Development and Assessment of Cooperative V2X Applications for Emergency Vehicles in an Urban Environment Enabled by Behavioral Models

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Abstract Statistically, emergency vehicles (EVs) encounter a higher risk of getting involved in accidents during their missions than other road users. The successful completion of these missions can be facilitated by new applications. Simulations may support the development of applications, as it is not possible to test them in a real traffic system. Simulation of Urban Mobility (SUMO) is one possible tool to conduct simulations of real traffic systems. However, SUMO is not capable of modelling a realistic behavior of EVs, new types of infrastructure, and individual vehicles (IVs) concerning EVs by a predefined function. We propose models for each of the missing pieces towards an integrated approach to simulate EVs in an urban environment. Therefore, we adjust them with a video analysis and simulate them. Further, an assessment analyzes their usability as a reference for testing new applications. In order to identify supportive applications, we created and carried out a survey with 252 EV drivers. The deduced applications are a traffic light preemption via V2I and an automated formation of a rescue lane via V2V. We assess the models and applications by evaluating the travelling time, a speed profile of the EV, and speed profiles of the IVs. Additionally, we show the usefulness of the two applications for the EV as well as the IVs.

Keywords Simulation of an emergency vehicle · Simulation of EVs · Urban · Intersection · Real EV behavior · Rescue lane · Intelligent transportation system · Intelligent traffic light · V2X · Preemption · Automated formation of a rescue lane · Travelling time

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1 Introduction

Statistics about missions of rescue services in Germany indicate over 14 million missions a year [1]. This corresponds to several ten thousand missions of emergency vehicles (EVs) every day. Each mission is carried out under enormous time pressure as regional response time regulates the maximal time difference between the incoming call and the arrival of the rescue team [2]. The travelling time of an EV may be influenced by any incident on the road. Especially in an urban environment, red traffic lights are a serious threat for reaching the destination in time [3–6]. A red traffic light has two effects on the trip. First, the red light itself which indicates possible crossing traffic and second the obstruction by other road users waiting in front of the red light. This leads to a reduced speed as well as a higher risk of getting involved in an accident [7, 8]. A study examined the likelihood of having an accident by comparing accidents per kilometer of EVs and individual vehicles (IVs). According to the study, the risk of being killed is four times higher, being severely injured is eight times higher, and having a material damage is seventeen times higher while being on a mission in an EV [8].

For supporting EVs in urban situations, research and development presented various systems [4–6, 9]. A new set of applications for EVs may further enhance the safety and efficiency of rescue services. These applications may require new types of traffic infrastructure and communication among vehicles (V2V) and vehicles and infrastructure (V2I). In short this communication is called V2X communication. In order to evaluate the potential of new applications, prototype systems need to be deployed in a real traffic environment and analyzed over a long time period. As this is a severe alteration of the traffic system, it is hardly imaginable that local authorities allow such a procedure. However, simulations are a suitable tool to perform the necessary potential analysis.

2 Survey of EV Drivers

Only few studies investigate accidents related to missions of EVs. Müller [8] did his studies based on traffic data from 1994. Since then, no reliable source stated data in comparable quality. One reason might be that accidents involving EVs are not monitored centrally. Potential sources to collect relevant data are emergency vehicle drivers who know about the problems and dangerous situation which occur on missions. Hence, we carry out a systematic survey with EV drivers, aiming to discover critical traffic situations and deduce possible solutions. In the following, we present the survey and an initial analysis. We intent to give a first outline about the answers on selected questions.

The online survey enfolds 252 drivers of police cars, ambulances, and fire trucks. Personnel driving fire trucks comprise drivers within the professional fire brigade and the voluntary fire brigade. The survey starts with sociodemographic questions, continues with statements about “Driving and Situational Awareness” and “Accidents”, and closes with opinions about technical assistance systems.

Within the “Driving and Situational Awareness” section, the drivers have to answer questions concerning their medical condition before starting a mission and the assessment of different situations on their missions. 54 % of EV drivers indicate that pull-outs are routine for them.

However, 55 % admit that a mission means stress and 84 % say they are tensed during the pull-out. For 98 % of the interviewees, safety is more important than celerity. Regarding the different traffic situations, it becomes apparent that drivers categorize intersections as more critical than any other type of street. Moreover, they perceive driving through red traffic lights (96 %) and crossing intersections without traffic lights (80 %) as critical, while only 12 % define straight roads as critical. Blue light and siren gain enough attention to make others aware of the approaching EV according to 59 % of the EV drivers. The 41 % denying this statement mention that other drivers are distracted by media such as mobile phones or the radio. Additionally, the harmonic tone sequence might reduce the perceptibility of the siren.

The section “Accidents” reveals that 35 % of the interviewees already have had an accident. 93 % agree with the sentence “Accidents are caused by the individual traffic”. Moreover, 91 % think that abrupt braking and wrong steering reaction cause accidents. These maneuvers are more critical than not reacting at all according to 79 % of the interviewees. Beyond, 56 % agree that “Accidents are caused by EV drivers”.

The reasons of accidents may be divided into driving too fast near/in the intersection area (92 %) and driving through red lights (91 %). Moreover, they think that accidents mostly occur on the way to the place of assignment (91 %) and not on the way back to the department (13 %).

Concerning the technical assistance systems, we classified two different types: assistance systems for the EV and assistance systems for the IV. For the EV, we asked for the usefulness of a preemption system. For IVs, we wanted to know if additional information or even an automated reaction of IVs may help. The interviewees say that preemption systems can save time (92 %) and reduce the danger of driving through intersections (90 %). This also leads to less stress (75 %). Regarding the IV, we divided systems into three types: warning IV drivers about an approaching EV, advising the drivers on how to react, and an automatically reacting system that may override the drivers. Interviewees categorize that “detailed warning about the approaching EV” (91 %) is useful, 64 % think that “the advice on how to react” helps drivers. 30 % of the EV drivers find a system useful that conducts automated reactions on EVs. Concluding the comment areas of this last application, we can see that automated systems achieve only small acceptance because the drivers apprehend technical difficulties and the lack of robustness. Figure 1 shows the results in short.

Summarizing this initial analysis of the survey, we gather information on what would make missions of EVs safer. We deduce that assistance systems are useful

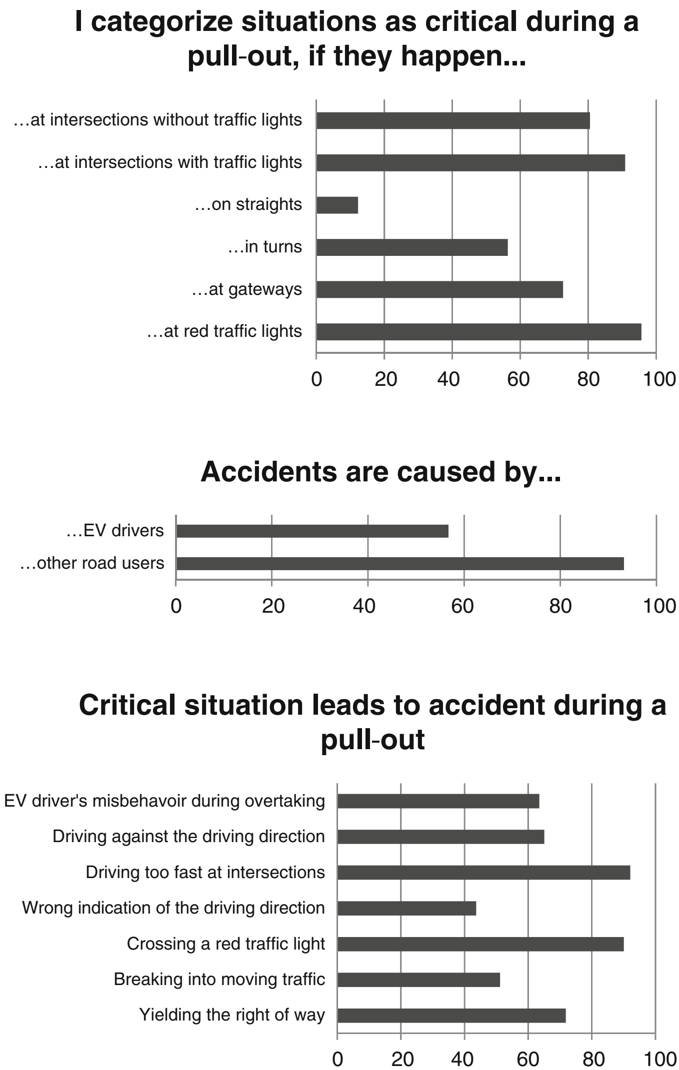


Fig. 1 Excerpt of answers to the EV survey (in percent)

for EV drivers. There is a demand for support at traffic light controlled and blind intersections. Moreover, the EV drivers state that the IV has a major influence and is responsible for hazardous situations. IV drivers could be supported by warning and advice systems. An automated vehicle reaction may also support the IV driver, but, according to the interviewees, such a system is beyond the technical possibilities and not realizable.

