POTENTIAL EFFECTS OF DATA INTERCHANGE BETWEEN VEHICLES AND INFRASTRUCTURE AT SIGNALIZED INTERSECTIONS

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ABSTRACT

The cooperation between vehicles and infrastructure by interchanging data particularly at signalized intersections has been a main focus of car manufacturer's and traffic operator's research over the last decade. The provision of information for car drivers regarding the remaining time up to the next change of signalization promises some positive effects on movement efficiency, fuel consumption and emissions by smoothing the traffic flow which approaches traffic lights. In return, passing vehicles could possibly improve the quality of signal control by leaving their dynamic data. In other words, the so called cooperative system realizes a win-win-situation where the broadcast of signal control information animates the drivers to voluntarily release their floating car data. This paper reports on the experiences with a pilot implementation of two cooperative traffic lights in the German city of Kassel, and additionally discusses some results of simulation studies.

Keywords: V2I communication, Cooperative traffic lights, Green Wave, Driver information

1 BACKGROUND AND MOTIVATION

Traffic lights have a strong impact on the continuity of movement of all road users in the road network. Especially at heavy traffic they are indispensable for the safe crossing of roads or the safe turning into it. For this, however, cyclical interruption of traffic flows has to be accepted. This is associated with a disturbed continuity of motion through occurrence of braking, holding and acceleration. These activities increase fuel consumption, emissions and possibly travel time compared to an unhindered drive. Last but not least the driving comfort suffers. The unwanted effects of traffic lights on the continuity of traffic flows can be mitigated in two ways: first, by a suitable signalization, second, by working towards a more energy efficient driving behavior.

Typically, it is attempted to control the traffic flow by traffic actuated signalization, in order that the interference in the sum is as minimal as possible. For the evaluation of the achieved quality of signal control the two parameters average waiting time and number of stops are used. Unfortunately, just these parameters are not directly measurable with the conventional infrastructure-sided detection technology.

Besides signalization, the driving behavior in the flow approaching to traffic signals could have a significant impact on the amount of emissions and on the energy efficiency of road traffic. A driver behavior which is adapted to the signalization can help to improve the parameters of emissions and efficiency. However, for this the driver has to know the length of time until the next signal change. In principle, there are two possibilities of information providing: road-sided variable message signs or in-vehicle displays.

The first one can be perceived depending on its size only about a more or less short distance. Therefore, it is predestined mainly for giving information about waiting time until next green. So, car drivers for example have a good basis for deciding to switch the engine off. By the way, pedestrians are the road users most sensitive to waiting times. Their safety particularly depends on the avoidance of red-walking. Based on a field study in the German city of Hamburg Celikkan et. al. (2008) have proved that stationary count-down displays improve the pedestrian's acceptance of the red signal. The impact of count-down displays additionally mounted next to corresponding signal heads for vehicles has been published in Celikkan et. al. (2009). Due to an already existing high acceptance of the red signal by motorized road users in Germany, almost no effects on traffic safety could be identified. Two behaviors have been detected: (1) a slight tendency to jump start in the red-yellow signal, and (2) a decreasing number of drivers passing at late yellow or early red signal. Therefore, the capacity of the intersection went down slightly.

As mentioned above, the second possibility for giving dynamic information to drivers is the use of in-vehicle displays. The first experimental study in Germany was the transmission of speed recommendations regarding the suitable position in a Green Wave, the so-called "Wolfsburger Welle". Zimdahl (1983) described the technical solution comprising stationary and mobile equipment using infra-red-based vehicle-to-infrastructure communication. The technical solution of the early 1980's suffered from high cost due to its specialty and missing standards, and it couldn't gain acceptance. However, the effects on traffic were promising: Hoffmann et. al. (1986) could prove a significant reduction in number of stops and waiting time.

Today's situation regarding the conditions for improving the continuity of movement is characterized in that, under certain conditions, signal control and vehicles have some data and information which are interesting for both. A related data exchange could bring a typical win-win situation. The vehicle delivers its driving history data indicating the number and duration of stops as well as the derived current queue length. The signal control provides the driver with its switching time data, then he can adapt his driving behavior with it.

