Simulation of Emergency Vehicles in Connected and Autonomous Traffic

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Simulation of Emergency Vehicles in Connected and Autonomous Traffic

Giel Oosterbos
January 2023

EINDHOVEN UNIVERSITY OF TECHNOLOGY

Stan Ackermans Institute

SMART BUILDINGS & CITIES

Simulation of Emergency Vehicles in Connected and Autonomous Traffic

By

Giel Oosterbos

A thesis submitted in partial fulfillment of the requirements for the degree of Engineering Doctorate (EngD)

The design described in this thesis has been carried out in accordance with the TU/e Code of Scientific Conduct

dr. Dujuan Yang and ir. Alex Donkers, university supervisors

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Executive Summary

In 2019, the number of deaths on European roads reached 22,800, with an additional 120,000 people suffering serious injuries. In this light, the European Commission's 'Vision Zero' target of reducing the number of road deaths and serious injuries to almost zero by 2050, seems extremely ambitious.
Research indicates that human error is the primary cause of 90% of all road accidents. This turns the European Commission into a big proponent of the upcoming digital technologies in road transportation: connectivity and automation.
In this study, the new opportunities that connected and automated mobility offer for emergency service operations are investigated. Three complementary services for Cooperative Intelligent Transport Systems (C-ITS) are proposed to improve the safety of emergency vehicles and to reduce emergency response time.
The first two services were implemented in the microscopic traffic simulator SUMO. The effectiveness of these services was evaluated in a realistic morning and evening traffic scenario on the road network of the city center of Eindhoven. The first service, referred to as the Traffic Signal Priority Service (TSPS), prioritizes emergency services at signalized intersections by adjusting the traffic light cycle in favor of the emergency vehicle (EMV). The service is activated when an EMV reaches a specified distance from the intersection.
Results of the simulation showed that the optimal activation distance for the service was 800 m. In this configuration, a thirty seconds reduction of the response time was achieved for emergency routes within the city center. Meanwhile, the average speed of the other traffic participants decreased by 0.7%. Furthermore, this service removes the need for emergency services to violate red traffic lights, improving their safety significantly.
The Vehicle Rerouting Service (VRS) redirects other traffic participants away from the emergency route to reduce delays for the EMV in high-density traffic. This service achieved a similar reduction in emergency response time as the TSPS, but had a greater impact on the average speed of the other traffic participants, which decreased by 13.8%.
The Maneuver Coordination Service was implemented as a ROS2 node and evaluated using the CARLA simulation environment and the Autoware.auto autonomous driving stack. This service prioritizes emergency vehicles at unsignalized intersections in fully connected and automated traffic. When an approaching vehicle transmits its priority request, the MCS determines an appropriate maneuver for all connected and automated vehicles (CAV). Based on their distance with respect to the intersection and their current speed, the CAVs either receive the advice to stop in front of the intersection or pass the crossing before the EMV arrives.
The MCS was tested in scenarios with varying request ranges, vehicle speeds, and communication latency. The service was demonstrated to ensure safety when applied to scenarios with a single CAV and an appropriately sized request

range. However, for scenarios involving multiple CAVs the MCS should be extended to provide the EMV with an alternative trajectory. Additionally, it is crucial that the autonomous vehicles have the ability to ensure their own safety in the event of a communication failure.
In summary, this study demonstrates that emergency services can definitely benefit from the introduction of connected and automated traffic. Customized services were found to effectively reduce response times and enhance road safety for emergency vehicles.

Acknowledgments

First of all, I would like to thank my primary university supervisor Dr. Dujuan Yang for her consistent guidance along the sometimes bumpy road of my (PD)Eng(D) program. I am very grateful for the freedom she gave me to explore different domains while always staying engaged and supportive.

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Ir. Alex Donkers, soon to be Dr. Ir., maybe some time Prof. Dr. Ir., and who knows what else? Thank you Alex for stepping into my project and sharing your ideas, your concerns, and your energy!

There is literally no chance that this document would exist without them, so a little shoutout to my boomers at home, merci Karen and Michel!

I obviously also want to thank the rest of my family, my friends, and my colleagues. Naming them would probably lead us too far. I'll just send all of you lots of love and appreciation!

#PositiveVibes< 3

Giel Oosterbos

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List of Abbreviations

ADAS Advanced Driver-Assistance Systems

C-ITS Cooperative Intelligent Transport Systems

C-V2X Cellular Vehicle-to-Everything

CACC Cooperative Adaptive Cruise Control

CAM Cooperative Awareness Messages

CAV Connected and Automated Vehicle

CEN European Committee for Standardization

CPM Collective Perception Messages

CPS Cooperative Perception Service

DENM Decentralized Environmental Notification Messages

DRAC Deceleration Rate to Avoid a Crash

EMV emergency vehicle

ETSI European Telecommunications and Standardization Institute

EVW Emergency Vehicle Warning

GLOSA Green Light Optimal Advisory

iTLC intelligent Traffic Light Controllers

ITS Intelligent Transport Systems

MCM Maneuver Coordination Message

MCS Maneuver Coordination Service

ODD Operational Design Domain

OEM Original Equipment Manufacturers

OHCA out-of-hospital cardiac arrest

PET Post-Encroachment Time

QALYs quality-adjusted life years

RR Request Range

SAE Society of Automotive Engineers

SSM Surrogate Safety Measures

TLC Traffic Light Controllers

TSPS Traffic Signal Priority Service

TTC Time-To-Collision

V2N Vehicle-to-Network

V2V Vehicle-to-Vehicle

VREM Vehicle Rerouting Effort Multiplier

VRS Vehicle Rerouting Service

1 Introduction

1.1 Background

As of 2023, the globalized world faces a plethora of challenges, ranging from climate change and environmental degradation to global health issues and inequality. Addressing these worldwide problems will require international collaboration and cooperation. Particularly in the current geopolitical climate, this may evoke pessimism. While some argue that scientific breakthroughs and technological advancements will play a crucial role in solving these issues over time, others also stress the potential drawbacks of upcoming disruptive technologies. In the past decades, digitization has had a profound impact on our society, changing the way people work, shop, and communicate. Current trends indicate that its role in our lives will only become bigger with the surge of artificial intelligence applications, greater connectivity, further virtualization, and increasing automation.

Digitization also has the potential to transform the transport system into a greener, smarter, and more resilient sector. The COVID-19 pandemic caused a shock that turned telecommuting into a mainstream business from one day to the next, avoiding millions of daily commuting trips worldwide [1]. Municipalities acknowledge the adverse effects of the endless stream of polluting cars that pass through their city centers and are therefore introducing low-emission zones and multi-modal mobility hubs [2]. Digital applications can facilitate smooth transitioning between different transport modes at these hubs.

On the road, there is a clear trend towards increased connectivity and automation. Standardization efforts are performed to enable the exchange of information between vehicles and the road infrastructure. Meanwhile, modern cars are equipped with an increasing amount of systems to automate specific driving tasks. Interconnecting vehicles and automating driving tasks go hand-in-hand to increase traffic efficiency and improve road safety. Some even argue that connectivity is a requirement to guarantee safe autonomous driving [3].

1.1.1 Connected Traffic

In a connected traffic system, vehicles are equipped with communication devices that enable them to exchange information with other vehicles and the road infrastructure. When these systems (vehicles and roadside units) can process each other's data to cooperate, they are called Cooperative Intelligent Transport Systems (C-ITS). The applications of C-ITS can be roughly divided into three categories: traffic safety, traffic efficiency, and value-added services.

In 2009, the European Commission requested standardization organizations CEN, CENELEC, and ETSI to 'prepare a coherent set of standards, specifications and guidelines to support European Community wide implementation and deployment of Co-operative ITS systems' [4]. Following this request, CEN became responsible for the domain of traffic efficiency, while ETSI focuses on traffic safety. In 2014, the basic set of standards for C-ITS was completed as the so-called Release 1 specifications [5].

The European Committee for Standardization (CEN) maintains the DATEX II standard, which is the electronic language that allows smooth exchange of traffic management information in Europe [6]. Furthermore, CEN developed standards for the eCall system, which automatically informs emergency services in case of a serious crash, reducing emergency response time [7]. Since April 2018, all new vehicle models and light vans are by European law required to be equipped with eCall.

The European Telecommunications and Standardization Institute (ETSI) defined standards for the entire C-ITS protocol stack. The standards relate to the network and transport layer, security and privacy, application requirements, and facilities to support C-ITS applications.

The cooperative awareness basic service is specified by ETSI to inform traffic participants and road infrastructure of each other's location, dynamics, and attributes, such as activated systems and vehicle dimensions [8]. This information is structured and transmitted in so-called Cooperative Awareness Messages (CAM).

Decentralized Environmental Notification Messages (DENM) are disseminated to indicate the occurrence of events that potentially impact traffic safety or road conditions [9]. In combination with the cooperative awareness service, DENMs can be used for applications like Intersection Collision Risk Warning [10] and Longitudinal Collision Risk Warning [11].

The Cooperative Perception Service (CPS) allows ITS stations to share information on detected objects with each other and could help in the detection of non-connected traffic participants [12]. Furthermore, the exchange of Collective Perception Messages (CPM) could lift autonomous vehicles from their single point of view perspective, allowing them to perceive their environment beyond the limitations of their own sensors.

ETSI is still working on the first public version of an Maneuver Coordination Message (MCM), which would mainly target applications for automated vehicles. However, the TransAID project has already experimented with this concept and has developed a message structure resembling the other ETSI messages very much [13]. Their MCMs allow vehicles to share planned and desired trajectories and enable roadside units to propose specific maneuver advice.

On the physical level, the 5.9 GHz frequency band is designated worldwide for C-ITS use cases. More specifically, the European Commission allocates the frequency range between 5,875-5,925 GHz for safety-related applications, while frequencies between 5,855-5,875 GHz can be used for non-safety applications [14]. Furthermore, the European Commission takes a technology-neutral position with respect to the use of this spectrum. This allows for competition between two access layer technologies, i.e., ITS-G5 and Cellular Vehicle-to-Everything (C-V2X).

ITS-G5 technology is an adaption of the IEEE 802.11p standard, part of the Wi-Fi family, and was standardized by ETSI. The name refers to Intelligent Transportation Systems communicating in the 5.9 GHz frequency band. ITS-G5

does not require an external network and is a so-called short-range technology. C-V2X, on the other hand, is based on cellular networks such as 5G and is developed by 3GPP. Vehicle-to-everything refers to the fact that vehicles can communicate with other vehicles (V2V), infrastructure (V2I), and an existing cellular network (V2N). Two modes are distinguished in C-V2X, a direct short-range mode and an indirect long-range mode that requires an existing cellular network.
An experimental comparison of the two short-range technologies indicate that while direct C-V2X has a longer range, ITS-G5 generally achieves a lower latency [15]. The same study showed that performing software-based security checks on the received messages drastically increases latency, though it stays below 100 ms for both technologies. For indirect 4G C-V2X, no packet loss was observed. However, the latency was significantly larger and occasionally increased above 100 ms, which should be treated as packet loss on the application level. Therefore, it is argued that long-range technology is less suitable for safety applications.
The scalability of these experimental tests is low, and more research is required to compare the behaviour of the short-range technologies in scenarios with a higher user density. Furthermore, both technologies are still under further development, supporting the European Commission's technology neutrality stance. Until a clear winner is identified, ITS-G5 and C-V2X will have to coexist in the 5.9 GHz band. This could induce interference conditions, potentially affecting the communication reliability if unsolved [15].
As the automation of vehicle functions advances, the importance of issues such as packet loss, communication latency, and cybersecurity becomes increasingly more pronounced.