3 Problem Statement

An applicable simulation framework allows us to conduct research concerning effects of new applications for EVs on the traffic system. We decided to use the simulation tool Simulation of Urban MObility (SUMO) as its strength is to simulate V2X applications improving traffic efficiency [10]. However, the simulation of special situations—e.g. situations comprising EVs—is not covered. EVs may override general traffic rules. They can drive faster, may drive through red lights, and are allowed to use their siren and light bar to inform others about their arrival and their right of way. Thus, the EV has an effect on the behavior of individual vehicles (IVs). The research community does not agree whether these effects need to be modelled in order to evaluate new applications e.g. preemption systems. Driving through red lights and the behavior of IVs may be neglected because only the difference in travelling time with and without the application is significant [11]. Others argue that by neglecting these effects the potential of new applications may be overestimated [12]. Bieker [13] does not implement a driving through red lights because the EV coincidental arrives during the green phase. According to her, a model needs to be investigated to overcome the red light issue. Additionally, the study implements the behavior of IVs as stopping when an EV is approaching.

The effects mentioned above issue a challenge for SUMO. Within this article, we want to present models enabling SUMO to simulate V2X applications improving traffic efficiency and safety involving EVs and conduct simulations of two applications, namely a preemption and an automated cooperative formation of a rescue lane by IVs. This article is organized as follows. Section 4 describes the simulative environment with all boundary conditions and input parameters. Section 5 explains the different implementations. Section 6 deals with the calibration of the proposed models. Section 7 describes two example applications as well as the simulation. Moreover, it contains the assessment of both the models and applications. Section 8 completes the article by giving a conclusion and outlook.

4 Simulative Environment

Material provided by OpenStreetMap is the basis for the traffic system used in this article. It is shown in Fig. 2 and includes three urban intersections in Braunschweig,[1] Germany. Apart from this realistic traffic system, a real traffic signal timing plan and a collected traffic census data is the basis for an approximated real traffic flow. Figure 3 shows the underlying data of the traffic census. Straight arrows and the corresponding numbers indicate straight traffic whereas angled arrows and corresponding numbers indicate turning traffic (left or right). The percentage share

[1] Intersections from west to east: Rebenring/Pockelsstraße, Rebenring/Hagenring, and Hans-Sommer-Straße/Langer Kamp.

Fig. 2 The simulated traffic system

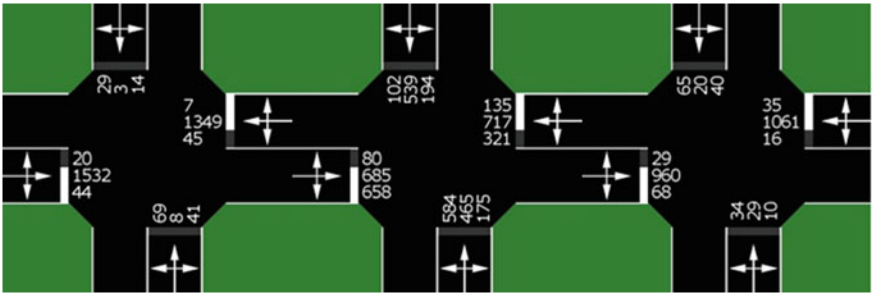


Fig. 3 Collected data of a traffic census at the relevant intersections during the peak hour

of trucks is 3 % with a distribution of semi-trailer trucks (Truck 1) and short trucks (Truck 2) in a ratio of 1:1. The remaining road users are passenger cars divided into three groups in a ratio of 1:2:1 (Car1:Car2:Car3). They differ in vehicle dimensions, maximal speeds, reaction times of the drivers, and driver's attention. Values for type Car 1 are comparable to the vehicles of the A00 segment. Type Car 2 represents the A segment, type Car 3 equals the B segment, and type EV a fire truck. Values for the maximal acceleration and maximal deceleration consider a comfortable acceleration and are not equal to the maximal physical values. Table 1 shows vehicle related parameters and used driver models (minGap, Sigma and Impatience). The table also contains parameters used for the EV.

Table 1 Vehicle parameters and driver behaviors

Type	Max. speed (m/s)	Speed-factor (–)	Max. accel (m/s^2)	Max decel (m/s^2)	Length (m)	minGap (m)	Sigma (–)	Impatience (–)
Car 1	40	0.8	1.9	3.0	3.5	2.00	0.6	0.3
Car 2	50	0.95	2.6	3.5	4.2	1.20	0.8	0.5
Car 3	60	1.0	3.1	4.0	4.7	0.65	0.8	0.8
Truck 1	22	1.0	0.8	3.5	18.4	0.75	0.9	0.7
Truck 2	22	1.0	0.8	3.5	12.4	0.75	0.9	0.5
EV	30	1.2	2.5	7.0	12.4	0.5	1	1

5 Models

5.1 EV Behavior

As stated before, EVs are allowed to override general traffic rules and SUMO is not able to model this necessary behavior with a predefined internal function. Our implementation concerning the EV's behavior considers speeding and the ability to drive through red lights. The usage of a siren and a light bar is not visualized within the simulation. However, their effect on the IV is described in Sect. 5.3.

5.1.1 Speeding

The EV may override speed restrictions by using the implemented speed factor. Table 1 shows the maximum speed of the EV (30 m/s) and the speed factor (1.2). By setting the speed factor to a value greater than 1.0 (=100 %), the related vehicle may drive faster than the speed limit. The speed limit is set to 13.8 m/s (equals 50 km/h), as the traffic system is located in an urban environment. Thus, the EV can drive 16.56 m/s (1.2 * 13.8 m/s ≈ 60 km/h) within the traffic system, as the maximum speed of the EV (30 m/s) is not exceeded.

5.1.2 Drive Through Red Lights

The TraCI (Traffic Control Interface) enables an enhanced alteration of the EV's behavior. Using this interface, the EV may cross an intersection while having a red light. Normally, an EV approaching a red traffic light in the simulation would start to brake in order not to violate traffic rules. Even if no vehicle congests the intersection, the EV will wait until the traffic light switches to green. Figure 4 shows a flowchart of the implemented algorithm which allows an EV to drive through red lights. First, the algorithm determines the speed and the lane of the EV as well as the signal state of the intersection. Additionally, a minimal and maximal speed value is read from a configuration file which allows modeling a realistic approaching behavior (see Sect. 6). Second, it checks whether the EV is in front of an intersection. As a third step, the EV's speed is checked against the minimal speed value and the maximal speed value. If the EV is driving slower than the lower threshold the green signal is held or the red signal is switched to green.

If the EV is driving faster than the upper threshold, the signal is held or switched to red. This leads to an averaged approaching behavior of the EV which can be observed in real situations with EVs approaching intersections. The algorithm is executed every time step in the simulation.

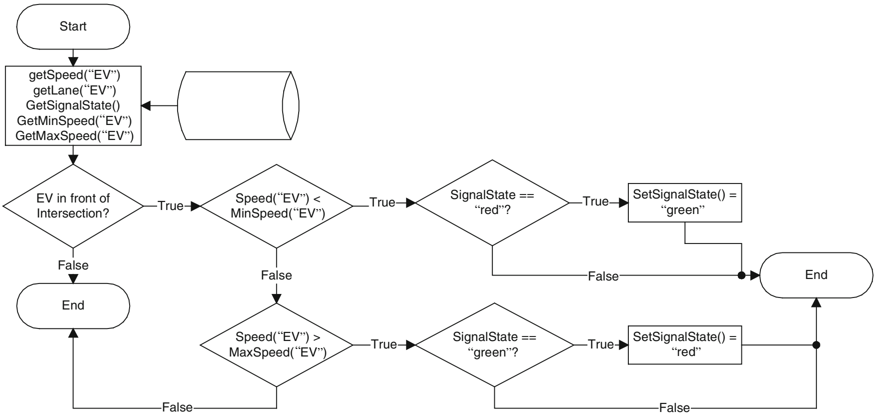


Fig. 4 Flowchart showing one EV model

5.2 *Intelligent Infrastructure*

New applications require a novel type of infrastructure. Characteristics of a new infrastructure, for instance accessibility by special road users, influence the modulation. We propose a model to interact with traffic infrastructure using TraCI and inductive loops. Inductive loops are a trigger to start an application on the infrastructure, e.g. setting a new traffic signal timing plan. The implemented loops only react to vehicles of the type EV. The distance between the loops and the intersection represents the V2X reception radius.

