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Improvement in Traffic State Estimation at Signal Controlled Intersections by Merging Induction Loop Data with V2X Data

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ABSTRACT

A proven method to minimise the number of stops at traffic lights is a good coordination of the traffic. The use of vehicle-to-infrastructure (V2X) communication allows new concepts to achieve a better coordination. The here described system comprises both the adaption of the traffic signal control and the improvement of a vehicle's approach to intersections. Both objectives require accurate data concerning the actual traffic state and in particular the current tailback length. Therefore two data sources are used to estimate the current tailback length. Existing detectors at traffic lights are taken as a basis for the estimation. For an enhancement V2X data is used. Equipped vehicles send their current position and speed and thus operate as virtual detectors. In a further step detector counts and the V2X data are merged. The process tested in simulations was implemented within a test site in Braunschweig, Germany.

KEYWORDS: tailback estimation, V2X communication

1. Introduction

Traffic flow in urban networks is essentially influenced by required stops at traffic lights which cause braking and reacceleration. This has a significant impact on the capacity of the urban network and the emissions of its motorised traffic. Within the German research project KOLINE a cooperative system was developed that makes use of the communication between vehicles and traffic light systems (V2X) to avoid stops of vehicles at traffic lights by optimising the vehicles' approach to a signal controlled intersection. Former research showed that therefore not only knowledge of future signal states but also proper data of the current tailback length is required [1], [2]. This paper focuses on the process developed within KOLINE that calculates the current tailback length and its prediction by combining detector counts and V2X data.

2. Components and Data Transmission

The overall architecture of the KOLINE system is given in a paper also presented at this conference (Naumann et. al., chap. 3). The following Fig. 1 shows the system´s components involved in the tailback estimation as well as the data transmission.

The calculation of the current tailback is implemented within three components. **Stationary detectors** measure the occupancy about 20 m in front of the stop line. Together with information about the actual signal state available in the **Traffic Light System** a tailback length is estimated once per cycle by **TRANSQest**. This calculation is taken as a basis for the estimation.

To improve the estimated value the system uses V2X data. The **Vehicle** is equipped with a device for wireless communication and transmits the standardised Cooperate Awareness Message

(CAM). In this way every vehicle sending a CAM operates as a virtual detector on the lane the vehicle drives on. The **Vehicle Data Based Tailback Estimation** uses every CAM to estimate the current tailback and to adjust the estimation respectively predict its developing.

In a further step the once-per-cycle calculated tailback estimation of TRANSQest and the estimation deriving from the Vehicle Data Based Tailback Estimation are merged within **TRANSFusion**. The result is a set of future tailback lengths with equidistant times which is send to the vehicle's **Assistant System**. This component computes the vehicle's optimal approach to the intersection in order to avoid a stop.

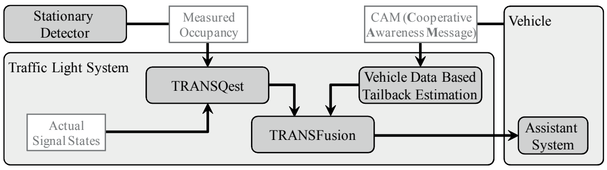

Fig. 1. Components and data transmission involved in the tailback estimation

3. Tailback Estimation Based on Stationary Detector

In the framework of the research project MOBINET TRANSVER GmbH has developed the component TRANSQest to estimate the maximum tailback at traffic lights, which uses data of stationary detectors (e.g. induction loops) and signal data of traffic lights. It can also be operated in overloaded traffic conditions. Based on green and red time as well as the number of cars counted TRANSQest estimates the tailback referring to the distance between detector and stop line (see Fig. 2).

The component has been integrated into a software module which, due to its simple interfaces, can easily be implemented into traffic control systems in traffic centres. TRANSQest estimates the tailback once per cycle of a traffic light system.