The article first describes the technical implementation of so-called cooperative traffic lights, and then outlines the simulation-based findings on the traffic-related potentials that result from the information of the driver about the time to the next signal phase change. It is assumed that these switching times are known or determined by appropriate methods. Regarding the occurrence of unexpected signal transitions due to emergency vehicles it should be noted that traffic lights always have the priority over on-board information.

2 COMPONENTS OF COOPERATIVE TRAFFIC LIGHTS

A cooperative traffic light system consists of at least two spatially and functionally separated components, vehicle's on-board equipment and a communication-capable signal control unit. The presented pilot solution includes three system components: a signal controller, a gateway computer and a nomadic device going with the vehicle. The system configuration and the basic path of communication with exchanged data can be found in Figure 1. Here, black letterings indicate selected functions which were implemented in our test site Kassel.

Nomadic Device

The on-board device with GPS and WLAN-module is used as multimedia interface by the driver. For this purpose, the nomadic device has to perform a number of tasks, including among others:

- receiving the intersection's signal layout plan and signalization data
- geocoding for selecting the signal head relevant to the driver
- calculation of vehicle's spatiotemporal position in the current Green Wave
- identification and transfer of the driving history data to the next signal control unit (disabled in the test site Kassel, therefore shown grayed out in Figure 1)

As shown by Priemer/Friedrich (2008) and Otto/Hoyer (2010b) the sought parameters, i.e. the number of stops, waiting times and queue lengths can be derived from driving history data. Visible to the outside are basically the two applications shown in Figure 2, one to display the remaining time until the next signal change and the other to visualize the spatial and temporal position of the vehicle in the Green Wave.

Signal Control System

Compared to the pilot solution of the German project "AKTIV-VM"[1] presented by Hoyer et. al. (2012) the field tests involving two traffic lights in the German city of Kassel were limited on the generation and transmission of information to the driver. The processing of the floating car data within traffic signal control was not the focus here because only the first driving impressions should initially be collected. The exact location of the two signal control units extended by a gateway computer with WLAN-module at the Dresden road in Kassel is shown in Figure 3.

Gateway Computer

A simple netbook computer was used in our test site Kassel as intermediary between the control unit of the traffic lights and the nomadic device (PDA here) which were connected over the respective standard WLAN (IEEE 802.11g). Signal information was transmitted to

[1] http://www.aktiv-online.org/

the PDA in the car when contact between the two occurred. The signalization status had been detected through the observation of the signal control behavior via a corresponding interface. Then the PDA identified in the further course the information on the current position in the Green Wave for example. Moreover, the gateway computer broadcasted the simplified signal layout plan that is needed by the nomadic device for selecting the appropriate information to the respective route, for example the relevant signal heads.