5.3 *IV Behavior*

Road users respond in a certain way when perceiving a siren or blue light. The most favorable way is to respond in a cooperative manner as discussed in [14]. One possibility to behave cooperatively is described in the Road Traffic Regulations [15] as creating a rescue lane in order to let the EV drive through the congested area quickly. A method to implement such a behavior is presented hereinafter. An example situation clarifies the functional principle of the method.

Figure 5 (top) shows a oneway road with three lanes. Ten vehicles drive on that road as an EV approaches on the middle lane from behind. In this example, the method clears the middle lane by forcing the obstructing vehicles to change the lane. It induces a lane change maneuver by using the SUMO internal ChangeLane ()-function based on the SUMO vehicle dynamics. Figure 5 (middle) shows the turn signals indicating a lane change of the obstructing vehicles. The direction of the lane change may be parameterized according to the vehicles' destinations. Figure 5 (bottom) shows the final rescue lane. The flowchart in Fig. 6 shows the algorithm.

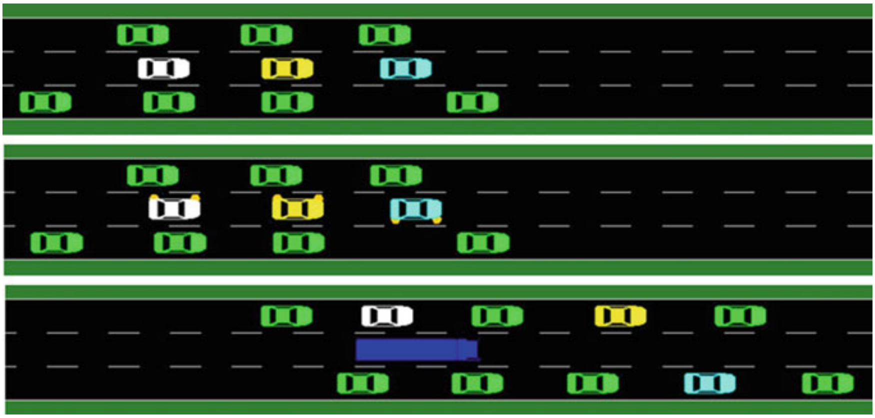


Fig. 5 Example situation for the IV behavior

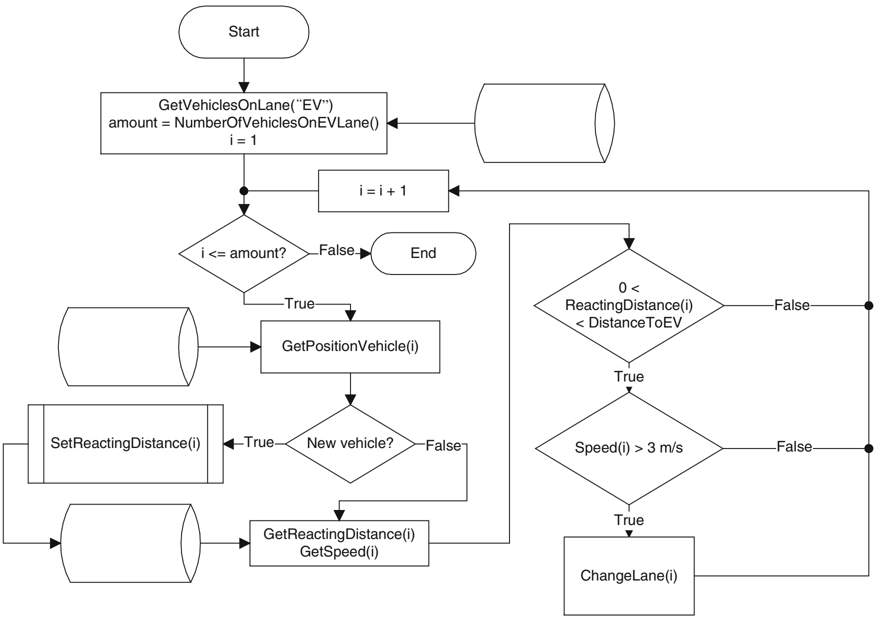


Fig. 6 Flowchart showing the model "IV behavior"

The algorithm determines the number of vehicles on the EV's lane (amount) and their identification number. After that, a procedure checks each vehicle. First, it determines the speed of the vehicle. Afterwards, a check clarifies if the vehicle entered the EV lane within the last simulation step. If so, a reacting distance is calculated in which the vehicle reacts on the EV's presence (see Sect. 6 for the sub function). If not, the old values are used. The algorithm calculates the distance between the vehicle and the EV. The calculated distance to the EV needs to be lower than the reacting distance and the vehicles speed needs to be higher than a certain value. This procedure is repeated for each vehicle and each time step in the simulation. In the following, two different settings will be presented: IV behavior a and IV behavior b. Both IV behavior models have a threshold of 5 m/s for the vehicle's speed to induce a lane change.

5.3.1 Behavior a

The algorithm induces a lane change without taking the route of the vehicles into account. It may be possible that a vehicle is not able to reach its destination, because the algorithm forces it to change the lane to an undesired one. This behavior is the base for the investigations in [16].

5.3.2 Behavior b

This model takes the route of the vehicles into account. That may lead to longer travelling times caused by obstructing vehicles but has the advantage that every vehicle is able to reach its destination.

6 Calibration

The calibration of the models implementing EV and IV behavior aims to resemble a realistic behavior. Therefore, different methods are conceivable. For instance, assessments of traffic census comprising missions of EVs indicate the effect on the EV's travelling time. Using this data, it is possible to estimate an average time loss. We forego using such a method. First, a traffic census in required dimensions involving EVs does not exist. Second, and more important, an average time loss may not be representative to the scene and ineligible to calibrate the models in required detail. Some intersections and urban roads may cause only little time loss whereas others are a major issue for EV's travelling time. That is why we focus on a real data analysis using videos at congested urban roads and intersections. The videos reveal the behavior and retarding effects in real situations. This analysis gives several example situations to adjust parameters of the models.

Buchenscheit et al. [17] assessed videos to gain insights of interactions between EVs and IV. They mounted a camera on the dashboard of an EV and recorded 21 typical emergency response trips with a total length of 147 min. They came to the conclusion that dangerous and/or retarding factors can be condensed to a late perception of the approaching emergency vehicle and a non-optimal switching of traffic lights. Red traffic lights, which occur in 50 % of the trips, cause a delay of 15–30 s each. Moreover, on average 2.5 drivers are misbehaving which leads to a loss of 1 min in average for each trip. As we want to calibrate the proposed models, we need a more detailed analysis. However, we seize the idea of assessing recorded EV missions. Because data protection laws require a certain protection for people, we decide to assess already declassified videos available of different rescue services in Germany. The selection of video files is based on the following factors:

- The regional rescue service declassified a couple of videos (not only a few). This reduces the risk of extracting unique environmental/traffic impacts and come to flawed conclusions.
- The database comprises different videos of different rescue services. This reduces the risk of adjusting the models according to a regional instruction of EV drivers.
- The videos do not include exceptional situations (e.g. missions during natural disasters, educational films).

The video database consists of urban and suburban/rural missions. Necessary parameters such as distances between road users and speeds are either recorded or estimated. The overall length of the video material is 90 min with 116 traffic light controlled intersections and a variety of numbers and composition of vehicles and environments. Concerning the traffic lights, the traffic light was red 56 times at the moment of passing whereas it was green in 60 instances. This indicates that the EVs had red in 48 % of the times an EV passes a traffic light controlled intersection. Although the EV drivers reduced their speed in these instances dramatically (on average 20 km/h), crossing IVs almost leads to accidents in two instances. Additionally, 36 instances showed heedless behavior of IV which leads to critical situations caused by wrong perception of the situation. Concerning the analysis of distance for the noticeable first reaction regarding the EV, the reacting distance is divided into the three clusters: “50 m and more”, “50–20 m”, and “20 m and less”. Depending on the environment and the perception of the EV’s presence, approximately 25 % of the IVs react in a distance of 50 m and more. Around 50 % of the IV’s drivers react in a distance between 50 and 20 m, whereas 25 % of the drivers react in a distance of 20 m and less. However, the time to form a rescue lane is strongly depended on the traffic density. This is why the model is adjusted concerning the distance for first reaction and not the time for successfully creating a rescue lane. With this analysis, the models can be calibrated. The average speed for the EV crossing an intersection while having a red light is about 20 km/h. Hence, the upper speed limit is set to 7 m/s whereas the lower speed limit is set to 4 m/s (see Fig. 4). Thus, the average speed equals 5.5 m/s (=19.8 km/h).

