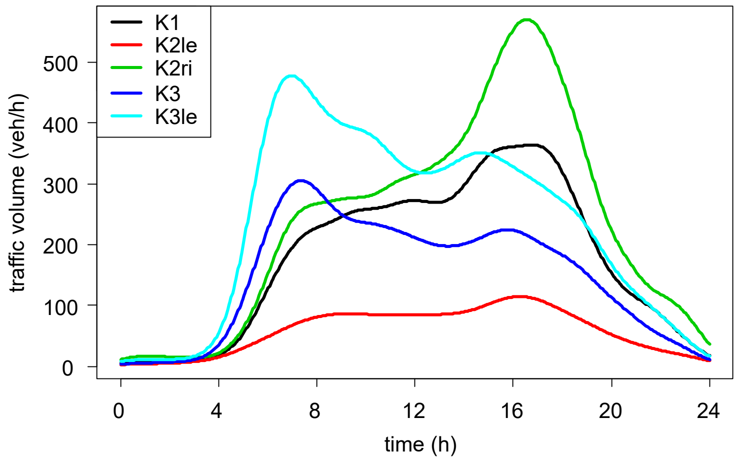

Fig. 5. Halle (Saale) – varying traffic volumes during the day, 28.06.16, classified by driving relations (le – left-turn, ri – right-turn).

The next step was to examine how well the three controls could handle these dynamics in traffic flow. The average delay time per vehicle was considered as an indicator, which was determined from the records. It was initially normalized over the test run duration and the number of vehicles that had passed, to ensure a reasonably comparison of all three control methods. The results of this comparison are depicted in Fig. 6 for the second test period. It can be seen that both VITAL control methods were able to achieve reduced delay times. On closer analysis of the individual signal groups, it becomes clear that these effects were obtained almost exclusively at the signal group K1. On this approach were regularly longer queues during the peak hours, which the VITAL methods cleared in a different manner, even all the three controls had the same boundary conditions, e.g. maximum permissible green times. Observations on site confirmed this different behavior.

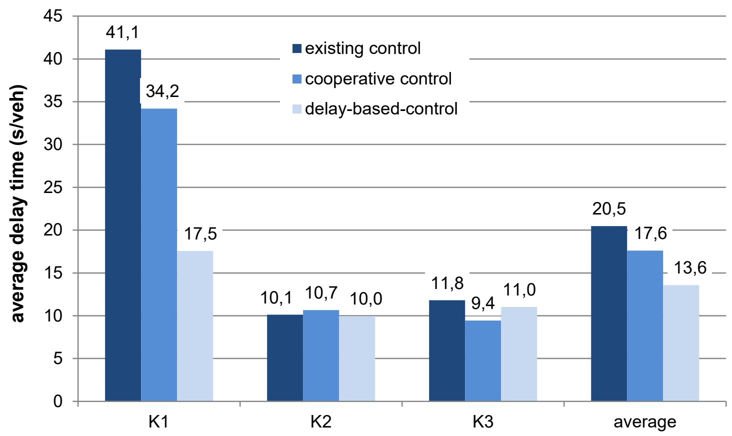

Fig. 6. Halle (Saale) – average delay time per vehicle during the period 05.09.-02.10.16, classified by signal groups K1-3 and average.

Since these observations include all traffic demand situations during the whole test period of at least one week, a further detailing was made on the basis of different demand scenarios. This should be used to investigate how the VITAL control methods behave in different traffic demand situations. For this purpose a low, a medium and a high demand scenario were defined. The total traffic volumes of the three control methods were initially aggregated into hourly values over their respective test period. Starting from the existing control as the reference, the peak hour with its traffic volume was determined and all other hourly values were classified:

- Low demand: 0-60% of the traffic volume of the peak hour
- Medium demand: 60-80% of the traffic volume of the peak hour
- High demand: 80-100% of the traffic volume of the peak hour

By means of this classification, the corresponding average delays times per vehicle were then assigned. The results of this procedure are shown in Fig. 7. The VITAL control methods show only slight differences in the case of a low demand compared to the existing control as the reference. The reason for this are the fixed minimum green times which are the same for all three controls and offer only little potential for a reallocation. With increasing traffic demand, the differences between the three controls steadily increase and achieve a maximum in the case of a high traffic demand. The delay-based control gains the lowest average delay times per vehicle in all three scenarios.