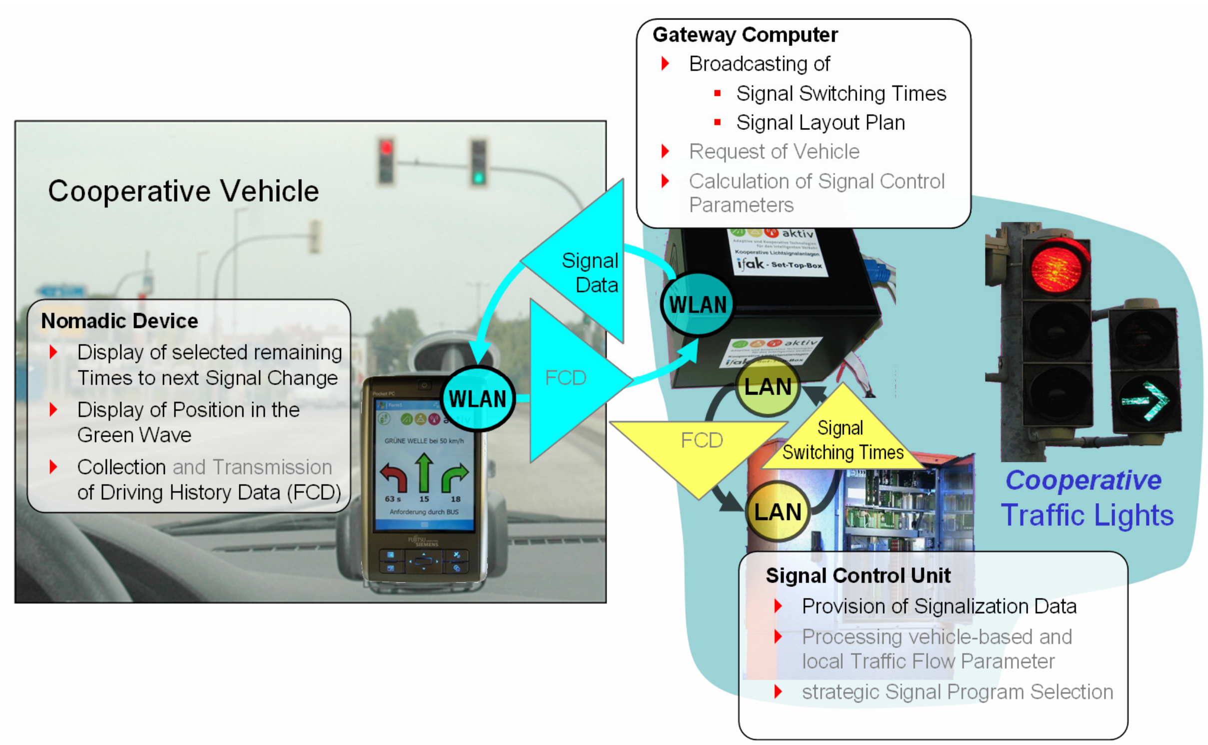

Figure 1 – Configuration and Functions of a cooperative Traffic Signal System

Figure 2 – Display of own Position in the Green Wave and remaining Time to Signal Phase Change