The IV reaction model is calibrated according to the estimated values which are used as shown in the flowchart in Fig. 6. The discovered distribution over the obtained reacting distances is modelled by a random, uniformly distributed float generator. Figure 7 shows the IV reaction model.

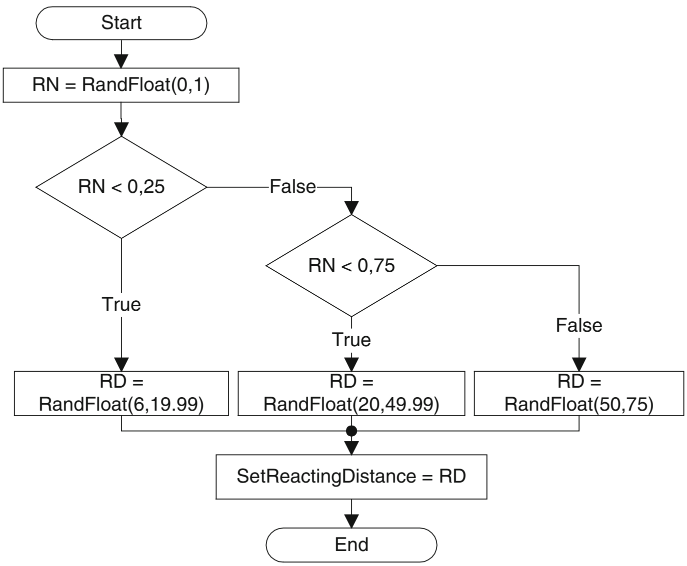


Fig. 7 Flowchart to calibrate the IV behavior model (SetReactingDistance)

7 Simulation of the Models and V2X-Applications

We present an intelligent traffic infrastructure and near realistic behavior of IVs and an EV to enable tests of different V2X applications related to EVs. We conduct a simulation with the normal SUMO models and a simulation with the proposed models to show differences. Afterwards, we conduct simulations for two applications: a preemption system and an automated formation of a rescue lane. The next subsections describe the applications, the simulation procedure, and their assessment.

7.1 Preemption

A preemption is a technical system that enables an EV to register its arrival at a traffic light regulated intersection. A special infrastructure at the intersection runs the necessary application. This application switches to a special phase program that allows the EV to pass while having green. The principle is shown in Fig. 8. The algorithm determines if an EV preemption program is active. If not, it checks for a request at the starting induction loop, which represents the V2I reception distance. When an EV triggers the loop, the signal program and signal phase is determined. Depending on the current program and phase, the algorithm chooses a suitable, German Guidelines for Traffic Signals (RiLSA) [18] conform, predefined EV preemption program and starts a timer. If the EV preemption is active, the algorithm

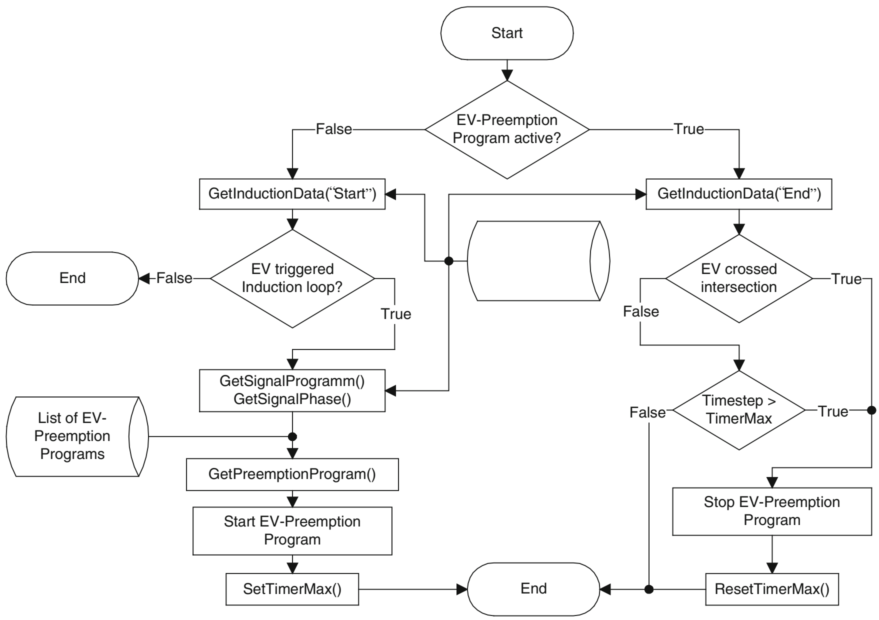


Fig. 8 Flowchart of the traffic light preemption

checks whether the EV triggered the ending induction loop or the maximal time-span has expired. There are two factors that influence the success of the preemption system.

First, the moment of registration at the infrastructure influences the possibilities to switch the signal phase according to the RiLSA.[2] Second, the communication distance depending on the intersection's topology and environmental message signal attenuation. In general, there are two initial states when the preemption request is sent: the EV's traffic light shows green or yellow/red. When having green, the green light may be held as long as the other directions do not have a red light for more than 3 min. When the traffic light is yellow or red, the phase program is shifted to a special phase program at the next possible moment. This also leads to the maximum requirement for the communication distance. When the EV is having a red light, under certain circumstances, the RiLSA standards require a secure time to shift the phase program. The distance between registration and the intersection must be great enough to allow the EV driving as fast as possible while the phase shift takes place. In this article, the communication distance for the intersections is (west to east) 165 m, 450 m, and 165 m. The goal of a preemption is to reduce the travelling time of the EV in an urban environment. Moreover, the safety of the EV and IVs may be enhanced while minimizing the adverse impact on IVs.

[2] By observing the guidelines, our method does consider pedestrians implicitly.

7.2 Automated Formation of a Rescue Lane

The second application is a system that supports drivers to automatically form a rescue lane. By doing so, it makes the vehicles behavior cooperatively according to an operationalization of cooperative behavior as shown in [14]. Applying the aforementioned concept of cooperative behavior, both the EV and the IV require a cost function. In this elementary assessment, the EV wants to pass through this area as quickly as possible, meaning that the cost increases when the travelling time increases. The IV wants to let the EV pass by, which results in a cost function that also increases when the EV has to wait longer. This means that every reaction of the IV improving the travelling time of the EV is a cooperative behavior. A conceptual system assisting drivers forming a rescue lane by proving additional information can be found in the literature [17]. Depending on the characteristic of the system, it gives additional information and thus assists the driver, gives direct advices, or induces maneuvers itself. V2X communication enables sharing necessary information. The information itself needs to meet two requirements: First, the obstructing vehicles know that they are blocking the EV and get helpful information on how to solve that issue. Second, the information needs to be consistent among different IVs. A cooperative coordination among IVs can be obtained by using different methods. In this application, a rule based approach is employed. Figure 6 shows the implemented algorithm to model IV behavior. The automated formation of a rescue lane is based on this flowchart, but the SetReactionDistance function of Fig. 7 is substituted by a constant value of 150 m. The threshold for inducing the ChangeLane() command is set to 10 m/s. The application obeys the route and the destination of the vehicles. It has one master and several slaves. The master with the implemented rules runs on the EV, determining what the IVs have to do. The slave instances run on the IVs which send ego information such as own lane and own position to the master. Additionally, it is assumed that the slaves execute the commands sent by the master without sending an acknowledgement.

7.3 Simulation Procedure

The simulation procedure describes the configuration of executed simulations. Table 2 shows employed models and applications for different runs of the simulation.

The simulation runs for 500 s without modification. After that, the EV enters the simulation and drives through the traffic system on a designated route. It always uses the most right lane possible to reach its destination. In contrast, the IVs starting on an edge with multiple lanes use a randomized departing lane.

The moment the EV enters the simulation is varied from the 500th s in steps of 1 s to the 585th s. The timespan of 85 s matches the timespan of one phase shift for all three intersections. Each test is performed 50 times to take randomized effects

Table 2 Setup of the different tests

No	Speeding	Driving through red lights	IV reaction	Preemption	Autom. rescue lane
M1	X				
M2 (b)	X	X	X		
A1	X	X	X	X	
A2	X			X	
A3	X	X	X		X
A4	X	X	X	X	X

into account and ends when the EV reaches a specific point at the end of the simulation. Models are implemented as discussed in Sect. 5. The two applications are employed as shown in Sects. 7.1 and 7.2. The first test has only the speeding model activated to show the travelling time of an EV as implemented in SUMO. The second test includes the proposed models to show the difference in travelling time.