1.1.2 Automated Traffic

The European Commission does not only support the development of connected road traffic, it also backs the trend of increasing vehicle automation. Current trends indicate the rise of Advanced Driver-Assistance Systems (ADAS), which can help human drivers by alerting them to specific events or even by performing individual driving tasks. Additionally, if the vehicle is connected, it can perform coordinated maneuvers, as in Cooperative Adaptive Cruise Control (CACC) [16]. In CACC, vehicles explicitly share their acceleration with each other, enabling stable longitudinal automated driving control.
However, ADAS are generally seen as just an intermediary step on the road to fully autonomous vehicles. Therefore, the Society of Automotive Engineers (SAE) came up with the J3016 standard, which indicates the degree of autonomy of a vehicle [17]. The standard distinguishes six different levels:

- **Level 0: "No Driving Automation"**

  The driver performs all driving tasks.

- **Level 1: "Driver Assistance"**

The system performs part of the vehicle motion tasks (acceleration or steering) within a specified Operational Design Domain (ODD).

- **Level 2: "Partial Driving Automation"**

  The system performs the vehicle motion tasks within a specified ODD, but has limited capability to react to external events.

- **Level 3: "Conditional Driving Automation"**

  The system performs all driving tasks within a specified ODD, but the driver needs to intervene in extreme conditions.

- **Level 4: "High Driving Automation"**

  The system performs all driving tasks within a specified ODD.

- **Level 5: "Full Driving Automation"**

  The system performs all driving tasks.

Today, many new vehicles are equipped with Level 1 automation systems such as adaptive cruise control and lane keep assist. Technology-wise, Level 2 systems are not much more complicated as this level requires a more complete set of ADAS that simultaneously control the lateral and longitudinal motion of the vehicle. Vehicles equipped with Level 2 systems were introduced over the passed years by brands like Tesla (Enhanced Autopilot) and Volvo (Pilot assist). Although Level 3 driving systems take all the burden of the driving tasks under normal operating conditions, the driver still needs to be alert for extreme conditions. Not only does this automation level require that the vehicle is completely aware of its environment, the safe hand-over of control in itself also raises a challenge. Brands like Mercedes Benz (Drive Pilot) and Audi (Traffic Jam Pilot) already introduced Level 3 automation systems, but within a limited Operational Design Domain (ODD). The ODD specifies exactly in which conditions the system is able to operate autonomously. Level 4 systems are currently being tested in controlled conditions for even more limited ODDs. These systems find their first applications in the form of shuttle busses, robotaxis, and yard automation. For example, Google's spinoff Waymoo already provides self-driving taxi services in Phoenix and San Fransisco.

A general system's architecture of a fully automated vehicle is depicted in Fig. 1. The vehicle uses sensors such as cameras, LIDAR, radar, inertial measurement units, and a global positioning system to monitor its environment. Additionally, a Connected and Automated Vehicle (CAV) can receive information about its surroundings through a communication device, which connects the car with other vehicles and the road infrastructure. The data from the sensors and communication is fused at the perception module to get a coherent understanding of the vehicle's environment and its location with respect to a digital high-definition map [18].

The planning module uses this model of the perceived environment and determines what actions the vehicle should take to reach a specific goal location.

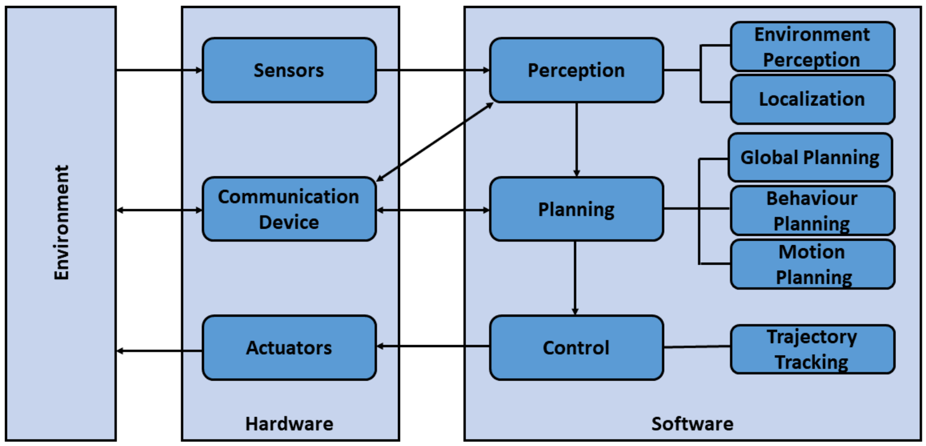


Figure 1: Schematic overview of the different components in a typical connected and automated vehicle (inspired by [19]).

The global planning system performs a graph search over a representation of the road network to determine the global trajectory toward the goal. Based on the global trajectory, the motion planner calculates local trajectories consisting of a sequence of vehicle states or vehicle actions. The behaviour planning system is responsible for selecting a local trajectory that complies with traffic rules and the behaviour of other traffic participants. Moreover, the behaviour planners perform the negotiations between CAVs that result in a cooperative maneuver. Finally, the control module needs to ensure that the vehicle actually traces the planned local trajectory by providing the appropriate actuation commands, i.e. gas/brake pedal and steering angle.
Autonomous vehicles hold the promise for safer and more efficient road traffic. However, the European Commission also believes that autonomous vehicles could be a means to help people that lack mobility, they could promote car-sharing services, stimulate vehicle electrification, and reduce the need for urban parking spaces [20].
At the same time, potential undesirable effects of such disruptive technologies need to be taken into consideration. For instance, the introduction of Level 4 automation systems for commercial and passenger vehicles could make road transportation more attractive, leading to more vehicle miles driven and urban sprawl [21]. Furthermore, the introduction of autonomous vehicles is expected to be a gradual process. As such, there will be a transition period in which Level 0 and Level 4 automation systems coexist. This raises challenges with respect to the interaction between human drivers and autonomous vehicles [22].

Finally, proper regulatory frameworks need to be adapted to safe-guard against issues regarding data privacy and cybersecurity [23].

1.2 Project Objectives and Outline

In the previous section, current developments regarding the digitization of road traffic were discussed. The mobility strategy of the European Commission states that by 2030 automated mobility will be deployed at large [24]. This major upcoming shift automatically raises questions for different stakeholders involved in road traffic.

First of all, there are the stakeholders responsible for the development, operation, and maintenance of future road traffic technology. The advent of connected traffic opens new possibilities for road operators regarding traffic monitoring and management. Simultaneously, they can play a facilitating role for infrastructure services that support automated driving. Original Equipment Manufacturers (OEM) are concerned with vehicle safety and introduce new automation systems to reduce the number of accidents of their customers. Telecommunication operators can tailor their services to the new requirements posed by connected traffic use cases. Governmental bodies have an import role to play by providing a clear regulatory framework that supports the development of connected and automated traffic without infringing the safety of its citizens.

On the other hand, there are the stakeholders that are affected by the introduction of these new technologies. For insurance companies, liability questions arise in case of a traffic accident involving automated driving systems. With increasing vehicle autonomy liability is expected to shift from the driver towards OEMs [25]. Meanwhile, law enforcement officers will have to deal with driverless vehicles that might occasionally violate a traffic rule [26]. If CAVs deliver on their promise to increase traffic efficiency and safety, road users will benefit from shorter travel times and lower risk for accidents.

Specifically, for emergency services, connected and automated mobility can drastically improve the operational efficiency. As previously mentioned, all new vehicle models in the EU need to be equipped with the eCall system, which automates the emergency call in case of a traffic accident. Furthermore, ETSI's cooperative awareness service can facilitate the Emergency Vehicle Warning (EVW) application [27]. Through this application, the emergency vehicle (EMV) notifies other vehicles of its presence by disseminating Cooperative Awareness Messages (CAM). In the receiving vehicle, either the human driver or the autonomous driving system can then adapt its actions to give way to the EMV. Similarly, CAMs can be used to inform intelligent Traffic Light Controllers (iTLC) of approaching emergency services, such that priority can be provided at signalized intersections. Moreover, other traffic participants could be pro-actively rerouted away from the emergency route to prevent the EMV to get delayed by dense traffic conditions. Although all these measures promise to improve the speed of emergency vehicles, their efficiency varies and depends on the implementation specifics. Therefore, it is vital to quantify and evaluate their impact both on the emergency response time and on the travel time of

other traffic participants.
The introduction of Level 4 automation systems on public roads requires them to be able to interact with emergency vehicles. This interaction should result in giving way to the emergency vehicle without causing a dangerous traffic situation. However, in dense traffic conditions the evasive maneuver of one CAV might require another CAV to also adjust its current trajectory, causing a cascade of maneuvers that need to be negotiated. Moreover, at unsignalized intersections multiple vehicles might approach from different directions, increasing the risk for occlusion. Such complicated traffic situations could benefit from a centralized coordination service to come to an efficient cooperative maneuver.
In accordance with the preceding analysis, the following project objectives were established:

1. **Quantify and evaluate the impact of connected traffic applications that improve the speed and safety of emergency vehicles in urban traffic.**

2. **Examine the prioritization of emergency vehicles by a centralized maneuver coordination service at unsignalized intersections in connected and automated traffic.**

In Chapter 2, the focus lays on the first objective. Two C-ITS services are proposed to reduce the delays emergency vehicles incur in typical urban traffic conditions. The Traffic Signal Priority Service (TSPS) prioritizes emergency vehicles at signalized intersections, while the Vehicle Rerouting Service (VRS) reroutes traffic participants away from the emergency route. Both services are tested in the microscopic traffic simulator SUMO.
Chapter 3 deals with the second project objective. It introduces a Maneuver Coordination Service (MCS) to prioritize emergency vehicles at unsignalized intersections in a connected and automated traffic context. This service is evaluated in the CARLA simulation environment, using the Autoware.auto stack to simulate the behaviour of the connected and automated vehicles.
Finally, Chapter 4 reflects on the project objectives and summarizes the conclusions of this work. Furthermore, drawing from the insights gained in this project, it presents a discussion on potential future developments for the main stakeholders involved.

2 Emergency Vehicles in Connected Traffic

2.1 Introduction

The United Nations project that the worldwide urbanization process, which has been ongoing since at least 1950, will continue for the coming decades [28]. This rapid population growth raises concerns regarding the deployment of emergency services in urban areas [29]. With its concomitant elevated number of injuries and accidents, a larger population increases the demand for emergency services. Additionally, it stresses the present traffic infrastructure, leading to more traffic congestion [30], possibly affecting the response time of emergency services.