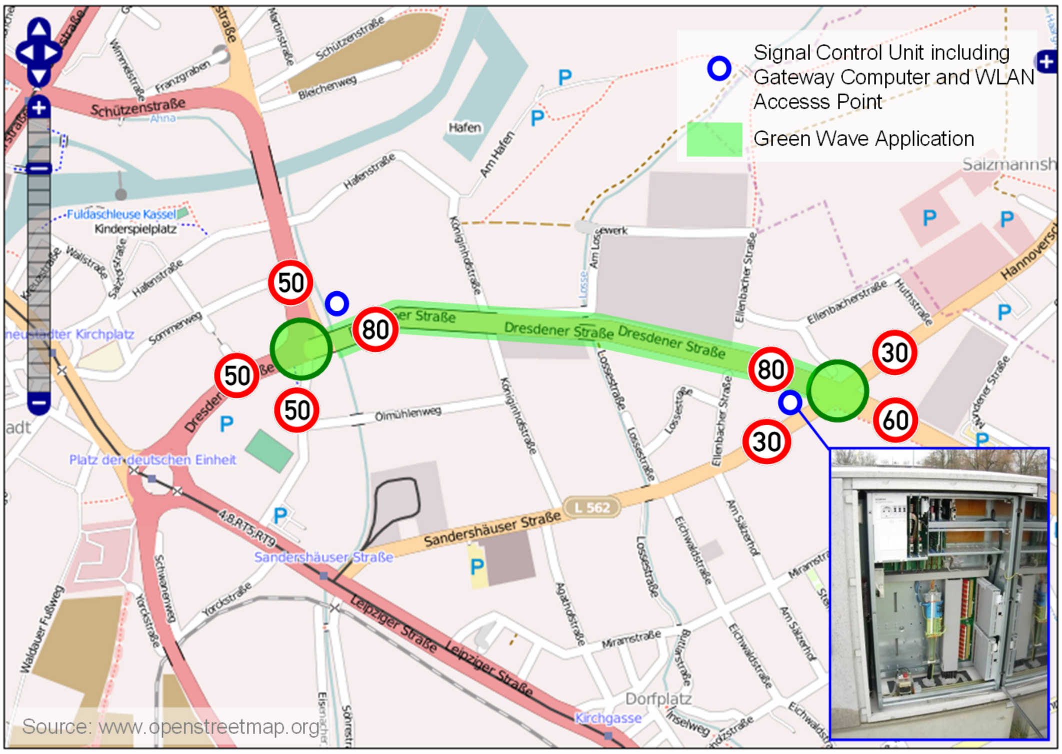

Figure 3 – Location of the two extended Signal Control Units in Kassel

3 DEVICES-IN-THE-LOOP APPROACH

The development of mobile software applications and infrastructure-side components for cooperative traffic control systems represents an outstanding challenge. Only the time-related error free interaction of all components, taking into account the extremely complex dependencies between the traffic flow, the stationary traffic control equipment, and the mobile devices can achieve the intended aim. The extract of the cooperative system's sequence diagram shown in Figure 4 gives an impression about these highly distributed complexity.

The development and testing of the individual components of the functionally and spatially distributed system for the realization of cooperative traffic-related applications required the stimulation of the individual components with the situation-consistent input data. These were supplied by a microscopic traffic simulation, taking into account the real dynamic behavior of all system components. Since the latter could not be simulated in the necessary detail, ,particularly due to reasons of expenditure, a hybrid development and test environment were built in which the real devices with their wireless communications were included into a microscopic traffic simulation. Figure 5 shows this, the laboratory setup realizing a so-called Devices-in-the-Loop approach (DiL). This extends the established Hardware-in-the-Loop method (HiL) to the extent that now even the traffic-related interactions of the vehicles are involved in an action cycle. These interactions concern both, among themselves as well as with the infrastructure-sided traffic control, including real vehicle-infrastructure communications (see Otto/Hoyer (2009)).

