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A Feasibility Study of Privacy Ensuring Emergency Vehicle Approaching Warning System

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Featured Application: Privacy ensuring emergency vehicle approaching warning system.

Abstract: With the deployment of Vehicular Ad hoc Networks (VANETs), new transport safety and efficiency applications are emerging. One of the fields where the adoption of information and communication technologies (ICT) is expected to bring great benefits, is emergency systems. A properly designed emergency vehicle warning system should provide car drivers with adequate reaction times and additional information, complementing the currently used lights and sirens. The objective is to increase road safety and to create conditions for a fast and reliable movement of emergency vehicles (EVs). The available literature addressing privacy issues in VANET-based emergency vehicle warning systems is strongly limited. In this paper, the privacy ensuring emergency vehicle approaching warning system (PEEV-WS) is proposed based on a requirements analysis. Privacy is ensured by avoiding transmissions of sensitive information (e.g., expected EV route) over the wireless channel. This is achieved by assigning the decision-making responsibility to an EV and determining which vehicles can potentially interfere with the EV in the near future, and to notify those vehicles only by unicasting vehicle-customized information. The performance of the system is evaluated by federated telco-traffic simulations in terms of end-to-end delay and message delivery probability for three commonly used ad hoc routing protocols—Ad hoc On-Demand Distance Vector (AODV), Greedy Perimeter Stateless Routing (GPSR), and Dynamic MANET On-demand (DYMO), as well as in terms of reaction time, which the system provides to the drivers. Despite low applicability of the ad hoc routing protocols for vehicular communication, especially for low-latency and high-frequency applications, the simulations of the communication network demonstrate that the AODV protocol, with the modified configuration, can support the emergency vehicle warning system. The traffic simulations confirm that the system has the potential to provide drivers with sufficient reaction time.

Keywords: emergency vehicles; connected intelligent transport systems (C-ITS); simulations; VANET; routing protocols; ad hoc networks

1. Introduction

Due to the exceptional progress in digital technologies made in recent decades, many aspects of our lives are subject to rapid changes. Technology has advanced the way we communicate, travel, and entertain ourselves. The automotive industry has been significantly transformed, and the latest cars provide many benefits to their passengers in terms of safety and comfort. However, we are still quite far away from an ideal state, represented by the Zero Accident Vision [1].

The automotive industry, public authorities, as well as researchers all around the world are addressing pressing issues related to road traffic, including traffic safety [2], environmental impacts [3], and traffic congestion [4]. One of the key technologies expected to bring major benefits towards achieving these goals is cooperative, connected, and automated mobility [5]. Despite some accidents occurring in the past, connected and automated vehicles are expected to be much safer than human-driven cars when the corresponding technology will be mature enough [6].

Until automated vehicles become an every-day reality, conventional vehicles can also benefit from vehicle-to-everything (V2X) communication [7]. The European Commission published a list of Day 1 Cooperative Intelligent Transport Systems (C-ITS) applications [8] that are expected to be supported first by connected vehicles. The list also includes an emergency vehicle approach (EVA) warning system. The initial idea leading to the system proposed in this paper was awarded by the European Commission in 2017 as a project with innovative potential in the transport area [9].

1.1. Previous Work

Emergency vehicles (EVs) have been using warning devices for a long time. Currently, the most used warning system deployed by EVs is a combination of flashing lights and sirens. This system has obvious disadvantages, as has been demonstrated by several studies. For instance, a siren is a severely limited warning device effective only for very short range and very low speeds. On top of that, hearing loss of siren-exposed personnel has also been documented in several studies [10–12]. Currently, many cars are equipped with multimedia entertainment systems, which can lead to a situation where a driver is not able to hear the audio warning system of the approaching EV. Furthermore, many cars are now virtually sound-proof. Due to the limited range of the audio alerts, even if a driver notices the siren, he/she often does not have enough time to react in time. Such situations may lead to traffic accidents, mostly occurring at intersections [13].

Both the scientific community as well as the public authorities believe that these limitations can be addressed by the deployment of information and communication technologies (ICT). There are two major communication technologies capable of transferring warning messages—Vehicular Ad hoc Networks (VANETs) and 5G [14,15]. Currently, it is not certain, which technology will dominate the future market, however, when it comes to the available standards (e.g., frequency allocations), VANET is the most mature technology [15]. Moreover, it provides an adequate communication range, non-line-of-sight message dissemination, and innovative use of data transmission methods, easing the information interpretation and thus leveraging the benefits of an electronic-communication-based warning system. For these reasons, we selected VANET to implement the privacy ensuring emergency vehicle approaching warning system (PEEV-WS).

Some works have already explored the possibilities of EVA implementation using VANETs [16,17]. All these works are based on broadcasting the expected EV route to all vehicles. Based on a projected route, a receiving vehicle determines whether the warning message is relevant or not. This practice introduces two issues. First, the EV route needs to be properly interpreted. The route can be transmitted in two forms—either as a sequence of geographical coordinates, or as a succession of map-specific edges (e.g., road segments and lanes). In both cases, the sender as well as the receiver must use the same reference map, to reliably recognize the transport infrastructure objects (e.g., lanes) which will be used by the EV. Hence, the map must be either agreed on in advance or transmitted together with the EV route. As presented in [18], updates of high-definition maps can take a significant amount of communication network resources, decreasing the available bandwidth for application payload, and increasing the communication latency. Difficulties of map exchanges can be avoided if the EV is responsible for the decision-making process and determines which vehicles can potentially interfere with the EV in the near future and notifies those vehicles only by unicasting the vehicle-customized information (e.g., a request to change the lane). To predict vehicle trajectory and the probability of a lane change, techniques based on the extended Kalman filter [19], long-short-term-memory networks [20], and support vector machine in combination with Bayesian filter [21] were already explored. Second, there is a significant risk that the information about the route of the EV can be misused. This can be prevented by encrypting the message content. In the general context, several research projects systematically targeted the security issues in the VANETs, for example the Cooperative Vehicle-Infrastructure Systems (CVIS), E-safety Vehicle Intrusion Protected Applications (EVITA), and Secure Vehicular Communication (SeVeCom) [22–24]. In [25], Ďurech evaluated various digital signature schemes [26]. However, when the number of messages becomes large, traditional per-message authentication schemes may generate unaffordable delays [27]. The privacy can be enforced even further by avoiding transmissions of sensitive information (e.g., projected EV route) over the wireless channel. This can be achieved by making the EV responsible for determining which vehicles can potentially interfere with the EV in the near future. To the best of our knowledge, this approach has not been previously addressed in the literature. Furthermore, the unicast eliminates the need of frequent resource-heavy map exchanges between communicating vehicles.

