Impact of ICT on Emergency Response Vehicle Driving Time in a Vicinity of Large Events

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1 Introduction

Connected and autonomous vehicles are supposed to bring major benefits in terms of increased traffic safety, efficiency, and decreased environmental impact. The expected benefits are mainly brought by the ability of vehicles to exchange information from their sensors and to communicate their state to the traffic management entities which can take educated decisions to control the traffic flows.

Means of communication between vehicles, infrastructure, and traffic management entities may vary from legacy traffic-light based systems to state-of-the-art electronic communication systems. In any case, it is extremely important to provide a backward compatibility for older vehicles which are not equipped with electronic communication modules. These vehicles are still an important, and for several upcoming years probably major, part of the traffic.

There were several algorithms presented, which use the data from connected vehicles' sensors to allow more efficient intersection management, reducing waiting times of involved vehicles, e.g [1, 2]. According to simulation results, these algorithms can help to minimize waiting time at the intersection and partly address traffic congestion.

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To tackle the increasing emergency response vehicle (ERV) driving time in congested cities, other relevant systems were either explored or already deployed. Among them, emergency vehicle preemption systems aim at prioritizing vehicles approaching from a certain direction, usually the one of the ERV [3, 4].

Another approach to potentially decrease the ERV's driving time by technological means is by early warning about the ERV's approach [5].

The system, whose feasibility is studied combines both approaches. Early warning for the connected vehicles which can benefit from the rich traffic information received by V2V and I2V communication is studied in conjunction with the principle of preemption by prioritizing traffic flow containing the ERV.

In this chapter, we would like to further explore to what extent Information and Communication Technologies employing Vehicle-to-Everything (V2X) communication and strategically placed Variable Message Signs (VMSs) could help to reduce the driving time of an ERV in a dense urban traffic scenario and what are the requirements for communication, to enable non-delayed transit of such a vehicle. Results from this research could be used as an input for dynamic intersection control algorithms optimized to ensure intersection preemption in a scenario with approaching ERV. In this study, we consider an urban road network during a peak hour near a site where a large cultural or sports event takes place. Driving time of the ERV is evaluated using a realistic simulation of both traffic scenarios as well as communication technologies deployment. In the simulation scenario, we consider a part of a traffic infrastructure near sports stadium in the city of Zilina in Slovakia. Simulations are based on the real traffic infrastructure and vehicle routes.

1.1 Overview of Traffic Control Approaches

According to the European Environment Agency, the passenger transport demand in the European Union increased by 30% between 1995 and 2017 [6]. Passenger cars remain the dominant transport mode with more than 70% share of all passenger transport. To fully utilize the existing transport infrastructure and meet the ever-increasing transport demands of the modern society, efficient traffic control management strategies have to be implemented. Figure 1 depicts the basic elements of a traffic control loop. The behavior of the traffic flow depends on Control inputs and Disturbances. Control inputs are fed to the control actuators (e.g., traffic lights, variable message signs, etc.) and can be manipulated by the traffic management entity. The disturbances (e.g., traffic demand, various traffic incidents, etc.) can be measured, detected, or predicted but cannot be manipulated. The performance of the traffic network is measured by a suitable performance metric. Surveillance helps to extend the measured data captured by sensors (e.g., loop detectors, cameras, even connected vehicles) as an input to the control strategy and provides an assistance to the human operator of the traffic control system. The control strategy lies in the core of the control loop and it is responsible for the real-time definition of control inputs in order to fulfill the pre-specified control goals despite the influence of the