The assessment of simulations enables to decide for a realistic reference. This reference serves to measure the effectiveness of the applications which are simulated and evaluated.

Test A1 includes the first application, which is a traffic light preemption system. Test A2 shows the effects on the travelling time when the models driving through red lights and IV reaction are not activated. The last two tests include the other application, the automated formation of a rescue lane. Test A3 simulates the application alone whereas Test A4 includes both applications. The figures in the following assessment have the following properties: The x-axis denotes the introduction second in which the EV entered the simulation whereas the y-axis indicates the travelling time of the EV through the traffic system. The gray area marks the range of values obtained during the 50 simulations. The dashed line represents the median of travelling times in order to classify the resulting range of the travelling time. The solid line is a trendline to illustrate the general course of the travelling times over the introduction second.

7.4 Assessment of Models

Figure 9 shows the travelling time of the EV within Test M1. The EV behaves like a normal road user, as none of the models is activated. The travelling time is not constant over the introduction second. This variance is caused by a randomized starting lane and behavior of IVs. This leads to direct interference (e.g. changing the lane very late) and indirect interference (e.g. that the EV is slowed down so that it does not arrive within the green phase at the next traffic light). At small introduction seconds, the first traffic light is red and switches to green. This leads to a delay of

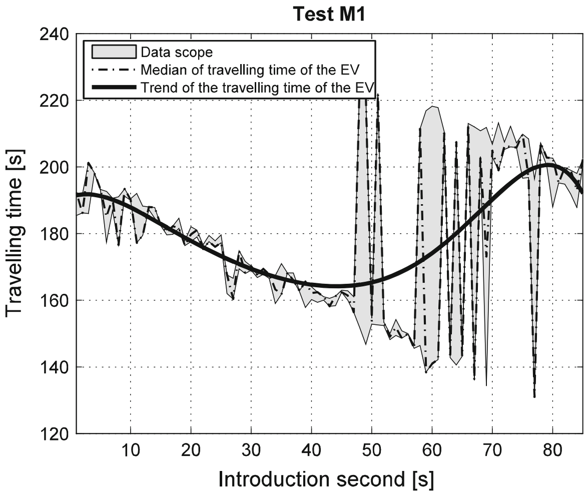


Fig. 9 Travelling time in Test M1

the EV due to waiting vehicles and causes a travelling time around 190 s. These vehicles have more time to start with increasing introduction time of the EV. Around introduction second 43, a green wave is established with a travelling time of around 165 s. After that introduction second, the travelling time is increasing and has its maximum value (about 200 s) around introduction second 78. Considering the data scope, noticeable differences around introduction second 50, 60, and 70 can be observed. These introduction seconds are mainly affected by waiting vehicles as the green wave breaks down and the EV has to wait for one complete cycle to cross at least one of the intersections.

Figure 10 shows Test M2 with all three models activated. It shows that the travelling time depends on the introduction second. Moreover, there are different

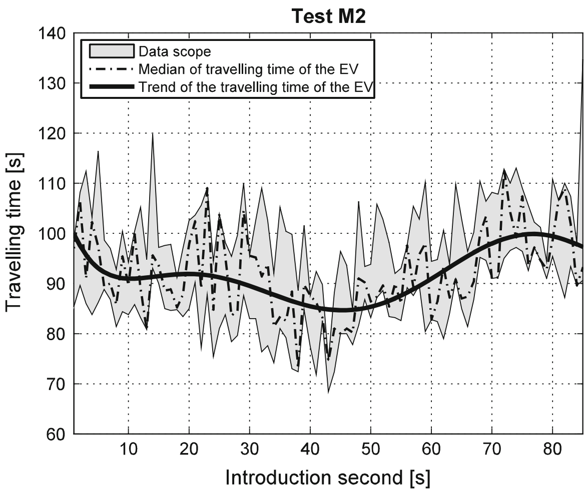


Fig. 10 Travelling time in Test M2

values for one introduction second. This distribution of values is also caused by randomized behavior of IVs. The trendline reveals four distinct areas that can be interpreted as follows. At introduction second 8 and a travelling time around 100 s, the EV approaches the first intersection while having a green light. The vehicles in line are already moving and are slowly clearing the path. In comparison with introduction seconds smaller than 8, the EV is approaching in an advantageous moment, because the waiting vehicles have more time to start. The second traffic light is red and some vehicles are waiting in line. If trucks are waiting on the EV's lane, the travelling time is severely affected (as indicated by the gray area). In introduction second 8, the vehicles waiting in front of the second traffic light can clear the lane quick enough so that the EV reaches the third traffic light at green.

However, around introduction second 23, the IV interferes with the movements of the EV in a way that it reaches the third traffic light while having red. This explains the local maximum of about 90 s around introduction second 23. The global minimum of 85 s around introduction second 43 can be explained as the optimal entrance second to catch the green wave. This introduction second is barely influenced by variations of IV behavior as the data scope is relatively small. Vehicles which are located at the intersections may start early enough to clear the route when the EV arrives. After that introduction second, the green wave gets interrupted easily by obstructing vehicles. Considering the median graph, introduction seconds 23, 28, 72, 75 and 82 have relatively high travelling times (about 100 s) for the EV. At least one traffic light is red with waiting and obstructing vehicles. This leads to an additional delay for the EV as a following traffic light also might change to red.

The comparison of the two simulations Test M1 and Test M2 shows that the travelling time of the EV is reduced by half by using the EV and IV models. Using the first simulation results as a reference, applications improving the EV's travelling time would be overestimated as the behavior of the IV and EV is neglected. Additionally, the peaks at introduction seconds 50, 60 and 70 can be considerably reduced. This is mainly caused by the EV model that allows the EV to drive through red lights. Therefore, it does not have to wait for one cycle in order to pass the intersection. That suggests using Test M2 as a reference estimating the potential of EV applications.

However, the following analysis compares the results of the two different IV behaviors, namely behavior a and behavior b (see Sect. 5.3). Figure 11 shows the results of IV behavior b. Remember the difference of IV behavior a and IV behavior b which is that within IV behavior a the vehicles clear the lane at any cost whereas IV behavior b takes the designated route into account. The results of Test M2b show that the course of the trendline fits the results of Test M2a with an offset of about 15 s. Moreover, the data scope is also greater which indicates a wider range of possible obstructions for the EV.

However, studying the different behavior models with the SUMO internal GUI yields arguments for IV behavior b: Vehicles that clear the lane at all costs can not follow their desired route and end up in a wrong lane obstruct succeeding traffic.

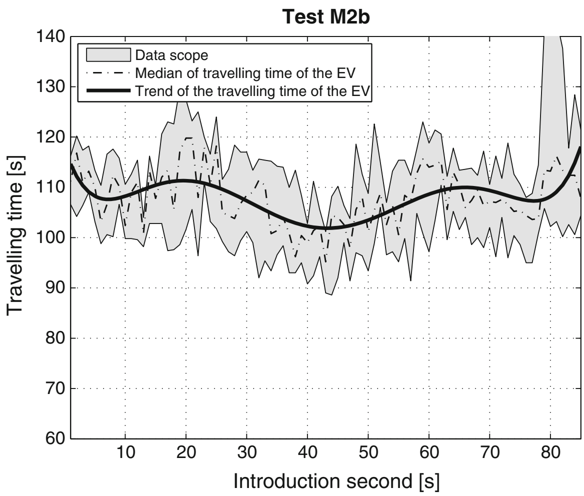


Fig. 11 Travelling time in Test M2b

This leads to situations in which vehicles end in a turning lane waiting to go straight which is not possible by settings. Finally, these vehicles are teleported after a period of 3 min. This situation does not occur in IV behavior b, because vehicles are only clearing the lane if they are still able to follow their route. This seems to be a more realistic behavior of the traffic systems. Consequently, the simulations use IV behavior b for further investigations and the results of Test M2b as a reference for estimating the potential of EV applications.

7.5 Assessment of Applications

The assessment is divided into two parts: Firstly, an analysis of the travelling time and the distribution of travelling times over the signal phase time takes place. Secondly, speed profiles of the EV give some indication about the usefulness of the two applications.