Especially in life-threatening situations, a shorter response time, defined as the interval between the start of the emergency call and the arrival of the emergency services, can significantly improve the survival rate and the medical outcome of patients [31] [32]. Therefore, the Dutch emergency services have set a norm to achieve a response time of less than 15 minutes in 95% of the life-threatening emergencies [33].

Different structural approaches to reduce the response time, such as reorganizing and relocating the ambulance bases, have been researched [34] [35]. However, in order to reduce the response time even further, this chapter investigates the use of emerging digital solutions. The European Commission identifies digitalization as an essential driver for transforming the transport system into a smarter sector [36]. Crucial building blocks in this vision are the so-called Intelligent Transport Systems (ITS) which use information technologies and contain communication devices to exchange information with other ITS.

In the Netherlands, the Talking Traffic consortium supports this transformation by replacing traditional Traffic Light Controllers (TLC) with intelligent Traffic Light Controllers (iTLC) [37]. The Dutch iTLC are connected to the cellular network and can interact with other ITS through the exchange of standardized messages, as defined by the European communication standards organization ETSI [38].

The introduction of iTLC facilitates the provision of basic C-ITS services such as Traffic Signal Priority Service (TSPS) and Green Light Optimal Advisory (GLOSA). Two pilot studies, part of the Urban Nodes project of C-Roads Germany, are testing these services to improve public transport flow in urban areas [39]. In contrast to the Dutch iTLC, the presented pilots have implemented the ITS-G5 communication technology, which has a limited communication range. In the pilots, the range varied between 250 meters in bad conditions and 600 meters at line-of-sight propagation [39].

In this chapter, which is set in the Dutch context, two cellular network C-ITS services are presented and evaluated using the microscopic traffic simulator SUMO (Simulation of Urban MObility) [40]. The services will be referred to as the TSPS and the Vehicle Rerouting Service (VRS). Both services aim to shorten the response time of emergency services by improving their flow in urban traffic. The first C-ITS service is an implementation of a TSPS for emergency vehicles. The implemented service provides emergency services priority when approaching signalized intersections. By informing the iTLC sufficiently in advance, potential queues in front of the intersection can be resolved by the time the emergency vehicle arrives, decreasing their incurred delays. The use of the cellular network, with a virtually unlimited communication range, is thus an important feature of the Dutch iTLC. Furthermore, this service could drastically improve the road safety of emergency services. In the Netherlands, 165 traffic accidents involved a priority vehicle in 2018 and 2019 [41]. Nearly one-third of these accidents happened when a priority vehicle crossed a red stoplight.

A lot of research has been done regarding the prioritization of emergency services at intersections [42]. In some research, the priority of emergency vehicles is based on virtual traffic lights [43]. This paradigm shifts the functioning of TLC towards the vehicles themselves, creating so-called self-organized traffic control. The virtual traffic lights allow controlling all intersections, even those without traffic light infrastructure. However, one dysfunctional communication device could have catastrophic consequences.

Other researchers have performed simulations that are more closely related to the work presented in this chapter [44]. In their simulations, the authors varied the traffic density and the radius at which the TSPS initiates, meanwhile evaluating the impact on the travel times of normal and emergency vehicles. However, the simulated scenarios span a limited area in which the trajectory of the emergency vehicles is predetermined and contains only one signalized intersection.

The second C-ITS service, the VRS, is designed and implemented to decrease the traffic density along the routes of emergency vehicles. This service can thus reduce the delays emergency vehicles incur on straight roads during high traffic density conditions [44]. Once an emergency call is made, an interval of thirty seconds is initiated in which the emergency services are being prepared. Simultaneously, the VRS is already activated to redirect other vehicles away from the planned route of the emergency vehicle, thus resulting in fewer interruptions.

The implementations of both the TSPS and the VRS were tested in city-scale traffic simulations based on real-world traffic patterns. More specifically, the simulated scenario was set in the city center of Eindhoven, demographically the fifth-largest city in the Netherlands, with a registered population of 235,691 [45]. The simulations were performed for the morning rush hour and the aftermath of the evening rush hour. For both scenarios, the traffic density was based on vehicle counts obtained through the municipality of Eindhoven. While both services achieved a significant reduction in the travel time of emergency services, the most promising results were obtained through the TSPS.

The specifics of the simulated scenarios will be further elaborated in section 2.2. Section 2.3 provides a more detailed description of the two C-ITS services, while section 2.4 presents and discusses the results of the performed simulations. Finally, in section 2.5 the conclusions of this work are drawn.

Figure 2: Road network of the Eindhoven city center, the red arrow indicates the fixed starting location of the emergency vehicles.

2.2 Simulation Scenarios

This section details the design of the two traffic scenarios used to evaluate the travel time of emergency vehicles in urban traffic. In general, a simulated traffic scenario can be decomposed into two components. The first component is the static data, consisting of the road network and associated infrastructure, e.g., traffic lights. The second component is the dynamic data, which entails the entities entering and leaving the simulation during the scenario, e.g., vehicles.

2.2.1 Static Data

The city center of Eindhoven was selected as a representative area to perform simulations of urban traffic. The topology of the car road network, the location of traffic lights, and the properties of individual roads, such as the allowed vehicle types and the maximal speed, were all extracted from OpenStreetMap [46]. This extraction was performed by the osmWebWizard.py script, which is part of the SUMO package [40]. Since the aggregation of OpenStreetMap data is based on the principle of crowdsourcing, the retrieved road network is not guaranteed to be infallible. Therefore, crucial locations in the network were checked and adjusted manually to correspond better with the real-world situation. The final road network is graphically represented in Fig. 2. All lanes combine for a total length of 366.89 km.

2.2.2 Dynamic Data

Another vital part of the simulated scenario is, of course, the traffic itself. In the macroscopic view of the simulation, both the traffic density and the global traveling patterns should correspond to reality. However, traffic patterns and

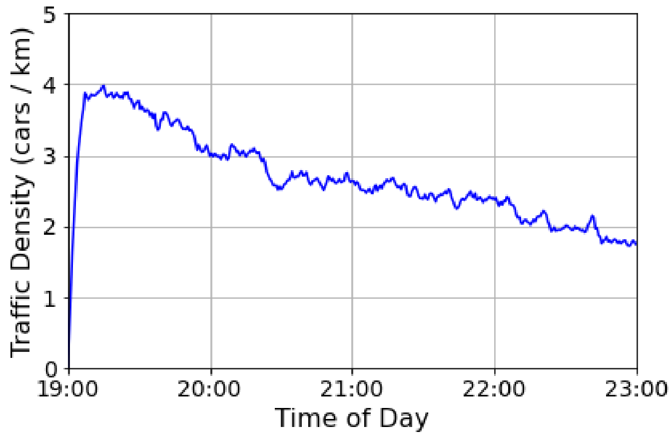


Figure 3: Evolution of the traffic density in the entire road network during the evening rush hour simulation.

densities depend heavily on the time of day and the actual day. Therefore, two sufficiently different, though representative simulation periods are selected, i.e., the morning rush hour (6-9h) and the aftermath of the evening rush hour (19-23h) on a regular Monday. The simulated traffic is limited to standard passenger cars and emergency vehicles. No other modes of traffic are considered.

Standard Vehicles

The simulation of the urban traffic flow is based on real-world traffic patterns, obtained through the TomTom MOVE portal [47], and on real-world vehicle counts provided by the municipality of Eindhoven. First, the O/D Analysis tool of the TomTom MOVE portal was used to subdivide the road network into a grid with a unit length of 0.5 km. The API returned the origin-destination matrices of the defined grid for the requested periods, i.e., Monday 27/01/2020 between 6-9h and between 19-23h. The origin-destination matrices contain the number of vehicle trips between each square of the defined grid, as registered over these entire periods by TomTom. Next, the Traffic Stats tool, also part of the TomTom MOVE portal, was used to determine the relative traffic densities on an hourly basis, which were further refined by linear interpolation to obtain smoothly varying traffic densities. Finally, the municipality of Eindhoven provided vehicle count data at specific locations in the city center. These absolute counts were used to scale the number of trips registered by TomTom to the total number of vehicles on the roads. A profile of the traffic density during a simulation of the evening traffic is presented in Fig. 3.

Emergency Vehicles

The simulated emergency vehicles are assigned the SUMO emergency vehicle (EMV) class, allowing them to overtake on the right and on the opposite lane. Their 'impatience' attribute is set to 1, i.e., they consider all maneuvers which do not lead to a collision as safe, disregarding the fact that they might cause the need for emergency breaks. Furthermore, their 'speedFactor' is set to 1.5, which indicates that they can violate the speed limits by a factor of 1.5. Finally, the EMVs are equipped with a built-in device, called the 'blue light device' [48]. This device provides the EMV with special rights such as ignoring red traffic lights, and it causes the formation of a rescue lane by vehicles within a downstream distance of 25 meters.
Emergency calls are simulated to occur at a steady interval of five minutes. This allows studying the behavior of the emergency vehicles without the added complexity of interacting EMVs. The starting location of the EMVs is predetermined and corresponds to an actual hub of ambulances, indicated by the red arrow in Fig. 2. The destination of the EMVs is determined by sampling random coordinate pairs within the network and finding the nearest accessible street. Once the starting and ending location of the EMVs have been established, the Dijkstra algorithm [49] is used to find the fastest route. Finally, the EMVs are inserted into the simulation thirty seconds after receiving the emergency call and calculating the fastest route. This interval represents the preparation time of the emergency services and is of importance for the Vehicle Rerouting Service.

2.3 Implemented Services

This section discusses the implementation of the two C-ITS services in the simulation environment. The objective of the services is to decrease the response time of emergency services by improving the flow of emergency vehicles in urban traffic. Both services are implemented using the Python version of TraCI [50], short for Traffic Control Interface, which allows interacting with SUMO simulations during run time.

2.3.1 Traffic Signal Priority Service

Densely populated areas introduce a heavy load on the main intersections of cities. Traffic lights are essential to control the flow safely and proportionally at these junctions. However, every traffic light along the emergency vehicle route is another hurdle to overcome. Though emergency vehicles are allowed to cross the stopping light in case of high emergency, often they are still delayed by the queue in front of the traffic light. Furthermore, a significant risk of causing an accident is associated with the negation of the stopping light. Therefore, the TSPS is designed to smoothly transition the traffic signal to a state in which approaching emergency vehicles are provided with a green wave.
The TSPS is triggered at the insertion of an emergency vehicle into the simulation, i.e., thirty seconds after receiving an emergency call. First, the Dijkstra

Table 1: The traffic light state transitions as defined in the TSPS.

Order	Traffic Light Controller	Transition Condition
1	Actuation program	EMV enters TSP radius
2	Yellow Change	4 seconds
3	Green EMV Approach	EMV passes TLC
4	Yellow EMV Approach	3 seconds
5	Red Clearance	2 seconds

algorithm is used to calculate the fastest route, based on the current estimated travel times of all road segments, to the emergency location. Subsequently, all the traffic lights along the route are identified. The state that will provide green signals for the approach of the emergency vehicle and stopping signals for the other approaches is determined for each traffic light. As all lanes of the approach of the EMV are provided with a green signal, all vehicles entering the intersection from that direction can pass. This results in a smoother traffic flow and, in practice, it allows emergency services to make last-minute changes to their crossing direction.