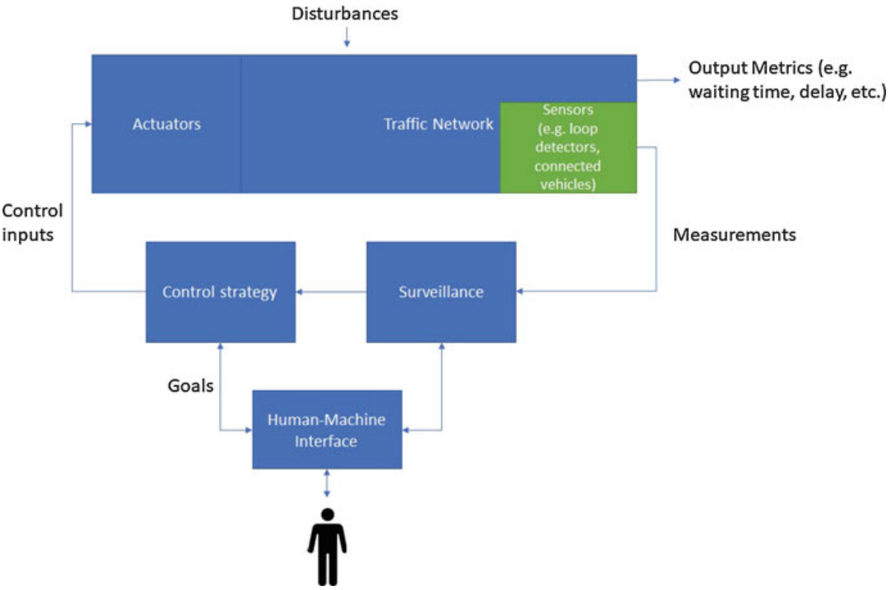

Fig. 1 Basic elements of a traffic control loop [7]

disturbances in the traffic network. The decision process of the control strategy is supported by available measurements, estimations, or predictions.

Intersection traffic control strategies can be divided according to various criteria. Considering the action scale of the employed traffic control mechanism, isolated or coordinated traffic control strategies are widely used.

Isolated strategies focus on controlling a single intersection, while coordinated strategies are used to control a wider urban area or even a whole network consisting of many intersections.

In the context of adaptability of a control strategy to the current traffic flow, fixed-time or traffic-responsive control strategies can be employed. Fixed-time control strategies often use historical data to derive intersection control parameters for a given time of day. The timing of the control signals remains constant for an extended time period. Traffic-responsive strategies use real-time measurements of the traffic situation (e.g., by inductive-loop detectors) to optimize the traffic control parameters. At the expense of necessity of an additional measurement infrastructure, they can achieve higher efficiency in satisfying the instantaneous traffic demand [7].

1.2 Overview of Current Emergency Vehicle Warning Systems

Current emergency vehicle warning systems can be divided into three basic groups. These are almost always combined to make strong visual and audible impact on the driver's senses.

1.2.1 Visual Warning Systems

Hills [8] estimated that a driver in a motor vehicle obtains more than 90% of the sensory input visually. Furthermore, several studies [9, 10] have shown that flashing signals are more likely to attract a driver's attention than steady lights. Even though a human eye is most sensitive in the yellow-green spectrum, red color has gained popularity as a warning identifier since it is associated with "danger" [11]. However red lights have been shown to be weakly visible [12] and in traffic easily lost in vehicle tail lamps [13].

1.2.2 Markings

The markings of an emergency vehicle play a crucial role in the ability of a driver to detect and identify the approaching ERV. Markings are particularly important in a case of ambulances which resembles commercial vehicles [14].

However, Allen [12] argues that a single-colored vehicle is more likely to be visible than a vehicle with a multitone body color. This effect is even more obvious in an urban environment according to findings by Hills [8, 15].

1.2.3 Audible Warning Systems

Sirens have been used for a long time as an emergency vehicle warning system. Recommended characteristics of an audible warning signal include sufficient power and a wide frequency spectrum for overcoming a masking noise [16], fast variation of pitch [13], and relatively rapid cycling time [17]. The recommended frequency range is between 1 and 4 kHz [18].

Siren, in order to be effective as a warning device, has to compete with the noise generated by the traffic flows, ambient noises, and other sources of audible noise. Some studies [17, 19] claim that an effective range of a typical siren used as emergency vehicle warning system yields from 8 to 12 m, when considering car's noise insulation characteristics.

Studies demonstrate that an efficiency of a siren as a warning device is severely limited. It is effective only at low speeds and on a very short range. Moreover, a siren mode (e.g., wail, yelp, high-low) does not significantly affect the efficiency of the siren.

1.3 Overview of Cooperative ITS and ITS Applications

The ITS architecture consists of three main communication domains – the in-vehicle, V2X domain, and the infrastructure domain. The high-level ITS architecture can be seen in Fig. 2 [20].

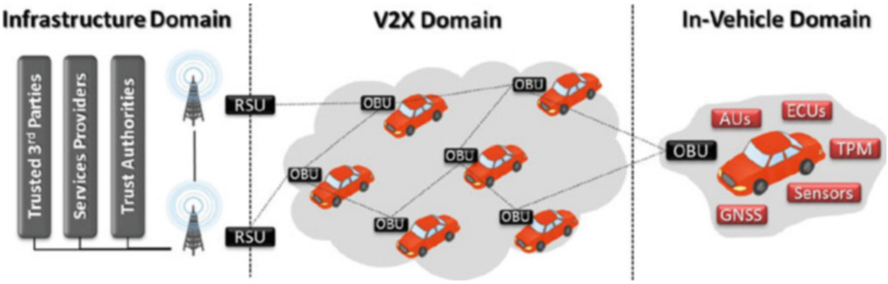

Fig. 2 The high-level ITS architecture [20]