To communicate the vehicle-customized information, the network routing protocols have to be used. It is worth noting that the performance of ad hoc routing protocols in the specific conditions of VANETs has been questioned in some studies. For example, Sommer et al. [28] concluded that the ad hoc routing protocols fail to deliver the performance needed to reliably support the variety of proposed VANET applications and should not be used as a universal method for information dissemination in the VANETs. The authors of the study [29], dealing with the performance of the Greedy Perimeter Stateless Routing (GPSR) protocol in vehicular networks, conclude that due to its performance limitations, GPSR seems to be unsuitable for vehicular communication applications. The usage of certain network-layer protocols can be restricted for certain services in Europe. For instance, the European Telecommunications Standards Institute (ETSI) European Standard (EN) 302 636-3 [30] requires the use of ETSI GeoNetworking [31] as the only network-layer protocol for safety-related communications in ETSI ITS-G5A band. However, for a certain sort of application, e.g., warning applications, that have less strict delay requirements than the safety-related applications, deployment of ad hoc routing-based communication can still be justified and considered as a legitimate approach. Moreover, an ability to implement relatively reliable unicast communication can even be, for some applications, preferred over the sheer value of the end-to-end delay.

1.2. Scientific Contributions and Structure of the Paper

The amount of available studies addressing privacy issues in VANET-based emergency vehicle warning systems is rather small. Our main scientific contribution is constituted by the proposed privacy preserving concept and by the feasibility study of the application protocol for the emergency vehicle warning system. Specific contributions of this work can be summarized as follows:

- Formulation of the requirements and the concept of the application protocol for an emergency vehicle warning system based on VANET, with low risk of EV location disclosure;
- Application of the federated telco-traffic simulator and benchmarking of the communication performance of the Ad hoc On-Demand Distance Vector (AODV), GPSR, and Dynamic MANET On-demand (DYMO) routing protocols using realistic scenarios;
- Evaluation of the proposed system in the transport domain in terms of reaction time available to drivers.

The rest of the paper is organized as follows. System requirements and assessment of communication technologies are given in Section 2. Section 3 presents the concept of the proposed system. Simulation scenarios and simulation results are presented in Sections 4 and 5, respectively. Discussion and summary of conclusions are provided in Section 6.

2. Definition of System Requirements and Assessment of Fitting Communication Technologies

The EV interacts with other vehicles by sending request messages. Drawing the line between what the EV could and what it should not request from drivers (or in the future from autonomous vehicles) is a complex problem requiring thorough philosophical and technical discussion. We assume that the EV uses PEEV-WS to notify other vehicle drivers about approaching them, about an action (e.g., change lane) necessary to free transport infrastructure for the EV, and about the expected time to reach them. It lies in the driver's responsibility to make a decision on which concrete action to take (e.g., change lane to the right or to the left, stop the vehicle, etc.). Considering the standard set of criteria and the available literature, we define technical requirements for the emergency warning system, and we discuss how the VANET technology fits to this purpose.

2.1. Timely Message Dissemination

To react adequately, the drivers (or electronic system, in the case of an autonomous vehicle) have to be informed about an approaching EV early enough. Surveys conducted amongst the EV crews suggest that 30 s represents a sufficient time for drivers to react properly under most conditions. However, it was suggested that this value should be examined more accurately by further studies [16]. To facilitate the assessment of the feasibility of reaching a 30 s reaction time, we illustrate in Figure 1 the relationship between the available reaction time, t_{art}, and the relative speed, Δv, of two vehicles (the EV and the vehicle that should be warned about the approaching EV), for six different values of the communication range, s. The curves, shown in Figure 1, are obtained by considering the mathematical relationship $t_{art} = s/\Delta v$. Hence, here we consider only the time the EV needs to reach the considered vehicle and the communication delay is neglected.

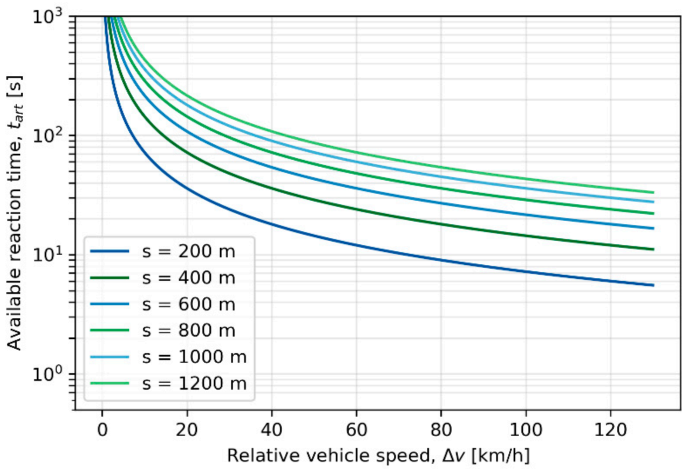

Figure 1. Estimate of the reaction time available to the driver, for various values of the communication range, s, as a function of the relative speed of the emergency vehicle (EV) and the vehicle.

Let us first consider the worst-case scenario in Figure 1, when the EV travels with maximum speed and the informed vehicle moves extremely slowly or even stops, e.g., because of construction work or an accident on the highway. The communication range must be approximately 1000 m to ensure a 30 s reaction time. Consequently, the vehicle's onboard unit must switch to the highest allowed transmission power. Typically, achieving the maximum communication range s = 1000 m in a highway scenario is feasible, as there are rarely any major obstacles to attenuate the signal along the road. The situation is, however, completely different in an urban environment with dense built-up areas, in which the receiving vehicle is often not in line-of-sight with the transmitter. Fortunately, in these areas, the speed limits are much lower. If we consider the maximum speed limit for urban areas, which is 50 km/h in most states of the European Union, the minimum distance needed to ensure sufficient reaction time is approximately 400 m. Thus, a rough estimation indicates that a deployment of technology with a communication range reaching 1000 m could be sufficient.

According to Oh et al. [32], three performance classes for the VANET applications can be established. Considering the scale of the reaction time and the required communication range, the PEEV-WS falls under the high frequency and low latency performance class, implying a required message generation frequency of about 1 s.

2.2. Interoperability

Interoperability is achieved when components of the system can communicate properly [33]. The choice of the VANET technology, which is supposed to be available in cars, implies that all vehicles should comply with IEEE 802.11p-based physical and medium access communication layers [34] and with Internet Protocol-based network layer. Moreover, vehicles should be capable of fully processing messages generated by the proposed system.

2.3. Versatility

There is a potential to utilize PEEV-WS in an extended context. For example, it could support a communication with traffic lights, or coordination of EVs. To consider this possibility in the simulation model, additional data fields carrying general data and thus left for future use were included in the message format.