Proceeding the simulation, at every step, the distance of the emergency vehicle to its first upcoming traffic light is obtained and evaluated with respect to the predefined TSP radius, a parameter that will be varied in section 2.4.2. When the emergency vehicle enters this TSP radius, the actuation program of the traffic light is interrupted, and the traffic light is brought into a transition state. All signals are turned yellow (Yellow Change), indicating that the intersection should be cleared. Four seconds later, the traffic light enters the state that provides a green wave for the approach of the emergency vehicle, while all other lights are turned red (Green EMV Approach). After the emergency vehicle has safely passed the intersection, the green lights are turned yellow while the red lights remain unchanged (Yellow EMV Approach). This state lasts three seconds and is followed by an all-red clearing state (Red Clearance) which lasts two seconds. This final state ensures that the intersection is empty before the traffic light resumes its usual actuation program. Meanwhile, the emergency vehicle moves on to its destination, safely passing subsequent traffic lights in the same way.

Table 1 shows an overview of the successive state transitions defined in the TSPS. The timing of the transition states corresponds to general recommendations [51].

2.3.2 Vehicle Rerouting Service

High travel demands are a determining factor in the formation of urban traffic congestion [30]. The slower speeds associated with this congestion introduce another delay in the response of emergency services. The VRS is proposed to mitigate these delays by encouraging other vehicles to take routes that do not overlap with the predetermined route of the emergency vehicle.

The implementation of the VRS is based on the notion of edge efforts. In SUMO, every road consists of multiple connected segments, called edges. These edges can be assigned an arbitrary effort value. Then, instead of calculating the shortest or the fastest route between the origin and destination of a trip, the route which minimizes the total effort value can be determined by the Dijkstra algorithm.

The VRS is triggered immediately after a simulation is initiated. The service starts by assigning all edges an effort value proportional to their length. Once an emergency call is made, the edge closest to the emergency location is identified as the destination. Starting at the hospital, the fastest route is then calculated based on the current estimated travel times. Subsequently, the efforts of the edges along the route of the EMV are multiplied by the Vehicle Rerouting Effort Multiplier (VREM), a parameter that will be varied in section 2.4.3. All vehicles in the simulation are immediately rerouted with respect to the updated edge efforts, i.e., such that their total route effort is minimized. As mentioned in section 2.2.2, the EMV is only inserted into the simulation after a preparation time of thirty seconds has passed. This provides time for the standard vehicles to clear the route of the EMV. Standard vehicles entering the simulation after the efforts have been updated and before the EMV has arrived at its destination are ensured to be rerouted according to the new efforts. Finally, as the EMV passes the edges along its route, their efforts are reset to their initial values one by one until the EMV reaches its destination.

2.4 Results and Discussion

This section investigates the impact of the TSPS and the VRS on the travel times of both standard and emergency vehicles. Finally, a rough estimate of the societal value of the services will be made.

2.4.1 Benchmark

First, simulations are performed in which the C-ITS services are not activated. The results of these simulations establish a benchmark for the remainder of this chapter. The benchmark simulations are run for the morning rush (6-9h) and the evening relax (19-23h) scenarios. In the morning rush simulations, on average 17,650 standard vehicles reached their destination per hour. The traffic density in the evening relax scenario is significantly lower with an average of 12,681 standard vehicles finishing their trip per hour. A comparison of the trip statistics of the benchmark simulations is presented in the first two rows of Table 2. The errors on the last digits of the shown numbers are calculated as the standard deviations acquired after ten simulations. They are indicated between parentheses.

The average length of the trips made inside the city center is observed to be around 2.7 km. The higher traffic density during the morning rush makes stan-

Table 2: The average trip statistics of Standard Vehicles (SVs) and Emergency Vehicles (EMVs) for two traffic scenarios and different configurations of the TSPS and the VRS.

Scenario	TSP Radius [m] - VREM	Trip Length [m]	Total Travel Time [h]	SV Travel Time [s]	EMV Travel Time [s]	SV Speed [km/h]	EMV Speed [km/h]	Societal Value [euro/h]
Morning Rush	/ - /	2,780(20)	4,982(20)	339(24)	220(47)	29.6(5)	44(1)	Ref.
Evening Relax		2,634(3)	3,934(20)	279.0(4)	210(12)	33.99(7)	47.7(7)	Ref.
Morning Rush	800 - /	2,784(8)	5,021(20)	341(15)	179(30)	29.4(4)	54(2)	827
Evening Relax		2,635(3)	3,964(20)	281.2(7)	175(12)	33.74(7)	57(1)	726
Evening Relax	/ - 4	2,549(3)	4,413(20)	313.1(6)	166(8)	29.31(3)	59(1)	-140
Evening Relax	800 - 4	2,550(4)	4,442(21)	315(2)	159(7)	29.1(1)	62.1(9)	-40

*The errors on the last digits of the shown numbers, which are calculated as the standard deviations acquired after ten simulations, are indicated between parentheses.

dard vehicles choose for slightly longer (5%) trips than in the less busy evening scenario. Moreover, the more densely occupied road network leads to increased waiting times (68%) and lower driving speeds, both for standard vehicles (12%) and emergency vehicles (8%).
The higher speeds of EMVs compared to standard vehicles result from their specific attributes, as has been discussed in section 2.2.2.

2.4.2 Traffic Signal Priority Service

Next, the performance of the TSPS is investigated using the same scenarios. As discussed in section 2.3.1, the so-called TSP radius, i.e., the distance at which the traffic signal preemption is initiated, is an essential parameter of the TSPS. In order to determine a suitable radius, a parameter sweep, ranging from 100 to 900 meters, is performed using the evening scenario. The results of the sweep are presented in Fig. 4.
The graph shows that the average travel time of emergency vehicles (black dots) decreases when the TSPS is turned on. Moreover, the travel time of the EMVs decreases monotonously with increasing TSP radius, up to a length of 800 meters. This behavior can be explained as the result of vanishing queues

along the oncoming lane of the EMV when the corresponding traffic signal is prematurely switched to green, thus decreasing the delay of the EMV at the intersection. When the TSP radius is set above 800 meters, the queues have dissolved, and the travel time of the EMVs starts to increase slowly. This increasing travel time is due to the growing inefficiency of the traffic signals, which causes a higher effective traffic density.

Moreover, the average travel time of standard vehicles (black crosses) grows only marginally with increasing TSP radius. However, as standard vehicles massively outnumber emergency vehicles, the total travel time (blue dots), i.e., the sum of the travel times of all vehicles in the simulation, does increase with increasing TSP radius. The determination of the optimal TSP radius does thus consist in balancing the time lost due to the inefficiency of the traffic signal control and the improved response time of emergency services.

The main objective of this chapter is to prove the potential of communication devices in improving the flow of emergency vehicles in urban traffic. Therefore, the TSP radius of 800 meters is deemed optimal within the scope of this work and will be used for further simulations.

The quantitative results for both the morning rush and the evening relax scenarios using the TSPS with a TSP radius of 800 meters are shown in Table 2. The average speed of standard vehicles is observed to decrease by 0.7% compared to the benchmark results for both scenarios. Meanwhile, the speed of emergency vehicles increases by 22.7% and 19.5% for the morning rush and the evening relax scenarios, respectively.

For emergency calls within the city center of Eindhoven, the increase by approximately 20% in the speed of emergency vehicles translates to a reduction in response time of roughly thirty seconds. This time gain could be life-saving in acute emergency cases like cardiac arrests [31].

2.4.3 Vehicle Rerouting Service

The VRS was also tested and evaluated for both scenarios. However, the VRS, as implemented in this chapter, was found to be unsuitable for the very high traffic density during the morning rush scenario. When the VRS is turned on, standard vehicles are rerouted away from the emergency vehicle routes, effectively reducing the available road network. The combination of a high traffic density and the decreased availability of roads caused severe gridlocks, rendering unrealistic traffic simulations. Further discussion of the VRS is therefore limited to the evening relax scenario.

Similar to the TSP radius in the TSPS, the VREM is an adjustable parameter in the VRS. Its influence on the simulation results is studied through another parameter sweep. The results are shown in Fig. 5.

For the smallest VREM (equal to 1.1), the average travel time of the EMV's (black dots) decreases as expected. However, the average travel time of standard vehicles (black crosses) increases roughly by a factor of four more. This significant increase is caused by the rerouting of standard vehicles from the main roads towards local roads, which are less suited to deal with large amounts of

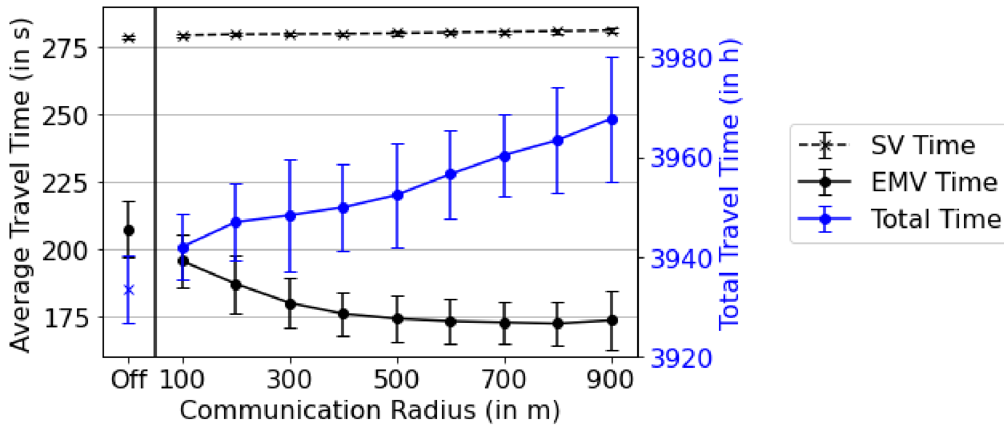


Figure 4: The total travel time of all vehicles in the simulation combined and the average individual travel times of standard vehicles (SV) and emergency vehicles (EMV) for different values of the TSP radius. The error bars mark the standard deviations obtained after ten simulation runs.

traffic. When the VREM is further increased, the travel time of standard vehicles grows slowly, while the gain in speed for emergency vehicles is significant. For the VRS to be effective, it is thus vital to use a VREM of at least three.
Table 2 summarizes the quantitative simulation results for the evening relax scenario using the Vehicle Rerouting Service with a VREM of four. Compared to the benchmark simulations, the speed of emergency vehicles increases by 23.7%, while the speed of standard vehicles decreases by 13.8%.
Both the Traffic Signal Priority Service and the Vehicle Rerouting Service lead to a reduction of the travel time of emergency vehicles on the order of 20%. However, for the VRS, the time loss of all the other traffic participants is much larger, resulting in an increased economic cost due to congestion [52]. Furthermore, the service shifts traffic from the main roads to local roads, disturbing quiet residential areas and potentially raising safety concerns [53].
A much less intrusive method to improve the flow of emergency vehicles is the so-called Emergency Vehicle Approaching service, which is part of the list of Day 1 C-ITS applications presented by the European Commission [54].