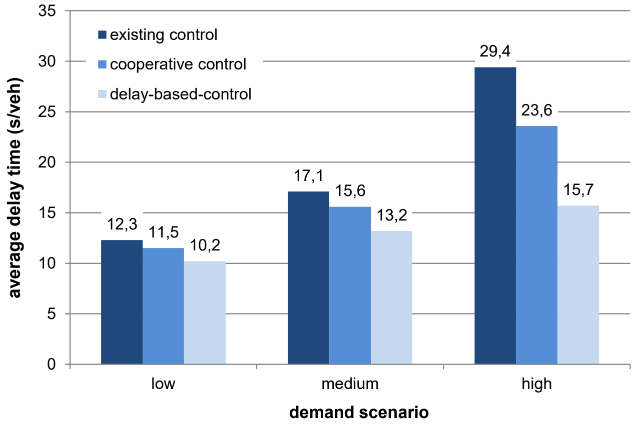

Fig. 7. Halle (Saale) – average delay time per vehicle during the period 05.09.-02.10.16, classified by demand scenario.

Finally, the cycle times were analyzed. These are related to the observed delay times and directly determine the green times. In Fig. 8 the probability density of the measured cycle times are plotted for the three controls. It can be seen that the existing reference control and the cooperative control have a very similar course, whereby the existing control tends to switch more frequently with shorter cycle times. This corresponds exactly to the character of the cooperative control, which phases tend to be more forward-looking and thus longer. This behavior could also be seen in the on-site traffic observations. The delay-based control, on the other hand, shows a completely different behavior, both in relation to the existing reference control and to the cooperative control. Very short cycle times are more often, which is corresponding to more frequent phase changes since no phase can be skipped. This very agile switching behavior could also be observed on site. That means the differences between the cooperative control and the existing reference control are apparently derived from the forward-looking switching behavior. The differences in the delay-based control, on the other hand, are obviously caused by a more rapid phase switching behavior. The very short or long cycle times in the figure result from program changes as well as switching the signal controller on and off.

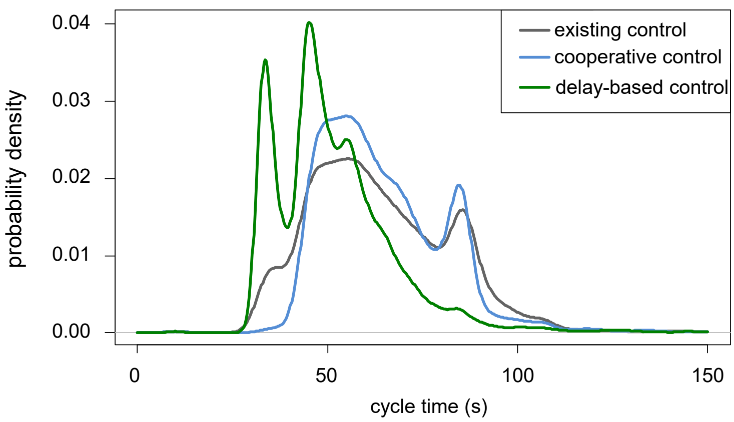

Fig. 8. Halle (Saale) - probability density of the measured cycle times during the period 05.09.-02.10.16.

In the same way, the two VITAL control methods were compared with the existing reference control in Braunschweig. The results of this comparison are depicted in Fig. 9. It can be seen that both VITAL control methods gained reduced average delay times per vehicle, compared to the existing control. The more detailed view is focused on the individual signal groups K1, K3 and K4. The signal group K2 was not further investigated, because this is a small access road only with very few vehicles. The greatest difference compared to the existing reference control was observed at the signal group K4. As in Halle (Saale), there are regularly longer queues on this approach, which the VITAL control methods processes in a different manner, compared to the reference control. This was again confirmed by on-site observations.

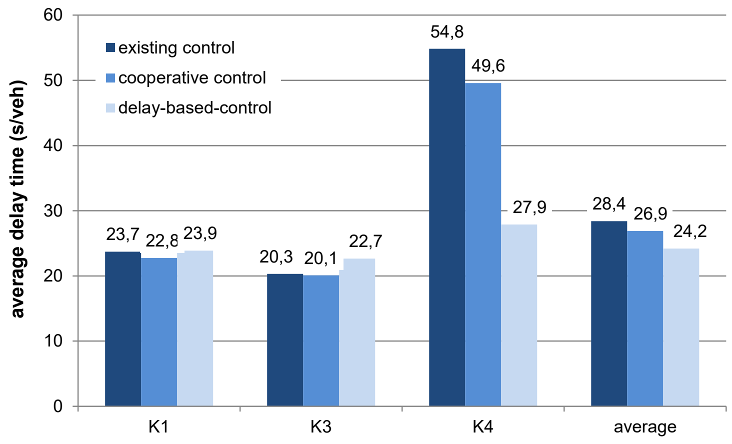

Fig. 9. Braunschweig - average delay time per vehicle during the period 16.09.-26.10.16, classified by signal groups K1, K3, K4 and average.

In a last step, the controls were compared according to the previously defined traffic demand scenarios (see Fig. 10). The differences between the three controls are the smallest in the scenario of low traffic demand and constantly increase with growing demand, similar to the results in Halle (Saale). In all scenarios, the smallest average delay time per vehicle could be observed for the delay-based control.

