A Simulation Study of Traffic Efficiency Improvement Based on Car-to-X Communication

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ABSTRACT

There are several promising applications for car-to-x communication that aim at the improvement of traffic efficiency. With the increasing maturity of car-to-x communication systems, insights into the impacts of these applications on vehicular traffic are required. In this paper, we present a simulation study of traffic efficiency improvements that can be obtained by the utilization of a merging assistance application ahead of a freeway lane drop. Our investigations are based on the traffic simulation tool AIMSUN. We connect the traffic simulator with a simulation model that implements the merging assistance application as well as the message exchange between vehicles and a roadside unit. Simulation results show significant traffic efficiency improvements indicated by travel time reductions of up to 30% in dense traffic under ideal conditions.

Categories and Subject Descriptors

C.2.1 [**Network Architecture and Design**]: Wireless communication; C.2.2 [**Network Protocols**]: Applications

General Terms

Algorithms, Design, Performance

Keywords

Car-to-x communication, vehicular networks, VANET applications, simulation, traffic control, traffic efficiency optimization

1. INTRODUCTION

In recent years, research activities in the field of vehicular communications achieved considerable progress and experienced large interest throughout the world. Car-to-x communication involves wireless connectivity among vehicles (car-to-car) as well as between vehicles and fixed network infrastructure elements (car-to-infrastructure). The large variety of use cases motivating car manufacturers, suppliers and researchers to support the development of this technology includes safety and infotainment applications as well as use cases related to the improvement of traffic efficiency.

In consideration of increasing traffic demand and escalating energy costs, traffic efficiency applications seem to be particularly promising. In this context, traffic control methods based on car-to-x communication provide major advantages over conventional traffic control strategies that build on static traffic signs or variable-message signs (VMS), displaying speed limits, for example. Although VMS, in contrast to static signs, also allow dynamic traffic control approaches which adapt to traffic conditions measured by detectors that belong to the road infrastructure, car-to-x communication can provide dynamic traffic control with significantly more flexibility: Any kind of traffic control information can be delivered to the driver at any position, independently of a fixed infrastructure in terms of signs as well as traffic detectors. Thus traffic control systems can be established inexpensively and even in an ad hoc approach.

The benefits of car-to-x communication are generally undisputed, but there are few research results available addressing the impacts of car-to-x applications in order to verify these assumptions. As the maturity of car-to-x communication systems increases, insights into their impacts on vehicular traffic are indispensable prior to a market introduction. On the one hand, the processes in traffic networks are too complex for an analytic investigation. On the other hand, field tests are costly and time-consuming and thus have a medium-term or long-term orientation. Therefore, a simulation approach seems to be adequate, motivating us to study the impacts of a selected car-to-x application aiming at the improvement of traffic efficiency with the help of the commercial road traffic simulator AIMSUN.

For this purpose, it is possible to model the involved radio channel and the protocol stack in a fairly abstract way, because only effects of the application are to be evaluated. As an exemplary use case is needed in this context, we designed a merging assistance application for a freeway lane drop scenario that builds on a message exchange between vehicles and a roadside unit (RSU). It provides drivers with individual speed limits and merging positions which can be displayed inside the car, for example on a head-up display (HUD) or a conventional display. In order to assess the impacts of the application, a realistic model of a freeway lane drop was built in AIMSUN that serves as a reference scenario for the simulations. Simulation results show that a significant improvement of traffic efficiency can be achieved by the utilization of the merging assistance application, as mean travel times in dense traffic can be decreased by up to 30% assuming ideal conditions.

VANET'09, September 25, 2009, Beijing, China.

Several authors address similar issues, either focusing on simulation methodology or on traffic flow analysis. Tondl presents an elaborate traffic simulation environment as well as approaches to optimize traffic flow by dissemination of local information based on car-to-car communication [17], but merging scenarios are not examined. The impacts of an Intelligent Speed Adaptation (ISA) system on traffic flow are studied by Hogema et al. [13]. Car-to-infrastructure communication is used to provide vehicles with dynamic speed limits in a simulation scenario containing a freeway lane drop. ISA focuses on speed limits and does not consider merging positions. Chen et al. [7] address the effects of two exemplary applications based on traffic data dissemination. The highway simulation scenarios include distributed computation of variable speed limits building on periodic speed and position data broadcasts as well as accident alerts. Other contributions focus on the impacts of Cooperative Adaptive Cruise Control (CACC) systems on traffic flow [20, 21].

An interesting contribution is presented by Eichler et al., involving the coupling of the traffic simulator CARISMA and the network simulator NS2 [8]. The authors examine an urban scenario where cars disseminate warning messages after a breakdown, causing vehicles that receive the message to choose alternative routes avoiding the danger area. Sommer et al. [16] present a similar approach that builds on a sophisticated coupling of the traffic simulator SUMO and the network simulator OMNeT++. The simulation environment is used for the evaluation of protocols for incident warnings which enable vehicles to find routes around blocked sections.

The paper is organized as follows: After an overview of relevant traffic engineering concepts in section 2, we outline the traffic simulator and the reference scenario in section 3. Section 4 presents the communication model and the merging assistance application we developed as well as the simulation results and finally section 5 contains a short conclusion and an outlook.

2. TRAFFIC ENGINEERING CONCEPTS

In this section, we present a short overview of traffic engineering concepts that are important for our simulation study. Fundamental parameters for the description of traffic streams are introduced as well as traffic control strategies that influenced the design of the merging assistance application.

2.1 Traffic Flow Fundamentals

In order to be able to evaluate the simulation results in terms of traffic efficiency, it is necessary to introduce some fundamental macroscopic traffic-stream parameters which are essential for this purpose. Definitions of the most important macroscopic parameters are given in the following.

The *flow rate* q is defined as the equivalent hourly rate at which a number of vehicles n_q passes a fixed point in a given time interval Δt, expressed in vehicles per hour (veh/h):

$$q = \frac{n_q}{\Delta t} \tag{1}$$

The choice of the observation period Δt strongly influences the measured flow rate. If Δt is very small, this will result in large variations between single measurements. If a long observation period is chosen, the measured flow rates remain stable over time, but characteristic traffic peaks may become unobservable. Thus the observation period has to be chosen carefully and depending on the scenario being investigated. The maximum sustainable flow rate at which vehicles can be expected to traverse a given point of a lane under given roadway, traffic and environmental conditions is called its *capacity* C.