7.5.1 Travelling Time and Their Distribution

Figure 12 shows the travelling time over the introduction second for Test A1. The course of the trendline drops from a value of around 95 s at introduction second 1 to a minimum of 82 s around introduction second 35. Afterwards, it rises to a travelling time around 105 s at introduction second 78. Then it decreases again. The maximum at small introduction seconds can be explained by the late preemption at the first traffic light. The congested intersection cannot be cleared in time so that the EV has to wait. Between introduction seconds 15–45, the preemption comes in time

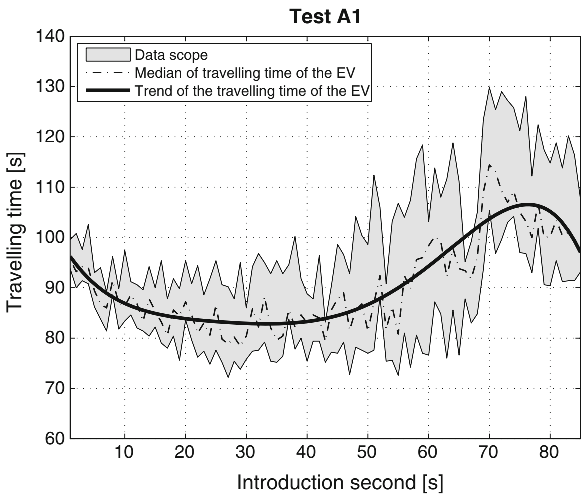


Fig. 12 Travelling time in Test A1

to either hold the green phase or change the red/yellow traffic light to green. The variances are caused by IVs randomly merging into the EVs lane. Taking median values into account, introduction seconds 26, 28, 43, 53, and 55 are advantageous moments for the preemption so that the travelling time is less than 83 s. Introduction second 65 shows that the randomized IV behavior does not necessarily have an effect of the EV's travelling time as the maximum and minimum values of the 50 runs are in a range of 2 s.

Overall, the travelling time can be reduced by using a traffic light preemption system. The trendline indicates that the EV is faster for all introduction seconds compared to results of Test M2b. The difference in travelling time is about 15 s for all introduction seconds except for a range of 15 s from introduction second 65 up to introduction second 80 in which the difference is smaller. During these introduction seconds, the preemption system for all three traffic lights needs to be triggered. The queue of vehicles obstructs the EV three times. This leads to the insight that a more detailed calibration of the traffic light preemption should take place. Analyzing the influences of parameters such as the distance between the induction loops and the intersections, congestion in front of the intersection, and the speed of participants will help to adjust a better system behavior. This study is out of scope of this contribution but will be addressed in further work.

The travelling time of Test A2 is represented by the graph in Fig. 13. The gray area is not very distinct as the IV behavior and the drive through red lights models are deactivated. From this point of view, it is comparable to Test M1. The course of the trendline starts at a travelling time of about 95 s, then declines to a minimum around 80 s at introduction second 36 and eventually rises to a maximum of 105 s around introduction second 75.

For small introduction seconds, the EV encounters delays by obstructing vehicles at the first intersection. However, for later introduction seconds, the vehicles

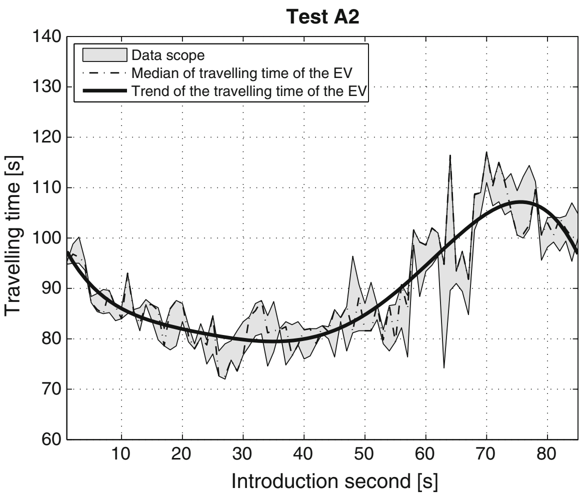


Fig. 13 Travelling time in Test A2

have more time to start. Moreover, the preemption shows its efficiency by holding the green phase at the first intersection. After a minimum around introduction second 35, the EV reaches the first traffic light while it changes to red. The preemption takes some time and does not switch to green fast enough which causes the EV to slow down. As none of the two models IV reaction and drive through red light is active, IVs do not clear the lane while waiting at a red traffic light to let the EV drive through. Additionally, they stay in the EV's lane and obstruct its mission until they voluntary change the lane or turn at an intersection. The maxima at introduction seconds 64 and 68–79 are caused by this effect at one and/or multiple intersections.

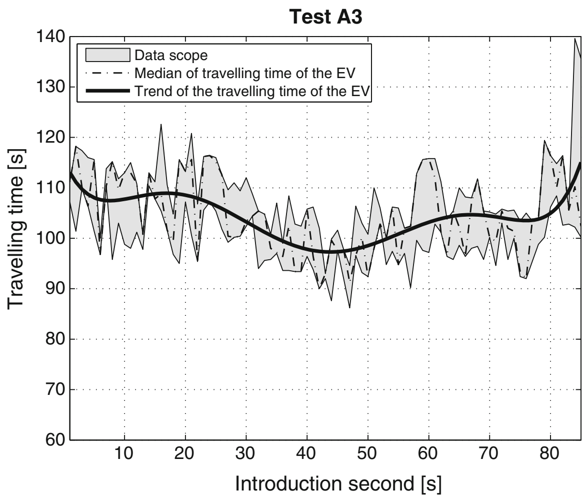
The results indicate that the travelling time is dramatically reduced compared to Test M1. The difference to Test M2b is much smaller. This indicates that studies comparing a preemption system to a reference situation without considering IV reaction and the EV behavior vastly overestimate the potential of a preemption system.

Comparing the results of Test A1 and Test A2 shows that the data scope of Test A2 is much smaller. The trendline of Test A2 drops below a travelling time of 80 s whereas the trendline of Test A1 has its minimum around a travelling time of 83 s. Except for this range around the minimum, the travelling times of Test A1 are slightly smaller. This shows that the IV behavior models have only little effect on the travelling time when the preemption system is activated.

Figure 14 shows the travelling time with the second application, namely the automated formation of a rescue lane. Taking a look at the trendline, the graph drops until introduction second 8, then increases until introduction second 18, declines until second 43, rises until second 85 with a local minimum at second 75.

Starting from introduction second 1 to 8, the first traffic light switches to green, and vehicles have more time to start and clear the lane for the EV. On the EV's

Fig. 14 Travelling time in Test A3



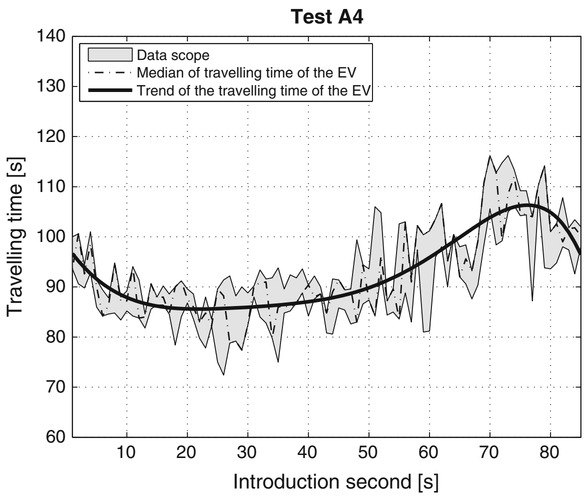
route between the first and the second traffic light, the vehicles clear the lane for the EV if this corresponds with their route. Results of vehicles clearing the lane despite their routes can be found in [16].

The travelling time starts around 112 s and decreases to a minimum around introduction second 43 with a travelling time of 97 s. Afterwards it rises until a travelling time of 115 s for introduction second 85. The course of the graph is very alike compared to the results of Test M2b. However, the data scope is smaller in tests with the application running. This means that the 50 simulations for one introduction second lead to similar results.

The application may support the EV in reaching its destination in a more deterministic manner. The main issue, the waiting vehicles that obstruct the EV's route, cannot clear the lane because of the small speeds. This simple approach with fixed distances and fixed speed thresholds shows that the application does not decrease the performance. However, additional potential may be addressed by smart rules. For instance, the IV can be forced to slow down to reach their individual goals after the EV drove away. Additionally, the lane change of other vehicles to the EV's lane should be prohibited. Even if the vehicle tries to immediately leave the EV's lane after it changed to it, the EV still needs to slow down.