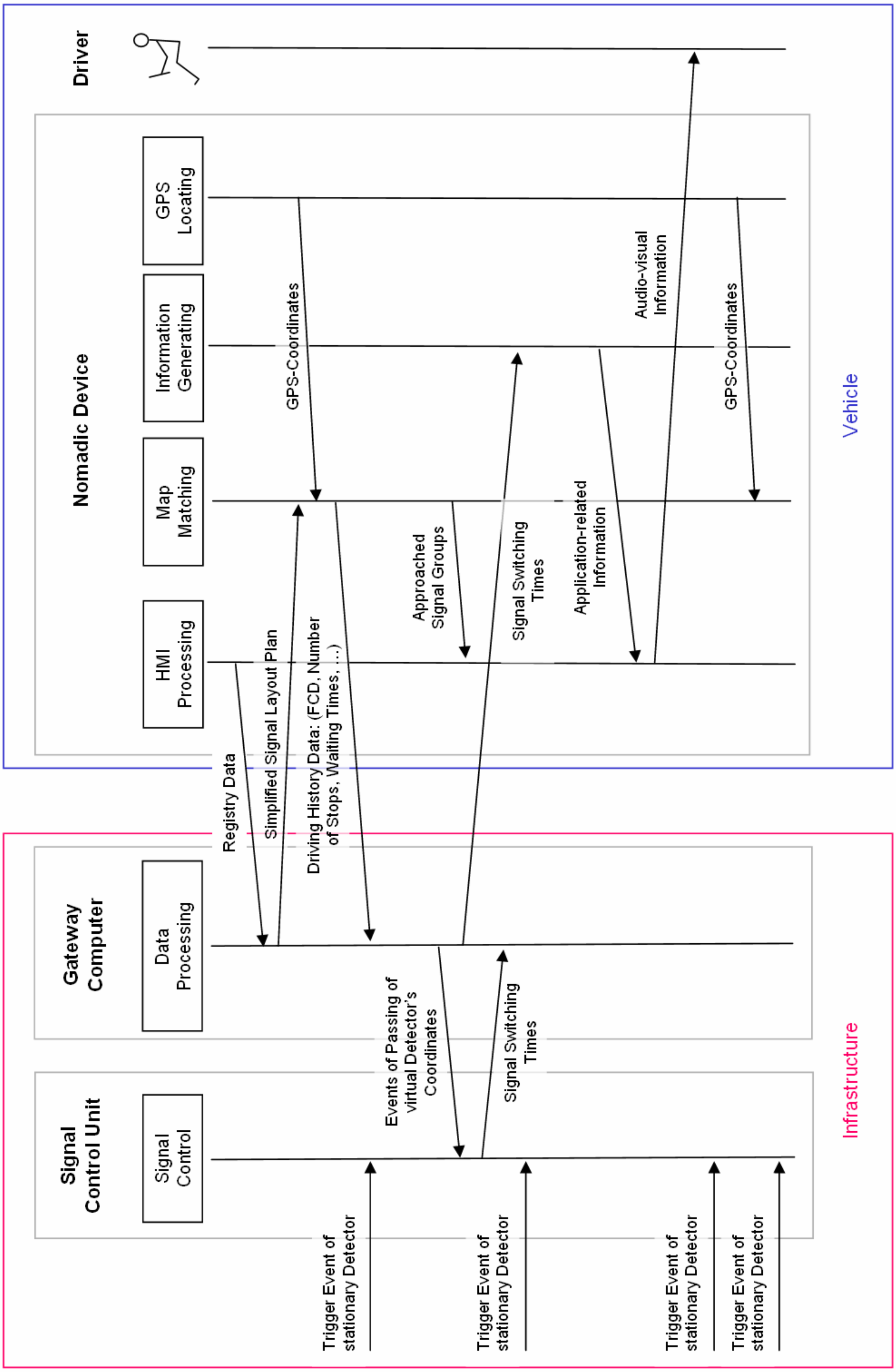

Figure 4 – Sequence Diagram of coordinated Data Flows (Extract)

Figure 5 explains the procedure using the example of our development and test environment as follows: The GPS coordinates of a selected vehicle in the simulated traffic flow of the test site are transmitted every second via Bluetooth to the PDA with the application under test (①). It must be stressed that coordinates and therefore the test site necessarily have to be authentic. The PDA is connected via WLAN - later also in real traffic - with a gateway computer (GWC) as part of a control unit for traffic lights. Vehicle positions and parameters derived therefrom to optimize signalization (waiting time, queue length or number of stops), and possibly requests are transmitted to the GWC (②). In return, the PDA receives from the GWC the digital map of the intersection geometry (simplified signal layout plan) and the current phase change times (⑦) from which driver information about remaining time to the next switch and the position in the Green Wave can be derived.

The GWC obtains again the current phase change times via LAN (⑥) from the signal control whose algorithms are executed on the simulation computer in our setup. Using the available traffic parameters the GWC determines control information for signalization and transmits it also via LAN (③) to the (here simulated) signal control.

With the observance of the signalization by the vehicles in the simulated traffic flow (④) a loop with real devices in a virtual world is closed. Its functional behavior significantly determines the effectiveness of cooperative systems. This behavior is strongly influenced by the quality of hardware and software implementations, both the actual communication characteristics between several devices and the driver's actions, and thus the HMI concept.