The *time mean speed* $\overline{v_t}$ is defined as the average speed of all vehicles passing a fixed point in a given time interval Δt. It is represented by the arithmetic mean of observed speeds v_i for a number of observed vehicles N:

$$\overline{v_t} = \frac{1}{N}\sum_{i=1}^{N} v_i \tag{2}$$

On the other hand, *space mean speed* $\overline{v_s}$ can be computed by dividing the length of the section Δx by the average of the vehicles' travel times t_i, which corresponds with the harmonic mean of vehicle speeds v_i observed on the section:

$$\overline{v_s} = \frac{\Delta x}{\frac{1}{N}\sum_{i=1}^{N} t_i} = \frac{N}{\sum_{i=1}^{N} \frac{1}{v_i}} \tag{3}$$

Traffic density k constitutes another important parameter for the characterization of road traffic. It is an indicator for the freedom of movement in a traffic stream. Traffic density is defined as the number of vehicles n_k per unit of length occupying a given length Δx of a lane or section at a certain point in time, usually expressed as vehicles per km.

$$k = \frac{n_k}{\Delta x} \tag{4}$$

While the flow rate is a local parameter, i.e. it can be measured at a certain position over a period of time, traffic density is a momentary parameter, i.e. it has to be measured within a road section at a certain point in time. As this is difficult to realize, local parameters are mainly metered in practice. However, traffic density can be computed by applying the fundamental relationship among the three parameters density k, space mean speed $\overline{v_s}$ and flow rate q:

$$q = k \cdot \overline{v_s} \tag{5}$$

2.2 Traffic Control Strategies

As mentioned in section 1, we chose a freeway scenario for our simulation study that includes a lane drop accompanied by a transition from three to two lanes. The reference scenario is presented in detail in subsection 3.2 of this paper. Two major effects can be observed ahead of lane drops on freeways: On the one hand, drivers are prone to stay on the closed lane too long, which often results in so-called forced merges associated with braking and frictions between vehicles on the closed and the open lane. On the other hand, drivers merging too early cause the capacity of the freeway section to be suboptimally utilized, which especially has disadvantages in dense traffic situations. Various conventional traffic control strategies were developed that aim at the optimization of traffic flow in lane drop areas. Some of these strategies that influenced the design of the merging assistance application which is described in subsection 4.2 are introduced in the following.

2.2.1 Early Merge Strategy

The Early Merge Strategy is a conventional traffic control approach which aims at facilitating the merging procedure ahead of freeway lane drops or lane closures. Warning signs announcing the lane drop are placed significantly further upstream, encouraging drivers to merge to the open lane earlier than usual. This method reduces frictions during the merging procedure as it avoids forced merges in the vicinity of the lane drop. Furthermore, an explicit merge point can be indicated. In order to prevent the drivers from passing after the merge point, a no passing zone can additionally be applied downstream of the merge point. This strategy is depicted in Figure 1.

While the Static Merge Strategy keeps all parameters steadily unchanged, the Dynamic Early Merge Strategy includes the adaption of the merge point's position and the length of the no passing zone to current traffic conditions. In the event of increasing traffic density, the merge point is shifted upstream. The Early Merge traffic control approach provides good results in situations of low traffic densities and high speeds, but travel times are increased when traffic densities and flow rates are high, as vehicles are more likely to be delayed by slower vehicles ahead of them [15].

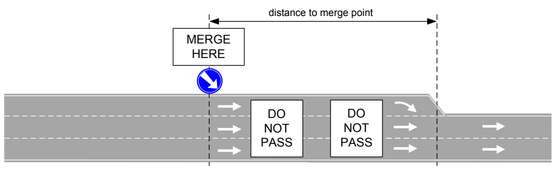

Figure 1: early merge strategy

2.2.2 *Late Merge Strategy*

The Late Merge Strategy presents a contrary approach, where drivers are advised to stay on their lane until they reach the merge point which is located near the lane drop. Figure 2 sketches the concept. With this method, the capacity of all three lanes is utilized in an optimal way, which is especially important when congestion occurs. While difficult to apply at high speeds, the Late Merge Strategy performs significantly better in congested situations involving high densities than the Early Merge Approach [15]. For this reason, a Dynamic Late Merge concept is presented by the authors in [14] that combines both strategies. Early Merge is used during periods of high speeds and low traffic density, but the dynamic approach switches to Late Merge traffic control when congestion occurs.

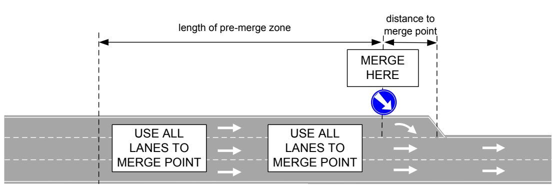

Figure 2: late merge strategy

2.2.3 *Gradual Speed Limit*

Another well-known method to improve traffic flow ahead of a lane drop is the application of a gradual speed limit. Particularly in freeway scenarios, where a significant speed reduction is desired, the speed limit should be decreased in several zones as depicted in Figure 3. In *static* gradual speed limits, the permissible speeds within these zones and the distances between them remain constant, while these parameters can be adapted to current traffic conditions in *dynamic* gradual speed limits. The effects of gradual speed limits are a harmonization of traffic as less frictions occur between vehicles, accompanied by an increase of traffic safety.

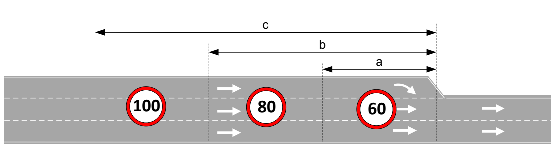

Figure 3: gradual speed limit ahead of a lane drop

3. TRAFFIC SIMULATION

In this section, we present the traffic simulation environment, which is based on the microscopic traffic simulator AIMSUN [18]. We analyze the application of car-to-x communication for the control of a merging procedure at a typical lane drop bottleneck on a freeway. Our aim is to increase capacity as well as to avoid traffic jams by providing vehicles arriving at the lane drop with behavioral recommendations through the reception of traffic control messages. In order to analyze the impacts of car-to-x communication on traffic flow optimization, we compare the traffic behavior of the selected freeway scenario applying the implemented message exchange procedure with the behavior of the same scenario under equal conditions without using the message exchange. This section introduces the microscopic traffic simulator AIMSUN as well as the reference scenario that consists of a simulation model based on an empiric traffic study.