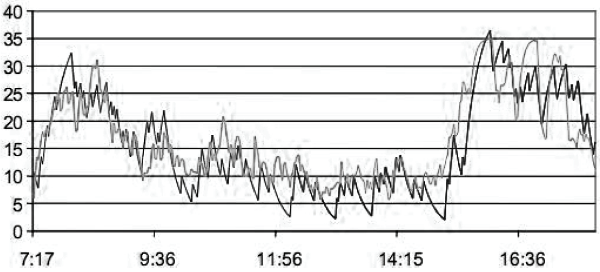

Fig. 2. Tailback lengths of a traffic light system in Munich, light: measured, estimated: dark

The algorithm has been developed to identify online tailback lengths of up to approximately 5-10 times of the distance between detector and stop line, particularly using the stationary detectors which are often already existing and positioned "in the middle of the tailback". It can be applied with "short" detectors expanding 1 m in the direction of traffic. The core of the estimation algorithm is a model to measure maximum tailback lengths.

The traffic flow within the range of detectors positioned close to stop lines is significantly influenced by the respective traffic signals. If this influence is not considered a disturbance but a "modelling" of the traffic flows, important parameters can be derived. One parameter is especially important for the evaluation of traffic quality: The fill-time, which is the period of time between the begin of red and the permanent occupancy of the detector. It can be derived whether vehicles at the end of the green time are driving fast or slowly towards the traffic light.

The algorithm is based on defined fill-time correlated circumstances: If tailbacks occur at signal controlled intersections, which are not resolving after the green time has ended, the vehicles which have not flown-off will halt faster at the stop line as compared to having freely flown. In this case the fill-time significantly often falls below a specific reference fill-time depending on the distance between detector and stop line. Empirical data show that the incidence for falling below that reference fill-time is correlated to the tailback length to a certain degree: The event "falling below a reference period" can be included by defining a "tailback parameter" and exponentially smoothed for each period. The maximum tailback length can also be smoothed that way. Then, by means of correlation calculation a correlation between these continuous values can be calculated in terms of a source-regression line.

When the tailback parameter has been identified by measurements, the tailback length can be derived from an existing gradient m which enables to use a determination equation to calculate an unknown maximum tailback length. It is an estimation of a slightly smoothed maximum tailback length.

The last counted vehicle that comes to a halt on the detector defines the duration of the fill-time. If this occurs shortly after the green time has ended, there is a high probability that the vehicle has moved within a slowly moving cluster as it is typically found in tailbacks. As the vehicles have all been positioned in the tailback upstream of the counting detector, an inequation for the actual maximum tailback length can be derived in correlation with an average count of vehicles downstream of the detector. If the fill-time exceeds the reference value, the inequation is valid inversely relational.

4. Tailback Estimation Based on V2X Data

The core principle of cooperative traffic systems is the exchange of information between road users and infrastructure by using modern communication technology such as wireless LAN (IEEE 802.11p). Therefore a range of different message types designated for different types of information is defined. The interface used here is compliant to the research project sim^{TD} [3]. One type of message which is especially useful for the purpose of tailback determination is the CAM. It is broadcasted every second by vehicles equipped with communication tools (in the following called ccars) and contains information about the position, speed, heading and identity of the ccar. It allows to use ccars approaching the intersection as virtual detectors.

Since new technologies such as the described cooperative ccars will only slowly reach a larger penetration of the market, it cannot be guaranteed that every road user is using such a ccar. On this account the tailback cannot be measured directly and must rather be estimated by using a model. To enhance the estimation furthermore the advanced sensor technologies provided by vehicles and infrastructure within the KOLINE system are used.

4.1 Methodology

In urban road networks the waiting process and therefore the tailback lengths within signal controlled intersections depend on two processes: the arrival process described by the arrival rate λ and the service process described by the service rate μ. Based on former research works [4] a method to estimate the arrival and service rates and thereby the maximum tailback length per red time can be utilized. The method merges current and historical V2X data with information of the signal control (Fig. 3).

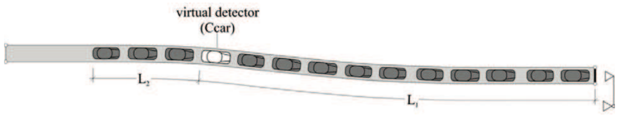

Fig. 3. According to the method of Mück [5] the maximum tailback length can be estimated by dividing the entire tailback length L into the two parts L1 and L2, whereas L1 is the determinable tailback length and L2 the length to be approximated. Due to the available V2X- data, L1 can further be defined as distance between virtual detector (position of the ccar standing within the tailback) and stop line

The approximation of L2 is based on the estimation of the arrival rate λ of the vehicles standing in the tailback by considering the start of the red time period and the time the ccar arrives at the end of the tailback. Knowing the arrival rate λ and the remaining red time, L2 can be approximated for every moment within the red time period. As soon as the red time ends the tailback length decreases according to the service rate μ which can be estimated using historical data.