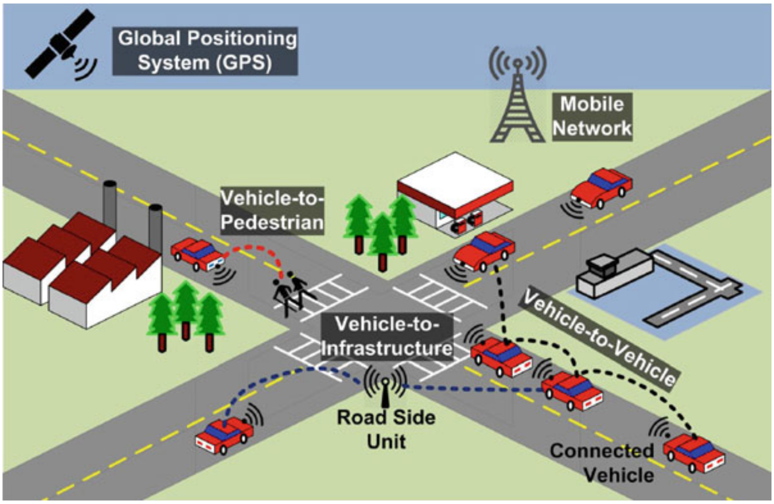

Fig. 3 V2X communication in ITS environment [20]

The infrastructure domain consists of the trusted third parties (e.g., vehicle manufacturers), service providers, and the trust authorities. Trust authorities provide registration and authentication of roadside units (RSUs) and onboard units (OBUs). The service providers provide applications and connectivity to the vehicle's application units (AUs) as well as the software updates, billing, and other services. RSUs interconnect the V2X and the infrastructure domain.

Vehicle OBUs and RSUs form the V2X domain, which is often called the ad hoc domain. Data from previous communication and vehicle sensors can be stored in the OBU and then transmitted to other OBUs, RSUs, or pedestrian communication units by wireless communication means as can be seen in Fig. 3 [20]. Four main types of vehicular communication technologies can be distinguished:

- Vehicle-to-Vehicle (V2V)—direct communication between nearby OBUs
- Vehicle-to-Infrastructure (V2I)—communication between OBUs and RSUs

- Vehicle-to-Pedestrian (V2P)—communication between OBUs/RSUs and the pedestrians in the range
- Vehicle-to-Network (V2N)—communication between OBUs and base station of the existing cellular network infrastructure

The in-vehicle domain contains all of the vehicle's electronic equipment—the electronic control units (ECUs), onboard units (OBUs) for wireless communication, application units (AUs), and a trusted platform module (TPM). ECUs collect data about vehicle's speed, direction, location, neighboring vehicles, traffic conditions, etc., and control the vehicle's functionality [20]. AUs are capable of running applications provided by the service providers using the OBU communication module [21]. The TPM is a secure cryptoprocessor which uses cryptographic keys, passwords, and digital certificates in order to enable secure communication and authenticate vehicles [22]. The Global Navigation Satellite System (GNSS) is used to retrieve a precise location of the vehicle itself.

A big variety of wireless communication technologies, including dedicated short-range communication (DSRC), Zigbee, Wi-Fi, IEEE 802.11p-based technologies, Wi-MAX, and cellular networks can be deployed to support various communication tasks in the ITS system.

1.3.1 V2X Applications

Five basic groups of VANET applications can be recognized—applications for traffic control, logistics and freight transport management, safety applications, maintenance applications, and added value services. Below are some examples of applications that can benefit from V2X communication [23].

1. Applications for traffic control
   - Route planning
   - Dynamic traffic signs displaying
   - Congestion-based route charging
   - Prioritizing various modes of transport
2. Logistics and freight transport management
   - Parking zones management
   - Route control
   - Dangerous goods transport control
3. Safety applications
   - Cooperative maneuvering
   - Emergency transmission
   - Danger warning
   - Coordinated braking

4. Maintenance applications
    - Sensor calibration
    - Remote diagnostics
5. Added value services
    - eCall emergency call system
    - Advanced navigation
    - Insurance services
    - Stolen vehicle tracking

Raya and Hubaux in [24] categorize applications for VANETs into two categories

- Safety-related applications which are related to the situations, where application presence may prevent life-endangering accident
- Other applications without direct impact on vehicle and crew safety

Cheng et al. in [25] divide applications into three categories:

- Infotainment delivery which offers convenience and comfort to the crew
- Road safety to prevent accidents
- Traffic monitoring and management to maximize road capacity and avoid congestions

For safety-related applications, various grades of performance demands can be required. Table 1 quantifies these parameters [26].

