Improving Emergency Response: An In-Depth Analysis of an ITS-G5 Messaging Strategy for Bus Blockage Emergencies at Level Crossings

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Improving Emergency Response: An In-Depth Analysis of an ITS-G5 Messaging Strategy for Bus Blockage Emergencies at Level Crossings

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Abstract

The Intelligent Transportation System protocol stack (ITS-G5/802.11p) has revolutionized traffic efficiency and road safety applications in vehicular environments. This study presents a novel architecture for communications, utilizing IPv4 multicast over 802.11p/ETSI ITS-G5, which addresses the challenges of a specific urban use case involving a Level Crossing (LC) in Bordeaux. Our proposed architecture focuses on the broadcast of Cooperative Awareness Message (CAM) and Decentralized Environmental Notification Message (DENM) to enhance road user safety. To prevent accidents, an algorithm for CAM and DENM dissemination has been devised, ensuring timely alerts for sudden vehicle blockage emergencies. Moreover, a comprehensive and optimized train braking strategy is introduced to further minimize accident risks. This strategy aims to provide efficient and timely train deceleration, allowing sufficient time for road users to clear the level crossing and mitigating the potential for collisions. To evaluate the system's performance, we analyze key metrics, including End-to-End (E2E) delay and Packet Reception Ratio (PRR). Furthermore, our work includes a comparative analysis between our proposed edge-server-based architecture and a cloud-based architecture. This analysis provides valuable insights into the strengths and weaknesses of each approach. Through comprehensive experimentation and evaluation, our proposed approach demonstrates its efficiency and effectiveness in mitigating accidents and enhancing road safety. By leveraging the capabilities of ITS-G5, our research contributes to the advancement of communication systems for intelligent transportation. The findings of this study provide a foundation for future deployments and improvements in urban environments, fostering safer and more reliable transportation systems.

Keywords: CAM, DENM, ITS-G5, Level Crossing

1 Introduction

In recent years, Intelligent Transportation Systems (ITSs) have witnessed significant advancements, aimed at improving road traffic safety, mobility, and overall transportation development [1]. These systems integrate advanced technologies, particularly in vehicular communications, to facilitate seamless connectivity. This integration encompasses various elements such as controllers and specific transportation infrastructure that enable Vehicles-to-Infrastructure (V2I) connections, including Road Side Units (RSUs). Furthermore, vehicles engage in Vehicle-to-Vehicle (V2V) communication to exchange messages. This interactive V2V mode, with distinct message definitions, types, and structures for each advanced technology, forms the environment known as the Internet of Vehicles (IoV). The IoV also encompasses other communication types, such as Vehicle-to-Everything (V2X), Vehicle-to-Network (V2N), and Vehicle-to-Pedestrian (V2P) communications [2].

These communication modes play a pivotal role in establishing a cohesive architecture that ensures high Packet Reception Ratio (PRR) and low End-to-End (E2E) delay within the designated geographical scope [2]. To ensure real-time transmissions and meet the Quality of Service (QoS) requirements of the IoV paradigm, connections rely on the European Telecommunications Standards Institute ITS 5.9 GHz band (ETSI ITS-G5) protocol, which builds upon the IEEE 802.11p access layer developed for vehicular networks [3].

Within the realm of ITS applications, the utilization of the ITS-G5/IEEE 802.11p protocol stack necessitates a communication strategy that incorporates two fundamental messaging services, known as facilities. These facilities are an integral part of the communication stack, serving as a common exploitable middleware. The first service is the Cooperative Awareness Basic Service (CAservice), which encompasses the Cooperative Awareness Message (CAM). The second service is the Decentralized Environmental Notification Basic Service (DENservice), defining the Decentralized Environmental Notification Message (DENM) [4]. As defined by the ETSI, cooperative services are provided by Personal, Vehicle, Roadside, and Central ITS-Stations (ITS-Ss) that communicate within an ITS network. ITS-Ss periodically exchange CAM messages to inform each other of their presence, positions, and status within a single hop distance. On the other hand, DENM messages can be sent in a multi-hop manner to cover a specific geographical area in emergency situations. Although the format and specifications for CAM and DENM messages are standardized, the implementation choices are left to the developers. Currently, there are limited implementations of CAM and DENM on the vehicular communications stack, leading to ongoing debates among researchers regarding their performance in real-world vehicle contexts [5]. The evaluation of these messaging services requires the use of communication methods specifically designed for their transmission.

This paper presents the integration of CAM and DENM messaging facilities and validates their functionality through a prototype implementation within an architecture deployed at a Level Crossing (LC) in Bordeaux. The chosen LC site offers relevant complexities, comprising a railway for train passage and a tramway with frequent tram crossings.

Fig. 1 depicts a picture taken during a site evaluation visit to the LC, where we assume that the emergency situation of a blocked scholar bus, with numerous students on board, represents an extremely dangerous scenario.

Fig. 1 A railway crossing located in Bordeaux, France

Consequently, when the bus becomes blocked, the periodic transmission of CAMs is interrupted, and a DENM is initiated by the bus driver using our ITS application. The DENM is disseminated to alert road users about the incident. While the CAM and DENM packet formats adhere to ETSI standards, the transmission strategy of these messages varies depending on the scenario and the employed architecture. Hence, we provide a detailed algorithm that outlines the chosen dissemination procedure, aligning with the ITS-G5 specifications. The proposed scenario is set up in an actual urban site to validate the capabilities of CAM and DENM, evaluating their effectiveness while considering factors such as vehicle density and speed variations.

This paper presents the following contributions, which have been tested to validate the ITS application services at the selected site:

1. We propose a comprehensive communication architecture leveraging IPv4 multicast over 802.11p/ETSI ITS-G5. The architecture focuses on efficient message broadcast to enhance road user safety in urban environments, with a specific use case at LCs addressing scholar bus blockage emergencies.

2. We develop an algorithm for disseminating CAM and DENM messages, enabling timely alerts to road users in the event of sudden bus blockage, ultimately preventing accidents.
3. We present a specialized braking strategy for trains with the primary objective of reducing the risk of accidents. Our strategy not only prioritizes safety but also emphasizes the comfort of passengers, even during emergency situations like a bus blockage at the LC. By enhancing response times and optimizing braking operations, our strategy ensures effective deceleration, thus significantly enhancing overall safety measures.
4. We conduct a comprehensive performance evaluation, analyzing crucial metrics including E2E delay and PRR. Throughout the evaluation, we consider varying vehicle speeds and density to accurately assess the system's efficiency and effectiveness. This thorough evaluation enables us to gauge the system's performance in real-world scenarios and validate its optimal functioning, ensuring reliable and efficient communications.
5. We compare our proposed edge-server-based architecture with a cloud-based architecture, providing insights into the advantages of edge-server-based approaches in terms of latency (LAT) and Packet Loss Rate (PLR). This comparative analysis sheds light on the superior performance and reliability of our edge-server solution in real-world scenarios.

The application of our architecture to the scholar bus blockage emergency scenario in Bordeaux serves as a validation case, but the findings and solutions presented have broader implications for enhancing transportation systems' safety and reliability in urban environments.