2.4. Information Relevance

If the PEEV-WS messages were broadcasted, it would be difficult to judge if the message content, often a request to take an action, is relevant for the message recipient. For example, an EV sends a request to a vehicle that is interfering with an EV's trajectory. If the message is broadcasted, then all the vehicles in the communication range receive the message, so the vehicles need additional information to evaluate if they interfere with the EV's trajectory. Buchenscheit et al. [16] proposed to communicate a segment of the EV's route to other vehicles on the road. This can certainly solve the problem, but it introduces a risk that this sensitive data could potentially be abused. The solution adopted in this paper is to let an EV to determine who is interfering with its future trajectory and to select the specific and relevant communication targets only. Vehicles equipped with the VANET communication modules are exchanging cooperative awareness messages (CAMs) containing their instantaneous position, speed, heading, acceleration, and other parameters. This information can be used by an EV to identify a prospectively interfering vehicle. A routing protocol can then be used to find a communication route to the relevant vehicle.

2.5. Security

The PEEV-WS messages have to be secured to avoid the risk of fraudulent use. Security of vehicular communication itself is a complex and evolving topic, hence, it is difficult to cover it comprehensively within the scope of this paper. Considering [25], we adjust a communication message length of the proposed system to account for the use of future authentication and integrity check mechanisms. Therefore, the length of the communication message in the simulations was set to 300 B.

2.6. Privacy

The intended transport route and instantaneous position of the EV should not be publicly disclosed. In the proposed approach, a risk of misusing this information is minimized by replacing broadcasting by communicating the potentially sensitive messages to the relevant vehicles only. By design, it is the EV's responsibility to decide for which vehicle the message is relevant and to disseminate the information about the expected time and transport infrastructure to be used (e.g., emergency lane).

A communication route to the relevant vehicle is found on a network-layer level as presented in Section 3.

2.7. Unobtrusiveness

In the case of human-driven connected vehicles, the interface between the system and the driver has to be designed in a way that notifications and the information presented to the driver should not distract her/his attention, while the risk that drivers are not notified should be minimized. In [35], Lugano considers a usage of virtual assistants to accomplish similar tasks. For simplicity reasons, we assume in the simulations that the driver will notice the message immediately after its reception.

2.8. Communication Technology

Based on the abovementioned requirements, the VANET technology was selected as an appropriate communication technology. A communication route to each relevant vehicle is found by an ad hoc routing protocol. For this sake, we evaluated the performance of three commonly used reactive and hybrid ad hoc routing protocols, i.e., AODV, GPSR, and DYMO. The proactive protocols (including the Zone Routing Protocol which operates in a proactive mode within a single network zone) were not considered in this work for their relatively high signalization overhead, which makes them inapplicable in the context of the limited available bandwidth of the VANET. The values of parameters and the selected routing protocols are summarized in Table 1.

Table 1. Summary of the privacy ensuring emergency vehicle approaching warning system (PEEV-WS) specifications.

Parameter	Value	Requirement(s) Affecting the Choice
Message generation interval (Δt)	1 s	Available reaction time
Communication range	≥1000 m	Available reaction time
Carrier frequency	5900 MHz	Interoperability, versatility
Channel bandwidth	10 MHz	Interoperability, versatility
Physical and Medium Access layers specification	IEEE 802.11	Interoperability, versatility
L3 and higher layer protocols	Ad hoc routing (Ad hoc On-Demand Distance Vector, Greedy Perimeter Stateless Routing, Dynamic MANET On-demand) + User Datagram Protocol (UDP)	Interoperability, versatility, security, information relevance

3. Privacy Ensuring Emergency Vehicle Approaching Warning System

To avoid the need to broadcast the EV's route, we propose a novel privacy preserving emergency vehicle warning system, which utilizes a unicast communication to target the selected vehicles only, i.e., those whose action is required to ensure fluent transit of the EV. The proposed application message format can be adopted by any other vehicle-to-vehicle technology allowing unicast communication. This makes the proposed system transmission technology agnostic.

The proposed system assumes the following preconditions:

- All the vehicles are equipped with the compatible communication modules and other hardware necessary to either display the information to a driver or act autonomously following the received requests.
- All the regular vehicles except for the EV periodically disseminate the CAMs or other similar sources of data that can be used to estimate their current position at a lane-level resolution.
- All the vehicles are equipped with the proposed emergency vehicle warning system deploying the standardized request codes, and drivers obey the requests provided by the system.

In VANETs, the EV receives the CAMs [36] from other vehicles within its communication range. From the received data, the EV learns a topology of the network and extracts the information about other vehicles' locations and compiles a list of all reachable vehicles (see Figure 2). When the PEEV-WS is initiated, the main process executing the steps illustrated in Figure 3 is triggered. The main process updates the list of relevant vehicles based on CAMs. For each newly identified relevant vehicle, a communication handling process is triggered, and the communication process with already irrelevant vehicles is terminated. When an interference between EV trajectory and a vehicle is detected in the communication handling process, the corresponding warning message is created, and a routing protocol is used to find a communication route to the interfering vehicle (see Figure 3). This ensures that only the relevant vehicle receives the information about the approaching EV together with the specific request for the desired action. In general, to decide on a suitable action is a very complex problem and it is out of the scope of this paper. In simulations, we consider scenarios involving multiple lanes and the action is limited to changing lanes to one which is not interfering with the EV trajectory.