2.4.4 Combined Service

In the next step, the evening relax scenario was simulated using the TSPS and the VRS in parallel. Since both services improve different aspects of the flow of emergency vehicles, combining them is expected to result in an even more considerable reduction in response time.
For these simulations, the TSP radius and the VREM were set to 800 meters and 4, respectively. The results for this configuration are listed in Table 2. The combination of both services leads to a further increase in the speed of emergency

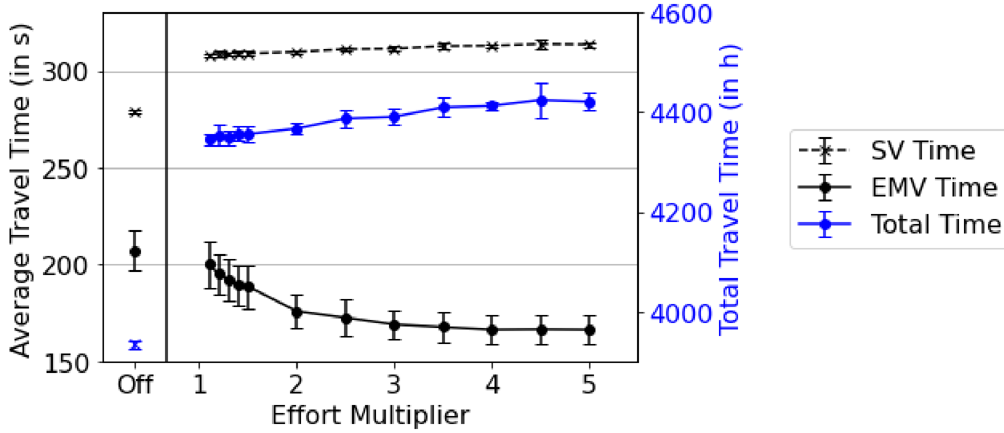


Figure 5: The total travel time of all vehicles in the simulation combined and the average individual travel times of standard vehicles (SV) and emergency vehicles (EMV) for different values of the effort multiplier (VREM). The error bars mark the standard deviations obtained after ten simulation runs.

vehicles. Compared to the benchmark situation EMVs travel 30.2% faster. This indeed shows that combining both services leads to an even further decreased travel time for emergency vehicles. However, since the VRS also decreases the queues along the lane of EMVs at signalized intersections, the services are not entirely complimentary. Furthermore, the combination of both services leads to a 14.4% reduction in the speed of standard vehicles, which seems like an exorbitant cost.

2.4.5 Societal Evaluation

Finally, a rough estimate of the societal value of the implemented services was obtained. The societal value is determined as the difference between the societal gain, resulting from a faster emergency response time, and the societal loss due to the delay inflicted on other traffic participants.

A large-scale study in the UK estimated that a reduction of the response time by one minute could improve the survival rate of an out-of-hospital cardiac arrest (OHCA) by 19%, meanwhile, no evidence of an improved survival rate was found for other clinical groups [55]. According to the study, this translates to 0.04% more survivors of life-threatening emergency calls per minute of reduced response time. For simplification purposes, this relationship between reduced response time and increased survival rate for OHCAs is assumed to be linear in the following calculations. Furthermore, a triage can categorize the emergency calls, such that the services can specifically be used for life-threatening cases only. Thus, for every minute of reduced response time in the morning rush (35 calls) and the evening relax (46 calls) scenario, 0.014 and 0.018 additional lives are saved, respectively. Moreover, the UK study estimates that on average a person surviving an OHCA will have five quality-adjusted life years (QALYs) left. In the Netherlands, the value that is assigned to an additional qualitative life year ranges between €10,000-80,000. Considering a reasonable QALY value of €60,000, saving a person with an OHCA results in a societal gain equivalent to €300,000. Finally, the societal gain of the services can be calculated by multiplying this number with the number of additionally saved people.

The societal cost of the services is approximated by multiplying the additional travel time of all vehicles with the value of travel time for cars in the Netherlands, i.e., €9 per hour [56]. The cost for other traffic modes is not taken into account, since the simulated scenarios only consist of standard passenger cars.

The subtraction of the societal cost from the societal gain results in crude estimates of the societal value of the implemented services for all the presented simulations. For comparison, the results for the two scenarios were scaled by the simulation time and listed in the final column of Table 2. The positive societal value for the TSPS indicates that this service could be a valuable asset to society. On the other hand, the VRS and the combination of both services simultaneously have a negative societal value. This shows that the VRS has too large of an impact on the other traffic participants to be a viable service when a QALY is valued at €60,000. However, for a QALY value of €80,000, the VRS and the combined service also become viable.

Finally, it is important to stress that the presented societal values are very crude approximations, based on numerous assumptions. For instance, the calculation of the societal gain is only based on the improved survival rate of OHCA patients, while a faster response time of emergency vehicles could be beneficial with regards to many aspects, such as revalidation, and lowering of stress and anxiety [55].

2.5 Conclusion

In this chapter, two C-ITS services were proposed to reduce the response time of emergency services in urban areas. Both services were implemented in the microscopic traffic simulator SUMO. The C-ITS services were evaluated in two traffic scenarios, set within the city center of Eindhoven.

The Traffic Signal Priority Service ensures that emergency vehicles are prioritized at signalized intersections. It was shown that initiating the service at a distance of 800 meters resulted in the optimal flow for the emergency vehicles during the aftermath of the evening rush hour. The service was observed to reduce the response time of emergency vehicles by roughly thirty seconds. Meanwhile, the average speed of the other vehicles decreased by only 0.7%.

The Vehicle Rerouting Service guides vehicles to roads that do not overlap with the routes of emergency vehicles. For the very dense traffic scenario of the morning rush hour, the rerouting of vehicles resulted in massive gridlocks. In the less busy evening scenario, the VRS could reduce the response time slightly more than the TSPS. However, the average speed of the other vehicles decreased by 13.8%.

When looking at the combination of both services, a 30.2% decrease in the emergency vehicle travel time and a 14.4% increase in the travel time of the other traffic participants is observed.

In order to evaluate the services according to their societal value, rough estimates of the societal gain corresponding to the reduced response time and the societal cost due to the additional delays for other vehicles were made. For the TSPS, the number of saved QALYs, due to the shorter response time, resulted in a net positive societal value, indicating that the implemented TSPS could be a valuable service for society. For the scenarios involving the VRS, the delays inflicted on other vehicles caused a net negative societal value. Apart from the economic cost, the VRS could also raise safety concerns due to an undesirable increase in traffic in residential areas. Implementing this service in the real world thus seems less attractive.

In the presented scenarios, urban traffic is simulated using a single standard vehicle type. In future work, a more realistic representation of urban traffic could be obtained by including other traffic modes such as cyclists, buses, and trucks. Furthermore, the presented implementation of the Traffic Signal Priority Service lacks efficiency through the use of a single Traffic Signal Priority radius for all signalized intersections. A more efficient service could be obtained by tailoring this parameter for all intersections individually or by considering real-time queue lengths.

3 Emergency Vehicles in Connected and Automated Traffic

3.1 Introduction

In the summer of 2020, the General Assembly of the United Nations adopted the 'Improving global road safety' resolution, in which they proclaimed the ambitious target to half the number of road deaths and injuries globally by 2030 [57]. The resolution recognizes the breakneck speed at which automotive technologies are developing and notes that these could help improve road safety significantly.

On the European level, even more ambitious goals are set in the longer term. According to their 'Vision Zero' [58], the European Commission sets out to reduce the number of road deaths and injuries to near zero by 2050. Although, Europe has the safest roads in the world [59], in 2019, around 22,800 people were killed and 120,000 were seriously injured in crashes on EU roads [60]. Meanwhile, the accidents were estimated to account for EUR 280 billion, or nearly 2% of GDP, in costs [61].

Vehicle safety is identified as one of the main intervention areas to improve road safety [59]. In this respect, the EU has played a vital role by imposing regulations that require vehicles to be equipped with both passive safety features, such as airbags and safety belts, and active safety features, such as Advanced Emergency Braking and Lane Departure Warning. Moreover, the EU is currently devoting major investments to the development of connected and automated vehicles (CAV) [59]. It is estimated that around 90% of EU road accidents are caused by human error [62]. Therefore, the European Commission came up with a legal framework for the approval of autonomous vehicles and a general strategy for the development of connected and automated mobility [20].

Vehicles equipped with Level 4 autonomous driving systems should perceive their surroundings and operate safely without the need for human intervention. A multitude of sensors provides raw information that is processed by sensor fusion algorithms to generate a coherent understanding of the vehicle's environment [63]. Meanwhile, planning algorithms compute real-time suitable trajectories and control algorithms ensure that these trajectories are tracked [64]. Over the past decades, great progress has been made in the development of these autonomous driving agents, however, a lot of skepticism remains for their adoption [21]. Statistics show that self-driving vehicles are more likely to be involved in road accidents, although the crash severity tends to be lower [65].

In order for autonomous vehicles to deliver on the promise of significantly improving road safety, further advancements in their performance are imperative. One such advancement is to enable vehicles to exchange information with other traffic participants and the road infrastructure. In this regard, the European communication standards organization ETSI is working on a framework to facilitate the implementation of Intelligent Transport Systems (ITS) services on EU roads [66].

For example, the Emergency Vehicle Warning (EVW) is a use case of the co-operative awareness service introduced by ETSI [27]. It is implemented in the C-Mobile project through the dissemination of Cooperative Awareness Messages (CAM) by the EMV [67]. Apart from the position and velocity of the EMV, these CAMs also contain the type of action that the emergency services are currently performing. On reception of a CAM from an active EMV, other connected traffic participants are thus notified of its position and direction, allowing them to take appropriate measures for the quick and safe passage of the EMV.

Furthermore, ETSI is investigating the proposal of a Maneuver Coordination Service (MCS) [68]. This service would enable connected traffic participants to share their intents and negotiate their future actions through the exchange of Maneuver Coordination Messages (MCM), in order to improve the safety and efficiency of their maneuvers. Although the service is still in a preliminary phase, within the TransAID project, a first experimental version and a second iteration of the MCM were already implemented [13].

The evolution towards connected and automated mobility is expected to have profound effects on traffic patterns and interactions. Traditionally, emergency services depend on a siren and blue light to draw attention and obtain priority over other traffic participants. However, in nearly one-third of the Dutch road crashes involving an emergency vehicle (EMV) and another traffic participant, the siren or the blue light was not noticed [41]. The introduction of communication channels between connected vehicles and emergency services could improve the awareness of approaching emergency vehicles [69]. Moreover, in fully automated traffic, the entire interaction could be handled without human intervention.

The aim of this chapter is to investigate how this interaction between connected and automated vehicles could be facilitated at unsignalized intersections by a centralized service via Vehicle-to-Network (V2N), or indirect C-V2X, communication. This setup is expected to result in a higher communication latency with respect to Vehicle-to-Vehicle (V2V) communication technologies such as ITS-G5 [70] and direct C-V2X [14]. However, the centralized service has the advantage that it provides a clear hierarchy for the coordination and that it has a more exhaustive view of all the traffic participants that are, or will be involved in the maneuver.