The remainder of this paper is organized as follows: Section 2 provides an overview of related works and existing solutions in the field. Section 3 presents our communication architecture, focusing on message broadcasting in urban environments. Section 4 outlines the algorithm for disseminating CAM and DENM messages. In Section 5, we delve into the details of our specialized braking strategy for trains. Section 6 evaluates the performance of our system, considering key metrics such as E2E delay and PRR. Section 7 compares our edge-server-based architecture with cloud-based alternative. Finally, Section 8 presents the conclusion, highlighting the contributions of our research, and discusses potential future work to further improve communication systems for intelligent transportation and enhance road safety.

2 Related Works and Existing Solutions

According to Ari Virtanen et al. [6], there has been limited attention given to investigating how vehicles can safely navigate LCs, particularly those without protection. The current state of LCs indicates that many of them remain unprotected. This study aims to address the challenges associated with vehicles approaching and traversing LCs, focusing on the behavior of vehicles, their information requirements, and safety considerations for both protected and unprotected LCs. The utilization of V2X messaging, environment perception sensors, and train monitoring technology is discussed as means to provide vehicles with the necessary information for safely crossing LCs.

It is important to highlight that the paper under discussion does not specifically propose an architecture for the broadcast of CAM and DENM messages using IPv4 multicast over 802.11p/ETSI ITS-G5. Additionally, the paper does not focus on a specific LC situated in an urban environment as an illustrative example showcasing the effectiveness of the proposed approach. Moreover, it lacks detailed information regarding the employed message structures and does not explicitly introduce a dissemination algorithm. Furthermore, the evaluation of the system does not encompass the performance assessment of DENM and CAM exchanges; rather, it solely focuses on analyzing the arrival times and directions of approaching trains at the LC. It is also worth noting that the paper does not specify any braking strategy for trains in case of emergencies.

Jayashree Thota et al. [7] conducted a study to evaluate the performance of safety broadcast messages, specifically focusing on Cellular-V2V (C-V2V) and IEEE 802.11p technologies. The objective of the study was to assess the interference between high-priority event-driven message delivery (DENM) and periodic status update messages (CAM) in a realistic highway environment. Performance metrics, including E2E delay and PRR, were utilized to evaluate the latency and reliability of the messages.

However, it is important to note that the study did not consider the impact of an urban scenario where factors like vehicle density and speed variations are significant. Additionally, the study did not provide details about the message structures employed and did not utilize the European Standard IEEE 802.11p/ETSI ITS-G5. Instead, the American Standard IEEE 802.11p/WAVE was utilized. Furthermore, it is crucial to highlight that the article exclusively focuses on Car-to-Car Safety Broadcast and does not mention the involvement of RSUs. As a result, the significant role of RSUs in disseminating CAMs, as well as decoding and rebroadcasting DENMs, is overlooked in the document.

Salim Bitam et al. [8] proposed a cloud computing model called VANET-Cloud applied to Vehicular Ad hoc NETworks in order to enhance road safety and improve the traveling experience in ITSs. The focus of their work is on providing flexible solutions to various road safety actors, such as police and emergency services, through cloud computing technologies.

While their approach offers benefits such as alternative routes and traffic light synchronization, it is important to consider the limitations of the cloud-based architecture. One significant drawback is the potential LAT and PLR associated with relying on a centralized cloud infrastructure. In contrast, our paper presents an edge-server based architecture, which offers advantages in VANETs by processing data locally. This localized approach reduces LAT and minimizes PLRs, resulting in improved real-time performance and responsiveness. By leveraging edge servers, our architecture can effectively address the challenges posed by LAT-sensitive applications in vehicular networks, ultimately enhancing road safety and user experience.

3 Enhancing Communications in Urban Environments: A Holistic Architecture

3.1 Message Formats for CAM and DENM

3.1.1 CAM message: Conveying essential status information

CAM is a recurring message of utmost importance in environments where safety is a concern, particularly for nearby ITS-Ss. The CAM comprises an ITS PDU (Protocol Data Unit) header and four containers, as depicted in Fig. 2.

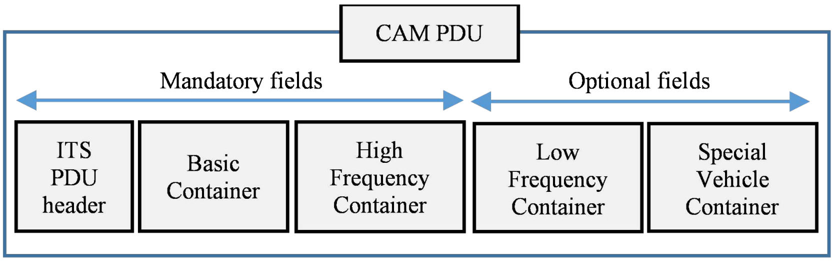

Fig. 2 CAM structure

These containers effectively organize the data fields based on the characteristics of the sender. The ITS PDU header contains critical details such as the protocol version, message type, and sender's address. The Basic Container (BC) provides essential information about the station type and its position. In contrast, the High Frequency Container (HFC) contains highly dynamic data, including vehicle heading, speed, driving direction, and acceleration. These three containers are mandatory components of the CAM. However, the inclusion of the Low Frequency Container (LFC), which holds less safety-critical data such as the sender's role or path history, is optional and may not always be included in the CAM. Similarly, the Special Vehicle Container (SVC), dedicated to special vehicle types like public transportation, hazardous material carriers, or ambulances, is included only when necessary. The container-based approach not only helps optimize the CAM size, thereby reducing the load on the wireless channel but also provides flexibility in message format customization. This allows tailoring the message format to meet the specific requirements of transmitting and receiving vehicles [9].

The rate at which CAM messages are transmitted can vary within the lower and upper limits defined by the CAM period, denoted as T. According to standardization, T_{min} is set to 100 ms, and T_{max} is set to 1 s. This implies that a CAM rate ranging from 1 to 10 messages can be achieved within a 1-second interval [9].

3.1.2 DENM message: Enhancing emergency situational awareness

When an ITS-S detects an emergency, it triggers the transmission of a safety message called a DENM. The DENM is designed to be disseminated across multiple wireless ITS-G5 hops, often employing the GeoBroadcast mode of the GeoNetworking protocol

[9]. Like the CAM, the DENM also adopts a container-based structure, as illustrated in Fig. 3.

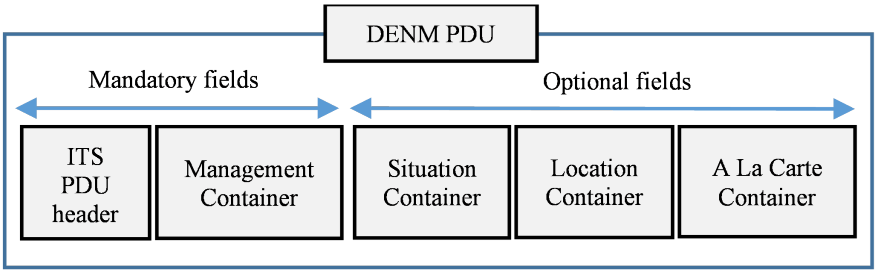

Fig. 3 DENM structure

The DENM message format incorporates the ITS PDU header and consists of several containers. The Management Container (MC) is the only mandatory container within the DENM, containing essential fields such as the action identifier (action Id), detection time, and event position. Other containers are optional and included based on specific transmission circumstances. The Situation Container (SC) provides information about the quality of information and the cause of the emergency, while the Location Container (LocCon) includes additional details such as the event's speed or heading. Additionally, an A La Carte Container (ALCC) can be introduced to convey specific content, such as lane position or road works [9].