4.2 Validation

To examine the accuracy of the tailback length approximation using V2X data, the mentioned method was implemented within a simulation model using the microscopic simulation tool AIMSUN [6] and the AIMSUN API module tool.

The simulation model allowed the testing of different scenarios regarding the penetration rate which varied in three steps between 10, 25 and 50 %. The example of one test run is shown in Fig. 4. It uses a penetration rate of 25 % and allows comparing the tailback estimation with two other parameters. The real tailback illustrates the actual end of the tailback. The position of the last standing ccar represents the measurement generated by the last ccar coming to halt. Comparing the values of the real tailback and the tailback estimation second by second just visually it can be stated that the estimation seems to be mostly accurate with a tolerance of 10 m.

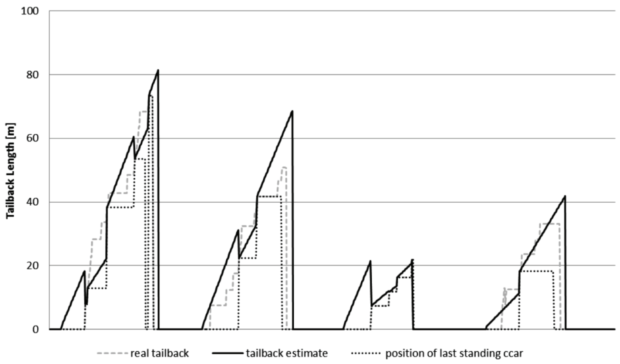

Fig. 4. Example of tailback estimation using a 25 % penetration rate

By carrying out a larger number of test runs than shown in the example this impression can be confirmed. For each test scenario (regarding the different penetration rates) twenty test runs of one hour length were performed. The results are shown in Table 1. Even with a low penetration rate of 10 % about 74 % of the time the estimation is within a tolerance corridor of 10 m. The ratio can only be slightly improved by increasing the penetration rate.

Table 1. Quality of tailback estimation depending on the penetration rate

Penetration rate	10 %	25 %	50 %
Share of tailback estimates within a tolerance of ± 10 m [%]	74,2	74,6	80,4

4.3 Enhanced Tailback Estimation Using Further Sensor Data

The correct determination of the distance and arrival time (between the last vehicle and the virtual detector) is normally only possible if the penetration rate of ccars is nearly 100 % because the precondition of a stable queuing process within one red time period is only a simplification. Usually vehicles do not follow each other with always identical spacing, which means the described approach over- or underestimates the arrival rate. A ccar can be followed by none or by a large group of vehicles which follow each other bumper to bumper. The uncertainty becomes even larger the older the underlying measured data is.

To enhance the data needed for the Vehicle Based Tailback Estimation within KOLINE two kinds of advanced sensor technologies can be used:

1. Sensor technology within the vehicle provides data concerning not only its own current situation but also determines position and speed of surrounding vehicles within the range of its sensors.
2. Radar sensors used instead of common induction loops provide not only a virtual loop to generate data for TRANSQest but also generate trajectories of all vehicles approaching the intersection within the range of the sensor.

The advanced sensors within the vehicles extend the V2X data which helps to increase the number of virtual detectors, since speed and position is not only known of ccars but also of the surrounding vehicles within the sensor range. Thus a single ccar provides the data of other vehicles on the adjoining lanes of an access and also vehicles that reach the tailback at a later moment. With this larger amount of data it should be possible to reduce the margin of error and maintain a high accuracy which is at about 80 % for a margin of error of 20 m (or 45 % for 10 m) without using the extended data.