3.1 AIMSUN Traffic Simulator

AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks) is a road traffic simulation tool that is accepted by a large community of traffic engineers. The simulator, which is able to handle urban networks as well as freeways, highways or rural roads, pursues a microscopic approach [3]. In contrast to macroscopic models, microscopic models focus on the behavior of single vehicles and their interactions, which is indispensable for the investigation of car-to-x communication aspects.

The behavior of each simulated vehicle is determined by the integrated car following and lane changing models as well as by user-defined traffic control elements. The car following model applied in AIMSUN is based on the empirical model by P. G. Gipps presented in [10, 12]. Furthermore, Gipps's model is enhanced by an additional two-lane car following model, which also considers maximum speed differences to vehicles on adjacent lanes. AIMSUN's lane-changing model can be regarded as an adaptation of the model presented by Gipps in [11]. The vehicle data (like position, speed and acceleration) is updated in discrete time steps. The length of a simulation step can be altered by the user, values ranging from 0.1 s to 1.0 s are possible. Details about traffic modeling in AIMSUN can be found in [18].

One of the simulation environment's most powerful features is the *AIMSUN Application Programming Interface (API) module*. The API module serves as an interface between the AIMSUN simulation model and user-defined *external applications* like implementations of traffic control or traffic management systems. Via the API module, AIMSUN provides the external application with simulation data concerning the road network, e.g. speed and position of vehicles, which can in turn be processed by the external application. In the opposite direction, the external application can send control commands (e.g. change of a vehicle's desired speed) via the API module to the AIMSUN simulator in order to influence traffic behavior. For this purpose, the API module and the external application can be compiled as a dynamic-link library which AIMSUN is linked against. Figure 4 shows the structure of the information exchange via the API module [19].

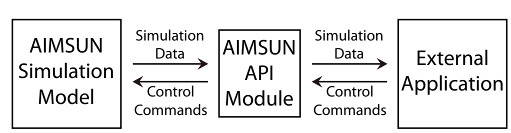

Figure 4: data exchange via AIMSUN's API module

3.2 Reference Scenario

The reference scenario that we designed in AIMSUN tries to model vehicular traffic as close to reality as possible and serves as a benchmark for the evaluation of communication impacts on traffic efficiency. In order to assure realistic simulation results, we decided to calibrate and validate the reference scenario with empiric measurement results. The scenario is based on an empiric traffic study on a freeway bottleneck between Heathrow and London that Bertini et al. present in [5, 4]. This bottleneck is caused by a lane drop of the passing lane involving a transition from three to two lanes. The freeway section containing the lane drop was monitored for a period of five days by means of detectors arranged in constant intervals.

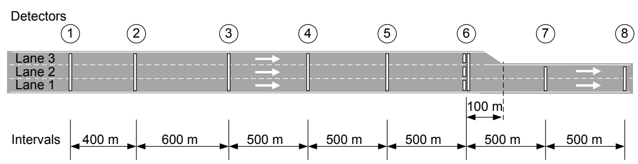

Figure 5: map of the reference scenario with distance intervals

Figure 5 shows a part of the reference scenario, which we adapted to right-hand traffic. The positions of the lane drop and the detectors were arranged exactly according to the measurement study. All detectors perform measurements accumulated over all the lanes. At the position of detector 6, we added three detectors measuring traffic on each single lane.

We calibrated the simulation model of the reference scenario in an iterative process adjusting the simulation parameters and comparing the behavior of the simulation model with the empirical data. The most important parameters in AIMSUN that had to be adapted to calibrate the simulation model are the capacity of the section, which was set to 2000 veh/h per lane, the section parameter *Time Distance on Ramp* and the vehicle parameter *Maximum Give-Way Time*. Furthermore, the section parameters *Distance Zone 1* and *Distance Zone 2* had to be altered as well as the global parameter *Reaction Time at Stop*. The two-lanes car-following model was enabled. There is a general speed limit of $112\,\mathrm{km/h}$ ($70\,\mathrm{mi/h}$).

Table 1: reference scenario simulation parameters

parameter	mean	standard deviation	min	max
global parameters				
reaction time at stop	0.75 s			
2-lanes car following model	enabled			
max. speed difference	30 km/h			
max. speed difference on-ramp	50 km/h			
parameters vehicle type *car*				
maximum give-way time	3 s	2 s	1 s	5 s
parameters vehicle type *truck*				
maximum give-way time	20 s	10 s	10 s	30 s
section parameters				
capacity (per lane)	2000 veh/h			
time distance on ramp	5.5 s			
distance zone 1	30 s			
distance zone 2	20 s			
section speed limit	112 km/h			

Table 1 shows the most important parameters of the reference scenario that had to be adapted and their respective values. Details about the parameters can be found in [18]. *Mean*, *standard deviation*, *min* and *max* are used as parameters of a truncated normal distribution. The scenario was simulated over a period of two hours with a two-staged traffic demand according to Table 2. While the first simulated hour represents free flow conditions, the demand of the second hour significantly exceeds the capacity which was set to $2000\,\mathrm{veh/h}$ per lane. There is a constant proportion of heavy vehicles of 15 percent. In order to compare the simulation results

Table 2: reference scenario traffic demand

time	traffic demand	heavy vehicles ratio
0 - 60 min	3100 veh/h	15%
60 - 120 min	5000 veh/h	15%

of the reference scenario with the empirical data, we use a graphical representation of the transformed cumulative number of arrived vehicles, which the authors also utilize in [4]. We present the cumulative number of vehicles counted at detector position x in the form of $N(x,t) - q \cdot t$, where q is a scaling factor for visualization purposes that can be understood as background flow rate. We chose q as $3100\,\mathrm{veh/h}$. In this representation, the slope of the graph describes the momentary flow rate and a horizontal line implies a flow rate of $3100\,\mathrm{veh/h}$.