DENM messages encompass four distinct types, each serving a specific purpose: (1) the new DENM is the initial message that informs about the occurrence of an abnormal event, (2) the updated DENM allows modification by the DENM's originator in cases where the position of the abnormal event changes, (3) the negation DENM is broadcasted by a different ITS-S to refute or counteract a previously issued alert, and (4) the cancellation DENM is issued by the source of the event once the emergency situation has concluded [9].

In our paper, we utilized these message structures due to their inclusion of essential data that aligns with the communication requirements of our approach.

3.2 A novel architecture for enhanced connectivity

In our proposed approach, we introduce the implementation of an LC infrastructure that enables seamless real-time information exchange, as illustrated in Fig. 4.

The process initiates with the detection of emergencies within the LC zone by utilizing a combination of Light Detection and Ranging (LiDAR) and two cameras. These sensors offer extensive coverage of the LC area, enabling accurate detection of emergencies. Once an emergency is detected, the information is promptly relayed to the Edge server. Subsequently, the Edge server takes charge of transmitting the alert to the RSU, ensuring that the necessary notifications reach the appropriate entities in a timely manner.

The strategic placement of the Edge server in close proximity to the RSU and the LC ensures an efficient and cost-effective installation. Functioning as an advanced

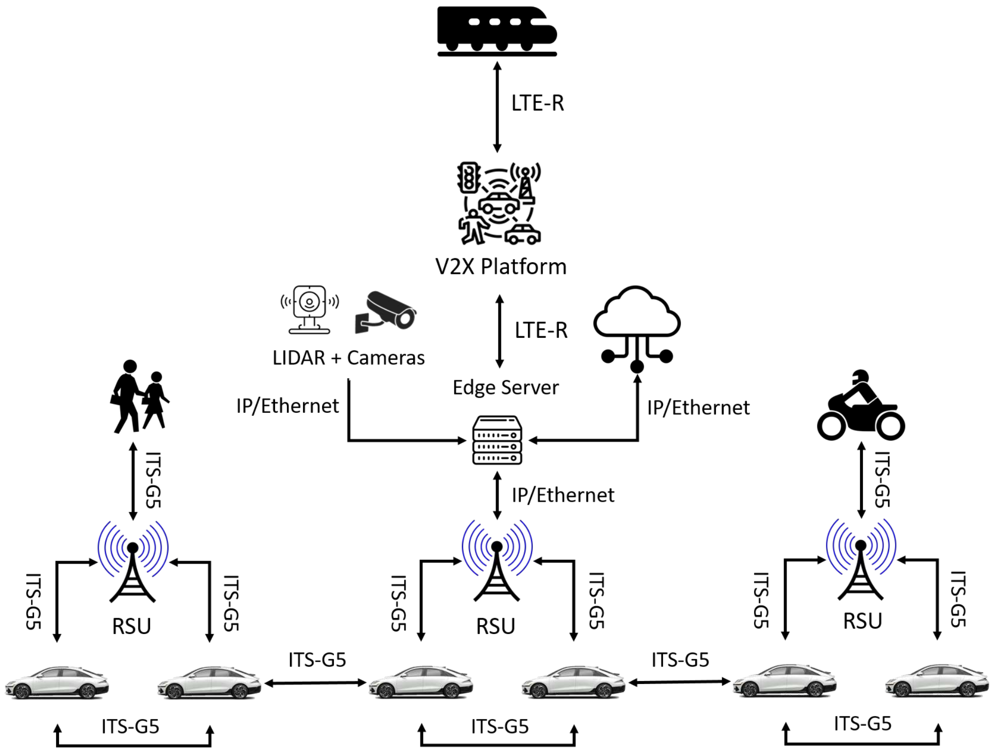

Fig. 4 Revamped Communication Architecture

computing platform at the network's edge, the Edge server enables local processing and analysis of data. This capability is vital for optimizing communication between road users and infrastructure, as well as managing the road-rail infrastructure effectively. Moreover, the Edge server serves as a higher-level computing platform that seamlessly facilitates communication and data processing between RSUs and other interconnected ITS-Ss, enhancing overall system performance and connectivity.

Furthermore, by harnessing the capabilities of the V2X platform, the Edge server establishes seamless communication with trains, promptly alerting them to any emergency situations that arise. Within a communication zone of approximately 500 meters, supporting ITS-G5/802.11p communications [10], the RSU broadcasts a DENM to nearby connected road users, effectively announcing the emergency scenario. For our study simulations, we adopt a DENM size of 300 bytes [11].

In addition to DENMs, CAMs are periodically exchanged among the various components within the environment, with each CAM message occupying a size of 500 bytes [12]. In exceptional circumstances, CAMs are transmitted with a lower priority order ρ_n, while DENMs hold the highest priority order ρ_0 on the 802.11p channel [13]. This prioritization scheme ensures that critical emergency messages (DENMs), receive immediate attention and response, while non-emergency CAMs are handled with lower priority to maintain efficient communication flow.

In our proposed architecture, the core of the communication infrastructure relies on the widely adopted ITS-G5/802.11p standard. However, there are specific communication links within the system that deviate from this standard to enhance performance and effectiveness (Fig. 4).

Firstly, we utilize IP/Ethernet as a dedicated connection to ensure efficient and reliable communication between the sensors and the Edge server, as well as between the Edge server and the RSU. This dedicated link operates independently of the ITS-G5/802.11p standard and enables high-speed data transfer, allowing for the prompt relay of critical information to the Edge server for processing and analysis.

Similarly, the Edge server establishes communication with trains via LTE-R (Long Term Evolution-Railway) through the V2X Platform. The LTE-R connection is a dedicated communication technology designed specifically for railway systems [14]. In our proposed architecture, it allows for efficient communication between the Edge server and trains, ensuring timely alerts and notifications in emergency situations.

By integrating these complementary communication channels alongside the ITS-G5/802.11p standard, our proposed architecture maximizes the overall system performance and responsiveness. It effectively harnesses the strengths of each connectivity option to enable continuous information exchange and improve the efficiency of emergency response at LCs.

Fig. 5 provides an overview of the scholar bus blockage use-case we examined. In this illustration, the tramway is seen approaching the LC precisely when the bus blockage occurs. The alert is effectively disseminated to road users, while the train remains at a distance of 5 km from the LC.

4 Algorithm for Timely Alert Dissemination

Algorithm 1 provides an overview of the message exchange strategy implemented in our scenario and Table 1 showcases the parameters utilized in the proposed algorithm.

Under normal traffic conditions, both the train and tram arrive at the LC on schedule, and vehicles in the vicinity of the LC follow regular circulation patterns. Consequently, periodic CAM messages (denoted as cam_{msg}) are exchanged at every Middleware trigger() (CA_{ser} every M_{uI}).