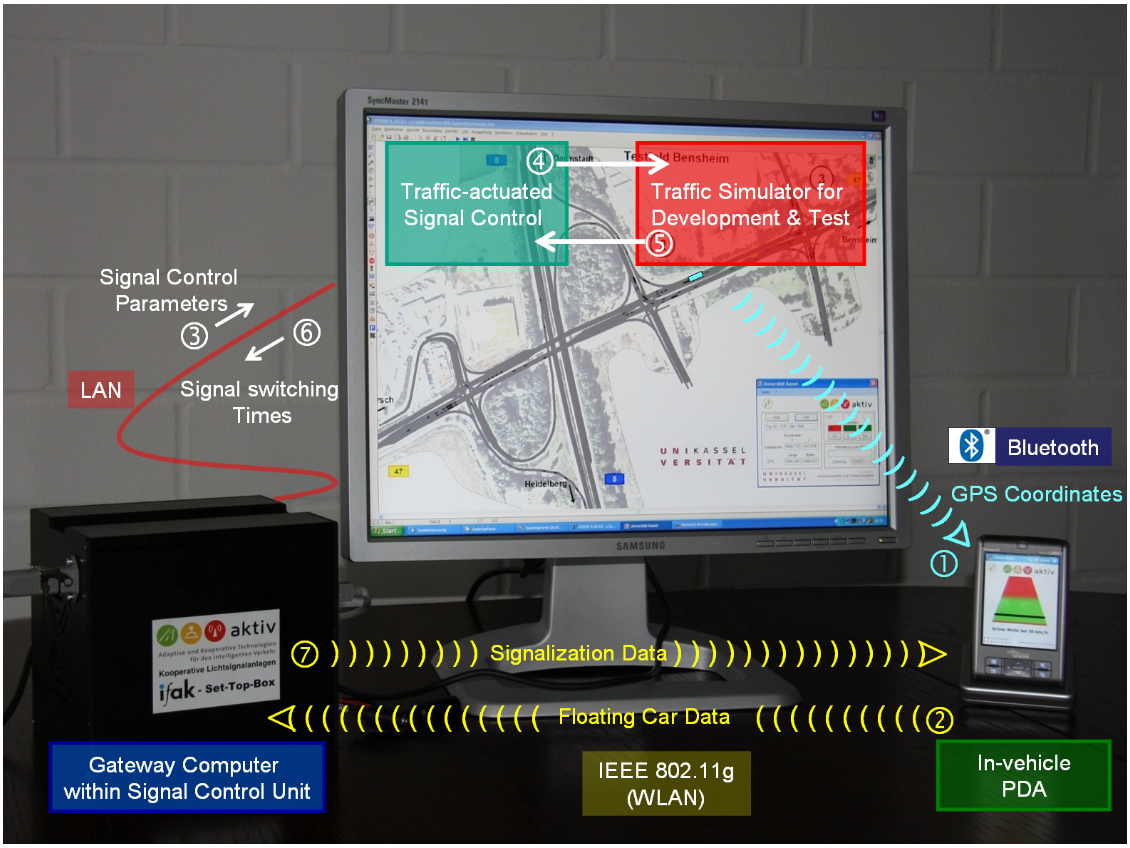

Figure 5 – Development and Test Environment based on the Devices-in-the-Loop Approach

The hybrid development and test environment proved to be a key to a number of successful pilot installations of cooperative traffic lights. Due to the Devices-in-the-Loop approach several errors in all system components could be quickly detected and efficiently eliminated.

A significant contribution was made by traceable stimulation of system components through reproducible input and output data provided by the microscopic traffic simulation which would not be feasible in real driving and traffic situations. Another advantage of the procedure was that traffic and its control, simulated on the computer, only had to be replaced with the actual traffic and the real signal control unit.

Deviations from the real system behavior during the trial runs arised because of the very variable quality of wireless data link between the nomadic device and the infrastructure-sided equipment what we quite expected.

4 FACTORS INFLUENCING THE EFFECTIVENESS

Penetration Rate of equipped Vehicles

The percentage of vehicles cooperating with suitably traffic lights especially affect the identification quality of traffic flow patterns on access lanes directly approaching the intersection. Coverage and distribution of sample have a relevant influence on estimation accuracy of queue length for example. First of all, a high as possible percentage of equipped vehicles helps to improve the quality of traffic-actuated signal control. However, it could partially enable to substitute stationary detectors. The percentage of cooperative vehicles increases or damps the effect of further factors mentioned below. A full description of the influencing factors can be found in Otto/Hoyer (2010a).

Coordination Quality of existing Signal Control

Obtainable coordination quality of successive traffic signalization depends, among other things, on the equability of distances between neighboring intersections and the current load relating to its capacity (loadfactor). In case of good coordination, the given speed advice differs marginally from the speed-limit or possible speed, taking into account traffic condition. So the driving behavior remains uninfluenced. The number of stops, waiting time and queue length do not depend on percentage of equipped vehicles. However, a speed advice to drivers can be noticeable,

- if different distances between successional intersections lead to progression speeds lower than speed limit, or
- if the progression speed varies from intersection to intersection.

In these cases, the driver information can result in changing number of stops, waiting time and queue length. Even a small percentage can already make an impact on traffic flow providing that there is only a single lane, and vehicles cannot overtake each other. Figure 6a illustrates effectiveness of cooperation-based green wave information depending on the percentage of equipped vehicles in case of strong and weak coordination quality.