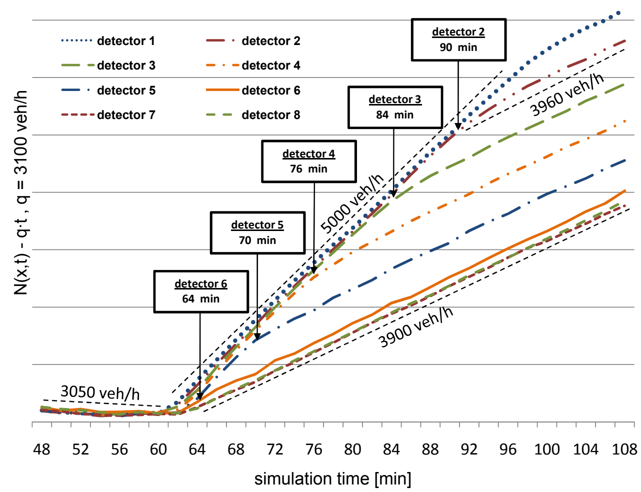

Figure 6: transformed cumulative arrivals N(x,t) of the reference scenario

The results are shown in Figure 6. Until the increase of traffic demand in minute 60, all detectors measure equal flow rates of about $3050\,\mathrm{veh/h}$. This corresponds with free traffic flow as the numbers of vehicles entering and those leaving the section are equal. After the demand increases in minute 60, only detectors 7 and 8 show equal flow rates, indicating free traffic in the area between them due to their location downstream of the lane drop. The plots of all other detectors which are located upstream of the lane drop (which is located between detectors 6 and 7) temporarily show a higher flow rate of about $5000\,\mathrm{veh/h}$.

After a certain period of time, each of the measured flow rates drops to a lower value of about $3900\,\mathrm{veh/h}$. From the moment of flow rate decrease which is specific for each detector, traffic density heavily increases at the detector position, because the number of vehicles that enter the area upstream of the detector is larger than the number of vehicles leaving the area for a period of time. This results in traffic breakdowns at the detector positions in conjunction with congestion and queuing at distinct points in time. These points are highlighted in Figure 6, indicating the arrival of traffic congestion which moves upstream. The simulation results show that the propagation speed in upstream direction as well as the flow rate values fit well with the measurement data in [5, 4].

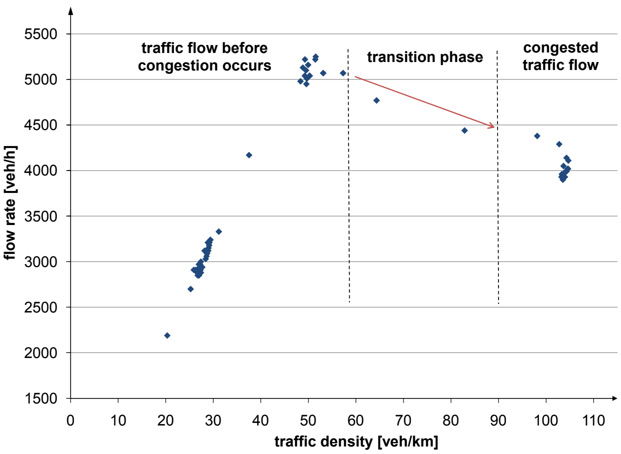

Figure 7: q-k diagram of detector 2

In Figure 7, the q-k diagram of detector 2 is depicted which reflects the traffic behavior at this specific position before and after the occurrence of congestion. It can be seen that flow rate as well as traffic density increase until congestion occurs, which takes place after approximately 90 minutes (see Figure 6). After that there is a short transition phase which represents the breakdown of free traffic flow. During this transition phase, flow rates decrease from values of about $5050\,\mathrm{veh/h}$ to approximately $4300\,\mathrm{veh/h}$. Simultaneously, traffic density increases from ca. $57\,\mathrm{veh/km}$ to $100\,\mathrm{veh/km}$. After the transition phase, there is congested traffic with a nearly constant flow rate of about $4000\,\mathrm{veh/h}$ and densities of about $100\,\mathrm{veh/km}$. This reflects the measurement data from [4] quite satisfactory, where the authors notice an approximate decrease of the flow rate from 4900 to $3800\,\mathrm{veh/h}$ accompanied by a traffic density increase from 62 to $115\,\mathrm{veh/km}$.

Other simulation results that we evaluated, e.g. time mean speeds on each of the lanes at detector 6, also show satisfying conformance with the measurement data indicating that the reference scenario model seems to reflect real traffic flow conditions in an appropriate way. It can also be stated that the lane drop causes severe traffic congestion due to the high traffic demand. For this reason, an optimization of traffic flow in connection with an increase of capacity by means of car-to-x communication is studied and presented in the following section.

4. TRAFFIC FLOW OPTIMIZATION

In this section, we present a merging assistance application that builds on a message forwarding algorithm aiming at the optimization of traffic flow as well as the mitigation of congestion. The first subsection describes the communication model which we implemented to simulate the message exchange between vehicles, followed by a characterization of the merging assistance application that builds on the message exchange. A presentation of the simulation results examining the impacts of the algorithms in terms of capacity increases concludes this section.

4.1 Communication Model

As described in section 3.1, AIMSUN's API module presents a well-suited interface to interlink external applications with the traffic simulation environment. We used the API module in order to provide AIMSUN with a simulation model of wireless car-to-car and roadside-to-car communication aiming at the improvement of traffic efficiency in the reference scenario described in section 3.2. The model was implemented in C++ and compiled as a DLL which AIMSUN is linked against. As a result, on the one hand the message exchange process can be controlled by AIMSUN by calling exported DLL functions at every simulation step as well as during the initialization and termination of the simulation run. On the other hand, we are able to read and write vehicle data, section data and global traffic simulation data by calling imported AIMSUN API functions from the DLL. In this section, we introduce the communication model which is part of the implementation.

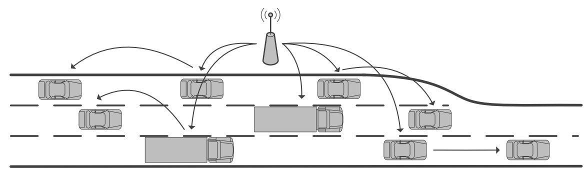

Figure 8: schematic message distribution in the simulation scenario

Figure 8 schematically shows the simulation scenario including the message distribution[1]. The scenario contains two types of nodes: Onboard Units (OBU) which belong to the vehicles and a single Roadside Unit (RSU) that we placed $350\,\mathrm{m}$ upstream of the lane drop which corresponds to a centered position between detectors 5 and 6. The RSU sends traffic control messages which contain the position of the lane drop and a number of other parameters. These messages are received by the vehicles' OBUs and processed depending on the vehicle's local attributes like position, speed and direction of travel. In order to increase the information range, the messages are forwarded by the OBUs in a multi-hop approach.