Given that our focus is on a specific LC with frequent bus traffic, we consider a scenario where a scholar bus suddenly stops at the LC due to a depleted battery, resulting in its speed dropping to 0 ($B_{sp} = 0$). In response, the bus driver broadcasts a DENM message ($denm_{bus}$ via $den_{ser(b)}$) with the highest priority order on the 802.11p channel (dcc::Profile::DP0). The disseminated DENM is received by an RSU (r_{RSU}), which decodes it and transmits it to the ITS-Ss within its dissemination zone ($den_{usecase(RSU)}$). Additionally, the RSU establishes IPv4 packet exchanges with the nearby Edge server ($udpapp$). These packets ($d_{m(dec)}$) contain information extracted from the received $denm_{bus}$. Subsequently, the Edge server forwards these packets to the connected infrastructure, allowing for the broadcast of the alert across a larger area. This dissemination enables other road users to become aware of the situation and adjust their behavior and speed accordingly. The transmission of DENM messages continues as long as the emergency situation persists and ceases once the unusual event concludes.

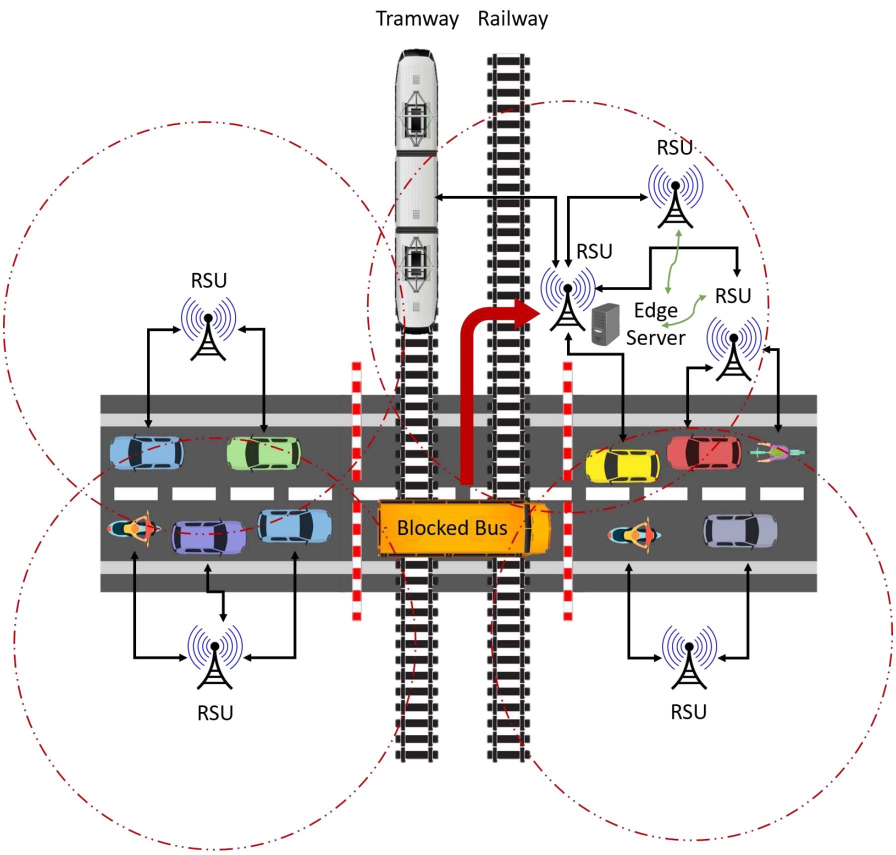

Fig. 5 Overview of Bus Blockage Use-Case

5 Optimized Braking Strategy for Trains: Enhancing Passengers' Comfort while Minimizing Accident Risks

In our experiments, we assume that the train receives the alert at the moment of the bus blockage emergency, five minutes prior to the closure of the barriers. It is expected that the train will be at a distance of five kilometers from the LC at that moment. For safety reasons, we assume that it is traveling at a speed of 80 km/h, considering it is in an urban area. To develop an optimized braking strategy that prioritizes passenger comfort and minimizes the risks of accidents, our focus lies on the driver command and its impact on the braking force in our proposed model.

In our model, the driver command, denoted as $d_c(t)$, takes its values in the interval [-1, 1], where -1 represents the maximum value for the braking force. This maximum braking capacity, determined by factors such as train speed, ensures passenger comfort while mitigating train coupler issues. When the driver applies the brakes, the driver

Algorithm 1 Messaging Strategy

Input: B_{sp}, r_{RSU}
Output: $d_{m(dec)}$, $denm_{bus}$, cam_{msg}
Initialize: CA_{ser}, $den_{ser(b)}$, $den_{usecase(RSU)}$, M_{uI}, *udpapp*

while *simtime* $t <$ *end simtime* t_{end} **do**
    Activate CA_{ser} every M_{uI}
    Disseminate cam_{msg}
    if $B_{sp} = 0$ **then**
        Activate $den_{ser(b)}$
        Disseminate $denm_{bus}$ (dcc::Profile::DP0)
    else
        Keepgoing()
    end if
    while $den_{ser(b)}$ is activated **do**
        if r_{RSU} = true **then**
            Activate $den_{usecase(RSU)}$
            Start *udpapp*
        end if
        while *udpapp* is launched **do**
            Decode $denm_{bus}$ (by the considered RSU)
            Send $d_{m(dec)}$ to the Edge server
            Send $d_{m(dec)}$ from Edge server to infrastructure
        end while
    end while
end while

Table 1 Identification of the employed parameters

B_{sp}	Bus speed
r_{RSU}	RSU reception of the DENM disseminated by the bus
$d_{m(dec)}$	Decoded DENM
$denm_{bus}$	Bus DENM diffused when the emergency takes place
cam_{msg}	CAM
CA_{ser}	CAservice for present ITS-Ss
$den_{ser(b)}$	Bus DenService
$den_{usecase(RSU)}$	RSU's DENM dissemination usecase
M_{uI}	Middleware updateInterval
udpapp	for ipv4 packets exchange between Edge server and RSUs

command becomes negative, indicating the utilization of the maximum braking capacity. For instance, a driver command of $d_c(t) = -0.7$ at a specific time t signifies that the driver is utilizing 70 % of the maximum braking capacity. By plotting the graph $d_c = f(t)$ and considering both the traction and braking torques, we gain valuable insights into the driver's braking behavior and the effective utilization of the braking force, thus enabling the development of an optimized braking strategy (see Fig. 6).