As KOLINE cooperates with the German Aerospace Center (DLR) and its "Application Platform for Intelligent Mobility" (AIM) [7] it was possible to use AIM-provided radar sensors instead of common induction loops within the project. In each approach one radar sensor is mounted. The sensor measures the target position (x,y) and speed (x,y) for up to 64 objects on the approaches' lanes simultaneously. In this way the trajectories of all vehicles within the range of the sensor are known. Within KOLINE the object's position and speed are transformed into a CAM and transmitting to the Vehicle Based Tailback Estimation. Additionally an algorithm allows choosing a value between 0 and 100 % and to transform exactly this percentage of objects into CAMs. This enables KOLINE to reproduce user-defined penetration rates of ccars in a real public road network.

5.Fusion of Data

The component TRANSQest estimates the maximum tailback at signal controlled intersections once per cycle time. The duration of those cycles varies between 60 to 120 seconds. This is too long for optimising an approach strategy.

Vehicles that communicate with the traffic light system can be utilized for the punctual determination of the tailback by means of the component Vehicle Based Tailback Estimation. These values, however, cannot be determined on a regular basis and do not render a sufficient number of values for a permanent estimation of the current tailback.

By combining and merging the periodical tailback estimations via TRANSQest and the additional tailback estimations by means of Vehicle Based Tailback Estimation, the component TRANSFusion is able to estimate current maximum tailback lengths of detected intersections for the entire period of time.

The merging of the maximum tailback lengths identified via TRANSQest and the Vehicle Based Tailback Estimation consists of a two-dimensional data fusion. On one axis the estimated tailback lengths are to be merged. On the second axis the merging is carried out with regard to the times when the tailback values were estimated.

As calculation base the estimated tailback values R(TQ) of the component TRANSQest are used as they are available continuously per cycle time of the respective traffic light system. When a cycle is completed, TRANSQest estimates the maximum tailback which is considered to be a safe value at the time of estimation. For each further second TRANSFusion sends the estimated tailback, which consists of the tailback value estimated last by TRANSQest R(TQ) and a prediction. The prediction is necessary as the tailback is most probably apt to change during the period between last and next estimation via TRANSQest. The part of prediction has a form reminding of a funnel and is calculated by two boundary terms.

The first boundary term is the term of increase **Z(s)**. This term implies that the tailback increases. The term of increase is either a linear function with an inclination which is determined on the basis of the last estimated tailback values, or an enhanced function which additionally considers the flow in dependency of the green time.

The term of flow **A(s)** is the second boundary term. This term presumes that the tailback decreases and no new vehicles extend the existing tailback. Depending on the last estimated tailback values the current flow can be identified. Minimum and maximum values are to be considered here.

The temporary result of TRANSFusion consists of the following two tailback values at every second:

$$RZ(s) = R(TQ) + Z(s) \tag{1}$$

$$RA(s) = R(TQ) - A(s) \tag{2}$$

This temporary result can also be described by these two terms:

$$RM(s) = (RZ(s) + RA(s)) / 2 \tag{3}$$

$$RD(s) = abs(RZ(s) - RM(s) \tag{4}$$

$R_M(s)$ is the mean estimated maximum tailback value and $R_D(s)$ the possible deviation.

If there are additional tailback estimations due to the component vehicle-based tailback estimations for a particular second, the values $R_M(s)$ and $R_D(s)$ as well as the functions Z(s) and A(s) are modified respectively. The weighting is based on the variances of the single values of the respective sources.

The variance of the merged estimated maximum tailback equals the value $R_D(s)$.

6. Conclusions and Future Works

The authors presented the methods to determine the actual traffic state and in particular the current tailback length developed and used within the cooperative KOLINE system in order to adjust the vehicles' driving strategy. The concept of the three components involved in the tailback estimation is described. Providing tailback estimation data allows improving the approach of vehicles to signal controlled intersections in order to reduce stops at traffic lights and therefore enhance the traffic flow and decrease emissions. Two examples based on a simulation respectively real measuring data illustrated the high potential of an optimized driving strategy.

The shown examples give an impression of the potentials the merging of data from stationary detectors with V2X Data has. The future work focuses on the aim to test the system which is already implemented within a public road network in Braunschweig, Germany. The network is made up of three intersections along an arterial road of the inner city and all intersections are equipped with the three components of tailback estimation and radar sensors. Field trials to analyse the accuracy of the estimation components will be carried out. This will also include the evaluation of effects the usage of advanced sensor data has.

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