Table 1 Performance parameters for safety-related applications [26]

Performance class	Latency (ms)	Packet generation frequency (p/s)	Communication range (m)	Application
Low latency, high frequency	≤100	10–20	≤150	Accident, control loss, cooperative collision warning
Medium latency, medium frequency	≤200	5–10	≤100–130	Intersection collision warning, lane overtake assistance, extended brake signaling
High latency, low frequency	≤1000	1–2	≤1000	Work zone warning, road condition warning

1.4 Communication Technologies for Connected Vehicles

To allow vehicular data communications, several communication technologies emerged which are described in this section. Two major families of technologies are dominant:

- Dedicated Short-Range Communications (DSRC)
- Cellular Vehicle-to-Everything (C-V2X)

Communication technologies based on the DSRC use the IEEE 802.11p communication standard to enable device-to-device communication [27]. Communication nodes (e.g., vehicles and roadside infrastructure) form a Vehicular Ad-hoc Network (VANET). VANET is a self-formed network without centralized management. Communication nodes exchange data using a predefined communication channel whenever they are in the communication range. There are two types of communication channels defined for VANETs—a Control Channel (CCH) for safety-related communications and one or more Service Channels (SCHs) for non-safety-related services. Channels use the 5.9 GHz frequency band.

C-V2X technologies emerged as an extension of the LTE standard in 2017 [28]. These technologies use existing cellular network infrastructure to allow vehicular communications. To address V2V and V2I communication scenarios where vehicles are outside of the base station's coverage a new radio interface (PC5) was developed. Since the vehicles do not use downlink nor uplink to exchange data the new communication mode, referred to as sidelink, was introduced.

The network resources are usually allocated by the base station. When the base station is not able to assign resources to vehicles (i.e., in a case of connection loss), the vehicles select communication network resources in the form of resource blocks autonomously [29].

As the C-V2X family of technologies was introduced relatively recently, it has to undergo extensive field testing to prove its operational readiness. For this reason, we decided to study the impact of DSRC-based technologies which are more mature technology [30].

From all candidate technologies, two families of DSRC-based C-ITS standards emerged as dominant:

- IEEE WAVE
- ETSI ITS

Both families of standards use the same IEEE 802.11p physical (PHY) and medium access (MAC) architecture layers (see Fig. 4). Lower communication layers are based on WiFi standard with channel bandwidth reduced to 10 MHz and channel-switching guard intervals doubled.

The key difference between the two families of standards is in their approach to addressing the communication channel congestion. IEEE WAVE uses multichannel operation, i.e., the transceiver is constantly switching between CCH and SCH every 50 ms. The main disadvantage of this approach is rather an inefficient channel