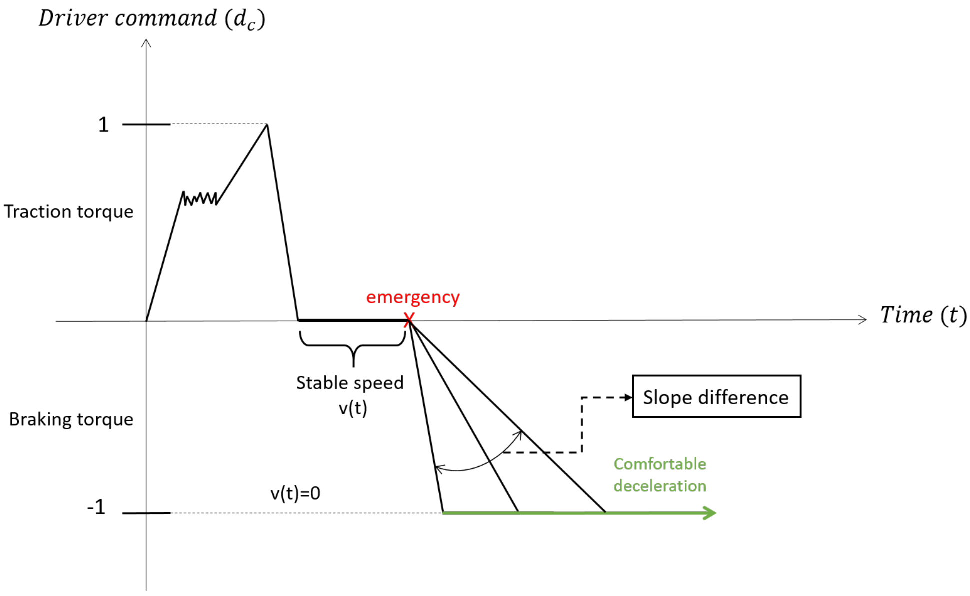

Fig. 6 Effect of Driver Command on Comfortable Braking

By focusing on the driver command within the specified interval and considering the interplay between the traction and braking torques, our goal is to design a braking strategy that enhances passengers' comfort while minimizing the risks of accidents during train operations.

Knowing the driver command allows us to accurately determine the Longitudinal Braking Force (F_{br}^{Long}(N)) in our optimized braking strategy for trains. This force is calculated by multiplying the driver command input $d_c(t)$ by the maximum braking capacity ($Cap_{br}^{\max}$(N)):

$$F_{br}^{Long} = d_c(t) \times Cap_{br}^{\max} \tag{1}$$

where,

$$d_c(t) \in [-1, 0] \tag{2}$$

To accurately estimate the train's deceleration, we divide the Longitudinal Braking Force by the total mass of the train ($Mass_{tr}$). The total mass of the train encompasses the combined weights of its various components, including passengers and cargo. Mathematically, the total mass of the train (expressed in kg) can be represented as the sum of individual component masses as shown in (3):

$$Mass_{tr} = \sum_{i=1}^{n} m_i \tag{3}$$

The deceleration ($Dec_{tr}(m/s^2)$) of the train, is then calculated as follows:

$$Dec_{tr} = \frac{F_{br}^{Long}}{Mass_{tr}} \tag{4}$$

The deceleration process during railway braking maneuvers is significantly influenced by the wheel-rail adhesion phenomenon, particularly under degraded conditions. Our objective is to optimize the anti-slip algorithms, aiming to minimize damage to the wheel and rail profiles while improving the overall comfort of the braking process, especially in emergency scenarios requiring sudden deceleration. Furthermore, the wheel-rail contact occurs in an open environment, where external elements can potentially alter the adhesion conditions, resulting in the formation of an intermediate layer between the two surfaces. Various substances like water, oil, grease, leaves, and snow can be present at the wheel-rail interface, significantly affecting the adhesion coefficient.

In order to incorporate the influence of meteorological factors on the deceleration process, we put forward a refined approach that involves calculating the adjusted deceleration $\tilde{Dec}_{tr}^{adj}(m/s^2)$. This calculation takes into account both the previously estimated deceleration and the adherence coefficient, as represented by (5):

$$\tilde{Dec}_{tr}^{adj} = Dec_{tr} \times \mu_{adh} \tag{5}$$

The adherence coefficient represents the influence of external substances and environmental conditions on the adhesion properties between the wheel and rail surfaces. By incorporating this coefficient into the deceleration calculation, we can account for the specific meteorological factors affecting the braking performance. The following table presents the adherence coefficients we have proposed, taking into consideration various meteorological factors:

Table 2 Adherence Coefficients for Meteorological Factors

Meteorological Factor	Adherence Coefficient (μ_{adh})
Dry Conditions	0.95
Wet Conditions	0.80
Snow-covered Rail	0.60
Leaf-covered Rail	0.70
Oil or Grease on Rail	0.50

The values of the adherence coefficients in the table are determined based on empirical observations, experimental data, and prior research in the field of railway braking systems. They represent typical values that have been found to reasonably approximate the adhesion conditions under different meteorological factors.

For example, the coefficient of 0.95 for dry conditions indicates a high level of adhesion between the wheel and rail surfaces when they are free from moisture or contaminants. On the other hand, wet conditions reduce the adhesion, resulting in a coefficient of 0.80 to reflect the decreased traction between the surfaces.

Similarly, the coefficients for snow-covered rail, leaf-covered rail, and oil or grease on rail represent the further reduction in adhesion caused by the presence of these specific substances. These values, such as 0.60 for snow-covered rail, 0.70 for leaf-covered rail, and 0.50 for oil or grease on rail, reflect the additional challenges and reduced friction between the wheel and rail surfaces due to these factors.

It is important to note that these employed values may vary depending on specific environmental conditions, railway infrastructure, and the type of train and braking system being used. In this paper, they are provided as a general guideline to help account for meteorological factors in the proposed adjusted deceleration calculation, but further research and analysis may be necessary to fine-tune these coefficients for specific contexts or scenarios.

Upon receiving the alert, the train initiates the braking process. By employing the adjusted deceleration, we can determine the braking distance $D_b(m)$ using the following formula:

$$D_b = I_s \times (t_{p+e} + \frac{I_s}{2 \times (\tilde{Dec}_{tr}^{adj} \pm \frac{9.81 \times S_p}{10^3})}) \quad (6)$$

where,

$$t_{p+e} = t_p + t_e, t_p > 0, t_e > 0 \quad (7)$$

Here, $I_s(m/s)$ represents the Initial Speed of the train at the reception of the alert, t_{p+e} is the time required to establish the braking force, which is the sum of the propagation time in the train t_p and the setting time in the convoy's vehicles t_e. S_p represents the gradient (‰), which is negative only in descent.

The graph presented in Fig. 7 illustrates the calculated braking distances based on the DE-OCF diagrams of brake evaluations [15]. This method will be referred to as T1. Additionally, Fig. 8 provides a comparison between the values obtained in Fig. 7 and the calculated braking distances for the train [16] using equation (6). This method will be referred to as T2.

Upon close observation, it can be noticed that for a braking factor λ of 100 % and a speed of 80 km/h, T1 suggests a braking distance of 254.16 m, while T2 suggests a distance of 270.8 m for the train to come to a complete stop.

It is interesting to note that in our scenario, the train needs to be alerted in advance to ensure a safe braking distance, as it receives the warning notification at the moment of the bus blockage and begins braking five kilometers before the closure of the barriers. Considering that the train is a passengers' train, ensuring passengers' comfort is of utmost importance, and an increased braking distance provides added safety. Therefore, T2 is considered the preferable strategy for the train's braking.

Through the exchange of recurring CAMs, the local Edge node identifies the precise location of the train when the railway is obstructed by a scholar bus. Subsequently, upon receiving a DENM indicating the hazardous situation, the train enters a state of temporary suspension, awaiting further notification from the Edge node confirming the resolution of the issue. This mechanism ensures the safe resumption of the train's journey and effectively prevents potential collisions.