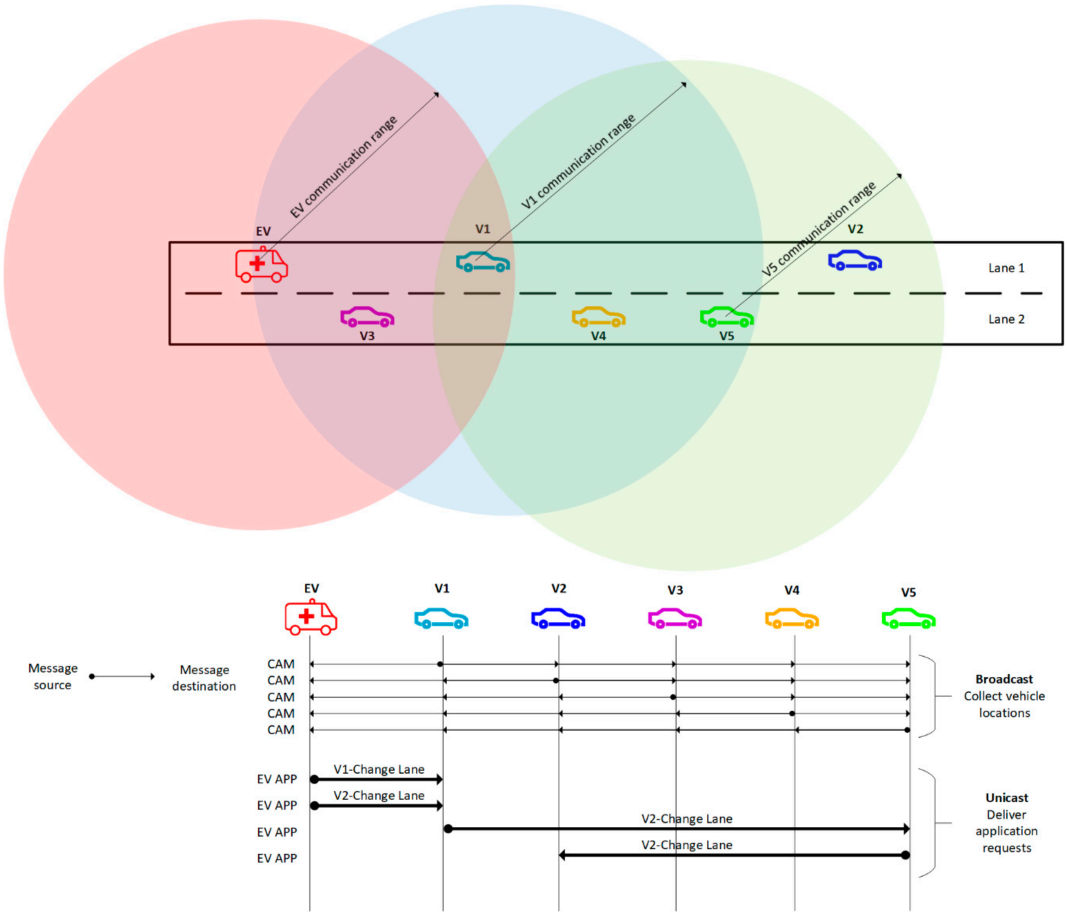

Figure 2. Illustration of the emergency vehicle warning system operation. The EV collects vehicle locations from cooperative awareness messages (CAMs), decides on the needed actions, and sends requests to corresponding vehicles. In this example, vehicles V1 and V2 are obstacles for the EV in lane 1. V1 can be reached directly. V2 is not in the EV's communication range, therefore a routing protocol is used to find a communication route to V2. Finally, the communication message is then sent from the EV, through V1 and V5, to its destination, V2.

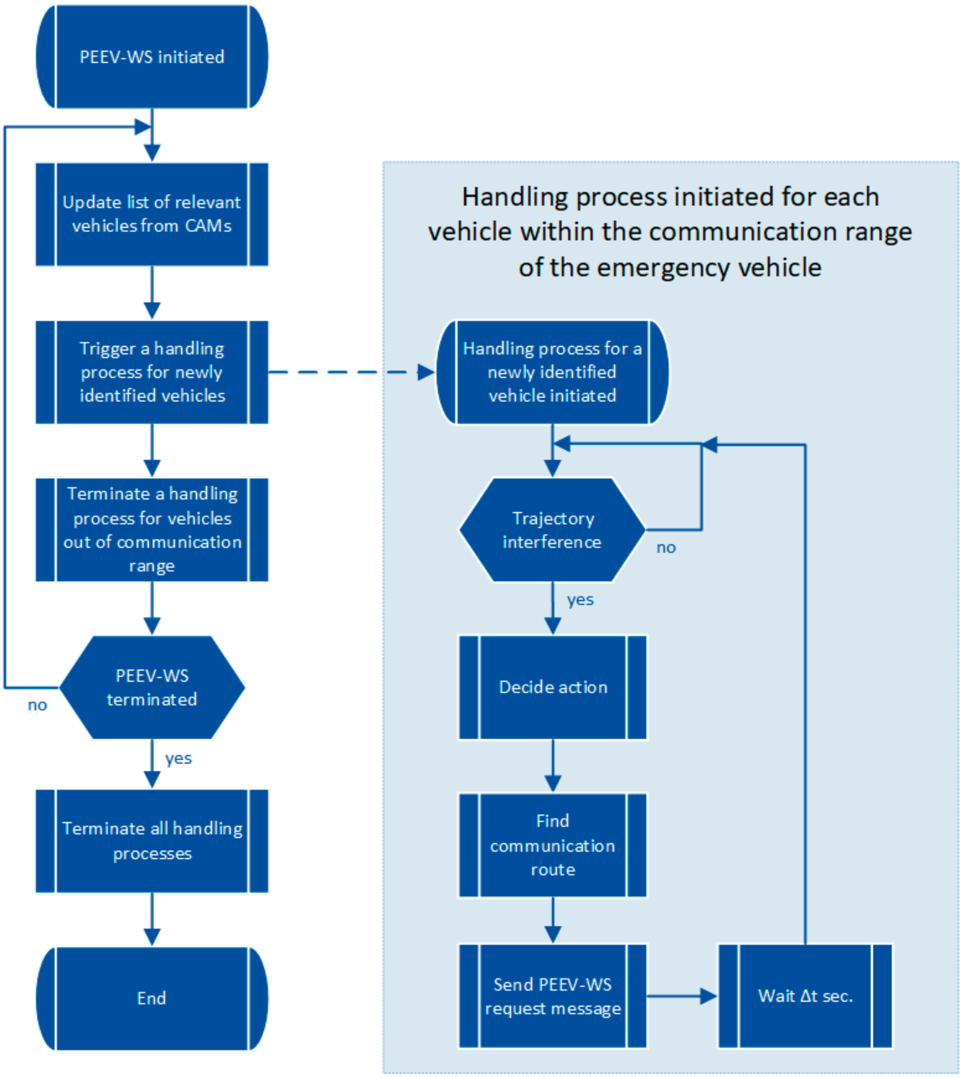

Figure 3. Flow chart of the main algorithm implemented by the PEEV-WS.

As communication between vehicles in VANET does not use acknowledgments, a sender does not have the information about the transmission result. Even if some messages may get lost the vehicles still have to be informed about the approaching EV. When the EV needs to communicate a request to a vehicle, it generates messages periodically with a specific interval Δt. The generation of messages continues until the EV detects the desired change in the vehicle's trajectory. When the vehicle again obstructs the EV's trajectory, this behavior is detected, and the communication loop is initiated again.

Considering the communication algorithm visualized in Figure 3, the time t_i when the vehicle receives the ith message from the EV is expressed by Equation (1):

$$t_i \cong \delta_{e_i} + \delta_{d_i} + \delta_{p_i} + \delta_{t_i} + \delta_{MAC_i} + (i-1).\Delta t + t_{start}, \tag{1}$$

where δ_{e_i} and δ_{d_i} are an ith message's encapsulation and decapsulation delays respectively, δ_{p_i} is a propagation delay, δ_{t_i} is a message transmission duration, δ_{MAC_i} is a medium access (MAC) delay, Δt is a message generation interval, and t_{start} is a start time of the message transmission. Please note that MAC delays arise due to the contention-based nature of the VANET MAC layer. A time t_{min} when the vehicle receives the information about the approaching EV can be obtained as $t_{min} = min\{t_i\}$. The difference between the time when an EV passes by the informed vehicle and t_{min} gives us an estimate of the available reaction time.