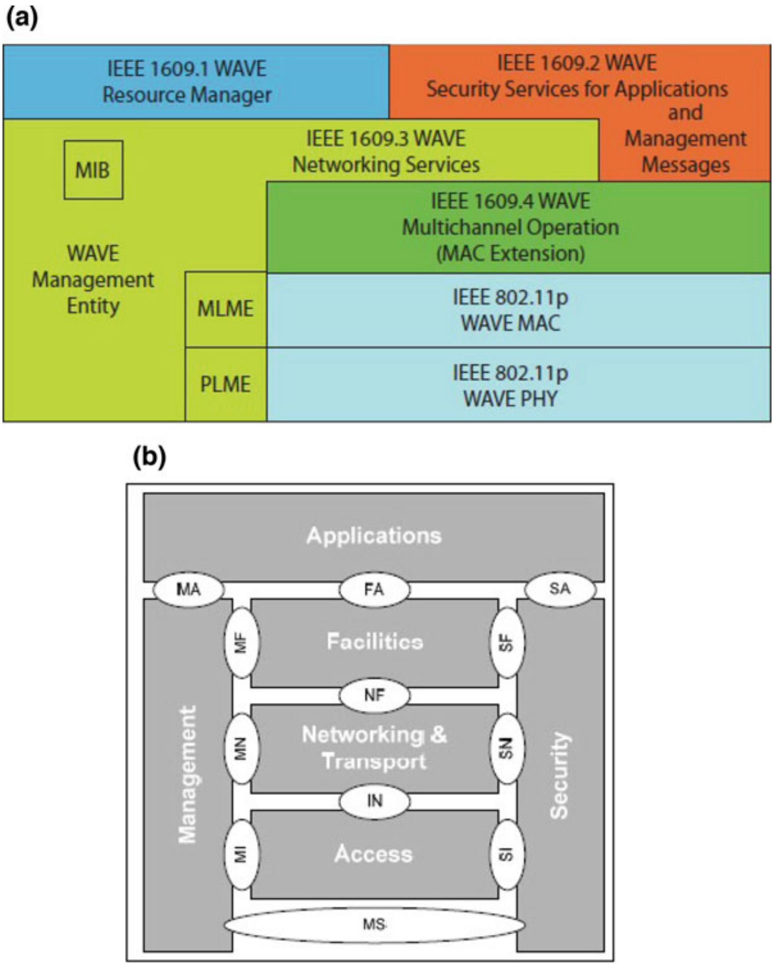

Fig. 4 Architectures of major DSRC-based C-ITS communication technologies. (**a**) IEEE WAVE; (**b**) ETSI ITS

utilization. While multichannel operation allows the use of a single transceiver for both safety-related and other communications, the peak channel utilization is only around 46% considering equal use of CCH and SCH and switching guard intervals. ETSI ITS uses Decentralized Congestion Control (DCC) mechanism to reduce the CCH load in the case of channel congestion. DCC is a state machine which switches between its states according to the detected busy time of the medium. Figure 5 shows the states of the DCC for CCH with 15% and 40% busy time being thresholds when a state change takes place [31]. Each state of the state machine has defined PHY and MAC parameters which are then applied to the system to reduce the CCH load. These parameters are shown in Table 2. The value *ref* means that the corresponding

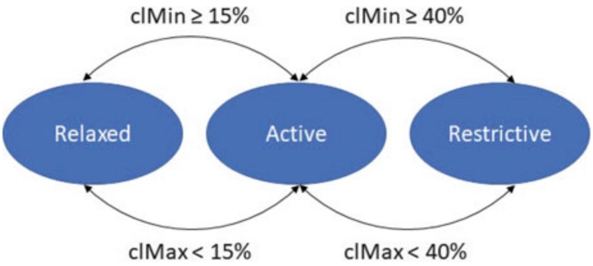

Fig. 5 DCC state machine for the CCH

Table 2 PHY and MAC layer parameters for the DCC state machine

	State					
	Relaxed	Active				Restrictive
		Access category				
		AC_VO	AC_VI	AC_BE	AC_BK	
Power (dBm)	33	Ref	25	20	15	−10
Interval (s)	0.04	Ref	Ref	Ref	Ref	1
Data rate (Mbps)	3	Ref	Ref	Ref	Ref	12
Radio sensitivity (dBm)	−95	Ref	Ref	Ref	Ref	−65

parameter is not changed after the transition to the respective state. However, as observed by Eckhoff et al. [31], with the increasing number of communicating nodes the DCC tends to start oscillating between its states, switching from Relaxed over Active to Restrictive states and back, which instantly affects the channel load forming a loop behavior of the system.

2 Traffic Flow Model

To model the traffic flows, the Simulation of Urban Mobility (SUMO) [32] was used. A real map of the road infrastructure from openstreetmap.org [33] was exported and traffic flow densities were modeled according to the Poisson distribution:

$$p(x) = \frac{\mu^x \mathrm{e}^{-\mu}}{x!} \tag{1}$$

where $p(x)$ is the probability for x vehicles arriving in a time interval, and μ is the expected rate of vehicle arrival in that interval.

Traffic scenario was selected in a way to represent the worst possible situation, when the road network is severely congested. We assume a scenario, when a cultural or sport event ends at a stadium and a lot of vehicles try to depart from the parking lot in a limited time. In this situation, an emergency vehicle has to pass the road segments congested by vehicles leaving the stadium's parking lot on its way to the nearest hospital.