The objective of the implemented simulation model is to investigate the impacts of the message dissemination on traffic efficiency. The involved communication network was deliberately modeled in a fairly abstract and technology-independent way and therefore does not represent a certain protocol stack. Nevertheless, we chose basic parameters like the simulated communication range with respect to the IEEE 802.11 family of standards and its 802.11p amendment for Wireless Access in Vehicular Environments (WAVE) [1, 2] as well as its European adoption, which is currently promoted by the Car2Car Communication Consortium [6].

Further abstractions in favor of simplicity of the model are related to propagation issues. Given the maximum permitted EIRP of $33\,\mathrm{dBm}$ defined by the IEEE 802.11p draft [2] and the European Commission Decision 2008/671/EC [9], we assume that each transmitting OBU as well as the RSU have a fixed circular communication range of $R = 500\ m$. All equipped vehicles[2] within the transmitter's communication range receive the transmitted message simultaneously. Instead of using a realistic propagation model, transmission errors can be modeled by frame error rates. Furthermore, we assume that every equipped vehicle is able to determine its own position, as the vehicle position is used to determine the relevance of the message (see section 4.2). We did not consider congestion issues as it can be assumed that the merging assistance application only has a very small impact on channel load (small messages, less than one message per second).

[1]Note that the communication distances in Figure 8 are not true to scale.

[2]i.e. provided with the necessary communication equipment in form of an OBU

Except for one RSU, no fixed network infrastructure is necessary. Instead, the OBUs apply a forwarding algorithm to disseminate the messages which is presented in the following. The RSU broadcasts traffic control messages in fixed intervals of 5.0 seconds. Message IDs are assigned to the control messages. These IDs are kept constant for each of the sent messages as long as the embedded traffic control information remains unchanged. If the information is updated according to the merging assistance application, the ID is incremented by the RSU. For details about the message contents and the merging assistance application, see subsection 4.2. The forwarding algorithm which we implemented in the OBU is based on the idea that it is only necessary to forward a message if no other node is currently distributing the message [17]. The OBUs store all received valid messages in a local buffer and observe the communication channel for a time period determined by an observation timer which is started for the first time when a valid and previously unknown message is received. We choose $t_{obs} = 6\ s$ as initialization value for the timer. One observation timer instance is necessary for each of the stored and valid messages.

The chosen time intervals for message creation in the RSU and message forwarding in the OBU are comparatively large in consideration of the dynamic VANET topology, resulting in low bandwidth requirements. However, this does not affect the performance of the merging algorithm as messages are stored by the vehicles which regularly check the relevance of the stored messages (see subsection 4.2.2). Furthermore, the message content is only updated by the RSU when a change of traffic conditions is detected, which occurs significantly less frequently than messages are created or forwarded (see subsection 4.2.1).

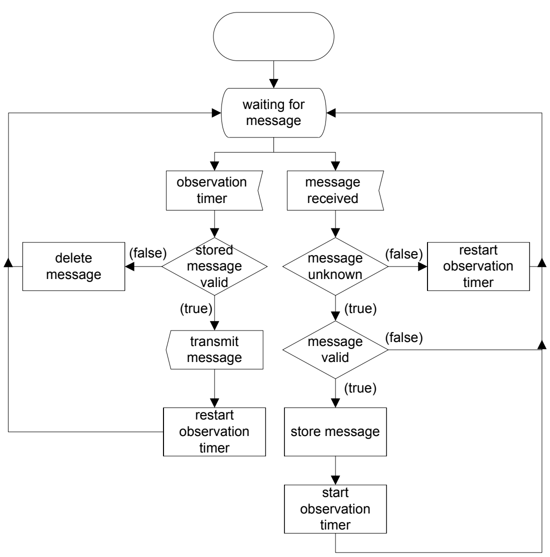

Figure 9: OBU message forwarding algorithm

Figure 9 shows a slightly simplified illustration of the OBU's message forwarding algorithm. After the reception of a message, regardless of whether it was transmitted by the RSU or by another vehicle, the receiving OBU checks the ID of the received message and compares it to the IDs of messages stored in its local buffer. If any of the IDs matches, the received message is considered to be already known to the receiver. When a known message is received, the forwarding of the message is not necessary and the observation timer of this message has to be restarted. If the received message is unknown, the OBU checks whether the message is valid. This validity check is currently only based on a time-to-live value, but can be enhanced by a position- and time-based decision in the future. If the message is unknown and valid, it is stored by the OBU and the observation timer is started. When the observation timer expires, the OBU checks whether the stored message is still valid. If this is the case, the OBU broadcasts the message and the observation timer is restarted. If the stored message is no longer valid, the OBU deletes it from the buffer and continues listening for additional messages.

4.2 Merging Assistance Application

The merging assistance application that builds on the message exchange procedure described in subsection 4.1 provides the drivers with individual speed limits and merging positions. Our algorithm is based on the concepts presented in subsection 2.2. We use the AIMSUN API to connect the implementation of the merging assistance application with the traffic simulator.

The implementation can be viewed as a variation of the Dynamic Late Merge (DLM) traffic control strategy presented in [14]. As mentioned above, Early Merge Strategies perform well when traffic conditions show low densities and high speeds, but suffer from travel time increases when traffic density is high, as the capacity of the section is reduced by early merging. Late Merge Strategies suffer from unnecessary frictions in front of the lane drop when speeds are high and traffic densities are low, but reduce travel times in congested traffic due to their capacity-increasing effect. Thus we chose to combine the advantages of the Dynamic Early Merge (DEM) and Dynamic Late Merge (DLM) strategies in connection with a dynamic gradual speed limit.

All parameters of the merging assistance algorithm like detector and merging positions as well as speed limits were iteratively optimized for the properties of the chosen specific scenario. Further investigations are required to assess their applicability under different conditions.

4.2.1 Message Creation in the RSU

In order to assure that the OBUs process the traffic control messages homogeneously and independent of the vehicle type, large parts of the merging assistance algorithm were implemented in the RSU. It analyzes current traffic conditions, determines relevant parameters for the behavioral recommendations and finally creates and transmits the control messages. The detectors 5 and 6, which are located $600\,\mathrm{m}$ and $100\,\mathrm{m}$, respectively, upstream of the lane drop (see Figure 5) monitor time mean speeds (TMS) of vehicles. However, further independence of fixed infrastructure can be gained by utilizing the vehicular network to achieve this task. In order to demonstrate this, virtual detectors were implemented in the RSU. The equipped vehicles transmit their current speeds to the RSU at virtual detector points determined by information elements in the RSU's control messages. Simulation results show that the TMS values subsequently calculated for each virtual detector by the RSU correspond to the values measured by the fixed infrastructure detectors.