The structure of the message was designed to accommodate all information required for the correct operation of the system (see Figure 4). Blue fields represent the message header while green fields are the system payload. The length of the payload field was chosen to allow the stacking of multiple requests linked with the same destination. This approach helps to decrease wireless channel congestion by transferring multiple requests within a single medium access procedure at the MAC layer. Two timestamp fields in the payload were introduced to get a high precision timestamp of the message encapsulation. The 64 bits correspond to the resolution of one nanosecond. Based on this information, the receiving node can estimate the end-to-end delay of the corresponding transmission, while gaining information about the timeliness of the received message. The calculated end-to-end delay could also be used by the routing process at the network layer to fine-tune a next-hop selection. A detailed description of the remaining message format fields can be found in Table 2.

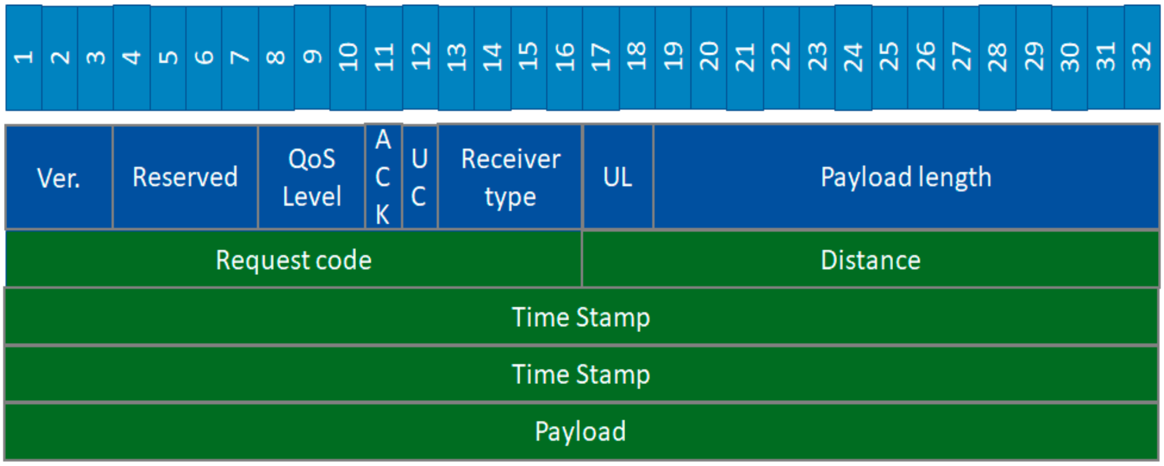

Figure 4. The message structure designed for the PEEV-WS.

Table 2. Description of message format fields.

Field	Length	Description
Ver.	3b	Version of the application-layer protocol.
Reserved	4b	Reserved for future use.
QoS level	3b	Definition of the used Enhanced Distributed Channel Access (EDCA) Access Category (AC).
Allow Acknowledgements (ACK)	1b	Allow acknowledgements: By default set to value 0. When set to 1, communication is acknowledged, and messages are not periodically resent to the destination.
Unicast mode (UC)	1b	Unicast mode: By default set to value 1 (allow unicast). If set to 0, messages are broadcasted. Broadcasting makes it possible to send PEEV-WS messages common to all drivers.
Receiver type	4b	Type of the receiver (e.g., passenger, police, public transport, etc.). Intended for future use cases, to enable coordination of emergency services.
Urgency level (UL)	2b	Urgency level: The value directly determining the mapping to the IEEE 802.11p access category, i.e., the QoS level.
Payload length	14b	Payload length.

Table 2. *Cont.*

Field	Length	Description
Request code	16b	Request code: Determines actions required from drivers.
Distance Timestamp	16b 64b	Distance in meters. Timestamp (nanoseconds).
Payload	32b	Data field containing additional information for drivers. The number of payload fields is given in the Payload length field.

4. Simulation Scenarios

To investigate the performance of the proposed system thoroughly, two traffic scenarios were designed using a realistic model of the road infrastructure of two Slovak cities: Žilina and Bratislava. These two scenarios were selected as they represent a typical layout of urban road infrastructure, where the emergency lane can be implemented. The Žilina scenario consists of a road segment belonging to the city circle, which has a higher speed limit (70 km/h) and is a highway-like multilane road without intersections. The selected road segment is frequently used by ambulance vehicles as the main ambulance station in Žilina and the hospital are located close to the endpoint. The Bratislava scenario represents a typical dense urban network with many intersections and a low-speed limit (50 km/h). Hence, the scenarios were designed to study how different environments affect the system's performance. The geometries of the road networks were extracted from the openstreetmap.org project [37] and can be compared in Figure 5. In all simulations, a sufficiently long initial phase was used to populate the road infrastructure with vehicles, before the EV entered the scene. The EV entered the simulation and started to transmit messages at the time t_{start}.

Figure 5. The road network with highlighted emergency routes (in blue): (**a**) Žilina—highway-like scenario; (**b**) Bratislava—dense urban scenario.

The movement of vehicles was modeled in the Simulation of Urban Mobility (SUMO) simulator [38]. Parameters of vehicular flows were set according to the values available in the general traffic city plans of Žilina and Bratislava [39,40]. The PEEV-WS was modeled in the Objective Modular Network Testbed in C++ (OMNeT++) discrete-event network simulator [41], using Vehicles in Network Simulation (VEINS) [42] and INET [43] simulation frameworks.

4.1. Traffic Simulation Settings

The vehicular flows were modelled by the homogeneous Poisson process. Utilizing the traffic flow data [39,40], we selected both scenarios in a way that the parameter $\lambda = 1384$ vehicles per hour, was the same for both scenarios. The initial speed of each vehicle was set to 13 m/s. The maximum speed of the EV was set to 150% of the road speed limit (in the Slovak Republic EVs can exceed the maximum road speed limits). The minimum separation between vehicles was set to 2.5 m and the Krauss car following model was used to model the behavior of drivers.

4.2. Communication Simulation Settings

Simulation parameters for the communication network were set according to the ETSI EN 302 663 [34]. Transmit power of all communication modules was set to 20 dBm, receiver sensitivity to −89 dBm, and we assumed the power of thermal noise in the communication channel to be −110 dBm. The maximum channel data rate was set to 6 Mbps to use the robust Quadrature Phase Shift Keying (QPSK) modulation. The signal path loss was modeled by the free-space path loss model.