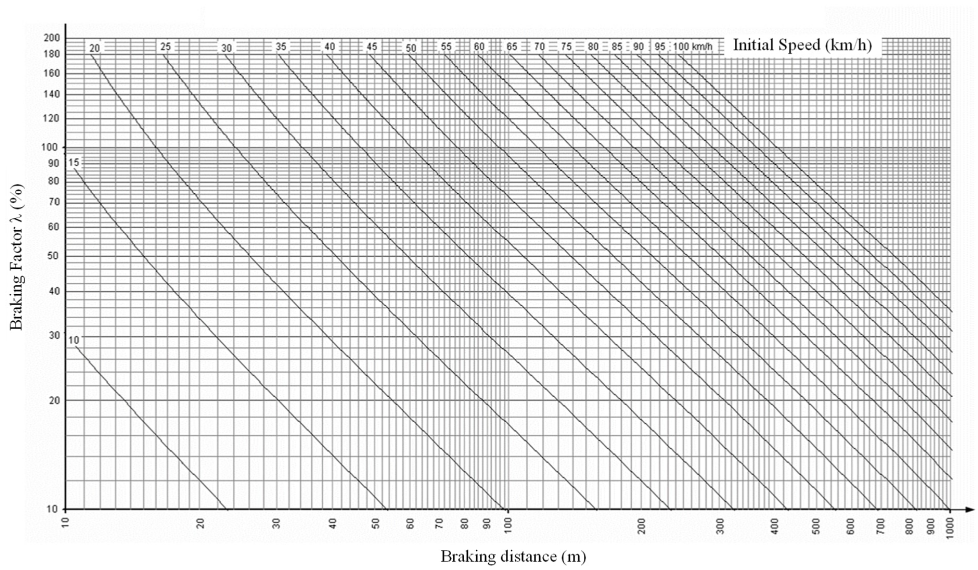

Fig. 7 Braking Distances Based on DE-OCF Brake Diagrams (T1)

6 Performance evaluation: Analyzing E2E delay and PRR with vehicle speed and density variations

We conducted simulations using OMNeT++ [17], SUMO Framework [18], and Unity 3D [19] to evaluate the proposed approach for the mentioned use case. Our primary goal was to validate the effectiveness of the suggested approach through these simulations. In this section, we present a performance evaluation of our scenario, focusing on E2E delay and PRR metrics. To assess its efficacy, we perform a comparative analysis between our findings and the results presented by J. Thota et al. in [7].

Fig. 9 illustrates the PRR for DENM exchange in the presence of interference from CAMs, considering the variation in vehicle flow.

The speed of the vehicles in this scenario is set to 30 km/h (an example value, as real velocities in urban areas can reach 50 km/h or higher). Observing the graph, it can be noted that the PRR for V2V transmissions (labeled as Vehicles PRR) ranges from 59 % to 51 % as the number of cars in the LC zone increases. Considering V2I communications (labeled as RSU PRR), the minimum PRR value is approximately 64 %, while the maximum value reaches 74 %.

We assume that these PRR values meet the requirements of our scenario. As shown in Fig. 9, the average PRR for all types of ITS Stations' connections (V2V and V2I) is around 57 % when the number and positions of vehicles change in the LC zone. It increases to 66 % when there are fewer cars in the LC zone. It is important to note

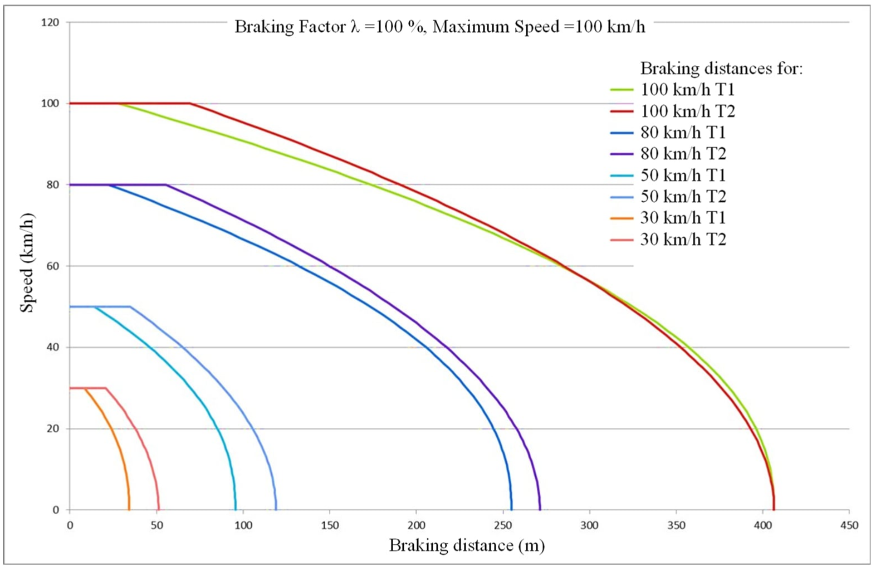

Fig. 8 Comparative Analysis of Braking Distances: T1 vs. T2 Strategies

that our PRR calculation strategy takes into account the Packet Error Rate, ensuring that the reported results are obtained after eliminating erroneous packets.

Fig. 10 provides a comparison of our PRR values with the results obtained in [7], which also examines the performance of a safety broadcast system under the transmission of emergency DENMs with interference from periodic CAMs.

Our scenario achieves a maximum average PRR value of 66 % when considering distances ranging from 520 meters to 600 meters from the LC (labeled as IEEE802.11p-Multihop (V2V/V2I) on the graph). This range corresponds to the point where cars start entering the simulated LC zone. We believe that this value is significant, especially when compared to a PRR value close to 0 for distances greater than 520 meters in the evaluation presented in [7]. Moreover, it is noteworthy that [7] focuses on a rural area where interferences are expected to be less prominent compared to an urban area. Despite using various Forward Error Correction (FEC) schemes such as repetition code, RQ code (APP), and RQ code (MAC), none of them contributed to achieving an acceptable PRR value beyond 520 meters.

In our simulation, we use the terms "latency" and "E2E delay" interchangeably. We consider the complete delay experienced by packets from source to destination. This approach allows us to focus on the overall delay without distinguishing between specific components.

Fig. 11 and Fig. 12 showcase the latency in our scenario, examining both V2V and V2I communications, while accounting for fluctuations in vehicle density. The vehicle speed is set to 30 km/h in the first case and 60 km/h in the second. Our approach exhibits latency ranging from 1 ms to 35 ms for vehicles traveling at a speed of 30 km/h. However, when the speed increases to 60 km/h, the latency remains below 33 ms with a minimum value of 1 ms. The average latency in our scenario ranges from

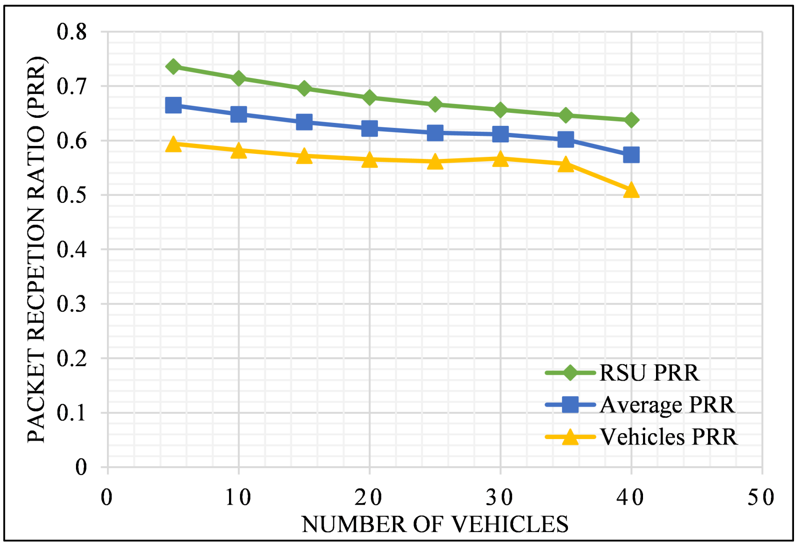

Fig. 9 Packet Reception Ratio (PRR) Variation with Vehicle Density in the Level Crossing Zone