In addition to the dynamic merge point and speed limit, a 'Stay in Lane' advice is displayed to the drivers upstream of the merge point as well as 'Do Not Pass' for heavy vehicles downstream of the merge point. The latter significantly reduces frictions during the merge procedure as no heavy vehicles are permitted on the lane being merged to. Based on the traffic conditions monitored at the detectors, the merging assistance application implemented in the RSU determines the stage of the traffic control strategy according to the algorithm which is depicted in Figure 10. All parameters were adjusted to the reference scenario, see subsection 3.2.

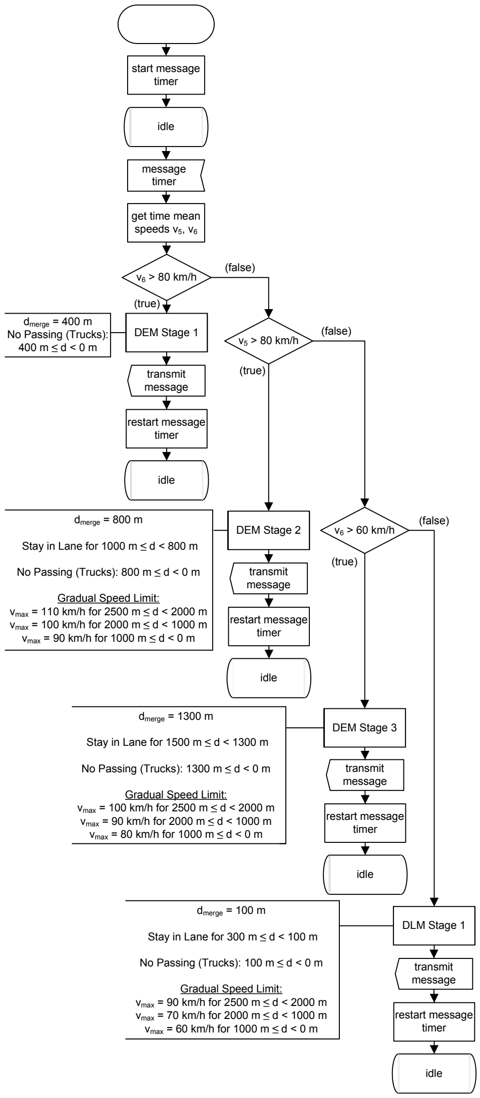

Figure 10: Merging assistance application implemented in the RSU. d denotes the vehicle's distance from the lane drop, d_{merge} the merging point and v_{max} the speed limit. DEM and DLM stand for Dynamic Early Merge and Dynamic Late Merge, respectively.

The stages of the algorithm are explained in the following. During free flow traffic in *DEM Stage 1*, the Early Merge Strategy is used. The algorithm assumes free flow conditions if the TMS at detector 6, which is located directly in front of the lane drop, is above $80\,\mathrm{km/h}$. In this stage, no additional speed limits are applied, the merge point and the beginning of the no passing zone for heavy vehicles are located $400\,\mathrm{m}$ ahead of the lane drop. As in each stage of the algorithm, the current traffic control parameters are encapsulated into a message, which is subsequently transmitted by the RSU. Finally, the message timer is restarted in order to trigger the next message creation after 5 seconds.

When the TMS measured at detector 6 drops below $80\,\mathrm{km/h}$ but the TMS at detector 5 still remains above $80\,\mathrm{km/h}$, *DEM Stage 2* is applied. The decrease of v_6 indicates increasing traffic density at detector 6, resulting in merging problems and braking vehicles. For this reason, the merge point is shifted 400 meters further upstream and ahead of it the 'Stay in Lane' zone is established. Furthermore, the gradual speed limit is activated in order to harmonize traffic with speeds of 110, 100 and $90\,\mathrm{km/h}$ in distances of 2500, 2000 and $1000\,\mathrm{m}$ ahead of the lane drop, respectively.

With the increase of length of the slightly congested area the merge point is shifted to a position further upstream. This is indicated by a drop of the time mean speed measured at detector 5 below $80\,\mathrm{km/h}$. As a result, *DEM Stage 3* is applied, resulting in a shift of the merging point to a position $1300\,\mathrm{m}$ ahead of the lane drop. The speed limits are lowered by $10\,\mathrm{km/h}$.

Simulation results showed that a traffic flow breakdown accompanied by severe congestion is encountered when time mean speeds measured at the detectors drop below $60\,\mathrm{km/h}$. As it is reasonable to utilize all lanes as long as possible in this phase to maximize the section's capacity, *DLM Stage 1* is applied. The merge point is shifted downstream to a position $100\,\mathrm{m}$ ahead of the lane drop and the positions of the 'Stay in Lane' and 'No Passing' zone are adjusted accordingly. In order to achieve further traffic harmonization, speed limits are reduced to 90, 70 and $60\,\mathrm{km/h}$, respectively.

4.2.2 Relevance Check in the OBU

As depicted in Figure 9, the vehicles's Onboard Units (OBUs) store received traffic control messages if they are valid and previously unknown. In addition to this, the OBUs perform a relevance check in each simulation step to determine whether one of the stored messages is currently important for the driver. For this purpose, all stored messages are checked and encapsulated geographic coordinates are compared with the current vehicle position. The message is generally considered relevant if the announced position of the lane drop is ahead of the vehicle and the vehicle's distance to the lane drop is smaller than $3000\,\mathrm{m}$ (relevance zone).

If a relevant message was identified, the necessary behavioral recommendations can be displayed to the driver depending on the vehicle's current position. The implicated actions which are carried out be the driver, e.g. a lane change or a speed reduction, are triggered via the AIMSUN API. As a result, the effects of the merging assistance application are reproduced in AIMSUN's microscopic simulation model of the reference scenario.

4.3 Simulation Results

In this subsection we present the results of evaluations we conducted with the simulation environment consisting of the reference scenario, the communication model and the merging assistance application (see sections 3.2, 4.1 and 4.2). In order to evaluate the effects of the merging assistance application, we compare the results of simulation runs with and without utilization of the message exchange procedure. For the assessment of the simulation results, local traffic parameters are not as convincing as parameters measured over the entire section. While these parameters are very difficult to measure in reality, AIMSUN offers the possibility of gathering global statistics of a whole section. The mean flow rate $\overline{q}$ represents the number of vehicles that traversed the section during an observation period measured in vehicles per hour. $\overline{T}_t$ $[s/km]$ denotes the mean travel time of vehicles that traversed the section during the observation period that we chose as $\Delta t = 120\,\mathrm{s}$. As $\bar{q}$ suitably reflects the traffic volume carried by the freeway section and $\overline{T}_t$ suitably reflects how quickly vehicles can traverse it, these parameters are appropriate for the evaluation of traffic efficiency and thus they are used in the following.