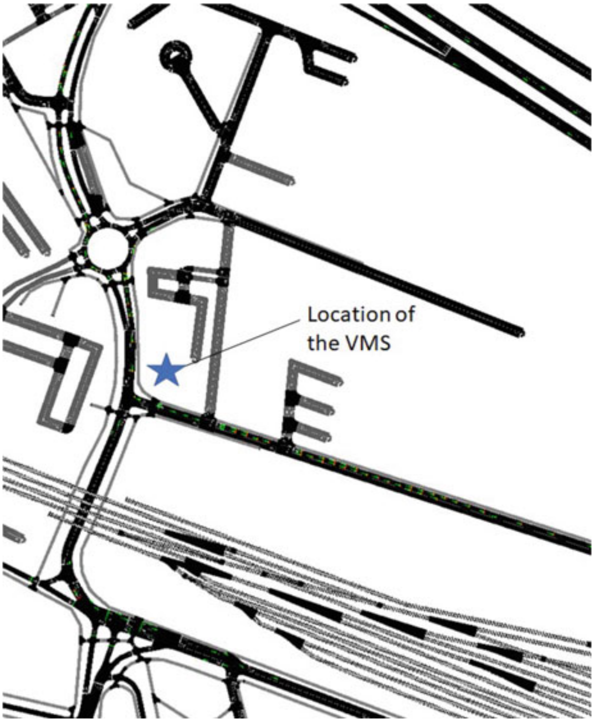

Fig. 6 Part of the simulated road infrastructure

Where possible, traffic densities in road segments surrounding the stadium were modeled according to mean values from a traffic survey conducted for the Traffic General Plan of the City of Zilina [34]. The resulting traffic flows in the simulation consist of vehicles generated according to the survey mean values and the vehicles departing from the stadium's parking lot.

Part of the simulated road network can be seen in Fig. 6. The VMS with RSU capability is located at the intersection of main road which an emergency vehicle has to pass and a side road leading from the stadium's parking lot. There is also a flow of vehicles approaching from the city ring through a roundabout at the main road. These vehicles do not have a visual contact with the VMS, but they are in the communication range of the VMS's RSU. If the vehicle entering the roundabout is connected, it can receive instructions via an electronic communication module, preventing the congestion of the roundabout.

3 Communication Architecture

Since it is expected that during upcoming years the traffic flow would consist of a mix of both connected and conventional vehicles without electronic communication capacity, the simulation experiment uses Variable Message Sign (VMS) to communicate the information also to conventional vehicles. In addition, used VMS is coupled with Road Side Unit (RSU) to provide more detailed control data beyond basic VMS information to connected vehicles. To disseminate Infrastructure-to-Vehicle (I2V) communication messages, the RSU uses 802.11p-based protocol stack (Fig. 7) running scalable Emergency Vehicle Warning Application (EVWA) proposed in [5]. The application uses 802.11p-based physical layer and medium access layer. On top of that, IP and UDP protocols are used for node addressing and packet routing. Since the controlled intersection is located in close vicinity of the RSU, only the limited communication range for the EWVA is required. Therefore, in simulated scenarios, EVWA packets are broadcasted and multi-hop transmissions are not used. More detailed study of multi-hop communication delays in the context of the proposed EVWA can be found in [5].

The VMS display panel as well as the RSU are controlled remotely from the Traffic Management Center via Transport Control Protocol (TCP) connection. Simulated communication architecture with data flow can be seen in Fig. 8.

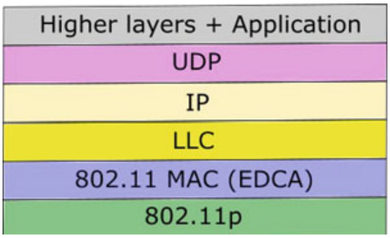

Fig. 7 RSU and vehicles' protocol stack used for simulation

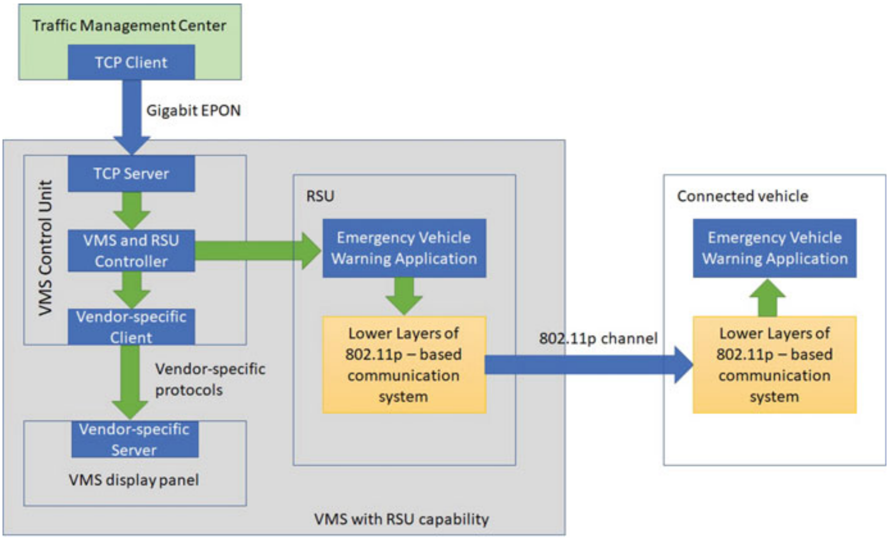

Fig. 8 Communication architecture of the simulated traffic control system

In the simulation of the communication network, VMS vendor-specific protocols were considered to be free from delay and any data loss.