The proposed maneuver coordination service (MCS) provides emergency vehicles with absolute priority at unsignalized intersections. It gathers information from all vehicles in the vicinity of the junction by listening to the MCMs they transmit via the cellular network. The aggregated vehicle states and planned trajectories are continuously processed by the service, such that when an EMV approaches, it can immediately determine an appropriately coordinated maneuver to prioritize the EMV at the junction. Once the EMV performs a priority request, the relevant vehicles receive an individual maneuver advice that ensures that the EMV can safely pass the intersection.

The operation of the service will be tested in a realistic 3D simulation environment. Its performance will be assessed by monitoring surrogate safety mea-

sures, such as the Post-Encroachment Time (PET) and the Time-To-Collision (TTC) [71], in a set of different scenarios. As the service is highly reliant on the communication channels between the vehicles and the central service itself, the investigation will also evaluate the impact of communication latency and packet loss on the operation of the service. Furthermore, potential risks, such as communication breakdown and advice rejection, will be discussed.
The maneuver coordination service as well as the setup of the simulation environment and the key performance indicators will be discussed in section 3.2. In section 3.3, the operation of the service is quantitatively evaluated for simulation scenarios involving one CAV and the EMV. Furthermore, in this section, a qualitative investigation is performed for multiple vehicle and edge scenarios. Finally, the conclusions of this chapter are presented in section 3.4.

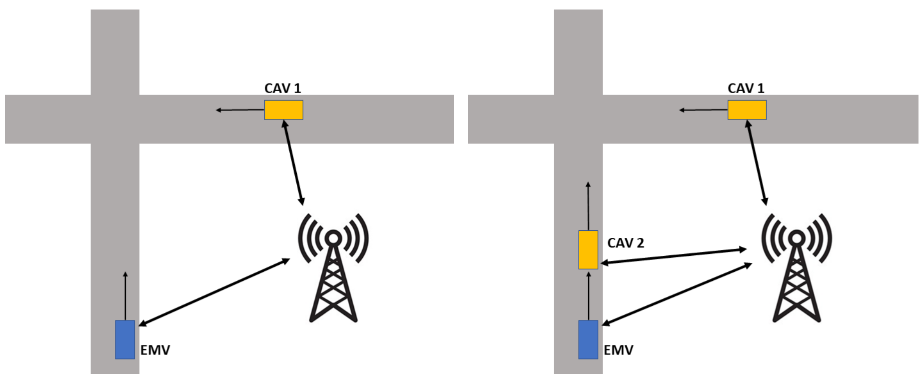
3.2 Methodology

The centralized Maneuver Coordination Service (MCS) proposed in this chapter facilitates the interaction between an emergency vehicle (EMV) and non-emergency vehicles approaching an unsignalized intersection in connected and automated context. A simulation framework is constructed to test this service in varying configurations and circumstances.
The CARLA simulator is used to simulate a realistic 3D environment in which the traffic scenarios takes place. CARLA is also responsible for simulating the driving mechanics of the vehicles. The automated systems in the vehicles are simulated by coupling the Autoware.auto autonomous driving stack to the CARLA simulator. The existing autonomous driving stack is complemented with a custom communication module. The coordination service itself is implemented as a ROS2 node that interacts with the communication modules of the connected and automated vehicles (CAV).
The setup of the traffic scenarios in which the service operates will be presented in section 3.2.1. The safety metrics that are used to evaluate the traffic scenarios are introduced in section 3.2.2. Section 3.2.3 will describe the autonomous driving stack ,as well as the custom communication module. The workflow and the theoretical backing of the maneuver coordination service will be discussed in section 3.2.4.

3.2.1 Traffic Scenario

The simulated traffic scenarios are centered around a four-way intersection. The perpendicular crossing roads consist of a single lane in each direction. The intersection is not equipped with a traffic light controller, but it is covered by a 5G network and a maneuver coordination service which will be detailed in section 3.2.4.
In the base scenario, depicted in Fig. 16c, a connected and automated emergency vehicle (EMV) approaches the intersection, while another connected and automated vehicle (CAV 1) closes in from the right. As the EMV is on its route

to an emergency, CAV 1 needs to be aware of the approaching EMV and yield its priority in the usual right-of-way situation.
In the advanced scenario, shown in Fig. 16d, an additional CAV (CAV 2) is placed in front of the EMV. In this situation, the CAV 1 still needs to be aware of the approaching EMV, though it might be harder for its own perception system to detect the EMV. Meanwhile, CAV 2 needs to be aware of the EMV on its tail and overrule the traditional right-of-way situation by assuming priority over CAV 1.
In both scenarios, it is vital that all the vehicles near the intersection are aware of the approaching EMV. Autonomous vehicles could use their perception module to detect EMVs based on the siren or flashing light. However, such a system could be error-prone and limited by the single perspective of the autonomous vehicle. An alternative is to use the capabilities of C-ITS.
Instead of using CAMs like in ETSI's Emergency Vehicle Warning application, this work proposes to use MCMs that include planned trajectories. A centralized Maneuver Coordination Service continuously aggregates the planned trajectories of all the vehicles in its vicinity. When an EMV approaches the intersection, the service proposes the most efficient coordinated maneuver prioritizing the EMV.



(a) Base scenario (b) Advanced scenario

Figure 6: Schematic representation of the traffic scenarios.

In the scenario described above, the starting positions of the vehicles will be varied along the distance of the incoming crossing roads. This will change the arrival time of the vehicles at the intersection and might thus impact the operation of the MCS. The vehicles will begin at a standstill with a speed limit of 50 km/h. The influence of slight variations in speed on safety will be evaluated by increasing the vehicle speed to 55 km/h.
Furthermore, communication and computation latency will change the time at which the MCS and the CAV are informed of the approaching EMV. This will impact the operation of the service. In the simulations, the maximum delay for a single message will be set at 500 ms, which is considered high for long-range

C-V2X communication [15]. Finally, the Request Range (RR) of the EMV's priority request will be varied.

3.2.2 Safety Assessment

The safety of a simulated scenario will be assessed through the use of Surrogate Safety Measures (SSM) [71]. These indirect measures allow for the investigation of traffic situations leading up to a crash and can help to evaluate the probability of an accident taking place. The validity of SSMs is observed through the strong relation between traffic conflicts and crashes [72]. The safety of a scenario also includes the potential crash severity or the seriousness of a sustained injury. However, evaluating injury risk is complex, especially if no actual crash occurs [73]. Therefore, this analysis will not elaborate on crash severity, but it is worth noting that higher approaching speeds typically increase the risk of injury.

This study considers three SSMs: Time-To-Collision (TTC), Post-Encroachment Time (PET), and Deceleration Rate to Avoid a Crash (DRAC). At an intersection, these measures define the traffic conflict area as the overlapping area of the vehicles' current trajectories.

TTC is a commonly used SSM, which is defined as the time until a collision would take place if two vehicles maintain their current crash course and speed [71]. For a crossing, the TTC can be calculated as follows:

$$TTC = \frac{\Delta x_B}{V_B}, \tag{1}$$

where V_B is the speed of the vehicle which arrives secondly at the conflict area and Δx_B is its distance to the conflict area. The risk of a crash is indicated by the minimum value of the TTC ($TTC_{\min}$) during an encounter. The threshold value for the $TTC_{\min}$ at intersections is considered to be 1 s, while it is desirable to keep the TTC above 1.5 s [74].

PET is another temporal SSM and refers to the time difference between the moment at which the first vehicle leaves (t_A) and the second vehicle enters (t_B) the conflict area [71]. The PET is thus given as:

$$PET = t_B - t_A. \tag{2}$$

Whereas the TTC is only defined when two vehicles are on a collision course, the PET can also indicate the crash risk in case of a close encounter. Commonly, traffic conflicts are considered to be critical if the PET is smaller than 1-1.5 s [71]. For the remainder of this work, a minimum safe PET of 1 s will be considered [75].

Finally, the DRAC assesses how much the second vehicle needs to decelerate to avoid entering the conflict area before the first vehicle leaves it [71]. For a crossing, this constant deceleration rate is calculated using the formula:

$$DRAC = \frac{2 \cdot (V_B - \frac{\Delta x_B}{\Delta t_A})}{\Delta t_A}. \tag{3}$$

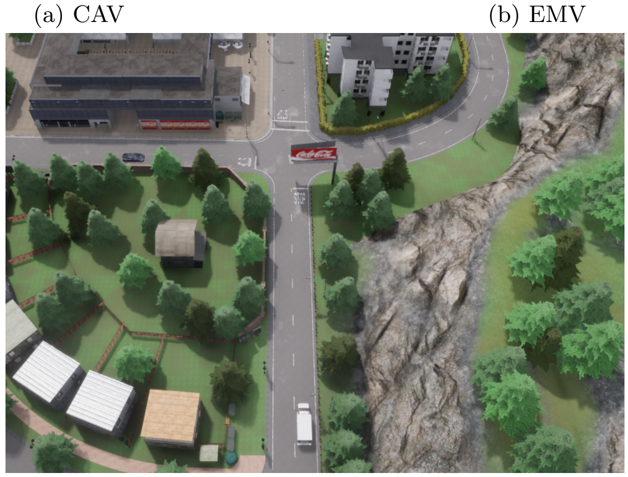
Though the threshold value for the DRAC depends on the deceleration capacity of the particular vehicle, literature typically suggests using a value of 3.4 m/s^2 [76].

3.2.3 Connected Autonomous vehicles

A simulation framework, combining CARLA and Autoware.Auto, was set up to test the coordination service in the presented scenarios.
CARLA is an open-source simulation platform that can replicate realistic 3D environments for autonomous driving research [77]. Fig. 7 displays a few screenshots of the environment simulated by CARLA. For this work, the Tesla Model 3 blueprint was used to simulate the CAV, while the Ford Ambulance blueprint was used for the EMV. An appropriate junction was found in map 4 of the CARLA assets. Fig. 7c shows a snapshot of the vehicles approaching the unsignalized intersection.

(a) CAV

(b) EMV



(c) Intersection

Figure 7: Screenshots of the Connected Autonomous Vehicle (CAV), the Emergency Vehicle (EMV), and the unsignalized intersection in the CARLA simulation environment.

Autoware.Auto is an open-source autonomous driving stack designed for real-world applications such as autonomous valet parking and cargo delivery [78].

However, it can also be used in simulation environments to test specific functionalities or to explore the implementation of new features. Autoware.Auto is designed in the ROS2 framework [79], which contains libraries and tools for robotics projects. ROS2 takes on a modular approach, dividing a complex system, like a robot, into several subsystems or nodes that pass the information on to each other. The interaction between the CARLA server and the ROS2 nodes takes place through the CARLA-ROS bridge provided by the CARLA platform.

In this work, the planning and control modules of the Autoware.Auto stack are used to simulate the behavior of autonomous vehicles in the CARLA environment. The orange blocks in Fig. 8 indicate which Autoware nodes are used for each vehicle.