5. Simulation Results

For each scenario and each routing protocol, we ran 15 independent simulation experiments. The average simulation run time varied strongly depending on the simulated routing protocol. For AODV and GPSR, the average simulation run time was about 30 min on the computer equipped with Intel Core i7 Central Processing Unit (CPU) and 16 GB of Random-access Memory (RAM.) A single simulation run of the DYMO protocol took up to several hours using the same simulation workstation. As the performance metrics for the communication domain, the end-to-end delay and the message delivery probability of the messages were considered. Both indicators showed high variability across individual vehicles as they strongly depend on the distance between the EV and the vehicle. For this reason, the values of indicators were evaluated for single vehicles by averaging over delivered messages. The results of the simulation experiments are presented in Table 3. The best-case value represents the average end-to-end delay calculated over all the received messages by the vehicle, with the lowest average communication delay in simulations. The worst-case value represents the same quantity for the vehicle with the maximum average communication delay. The analogous approach was applied to the average message delivery probability.

It is worth noting here that while the obtained message delivery probability values presented in Table 3 may appear to be very low even for the best-case scenarios, the values correspond to the previous observations made in the ad hoc network environment, see [44,45] for more details.

The performance of routing protocols for the two traffic scenarios differs due to the density of vehicles. Even though the traffic flow was the same in both scenarios, the lower speed limit in the Bratislava scenario implies a higher number of vehicles located in the EV's communication range. Moreover, vehicles often stopped at signalized intersections. Hence, the communication network was denser, the routing protocols could often find more than one communication route to the destination vehicle and the message delivery probability was increased.

The AODV protocol, even though reaching relatively high end-to-end latency, if compared to typical expectations, is sufficient to support the dissemination of warning system messages. The achieved latency is well below the value that could substantially affect the reaction time available to drivers. Moreover, the AODV protocol achieved the highest message delivery probability among the three investigated protocols. Unlike DYMO, the AODV protocol may use Hello messages through which a vehicle periodically checks the availability of neighboring vehicles. This helps to keep the routing table more up to date at the cost of slightly increased signalization overhead. A more up to date routing table implies increased reliability and decreased latency when transmitting payload messages. The GPRS protocol achieves very low latency and the message delivery probability is lower than 24%. This comes from the routing strategies behind the GPSR protocol as also reported in [29]. If the protocol is unable to find next hop that is geographically closer to the destination, then the protocol switches to the perimeter routing mode and the algorithm traverses the network in a counter-clockwise direction. The DYMO protocol achieves the highest end-to-end delay and its message delivery probability ranges from 4% to 53% in both traffic scenarios. Please note rather high values of the standard deviation of the end-to-end delay in the case of the DYMO protocol. These are caused by extremely large end-to-end delays of the first transmitted messages. If there is no communication route to the destination vehicle in the EV's routing table, DYMO initiates the route discovery process and the first messages are transmitted only when this process is accomplished, which in our simulation experiments took several seconds. The following messages are usually delivered with a delay in the range of tens of milliseconds.

Table 3. Comparison of routing protocols. We report the average values for the end-to-end delay of the EV to vehicle communication and the message delivery probability calculated over 15 independent simulation runs and over messages delivered to the best-case and the worst-case vehicles (row Value). The corresponding standard deviation (row σ) and the size of the 95% confidence interval (row CI95) are reported as well.

Parameter	Scenario	Vehicle		Protocol		
				AODV	GPSR	DYMO
Average end-to-end delay of EV to vehicle communication (ms)	Žilina	Best	**Value**	**0.60**	**0.73**	**48.03**
			σ	0.64	1.17	48.03
			CI95	0.02	0.10	4.77
		Worst	**Value**	**37.87**	**13.65**	**2668.90**
			σ	230.88	84.71	4588.95
			CI95	14.62	13.88	431.73
	Bratislava	Best	**Value**	**0.53**	**0.59**	**34.90**
			σ	0.12	0.11	132.18
			CI95	0.01	0.01	8.10
		Worst	**Value**	**34.95**	**6.31**	**984.85**
			σ	252.82	13.14	2713.85
			CI95	12.37	1.56	174.98
Average message delivery probability (%)	Žilina	Best	**Value**	**99.89**	**23.77**	**43.72**
			σ	0.20	2.71	3.86
			CI95	0.10	1.37	1.95
		Worst	**Value**	**22.89**	**1.11**	**3.67**
			σ	4.58	0.35	1.59
			CI95	2.32	0.18	0.81
	Bratislava	Best	**Value**	**99.90**	**23.39**	**53.41**
			σ	0.20	2.62	4.61
			CI95	0.10	1.33	2.33
		Worst	**Value**	**41.54**	**3.31**	**11.15**
			σ	16.24	0.63	8.03
			CI95	8.22	0.32	4.07

In summary, only the AODV routing protocol reached sufficiently high reliability and it will be further employed by the PEEV-WS.

When forming the emergency lane, the number of vehicles that need to be informed about an approaching EV depends on the traffic conditions (speed and traffic density). For example, considering the required communication range of 1000 m and the uniform separation between vehicles of 25 m, the number of vehicles that could occupy the emergency lane is 40. Through simulations, we investigated the number of vehicles the EV can communicate to. When using the default configuration of the AODV protocol, we found out that in the Bratislava scenario, the EV was able to communicate with all relevant vehicles, however, in the Žilina scenario, the EV could simultaneously communicate at maximum to 12 destination vehicles only, which was not enough to communicate with all relevant vehicles. Close investigations revealed that this limitation is caused by the parameter settings affecting the routing mechanism, in particular, it is given by the maximum number of route request messages that can be generated in one second, ρ_{max}. This value limits the number of messages that are sent out within one cycle by the EV, to discover the existing communication routes in the network. In the AODV protocol specification, this value is given by the value of the parameter RREQ_RATELIMIT. A relationship between the number of successfully addressed vehicles and the value of ρ_{max} is analyzed in Figure 6a while simulating the Žilina scenario.