Figure 15 shows the travelling time of the EV in Test A4. The trendline declines from a travelling time of 95 s at the first introduction second to a local minimum of 85 s at introduction second 20. After that, the trendline rises to a maximum of 105 s around introduction second 78 and then declines to 95 s of travelling time at introduction second 85. At small introduction seconds, the two applications cannot clear the path for the EV effectively which leads to delays. With rising introduction seconds, the effectiveness of the applications rises, because the obstructing vehicles have enough time to start and afterwards clear the lane. After introduction second 13, the first traffic light is green and the IVs have enough time to start without

Fig. 15 Travelling time in Test A4



obstructing the EV. The introduction seconds between 15 and 40 are advantageous for the EV, because green phases may be held by the preemption system and the intersections are too short to make the vehicles disappear, especially at the first and the third intersection.

Comparing these results to the reference Test M2b shows that the two applications are advantageous for the travelling time of the EV. Around introduction second 78, the travelling times for both tests are very similar. The relatively high values for Test A4 originate from obstructing vehicles in front of the third intersection. The preemption system switches the traffic light of the second intersection in time with the third intersection still having red. The vehicles approach the third intersection, slow down, and eventually have to stop again. Thus, the EV needs to decelerate as well, because the triggering point for the preemption of the third intersection is located too near to the intersection. So, the vehicles do not have enough time to clear the path.

Comparing Test A1 and Test A4, it becomes apparent that the trend lines are more or less identical with a much smaller data scope for Test A4. This means that the formation of the rescue lane leads to a more predictable travelling time for an EV in this traffic system. A combination of a traffic light preemption system and an automated formation of a lane change integrates the advantages of both systems to support the EV reaching its destination as fast and predictable as possible.

7.5.2 EV's Speed Profiles

Speed profiles enable statements about the trip of the considered vehicle. Deviations in the velocity profiles may lead to losses in comfort and safety. Strong gradients in the velocity express emergency stops which may be used to describe safety critical states. Especially braking needs a reaction of the adjacent traffic—thereby every braking situation is a potential danger.

The following figures express the results of three different tests: Test M2b, Test A1, and Test A4. The plots underlie the starting parameter (introduction second 18 for the EV) in which the travelling time does neither reach a maximum nor a minimum. Also the data scope has an average variation for this introduction second. Figures 16, 17 and 18 show the diagrams of the three difference applications. Within these plots, the x-axis denotes the travelling time in seconds while the y-axis denotes the velocity in m/s. Each plot contains 25 speed profiles of the EV. If the speed profiles are equal, they cannot be distinguished in the plot.

Fig. 16 EV in Test M2b

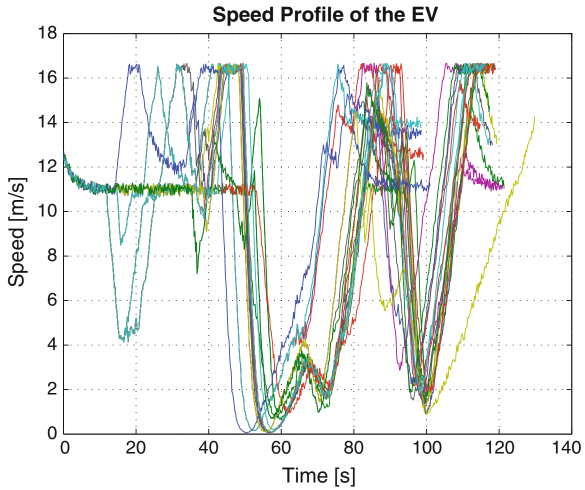


Fig. 17 EV in Test A1

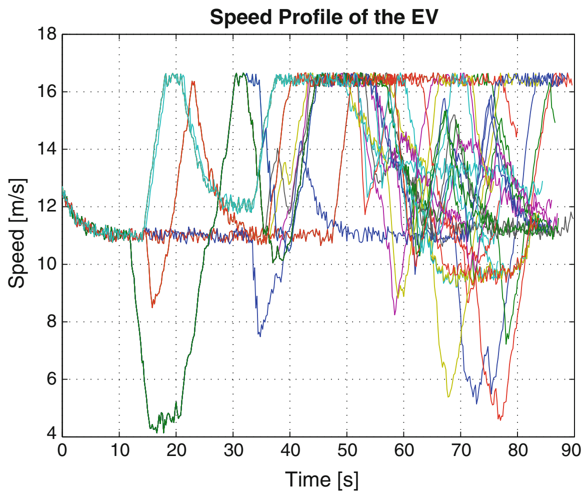


Fig. 18 EV in Test A4

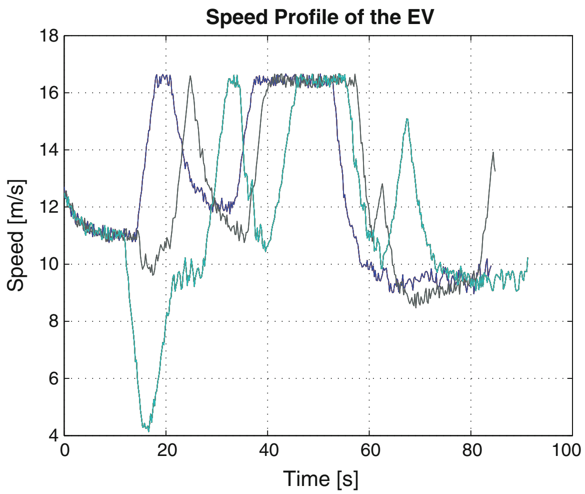


Figure 16 represents the reference behavior Test M2b. The speed profiles' trends are similar until second 12. During this time the EV is on its way to the first traffic light and not influenced by the IV. It only has to brake for slowly driving vehicles in front of it. After this period, distinctions become apparent caused by two stochastic effects: The first one makes vehicles use random lanes if they enter the simulation on a multi-lane road. As three different types of cars and two types of trucks exist, this leads to a variety in, e.g. the starting behavior and the maximum velocity. The dissolution to traffic jams is also influenced by this fact. The second effect deals with a randomized reacting distance model which allocates a reacting distance to each vehicle which is in the EV's way. The algorithm calculates the distance randomly in each run of the simulation. This leads to a different behavior of the IV which is still within the constraints and boundary conditions of the acquired IV model. As a consequence, the EV may reach the traffic light while having a green phase or a red phase. From second 50 to 80, the graphs show an approximated comparable trend. During that time span, the EV comes to a stop at the second traffic light and makes use of the "driving through red lights" model which leads to the W-shaped course of the graphs. After that, the courses of the graphs differ caused by the EV's arrival time at the traffic light. Except the short plateau in the beginning of the simulations, there is no continuous trend in the graphs. Rather, there is a temporal permanent braking, which is followed by acceleration to the maximum speed which cannot be kept for a longer time. This leads to the conclusion that the trends are neither comfortable nor time efficient in Test M2b.

Figure 17 shows the graph for Test A1. The graphs start around 12 m/s and drop until 11 m/s. Except for some outliers, the speed does not drop below 10 m/s for the entire simulation. In contrast, a plateau at a relatively high speed (16.56 m/s) emerges. Some graphs drop to low values. That is caused by a late preemption and thus a need for the driving through red light model at the third traffic light. Overall, there is less variance in the velocity profiles.

Comparing Fig. 17 with Fig. 16, it attracts attention that the second diagram has a plateau until second 40, which is visible in the first diagram, too. However, the second diagram has only few outliers. There is no distinctive minimum (W-shape) of the velocity between 60 and 100 s. Moreover, Fig. 17 shows a higher level of maximal speed than visible in Fig. 16. This leads to a reduction in travelling time by 20 to 30 s.

Figure 18 shows the speed profiles of Test A4. The speed profiles start around 12 m/s, drop until 11 m/s at 15 s. After that, three distinctive courses of the graphs can be observed. Two of those have in common that they drop and afterwards rise to the maximum of 16.56 m/s. The third graph rises to the maximum and decreases afterwards to rise to the same plateau with some delay. Together, they develop a plateau for about 20 s, and drop below 10 m/s. This speed is also the speed at the end of simulation after between 85 and 95 s.

Comparing these results with Figs. 17 and 16, the reduced variety of graphs attracts attention. The application formation of a rescue lane assigns a higher and consistent reacting distance to the IV. As planned by the algorithm the behavior gets more deterministic. The randomized entering lane and different vehicles types remain as variation parameter and lead to the derivations. The travelling time and speed profile gets more predictable by using both applications.