The properties of the communication network were simulated using OMNeT++ discrete event network simulator [35]. Communication delays acted as an input to the traffic simulator for calculation of the emergency vehicle's driving time.

4 Simulation Scenarios

For the purpose of the simulation we considered three types of vehicles:

- Conventional vehicle—vehicle with human driver without equipment to receive any electronic communication
- Connected vehicle—vehicle with human driver equipped with communication module fully compatible with RSU
- Emergency response vehicle—ambulance with human driver equipped with communication module capable of message exchange with the Traffic Management Center

Using the abovementioned three types of vehicles, four simulation scenarios were considered:

- No communication between vehicles and Traffic Management Center (TMC)
- Specifically designed Variable Message Signs (VMS)
- Isolated RSU without any means to communicate with conventional vehicles
- Infrastructure-To-Vehicle (I2V) communication enabled VMS

The impact of the communication on emergency vehicle's driving time was evaluated for varying penetration of connected vehicles from 0% to 100%. The emergency vehicle's route length was 3600 m. Part of the route with a length of 2100 m is covered by an uncongested city ring. The length of the emergency vehicle's route through the city streets is 1500 m—this is also the part of the journey, where undesirable delay in driving time is gathered.

The Emergency Vehicle Warning application simulated in the scenarios does not only provide the information about approaching emergency vehicles, but also transfers commands with a required action to the connected vehicles (beyond Day 1 C-ITS application [36]). In all simulation experiments, we assume drivers fully obey required actions.

5 Simulation Results

The driving time of the emergency vehicle without any intersection management was 217.7 s. As a next step, we studied the emergency vehicle's delay compared to free-flow conditions at the intersection. In this scenario, we assumed 100% of the

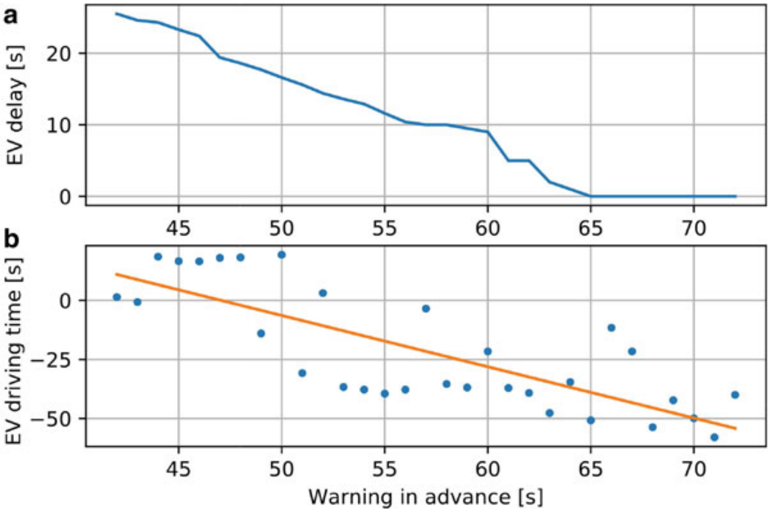

Fig. 9 Dependency of reduction of emergency vehicle's delay (**a**) and driving time (**b**) on advance warning time

vehicles, which have visual contact to the VMS will obey the traffic management request presented at the VMS. For this purpose, we treated both the connected and conventional vehicles the same way. As illustrated in Fig. 9a, in the studied scenario the delay which emergency vehicle experiences is dependent on how much in advance the information about approaching emergency vehicle is offered to regular vehicles. If drivers received the information more than 65 s in advance the emergency vehicle did not experience any delay. Total driving time of the emergency vehicle is reduced according to Fig. 9b. Blue dots represent the values from individual experiments, while the trend line is depicted in orange.

The impact on driving time lies in the range from −25% to +10%. The positive numbers mean, the system can even introduce a loss under specific conditions. This is due to fluctuations in the traffic flow that occurs when certain vehicles, due to their earlier arrival thanks to the preemption system, have to wait at the previous intersection for the green light and form an obstacle for the emergency vehicle. This issue indicates that traffic management in favor of emergency response vehicles should be done in a coordinated manner on a number of consecutive intersections along the route of the emergency vehicle rather than for isolated intersections.