Number of through Lanes

Multiple lanes enable an overtaking of vehicles driving more slowly as a result of speed recommendation. This fact weakens the positive effects and requires in compensation the increase of penetration rate. In the empirical studies, these overtaking maneuvers could be observed especially on the main road sections under test in the city of Kassel with its partial maximum speed of 80 km/h (see Figure 3). The difference by trend of driver information's effectiveness regarding the number of through lanes is shown in Figure 6b. The illustration below makes the reason clear that already in case of merely two through lanes the green colored vehicle accordingly equipped can be overtaken by other vehicles. In this way, the intended effect of the platooning controlled by driver information will be diminished. In this context, the question arises whether the number of bypasses would have been smaller if the drivers had known the reason and objective of unused speed limit before overtaking.

Minimum accepted Speed Recommendation

The driving tests in the various test sites quickly made it clear that speed recommendations, as they would surely prevent a stop at the next signal, are only marginally followed when too low. On one hand the test driver by himself didn't accept too low speeds, but on the other hand he found himself also exposed to the psychological pressure of the following (uninformed) driver. In a multitude of simulations Otto examined the traffic impacts of three scenarios of accepted speeds: ≥ 30 km/h, ≥ 20 km/h, and ≥ 0 km/h. The conditions and results in detail can be found in Otto (2011). As shown in Figure 6c the findings can be summarized as follows: If all the recommendations are accepted, the biggest traffic impacts are obtained. If only recommendations are followed near the speed limit, the effect is low and independent of the equipment rate.

Driving Routes

There may be different driving routes on a stretch with coordinated signalization. The most commonly encountered driving relation goes over the entire coordinated sequence of intersections. Here, the greatest benefit of the driver information is obtained.

Furthermore, there are drivers turning into coordinated section from a side direction. They have to accept a relatively low speed up to the next intersection in most cases in order to avoid a stop.

An increasing equipment rate can even worsen the situation for vehicles that intent to leave the coordinated direction. In case of unavailable overtaking possibilities they cannot reach their so-called leading green in time. Leading green is usually given to temporarily protected left-turning vehicles before opposing traffic flows arrive at the intersection. Here, it should be noted that leading green is most effective if left-turning vehicles already arrive at the stop line before the vehicle platoon of the Green Wave do this.

Figure 6d depicts the opposing trends regarding driver information's effectiveness by vehicles influenced through speed recommendations on route (A) and downstream left-turning vehicles on route (B) that are potentially obstructed by vehicles (A).

Travel time

The simulation studies have shown that the travel time is independent of the percentage of equipment.

Summary of results

The results of carried out simulation studies should only be interpreted and shown in a qualitative way. It must be taken into account that the findings arose from simulation scenarios which were chosen so that the single influencing factors became visible separately. In the reality, a various mix of conditions will have to be found which will probably lead to reciprocal enhancement or neutralization of the single effects. For this reason, Figure 6 only shows the tendencies of the results regarding the effectiveness of the co-operation-based Green Wave information. More details can be found in Otto/Hoyer (2010a) and Otto (2011).