When a vehicle is spawned in the CARLA server, the CARLA-ROS bridge receives information on its current status. The bridge then passes this information on to the ROS2 nodes of the vehicle. In the first instance, the global planner will process the vehicle's current pose, an externally supplied goal pose, and the map information to determine the shortest route to the goal pose. The global trajectory consisting of successive road segments is then passed on to the behaviour planner.

The behaviour planner is the central piece of Autoware's planning module. It will request the lane planner to process the global trajectory and to come up with a local trajectory consisting of a sequence of vehicle poses and speeds. Once a suitable path has been determined, it is passed on to the controller node. In this case, a pure pursuit controller calculates the longitudinal acceleration and steering angle to track the local trajectory. This information is received by the CARLA-ROS bridge, where a custom extension converts it into an actual CARLA vehicle control, and it is passed on to the vehicle in the CARLA server. The CARLA server runs in synchronous mode and with a fixed time-step of 1 ms. The CARLA-ROS bridge ensures that the simulation only proceeds once a vehicle control is received for every autonomous vehicle.

A communication device was designed to enable these autonomous vehicles to exchange information with other entities. The device abstracts information on the vehicle status and the planned local trajectory and converts it into a Maneuver Coordination Message (MCM). The MCM proposal of the TransAID project was used [13]. Its ROS implementation by DLR TS was slightly adjusted to make it more suitable for this use case [80]. For instance, a request-response list was added to the roadside unit maneuver container, for the MCS to respond to the EMV's priority request. The communication device was configured to generate MCMs at a rate of 10 Hz, similar to tests performed in the TransAID project.

The MCMs generated by the communication devices of the vehicles are passed onto the network simulator node. This node is designed to simulate network parameters such as communication latency and packet loss in a black box approach. That is to say, a predetermined latency can be appointed to each message, or a random value can be determined at runtime.

Next, the network simulator forwards the MCM to the MCS, which extracts

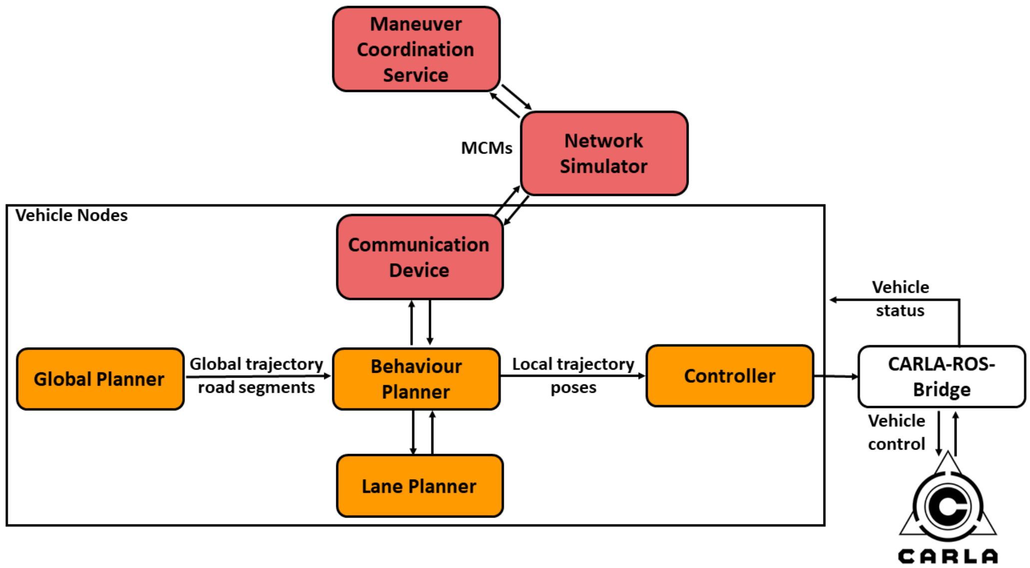


Figure 8: Schematic overview of the interactions between the components of the implemented CAVs. The orange components are based on the Autoware.auto stack, the white component is part of the CARLA platform, and the red components are custom ROS2 nodes.

and stores its content. If the particular message is a priority request from an EMV the MCS determines the appropriately coordinated maneuver and sends MCMs through the network simulator to all relevant vehicles.

3.2.4 Maneuver Coordination Service

The Maneuver Coordination Service proposed in this chapter has the specific function of providing emergency vehicles with priority at unsignalized intersections. The optimization of the traffic management of the other vehicles is outside of the scope of this work. First, the workflow of the service will be detailed by means of Fig. 9. Next, a mathematical formulation will be derived to back the operational safety of the service.

Workflow

In normal operation, the service processes and stores the incoming MCMs from all CAVs in the vicinity of the intersection. When an active emergency vehicle enters the Request Range (RR) encircling the intersection it will request priority from the service by filling its desired trajectory field in the MCMs it disseminates. As the station type in the MCM's basic container indicates that the requested trajectory originates from an emergency vehicle, the service is now alerted and initiates the priority request protocol.

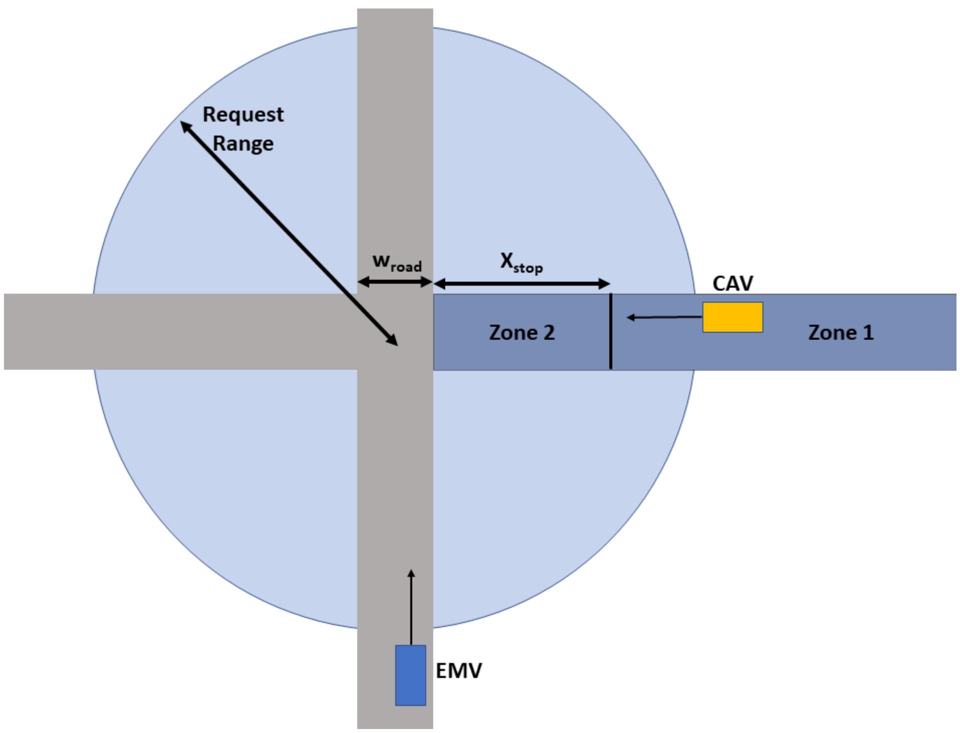


Figure 9: Schematic overview of the intersection and definitions related to the Maneuver Coordination Service.

Based on the MCMs it received, the service performs a check for all approaching CAVs to determine whether they are located in Zone 1 or Zone 2, as indicated for the left arm of the intersection in Fig. 9. The length of the zones is CAV-specific and depends on its current speed. Vehicles positioned in Zone 2 are considered to be unable to make a reasonable safe stop in front of the intersection and will not receive a maneuver advice from the MCS. How this impacts the operation of the service and the safety of the traffic situation will be further discussed below and in section 3.3. Conversely, for CAVs located in Zone 1 a safe stop at the intersection is expected to be feasible. As such, the coordination service will disseminate MCMs appointing an advised safe spot for these vehicles.

Once a CAV receives the coordinates of its safe spot, the vehicle's planning module verifies that this is a feasible stop and sends an advice acceptance MCM to the MCS. If the service has collected acceptance MCMs for every maneuver advice, it informs the approaching EMV that it can safely pass the intersection. The consequences of a CAV rejecting the proposed advice will be discussed in section 3.3.

At this stage, the MCS continuously monitors the progress of the EMV through its MCMs. When these indicate that the EMV has completely left the intersection, the coordination service disseminates MCMs to the waiting vehicles, canceling the earlier advice. The CAVs are now free to move on.

Mathematical Formulation

The separation between Zone 1 and Zone 2, indicated in Fig. 9, is determined by the stopping distance of the CAV (X_{stop}) at a constant and comfortable deceleration rate (a_{comf}). Using the kinematic equations, this distance can be determined as follows:

$$X_{\text{stop}} = \frac{V_{\text{CAV}}^2}{2 \cdot a_{\text{comf}}}. \tag{4}$$

As expected, the stopping distance is larger when the initial speed of the CAV V_{CAV} increases and it is inversely proportional to the deceleration rate. A safe and comfortable deceleration rate is strongly vehicle dependent, but a value of 3.4 m/s^2 is generally recommended and will be used for the implemented service [76].

If, at the time the priority request message is processed by the MCS (t_{req}), the distance of the CAV with respect to the intersection is larger than the stopping distance:

$$X_{\text{CAV}}(t_{\text{req}}) > X_{\text{stop}}, \tag{5}$$

the CAV is located in Zone 1 and the MCS will advise it to stop.