When only isolated RSU is used for message exchange, the percentage reduction of emergency vehicle's driving time, dependent on the penetration rate of equipped vehicles, can be seen in Fig. 10. Note, that in this scenario, only vehicles with V2X communication capability were able to receive the traffic management information. The connected vehicles were selected randomly according to the uniform distribution. In the studied scenario, we assumed the information about the approaching emergency response vehicle is available 30s before its arrival. According to the

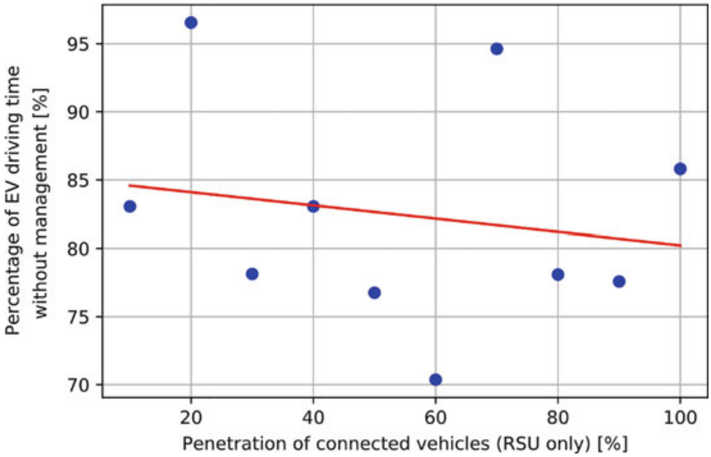

Fig. 10 Relation between the reduction of emergency vehicle's driving time and penetration of connected vehicles in the scenario with no means of communication between TMC and conventional vehicles

survey made among professional emergency response vehicles drivers in Germany [37], this is the appropriate reaction time needed for other drivers to correctly prepare for the emergency vehicle's approach.

The reduction of emergency vehicle's driving time can be expected in the range from 3% up to 30% for some specific cases.

The same traffic scenario was simulated also with the employment of VMS with integrated RSU. In this simulation scenario, all vehicles in visual contact with the VMS were considered to be able to comply with the requested traffic management operations, while vehicles on nearby roads were informed only via electronic communication. The dependence of emergency vehicle's driving time reduction for different penetration of connected vehicles on nearby road segments can be seen in Fig. 11. The expected reduction of the emergency vehicle's driving time ranges from 6% to more than 25%.

6 Conclusion and Further Work

In the chapter, a scenario of approaching emergency vehicles under specific conditions of congested road network in a vicinity of a large cultural or sports event was simulated. The impact of the deployment of Information and Communication Technologies (ICT) on the emergency vehicle's driving time was studied.

The results of the simulation experiments confirm that ICT deployment can reduce the emergency vehicle's driving time in dense urban traffic scenarios; however, the results also reveal, that if deployed in an isolated manner, the system can

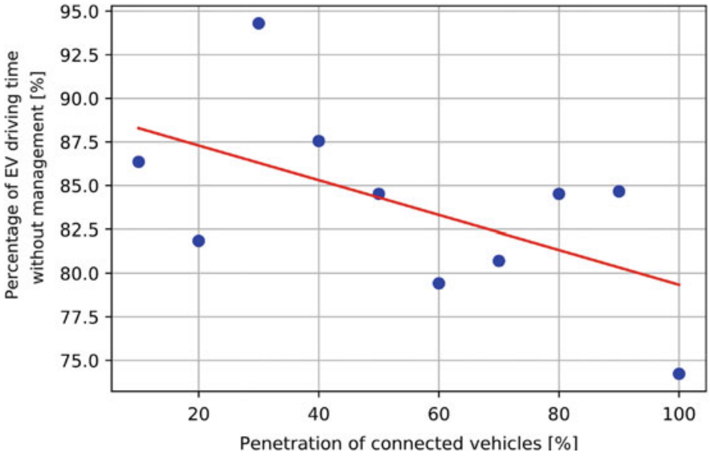

Fig. 11 Relation between the reduction of emergency vehicle's driving time and penetration of connected vehicles in the scenario with VMS and RSU communication employed

even introduce a loss. To foster the benefits of the intersection preemption system for support of emergency response vehicles, several consecutive intersections have to be controlled in a synchronized and optimized way.

In our future work, based on previous research in the field of vehicular networking [38–40], we would like to design communication architecture to support innovative intersection control algorithms for minimizing the driving time of emergency vehicles.

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