During all simulative evaluations presented below, three stages of traffic demand were used which are shown in Table 3. As stated in subsection 3.2, the reference scenario has a capacity of about $4000\,\mathrm{veh/h}$. Thus at the first stage of traffic demand the algorithm is evaluated under free traffic flow conditions. After 30 minutes,

Table 3: three-stage traffic demand

time	traffic demand	heavy vehicles ratio
0 - 30 min	3000 veh/h	15%
30 - 60 min	3800 veh/h	15%
60 - 90 min	4600 veh/h	15%

the traffic demand is increased to $3800\,\mathrm{veh/h}$, representing dense traffic close to the capacity limit. The third stage reflects traffic conditions that would normally result in heavy congestion, as traffic demand is significantly higher than the section capacity.

4.3.1 Communication Impacts on Traffic Efficiency

Our first simulation setup represents ideal conditions. We assume that every vehicle is equipped with an Onboard Unit, i.e. a penetration rate of 100% is simulated. Furthermore, we assume that all drivers obey the recommendations generated by the received traffic control messages.

It can be stated that the dissemination of the traffic control messages based on the forwarding algorithm worked without interruptions, so that each vehicle in the relevance zone starting $3000\,\mathrm{m}$ ahead of the lane drop received the traffic control messages.

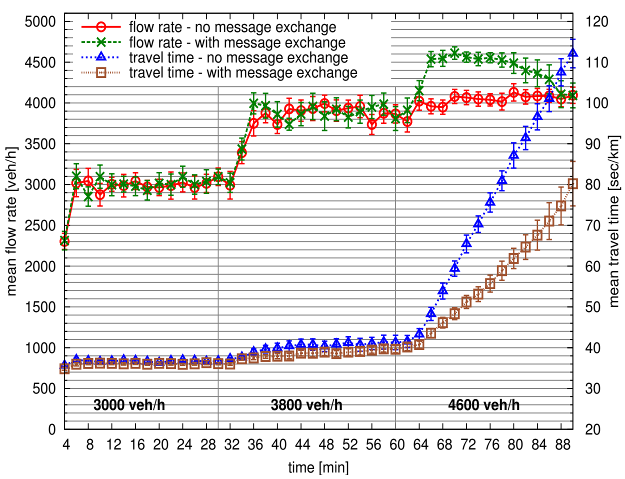

Figure 11: mean flow rates and mean travel times with penetration rate 100% from 25 simulation runs incl. 95% confidence intervals

In Figure 11, the resulting mean flow rates and mean travel times are depicted for simulation runs with and without the utilization of the message exchange. It is clearly observable that the message exchange does not cause any improvements in the free traffic flow stage, which is intuitively comprehensible. While flow rates with and without application of the message exchange are almost equal during the second stage, a minor increase of travel times can be observed if the message exchange is deactivated.

Significant traffic efficiency improvements evolve from the utilization of the merging assistance when the traffic demand is once more increased to $4600\,\mathrm{veh/h}$. Under these conditions, severe congestion is created if the message exchange procedure is deactivated, which is indicated by travel times increasing by approximately 70 seconds per km by the end of the simulation run. If the message exchange is applied, this travel time increase can be alleviated by approximately 45% and total travel times are decreased by up to 30%. In addition, the merging assistance results in a temporary flow rate increase of a little more than 10% in this stage of the simulation scenario.

4.3.2 Penetration Rate Impacts

In reality it can hardly ever be achieved that all vehicles are equipped with the necessary communication interfaces. For this reason, we also evaluated simulation runs with different penetration rates to assess their impact on the effectivity of the algorithm. For this purpose, two additional vehicle types were added to the simulation scenario, 'car unequipped' and 'truck unequipped', and the fraction of equipped vehicles r was varied among the simulation runs.

For easier visualization of the simulation results we define the normalized mean travel time $\overline{T}'_t$ as the ratio of mean travel time applying the communication procedure $\overline{T}_{t,Comm}$ to mean travel time without it $\overline{T}_{t,No\_Comm}$:

$$\overline{T}'_t = \frac{\overline{T}_{t,Comm}}{\overline{T}_{t,No\_Comm}} \tag{6}$$

Figure 12 depicts the resulting normalized mean travel times for penetration rates of 60% to 100%. The dissemination of the traffic control messages worked without interruptions for each of the simulated penetration rates. During free traffic flow, there is hardly any difference to the simulation runs without applying the message exchange ($\overline{T}'_t \approx 1$). After the increase of traffic demand to $3800\,\mathrm{veh/h}$ in minute 30, a minor decrease of normalized travel time can be observed for high penetration rates. After the beginning of demand stage 3 in minute 60 (traffic demand 4600 veh/h), simulation results indicate significant decreases of normalized travel times which are caused by the message exchange. While travel times can be decreased by up to 30% if all vehicles are equipped, travel time savings are less significant when lower penetration rates are assumed. Nevertheless, mean travel time decreases of up to 7% are possible if 60% of the vehicles are equipped.

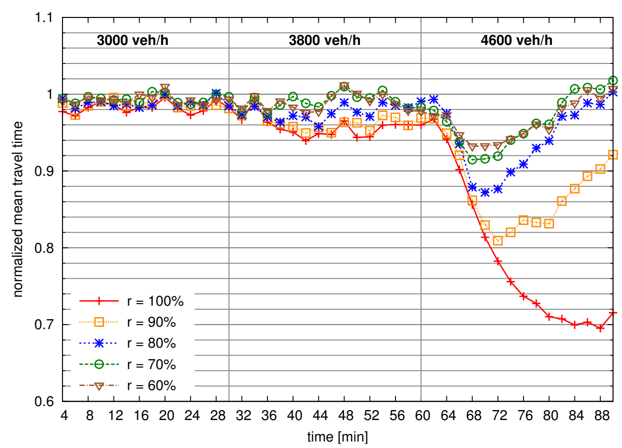

Figure 12: Normalized mean travel times for penetration rates 100% to 60%. Mean travel times measured without applying the message exchange are used as a benchmark, i.e. a value of 0.7 reflects a 30% mean travel time decrease caused by the message exchange procedure.