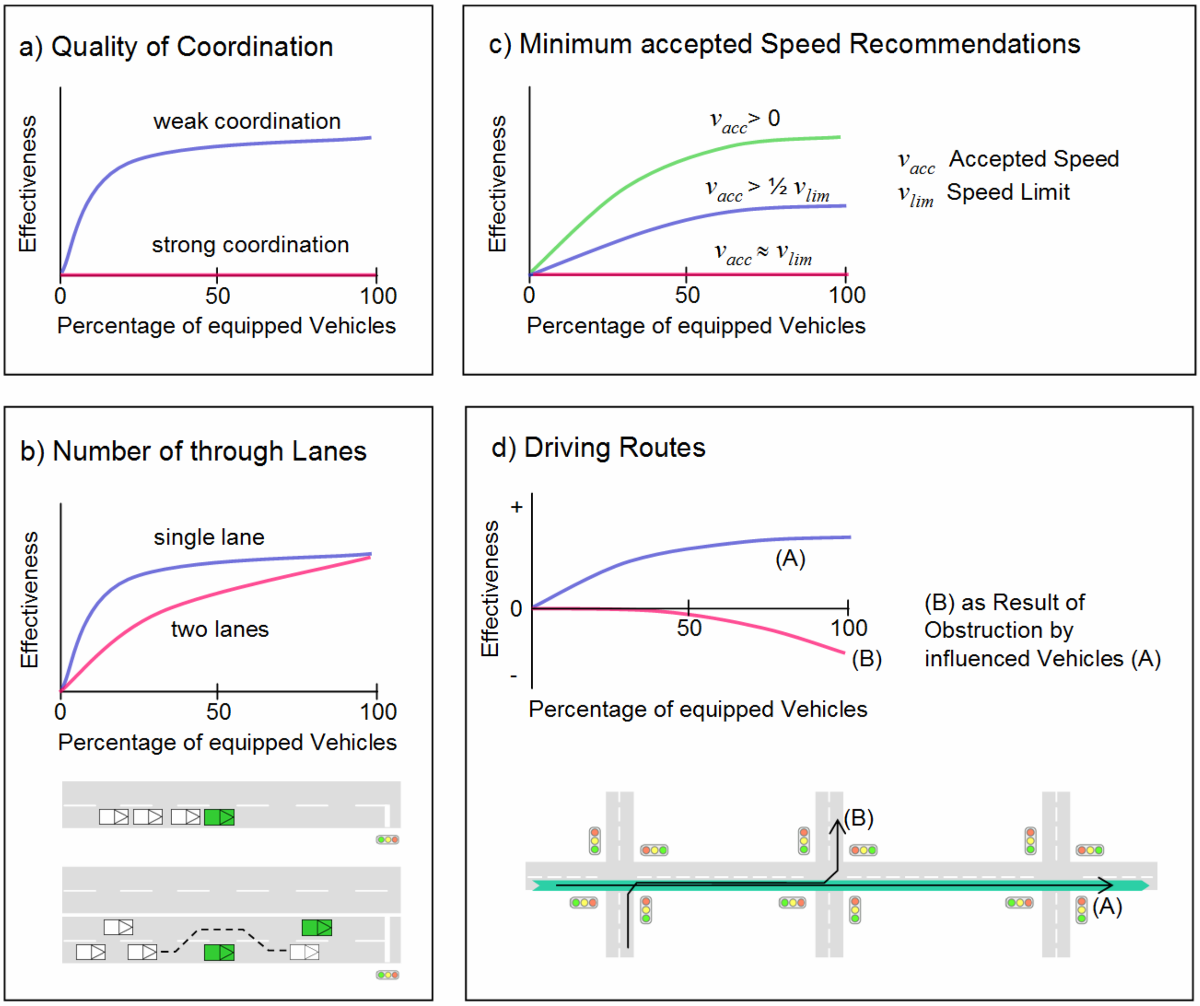

Figure 6 – Effectiveness of cooperation-based Green Wave Information: Tendencies and qualitative Results

5 CONCLUSIONS AND OUTLOOK

In various test drives the technological feasibility of cooperative traffic signal using a commercially available nomadic device with a GPS receiver and a standard WLAN module was proved. Here, initial driving impressions were obtained; however, these raised a number of new questions. A key point here is the acceptance of speed recommendations particularly in conjunction with the behavior of adjacent vehicles.

In addition to the traffic impacts within the meaning of this article the possible effects on traffic safety should absolutely be investigated. Although a gain in safety is regarded as possible by the certitude of the driver still being able to reach the next intersection with permissible speed at green. But also a negative adaptation in the form of violations is absolutely conceivable and must be taken into consideration. It needs to be clarified whether the presumed gain in traffic safety is thereby compensated. Another safety-related question concerns the design of the Human-machine interface (HMI) which should avoid driver's information overload and his dangerous distraction of attention.

A central question for the potential operators of cooperative traffic signals is still following focus: Are efficiencies or rather inefficiencies expected regarding traffic flow with complex interactions between vehicles with informed and uninformed drivers? Hereupon, future studies should give an answer.

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