7.5.3 IVs' Speed Profiles

While the models and applications have an effect on the EV, there should also be an effect on the IVs. Two different crossing vehicles represent the IVs in conflict situations with the EV. The first vehicle profits whereas the second vehicle is impaired by the EV applications. The assessment is based on speed profiles, too. The measurement of the speed profile begins when the EV enters the simulation and ends when either the EV or the considered IV leaves the simulation.

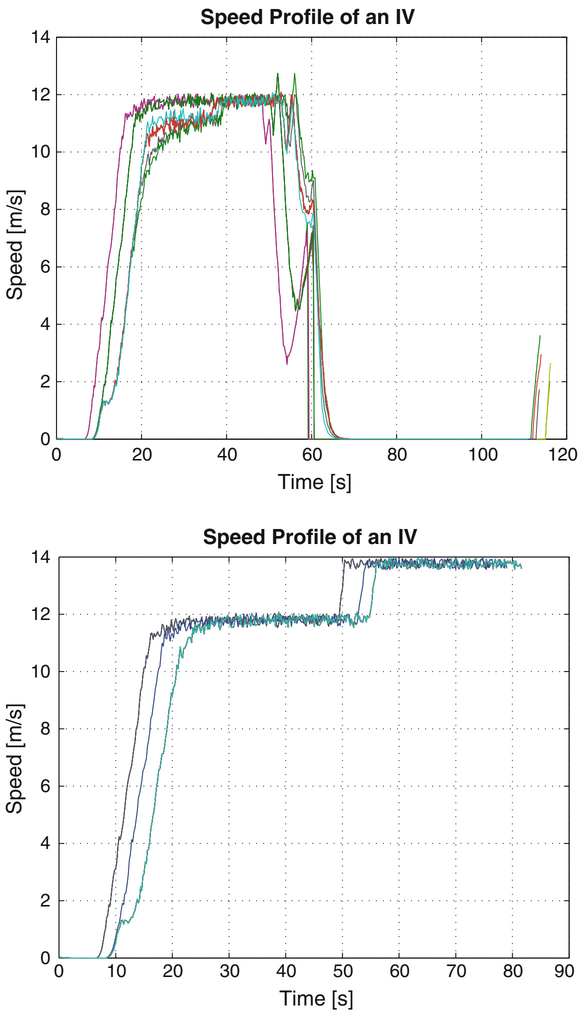
The two plots in Fig. 19 describe the vehicle that profits from the applications and Fig. 20 shows a vehicle getting delayed by the applications. The two plots in both figures show speed profiles during Test M2b (top) and Test A4 (bottom).

Each diagram contains 25 graphs. Some graphs may be hidden behind a graph of an identical simulation result.

In Fig. 19 it becomes apparent, that until second 50 both diagrams have nearly the same course. Due to the EV's driving through red lights model, the IV has to stop and wait until second 110 in Test M2. In Test A4 the preemption speeds up the EV, so that it is not relevant for the specific IV. Hence, the IV is able to cross the intersection without obstruction. The IV drives faster and is not forced to stop by the applications. Thus, it reaches its destination after around 80 s.

The considered vehicle of Fig. 20 loses time with applications activated. The first 20 s of the diagrams are comparable. Afterwards the vehicle comes to a stop in

Fig. 19 IV profits by the applications



both cases. In the upper diagram the IV is not obstructed by the EV at all. It only has to wait for the normal red phase and continues its route after the traffic light switches to green again.

In the lower diagram, the EV is preempted just in the moment before the IVs traffic light switches to green. Thus, the IV's red phase is extended and the IV has to wait for a longer period of time. Before the IV's traffic light switches to green again, the simulation ends because the EV reaches its destination.

As a brief conclusion, we can say that there are vehicles and situation which profit from the applications. Vice versa, the application may increase waiting times of IVs. Further work analyzes the effects and uses the obtained insights to develop an advanced cooperative system behavior.

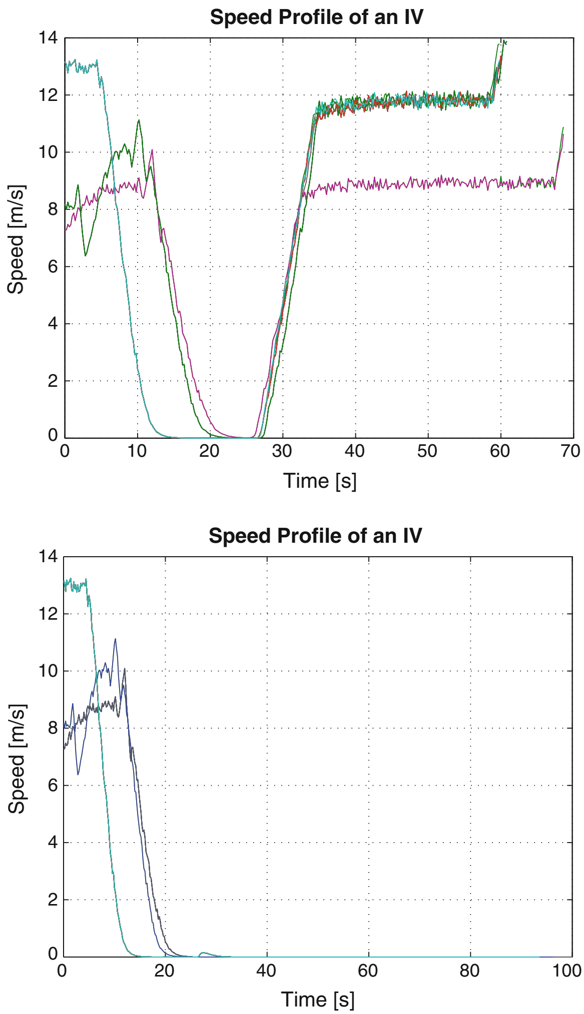


Fig. 20 IV needs to wait because of the applications

8 Conclusion and Outlook

Within this article, we showed that emergency vehicles (EVs) encounter a higher risk of getting involved in accidents during their missions. For supporting EVs, new applications may be developed and tested with the issue that such prototypes cannot be tested in real life traffic systems. Simulations however, are a suitable tool to do so. We decided to use SUMO as it is applicable to simulate V2X applications improving traffic efficiency. Yet, SUMO does not feature necessary models such as a realistic EV behavior, enhanced infrastructure, and realistic individual vehicle (IV) behavior responding to EVs. In addition, the research community disagrees whether these effects have to be modelled to assess applications regarding EVs. We created a traffic system based on a real traffic system in Braunschweig, Germany. The traffic flow within this traffic system was based on traffic census data during peak hour. We presented models regarding the road users EV and IV and the infrastructure. The EV model implements speeding and driving through red lights. The infrastructure model consists of an interface for access by special road users (in this case EVs) to initiate infrastructure based applications. The IV model implements a response behavior to the EV. A calibration of these models took place. We showed that a realistic reference scenario is needed to not overestimate the potential of new applications.

We created, conducted, and evaluated a survey with 252 EV drivers to deduce supportive applications. We simulated two applications: a traffic light preemption system via V2I and an automated formation of a rescue lane via V2X. By assessing the results of the simulations, we showed that neglecting aspects of EV or IV behavior leads to different travelling times of the EVs. Concerning the applications it can be stated that a preemption system reduces the travelling time of the EV compared to a reference travelling time. The automated formation of a rescue lane does not necessarily reduce the travelling time as it does not accelerate the queuing vehicles. However, a combination of both applications has the potential to support an EV on its mission best by allowing the EV to pass through congested and traffic light controlled urban environments quickly and predictable.

As the field of simulating EVs in urban environments is very important but only little investigated, further work needs to be done. As shown, realistic models are necessary to estimate the potential of EV applications. Hence, a wider calibration and validation for the proposed models may take place, e.g. by driver studies or suitable traffic data. We also want to investigate additional aspects that are not yet covered by our models. Some areas to mention are: realistic delays in road users' starting behavior (e.g. shown in [19]), IV behavior receiving multiple requests of EVs to form a rescue lane, occurrences of critical situations while forming a lane, and misbehavior and the consequences for the travelling time. Concerning the two applications, further research needs to be conducted as well. For the preemption system, a study concerning parameters such as communication distance, phase program, and communication requirements and their effect on the travelling time is necessary. The automated formation of a rescue lane needs to be further investigated, too. Challenges regarding penetration rate, communication requirements, and security need to be addressed as well as more enhanced methods to determine intelligent cooperative maneuver combinations for the IVs. We showed that even by enhancing the concept of static rules, a fairly good result can be obtained. However, instead of using static rules, other maneuver planning methods may calculate better behaviors of IVs by considering additional information.

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