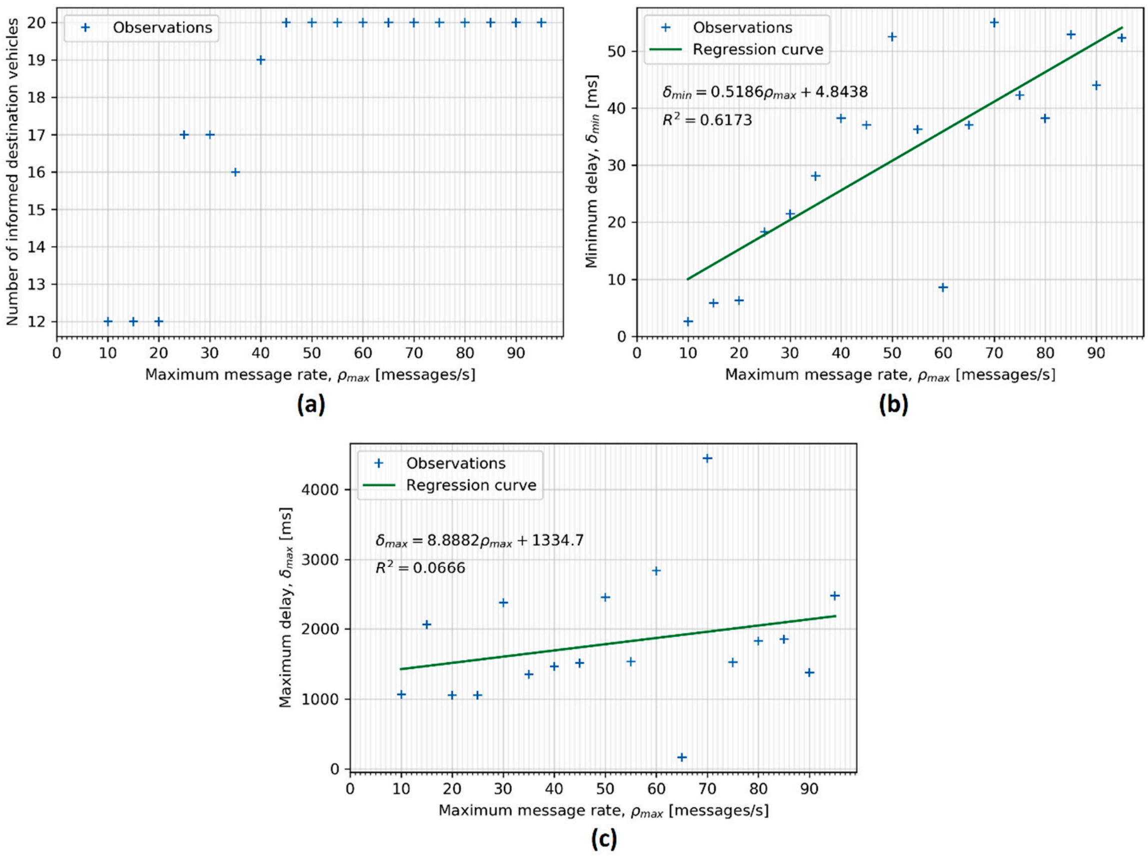

Figure 6. (**a**) The number of informed destination vehicles as a function of the maximum message rate, ρ_{max}. (**b**) The minimum end-to-end delay as a function of the maximum message rate, ρ_{max}. (**c**) The maximum end-to-end delay as a function of the maximum message rate, ρ_{max}. All panels were obtained by simulating the Žilina scenario. To facilitate the identification of the overall trend in panels (**b**,**c**), we show the line obtained by the ordinary least squares regression method.

By increasing the value ρ_{max}, the number of vehicles that the EV can communicate to increases as well. When ρ_{max} reaches 45, the number of vehicles saturates, as it has already reached the maximum number of vehicles that simultaneously occupied the emergency lane. The simulation results clearly indicate that the number of vehicles can be easily increased, however, increasing the ρ_{max} value increases the overall signalization traffic in the communication network and it could potentially increase the of end-to-end delays experienced by the PEEV-WS. In Figure 6b,c, we examine the minimum and the maximum end-to-end delay, i.e., the minimum and the maximum value of end-to-end delays across all PEEV-WS messages, as a function of ρ_{max}. In both cases, we find an increasing trend, however, considering the required reaction time, the increase in the end-to-end delay is not substantial.

To assess the system performance in the transport domain, the empirical reaction time available to drivers is evaluated. The available reaction time strongly depends on the distance between the EV and the involved vehicle at the time when the EV initiates the message transmission. Its value is naturally low for the vehicles close to the EV and it is different for every combination of transmission start time and vehicle positions. For this reason, we evaluate the system performance for individual vehicles considering the emergency scenarios Žilina and Bratislava.

The delivery time of the first message can be found in Figure 7. The time of the delivery of the first message is the difference between the time when the first message was received and the time when the first message was sent. Please note, if some messages are not delivered, then the time of delivery does not coincide with the end-to-end delay of messages.

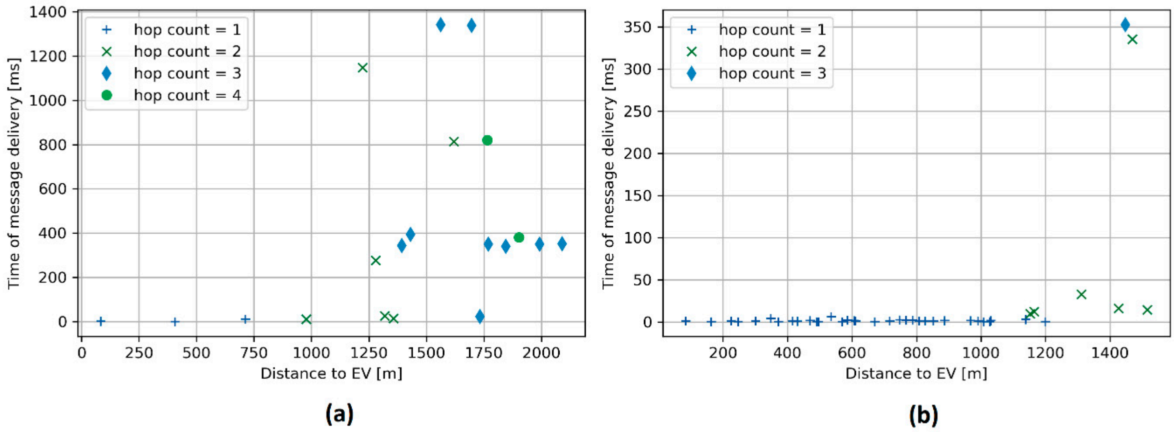

Figure 7. The delivery time of the first message versus the distance between the vehicle and the EV at the time when the first message was received in (**a**) the Žilina scenario and in (**b**) the Bratislava scenario.

If the distance between the EV and vehicle was less than 1000 m, the time of the first message delivery was negligible as in most cases one hop was sufficient. When more hops were needed the delivery time increased, nevertheless, it did not exceed 1.5 s, which is an acceptable value, considering the required reaction time. The three vehicles in Figure 7a with times of message delivery greater than 1 s, correspond to the cases when the first sent message did not reach the destination vehicle and the message was retransmitted during the following time interval.