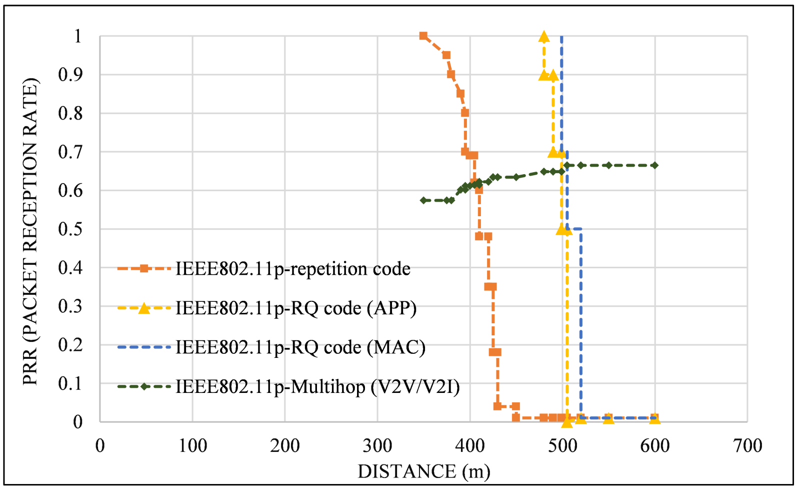

Fig. 10 Comparison of Packet Reception Ratio (PRR) Values at Varying Distances

2 ms to 20 ms for vehicles traveling at a speed of 30 km/h, considering variations in vehicle density. Similarly, for a speed of 60 km/h, the average latency ranges from 2 ms to 18 ms across all vehicles. Notably, we observe that latency improves as vehicle speed increases, bringing the vehicles closer to the LC and the infrastructure. These evaluations consider the nearest RSU to the LC.

Despite the variations in vehicle speeds, distances, and densities, our proposed approach consistently achieves an average latency of less than 20 ms. This value is noteworthy when compared to the E2E delay obtained in [7], which exceeds 20 ms when the distance exceeds 488 meters using various FEC schemes as depicted in Fig.

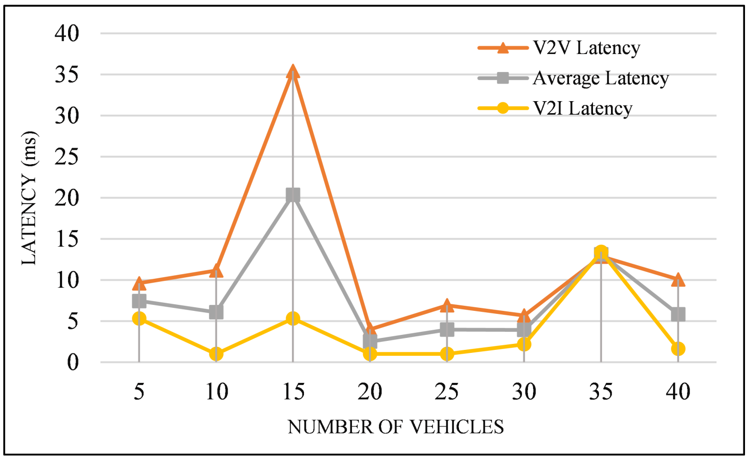

Fig. 11 End-to-End Delay Variation with Vehicle Density in the Level Crossing Zone at a Speed of 30 km/h

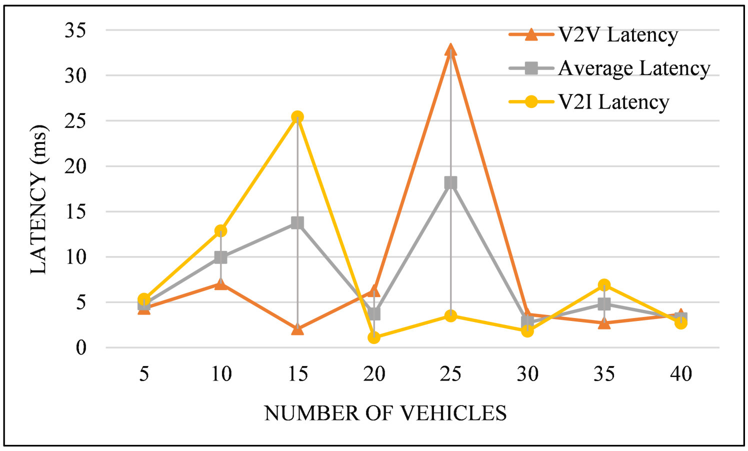

Fig. 12 End-to-End Delay Variation with Vehicle Density in the Level Crossing Zone at a Speed of 60 km/h

13. In our study, represented as IEEE802.11p-Multihop (V2V/V2I) on the graph, we demonstrate the effectiveness of our approach in maintaining low latency even under challenging conditions.

7 Comparative analysis: Edge-server-based vs. cloud-based architectures

Through the evaluation of our simulated scenario for detecting emergency situations involving blocked buses at the LC, we assess the performance of our communications based on the edge infrastructure and compare it to the performance of the centralized cloud-based communications [8]. This comparison demonstrates the effectiveness of

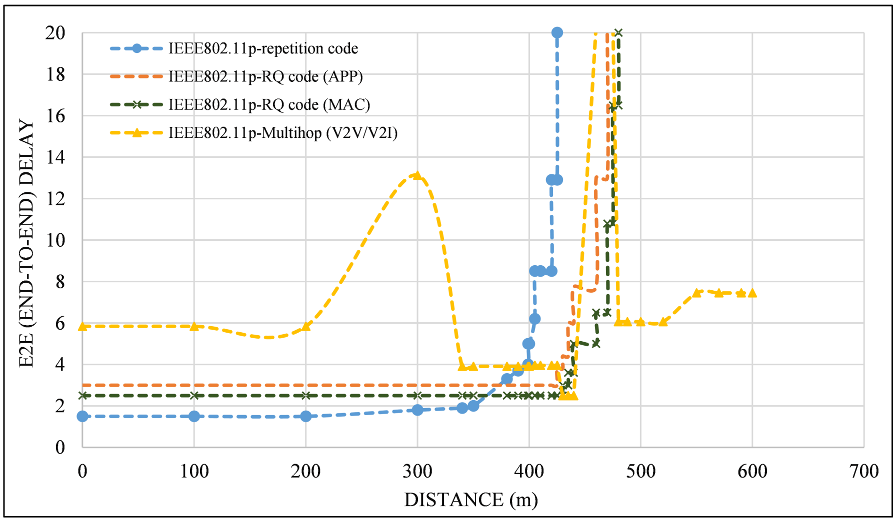

Fig. 13 Comparison of End-to-End (E2E) Delay Values at Varying Distances

our approach. Additionally, our goal is to showcase the real-time packet transmission capability of our proposed IoV paradigm. Contrasting the centralized cloud-based message exchange, Fig. 14 illustrates the relatively low message latency achieved through the utilization of the edge infrastructure.