It can be observed from the simulation results that for all penetration rates except 100%, a traffic flow breakdown is encountered during simulation time despite the message exchange. Normalized mean travel times significantly decrease when traffic demand is raised to 4600 veh/h, but start increasing at a certain point in time (e.g. $t = 68\,\mathrm{min}$ for $r = 80\%$) indicating the time of the breakdown and occurence of congestion. However, even with lower penetration rates traffic flow is still considerably improved by the merging assistance application in the period of congested traffic , as $\overline{T}_{t,Comm}$ remains significantly below $\overline{T}_{t,No\_Comm}$. Furthermore, simulation results show that the traffic breakdown can be shifted to a later point in time, indicating the capability to absorb temporary traffic peaks.

Considering all vehicle types (equipped and unequipped), no significant travel time improvements can be observed for penetration rates lower than 50%. However, simulation results indicate that equipped vehicles still benefit from lower mean travel times in these scenarios. In Figure 13, the simulation results in terms of normalized mean travel times for equipped cars are exemplarily compared to those of unequipped cars for a penetration rate of 40%. In this case, mean travel times of equipped vehicles can be decreased by up to 18%. This is accompanied by the disadvantage of mean travel time increases for unequipped vehicles.

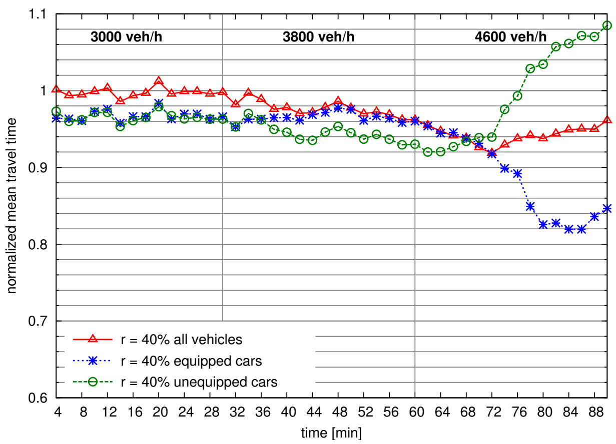

Figure 13: Normalized mean travel times of equipped vs. unequipped vehicles of vehicle type 'car' for varying penetration rates. Mean travel times measured without applying the message exchange are used as a benchmark.

Figure 14 shows the traffic efficiency improvement caused by the message exchange procedure in terms of mean flow rate increases depending on the penetration rate. While there are no significant differences until the beginning of the third traffic demand stage after 60 minutes, traffic flows are improved by up to 10% at this point in time. As assumed, the higher the penetration rate is, the higher the improvement and the later congestion occurs. While a penetration rate of 90% causes the traffic breakdown to occur approximately ten minutes after the beginning of the third demand stage, such a traffic peak can only be handled for six minutes with 70% of the vehicles being equipped before traffic breaks down.

Heavy vehicles also benefit from mean travel time decreases, but the effects are not as significant as for cars. This is due to the fact that the 'No Passing' zone for heavy vehicles that is implemented with the merging assistance application presents a minor disadvantage for this vehicle type compared to cars in favor of an optimized total traffic flow.

5. CONCLUSIONS AND FUTURE WORK

In this paper, we study traffic efficiency improvements that can be obtained by car-to-x communication in a freeway lane drop scenario. We used the traffic simulation tool AIMSUN to model a reference scenario according to an empirical traffic study which reflects real traffic conditions. Furthermore, we implemented a com-

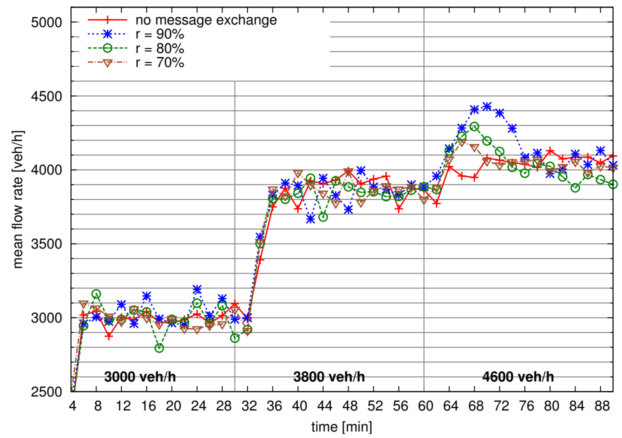

Figure 14: mean flow rates for different penetration rates

munication model including a simple message forwarding algorithm and an exemplary merging assistance application that builds on the dissemination of traffic control messages containing behavioral advices for the drivers. A comparison of results from simulation runs with and without the utilization of the merging assistance application shows that significant capacity increases are possible by the utilization of the message exchange procedure. Assuming ideal conditions and 100% penetration, travel times can be reduced by up to 30%, while a penetration rate of 60% allows travel time savings of up to 7% in dense traffic. Maximum flow rates can temporarily be improved by approximately 10%, indicating a significant capacity increase.

The presented simulation environment is supposed to serve as a platform for future work. While the simulation results in this paper assumed ideal conditions, a more sophisticated communication model in terms of propagation and protocol simulation is one of the issues we want to address for studying traffic efficiency improvements under more challenging conditions. In this context, an optimization of protocols adjusted to the requirements of the scenario will be examined.

Further enhancements aim at an extension of the merging assistance application including a detailed investigation of feasible additional improvements of traffic efficiency. Moreover, our current work focuses on the elimination of fixed infrastructure elements in the scenario. In a first step, fixed infrastructure detectors were replaced by 'virtual detectors' which are based on vehicles transmitting status messages containing their current speed at specific positions ahead of the lane drop. In a second step, an enhanced decentralized version of the merging assistance algorithm that considers cooperation between vehicles during the merging procedure will be investigated.

Acknowledgment

The authors thank Dr. Andreas Lübke from Volkswagen Research, Prof. Klaus Jobmann, Prof. Markus Fidler, Michael Bredel and Sebastian Sczyslo from the Institute of Communications Technology as well as Arkadi Seidscher for their support. Furthermore, we are grateful to the Ministry of Science and Culture of Lower Saxony for funding our work within the Connected Cars in a Connected World (C3World) project.

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