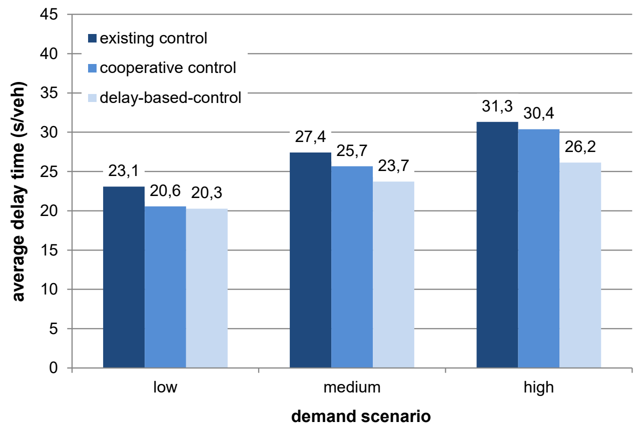

Fig. 10. Braunschweig - average delay time per vehicle during the period 16.09.-26.10.16, classified by demand scenario.

With the completion of the evaluations in Halle (Saale) and Braunschweig, some first observations were made for the practice application of the novel VITAL control methods. Obviously, both the delay-based control and the cooperative control have a different phase switching behavior compared to the existing reference controls. However, it should be emphasized that the results obtained during the test runs at the two intersections cannot be generalized, even if they seem to suggest a positive or at least no negative impact on the traffic flow. Additional test runs under different boundary conditions are therefore of great interest to the continuing work.

5. Conclusions

With the delay-based and the cooperative method, two new traffic signal approaches were developed, which are based on information from vehicle-to-infrastructure communication (V2X). These two methods have so far been tested and evaluated in extensive simulation studies. The goal of the research project VITAL (Vehicle-Actuated Intelligent Traffic Signal Control) was now to implement these two new control methods for the first time in the field and to validate them. For this purpose, two test intersections were set up in the cities of Halle (Saale) and Braunschweig, which satisfied certain requirements for the first test run. Since a vehicle-to-infrastructure communication (V2X) has not been sufficiently available so far, a workaround with fixed-location detectors had to be created. Magnetic field sensors were used, which were arranged in pairs on each approaching lane in order to form measurement sections. The two novel VITAL control methods were then integrated into the existing controls. The existing controls and their set parameters remained untouched, only the criteria for the decision when to terminate a running green phase was replaced. The delay-based control method could be implemented completely on the standardized signal controllers. However, the cooperative control method is more complex and requires an additional industrial mini-PC that has been connected with the signal controllers for an information exchange. Before these described modifications could be applied at the test intersections in Halle (Saale) and Braunschweig, further simulation studies and integration tests were done in the traffic signal laboratory of DLR. After the implementation in the field, several weeks of test runs were performed under real traffic. In the later evaluation of the measurements recorded during the test runs, a different phase switching behavior of the VITAL control methods could be observed, compared to the existing reference controls. Especially the cycle times and average delay times per vehicle differed. Obviously, the delay-based control as well as the cooperative control can have a positive or at least no negative impact on the traffic flow at a signalized intersection. These first observations are not yet generalizable; there is a need for further research and testing, especially with regard to longer-term effects. To investigate these effects, a long-term test run in Halle (Saale) was started in March 2017 and will last at least until the end of the year.

A reliable detection of the vehicles is of essential importance for the correct operation of the VITAL control methods. Although a workaround for compensating the insufficient availability of V2X data has been found, the approach of the use of magnetic field sensors is not optimal. For example, it has been shown in the test runs that inaccuracies in the vehicle counts can occur, as a comparison with the induction loops revealed. Since these differences have occurred only for few of the magnetic field sensors, it is assumed that this may be related to their position and the wireless connection. These inaccuracies were compensated by correction modules within the control logic. With the future use of vehicle-to-infrastructure communication (V2X) such inaccuracies could be reduced, even in the case that not each vehicle will be equipped.

Another important point is the further development of the VITAL control methods for the usage within signal coordination along an arterial. Until now, the VITAL methods are only intended for application at single intersections. Especially in urban road networks, however, many traffic signals are integrated into a green wave. In order to apply the VITAL control methods here as well, additional approaches for coordination have already been developed and successfully tested in the simulation. The next steps must also be first test runs in the field.

Since the VITAL control methods so far only use information from cars for control, there is a further need for research and development in the integration of public transport, emergency vehicles, pedestrians and cyclists. In principle, these could already be integrated into the VITAL control methods, because they do not distinguish between the modes of transport they receive information from. However, here a separate treatment would be advantageous, quite apart from the challenges in the detection of pedestrians and cyclists.

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