For clarity, the graph focuses on specific simulation time points without specifying the scale on the x-axis. The results reveal that the average latency for edge-based exchanges is significantly negligible, with packet transmission taking only a few microseconds on average (349.7254 μs), ensuring real-time communication. This is particularly crucial in our case as we strive to promptly notify other road users of emergencies as they occur. Conversely, the graph in Fig. 14 demonstrates that cloud-based communications exhibit a latency of a few milliseconds (average of 2.465361807 ms), which falls short in guaranteeing accident prevention.

In order to further highlight the effectiveness of our approach, we conducted an analysis of packet loss rates for both the edge-based infrastructure and the cloud-based alternative. The results, presented in Fig. 15, reveal an impressively low average loss rate of only 3.4375 % for the Edge Infrastructure. This stands in stark contrast to the loss rate observed in the cloud infrastructure, which varies from 66.66 % for the first sent packet to 16.16 % for the last sent packet. It is important to note that the x-axis of the graph does not have a specified scale, and only the most relevant moments of packet exchange during the simulation time are considered for clarity.

These findings clearly demonstrate the significant disparity in latency and packet loss rates between the two alternatives, providing strong justification for our choice of an edge-based infrastructure to ensure the security of the LC zone during emergencies such as the blocked scholar bus scenario.

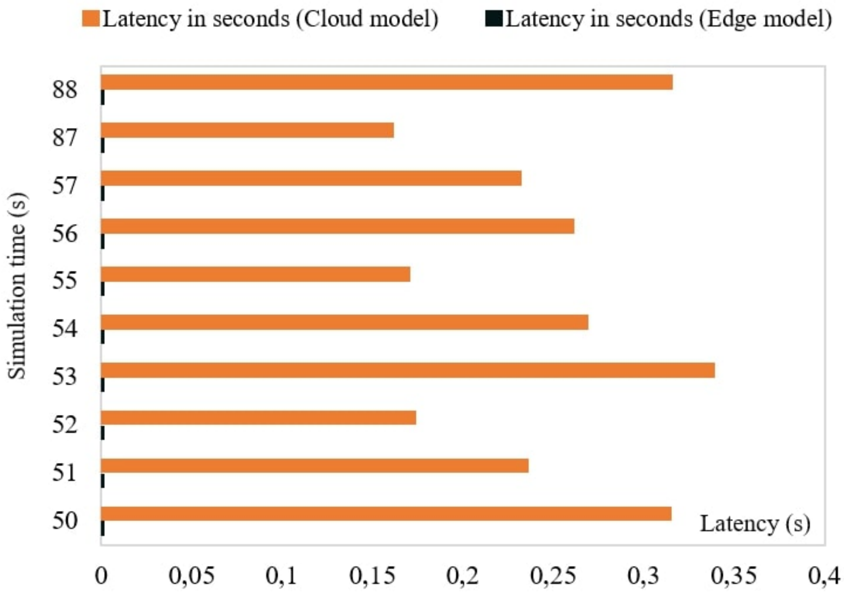

Fig. 14 Comparative Latency Analysis: Cloud-Based Architecture and Edge-Based Infrastructure

8 Conclusion and future works

In this study, we presented a novel approach for messages exchange in the context of ITS, focusing on the specific use case of scholar bus blockage emergency at the LC. By leveraging the capabilities of the ITS-G5/802.11p protocol stack, our proposed approach demonstrated its efficiency and effectiveness in enhancing road safety and mitigating accidents.

We developed a comprehensive communication architecture that utilized IPv4 multicast over 802.11p/ETSI ITS-G5, enabling efficient message broadcast for road user safety in urban environments. Our algorithm for disseminating CAM and DENM ensured timely alerts in the event of sudden bus blockage, thereby preventing accidents. Additionally, we introduced a specialized braking strategy for trains to minimize accident risks at LCs. Through extensive performance evaluations, we analyzed key metrics such as E2E delay and PRR, considering variations in vehicle speeds and density. The results validated the effectiveness of our architecture, showcasing low latency and high PRR.

Our comparative analysis between the proposed edge-server-based architecture and the cloud-based alternative provided valuable insights into the strengths of edge-server-based approaches, particularly in terms of latency and packet loss rate. The findings highlighted the superiority of our approach in ensuring real-time transmissions and reliable communication within the designated geographical scope.

Our research contributes to the advancement of communication systems for intelligent transportation, specifically in addressing bus blockage emergencies at LCs. The validated architecture and dissemination algorithm offer a foundation for future

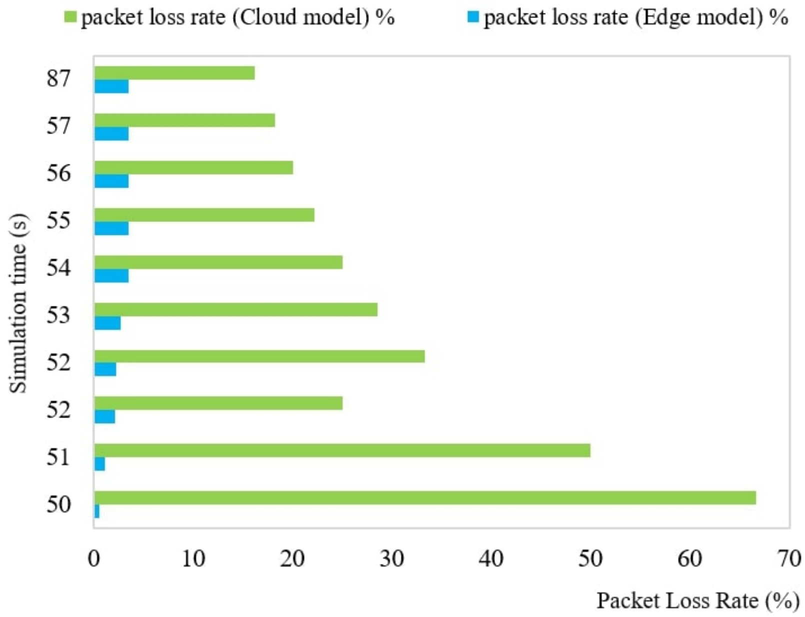

Fig. 15 Comparison of Packet Loss Rates between Edge-Based and Cloud-Based Models

deployments and improvements in urban environments, fostering safer and more reliable transportation systems.

For future works, we envision several directions for further enhancing communication strategies in ITS. Firstly, conducting additional field tests and validations in diverse urban environments would provide a broader understanding of the approach's applicability and effectiveness. Secondly, considering the scalability of the proposed approach and its compatibility with different vehicle types and communication protocols would be essential for wider adoption. Finally, conducting user studies and gathering feedback from stakeholders, including road users and transportation authorities, would be valuable in refining the architecture and addressing practical challenges.

Our research sets the stage for future advancements in intelligent transportation communication systems, emphasizing the importance of real-time, efficient, and reliable communication for enhancing road safety and mobility in urban environments.

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