For simplicity reasons, the time needed to present the content of the received communication message to the driver and the time a driver needs to learn the message content was neglected as it can vary depending on the utilized human-machine interface implementation. Hence, the available reaction time depends on the distance from the EV to the vehicle at the time when the first message was delivered, on the relative speed of the vehicles, and on the action taken by the vehicle driver. To estimate the lower and the upper bound of the available reaction time, we assume two hypothetical options for how the situation could unfold after the driver receives the first message informing about the approaching EV.

The first option is when the driver immediately stops the vehicle on the roadside not to be in the way of the EV (as it is currently required by the Slovak legislation). The second option is when the vehicle changes lane and EV, as well as the vehicle, continue without changing speed. In both cases, we can easily estimate the time when the EV will reach the vehicle and hence estimate the available reaction time.

In simulation, after receiving the first message informing about the EV approaching, vehicles change lane and continue driving with unchanged desired velocity. From the simulation, the available reaction time was evaluated as the difference between the time when the vehicle received the first message and the time when the EV overtook the vehicle. If in the simulation the EV did not manage to overtake the vehicle, then the value of the reaction time is not reported. All three values, the lower and upper estimates and the value of the available reaction time measured from the simulation are presented in Figure 8.

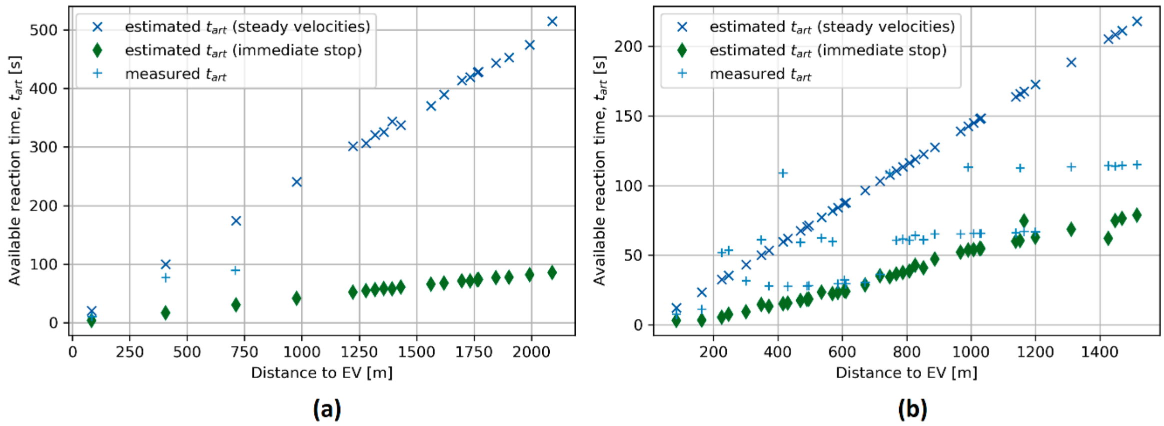

Figure 8. The available reaction time as a function of the distance between the EV and the vehicle, in (**a**) the Žilina scenario and in (**b**) the Bratislava scenario.

The linear dependency between the available reaction time and the distance from the EV to the vehicle, for the values of estimated reaction time (lower and upper bounds) indicates that the communication time takes only a small part of the reaction time. Hence, the PEEV-WS successfully manages to communicate the information about the approaching EV to the drivers. If the distance between an EV and the vehicle exceeds 300 m, the reaction time exceeds 25 s, which provides vehicle drivers with sufficient time to take an appropriate action.

In the Bratislava scenario, the free flow of vehicles is interrupted by several traffic-light-controlled intersections. The vehicles which received PEEV-WS request message changed to the rightmost driving lane. However, they could not continue their route as the rightmost lane is a turning lane. Hence vehicles stop at the intersection and wait until the EV safely overtakes them. This behavior can be observed in Figure 8b as groups of points formed at various distances and have very similar reaction times.

6. Discussion and Conclusions

The PEEV-WS, i.e., the emergency vehicle warning system deploying the VANET network, was proposed and implemented using the OMNeT++ network simulator and assessed by computer simulations. To facilitate the interpretation of the system messages, and to retain the privacy of EV's dynamic data, network layer routing was selected as the message forwarding approach for the system's messages. The performance of the three candidate ad hoc routing protocols (namely AODV, GPSR, DYMO) and the reaction time the PEEV-WS provides to drivers, were evaluated using realistic scenarios.

The simulation results suggest that the AODV protocol can support the communication generated by the PEEV-WS. The proposed system deploying the AODV network routing protocol complies with the latency requirements for the high-latency and low-frequency warning applications [32], in almost all situations. The average end-to-end delay exceeded 1000 milliseconds only for the dense urban network scenario when the EV transmitted messages to distant vehicles. In these cases, the reaction time exceeds 100 s, hence, larger delays do not affect the functionality of the system.

According to Emergency Medical Management Cooperative (EMMCO) West [46], the effective range of EV audio warning systems tops at less than 460 m in ideal conditions. When the environment is noisy and the vehicle's windows are closed, the reaction time can be as low as 4 s. The proposed EV warning system can increase reaction time significantly. Thanks to the larger communication range, which reached up to 1750 m, the maximum available reaction time reached 320 s. High values of available reaction time open a new set of issues that have to be addressed as there is no point for the driver to take any action for several minutes. On the contrary, such an action could disrupt traffic fluency and cause other unexpected effects. Therefore, especially when the available reaction time is large, the EV should update the vehicles with information about the estimated time when it is supposed to reach the informed vehicle. Hence, the methods providing predictions of the EV's driving time should be used in a V2X-based emergency vehicle warning system [47].

On one hand, the simulation results suggest that the proposed warning system is feasible. On the other hand, if the PEEV-WS is deployed in the real world, we can expect many more situations and variables that could affect the performance of the system, e.g., different traffic conditions, buildings or other constructions potentially blocking signal propagation, different routing protocols, etc. Consequently, the parameter and state spaces are huge and could not be fully explored in this paper.

It is worth noting here that the goals of deploying the V2X-based EV warning system are twofold: (i) to assist formation of an emergency lane free of obstacles; and (ii) to provide assistance in keeping the formed emergency lane clear. The system proposed in this paper covers the first aspect, while the second is left for future work. Furthermore, future work should extend the PEEV-WS to more complex use cases that go beyond the emergency lane. Another great research challenge is the transition period with a presence of mixed traffic (conventional and connected vehicles). Finally, emerging technologies with a high potential for reliable low-latency communication, in particular, 5G and vehicle-to-infrastructure communication, could be used to disseminate EV warning messages to the vehicles and connected infrastructure, e.g., traffic lights and variable message signs. The communication could be managed either via the traffic management center or locally, which will bring new challenges regarding communication latency as well as system security and safety.

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