On the other hand, if the CAV is located in Zone 2:

$$X_{\text{CAV}}(t_{\text{req}}) \leq X_{\text{stop}}, \tag{6}$$

it will not receive an advice and is expected to pass the intersection before the EMV arrives. The interval between which the CAV leaves the intersection and the EMV enters it, is given by the Post-Encroachment Time (PET). A projection of the PET can be made at t_{req} by extrapolating the current motion of both vehicles:

$$\begin{aligned}\mathrm{PET}(t_{\mathrm{req}}) &= t_{\mathrm{EMV}} - t_{\mathrm{CAV}} \\ &= \frac{\mathrm{RR} - V_{\mathrm{EMV}} \cdot \Delta t_{\mathrm{req}}}{V_{\mathrm{EMV}}} - \frac{X_{\mathrm{CAV}}(t_{\mathrm{req}}) + w_{\mathrm{road}} + l_{\mathrm{CAV}}}{V_{\mathrm{CAV}}}.\end{aligned} \tag{7}$$

The EMV sent its priority request when it entered the Request Range (RR). By the time its request is processed by the MCS (Δt_{req} later), the EMV will thus already have travelled a distance of $V_{\mathrm{EMV}} \cdot \Delta t_{\mathrm{req}}$. For the CAV to completely leave the intersection, it needs to cross the width of the road (w_{road}) with its full length (l_{CAV}).
Now, invoking equations (4) and (6), the PET for the scenario with the closest passing, i.e., when the CAV is located at the separation between Zone 1 and Zone 2, can be projected as:

$$\mathrm{PET}_{\mathrm{min}} = \frac{\mathrm{RR}}{V_{\mathrm{EMV}}} - \frac{V_{\mathrm{CAV}}}{2 \cdot a_{\mathrm{comf}}} - \frac{X_{\mathrm{cross}}}{V_{\mathrm{CAV}}} - \Delta t_{\mathrm{req}}, \tag{8}$$

where X_{cross} sums the width of the road and the length of the CAV.
However, by the time the advice is processed by the CAV (t_{adv}), its distance to the intersection will have further decreased to:

$$X_{\mathrm{CAV}}(t_{\mathrm{adv}}) = X_{\mathrm{CAV}}(t_{\mathrm{req}}) - V_{\mathrm{CAV}} \cdot \Delta t_{\mathrm{adv}}, \tag{9}$$

where Δt_{adv} is the delay on the advice message. If this delay would not be taken into account, the CAV would thus need to decelerate faster than a_{comf} to make the stop at the intersection. Therefore, the MCS should rather require that:

$$X_{\mathrm{CAV}}(t_{\mathrm{adv}}) \leq X_{\mathrm{stop}}, \tag{10}$$

in order to actually limit the CAV's deceleration rate to a_{comf}.
Based on equations (9) and (10), a new upper limit for the distance of the CAV with respect to the intersection at the processing time of the request message is found:

$$X_{\mathrm{CAV}}(t_{\mathrm{req}}) \leq X_{\mathrm{stop}} - V_{\mathrm{CAV}} \cdot \Delta t_{\mathrm{adv}}. \tag{11}$$

With this new limit in mind, the minimum PET that can be reached, according to equation (7), becomes:

$$\mathrm{PET}_{\mathrm{min}} = \frac{\mathrm{RR}}{V_{\mathrm{EMV}}} - \frac{V_{\mathrm{CAV}}}{2 \cdot a_{\mathrm{comf}}} - \frac{X_{\mathrm{cross}}}{V_{\mathrm{CAV}}} - \Delta t_{\mathrm{req}} - \Delta t_{\mathrm{adv}} \tag{12}$$

Finally, this formula can be used to determine the Request Range for which the minimum PET is ensured to be safe, i.e., larger than or equal to $\mathrm{PET}_{\mathrm{safe}}$:

$$\mathrm{RR} = \left[\mathrm{PET}_{\mathrm{safe}} + \frac{V_{\mathrm{CAV}}}{2 \cdot a_{\mathrm{comf}}} + \frac{X_{\mathrm{cross}}}{V_{\mathrm{CAV}}} + \Delta t_{\mathrm{req}} + \Delta t_{\mathrm{adv}}\right] \cdot V_{\mathrm{EMV}}. \qquad (13)$$

As discussed in section 3.2.2, an encounter is considered to be safe when the PET is larger than 1 s.
For a specific intersection, a generally appropriate Request Range can thus be estimated using equation 13. The speeds of the vehicles can be based on the speed limits at the intersection. Although the EMV is expected to exceed this limit in real life, in this work, both the CAV and EMV have the same constant approaching speeds. The delays on the request and the advice message are not known up front. However, a conservative guess of their maximum values can be made to find a suitable Request Range. Values for a_{comf} and $\mathrm{PET}_{\mathrm{safe}}$ can be chosen such that the CAV is not required to brake excessively hard and the encounter is safe.
Finally, the width of the road is a constant determined by the topology of the intersection, while the length of the CAV is a variable that impacts the PET in case of a passage scenario, i.e. for a long truck it takes longer to clear the intersection. This could either be accounted for by calculating the Request Range based on the length of a truck, or the service could adjust its coordinated maneuver based on the real-time vehicle lengths it receives through the MCMs.
Fig. 10 shows how the appropriate Request Range varies for different assumptions regarding the speeds of both vehicles ($V_{\mathrm{EMV}} = V_{\mathrm{CAV}}$) and the total latency on the request and advice messages ($\Delta t_{\mathrm{req}} + \Delta t_{\mathrm{adv}}$), according to equation 13. The Request Range should clearly be extended for increasing vehicle speeds and message delays. The effect of the latency on the required Request Range is larger for higher speeds.

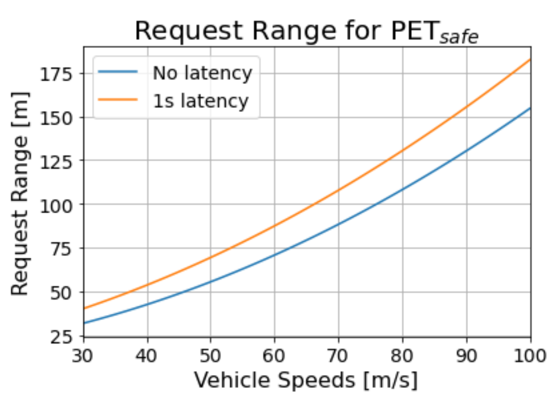


Figure 10: The minimum Request Range that ensures a safe Post-Encroachment Time (PET) for varying (but equal) vehicle speeds and latency.

3.3 Results and Discussion

This section presents and discusses the results of simulating different configurations of the basic scenario, which involves one CAV. Moreover, a qualitative analysis will be performed for the advanced scenario, involving multiple CAVs, and some edge scenarios. However, it is important to note that these scenarios were not explicitly simulated as they would require an extension of the coordination service.

3.3.1 Service Basic Operation

The functionality of the Maneuver Coordination Service is illustrated by simulating two distinct scenarios. The first scenario represents the case in which the CAV is located in Zone 1 (see Fig. 9) at the priority request time. Conversely, in the second simulation, the CAV is located in Zone 2 at the priority request time.

For both scenarios, the speed limit is set at 50 km/h and a latency of 500 ms is simulated between the transmission and processing of the priority request and the advice messages. The request range of the MCS is set at 70 m. The distinction between the two scenarios is realized by shifting the initial position of the CAV.

Safe Stop

Fig. 11 shows the evolution of the vehicle speeds and their distance with respect to the intersection during the stopping scenario. The CARLA simulator requires the vehicles to be spawned without initial velocity. After the simulation is properly initialized, both vehicles start accelerating until they reach the speed limit. The pure pursuit controller stabilizes the speed around the limit as the vehicles make their way to the intersection, approaching from perpendicular directions. When the EMV enters the request range, it transmits an MCM containing its desired trajectory, alerting the MCS 500 ms later to determine an appropriately coordinated maneuver. Another 500 ms later, the advice to perform a stop at the intersection is processed by the CAV, prompting it to start braking. As a result, the speed of the CAV gradually decreases until it almost reaches a standstill. Meanwhile, the EMV is informed that its priority request is accepted and continues its path at 50 km/h. During the entire encounter, the vehicles keep transmitting MCMs informing the service of their status and progress. Once the MCS notices that the EMV has passed the crossing, it sends an MCM to the waiting vehicle, canceling the stopping advice. Finally, the CAV can resume its initial trajectory and starts accelerating to cross the intersection.

The encounter can now be assessed using the three metrics introduced in section 3.2.2. First of all, it is important to note that the Time-To-Collision (TTC, threshold of 1 s) and the Deceleration Rate to Avoid a Crash (DRAC, threshold of 3.4 m/s^2) are only defined if the vehicles are actually on a collision course. Since the vehicles approach each other perpendicularly, there is a relatively small time window ($\frac{w_{\text{lane}}}{V} \approx 0.3$ s, at 50 km/h) in which this could occur. Moreover,

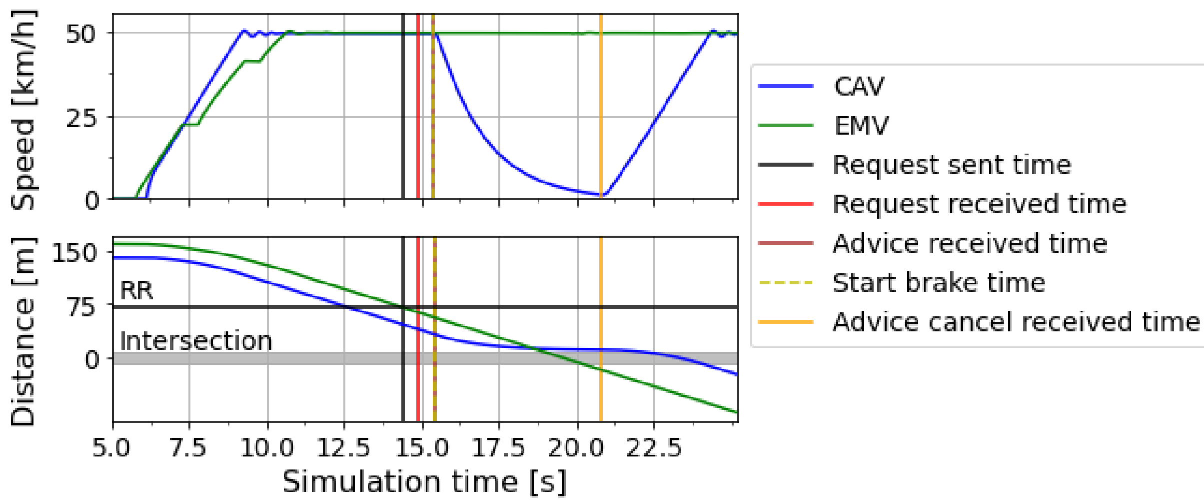


Figure 11: Evolution of the speeds of the vehicles and their distance with respect to the intersection in a stop scenario. The Request Range (RR) is indicated by the horizontal black line, while the grey area represents the intersection.

it was found that this collision course only arose when the braking maneuver of the CAV was already initiated and was thus merely caused by the differentiating speed of the approaching CAV. Furthermore, the coordination service was designed such that the vehicles are only expected to perform a stop if they would not exceed the comfortable deceleration limit of 3.4 m/s^2 in the process. This means that the DRAC will never cross this limit under normal operating conditions. Finally, in a stopping scenario, the Post-Encroachment Time (PET) is the time difference between the EMV leaving the conflict zone and the CAV entering it. Since the stopping advice for the CAV is only sent after the EMV has left the intersection, the actual PET should not infringe on the safety limit of one second.
A minimum TTC of 2.74 s was observed during the encounter, while the maximum DRAC amounted to 1.30 m/s^2. Comparing these extreme values to the thresholds, it can be seen that the scenario never turns into a conflict situation and can be labeled as safe. For the sake of completeness, the actual PET was measured and found to be 3.65 s, well above the threshold.

Safe Passage

In Fig. 12, the evolution of the vehicle speeds and their distance with respect to the intersection is shown when the CAV can not make a stop without exceeding the comfortable deceleration limit (a_{comf}). As in the previous scenario, both vehicles accelerate up to the speed limit and from then on approach the intersection at a constant speed. When the EMV enters the Request Range, it sends its priority request to the MCS. Due to communication and computational latency the request is processed 500 ms later. In this case, the MCS determines that the CAV is already located in Zone 2, and can not make a comfortable stop at the intersection. Therefore, both vehicles maintain their constant pace. The CAV crosses the intersection and is shortly followed by the EMV.

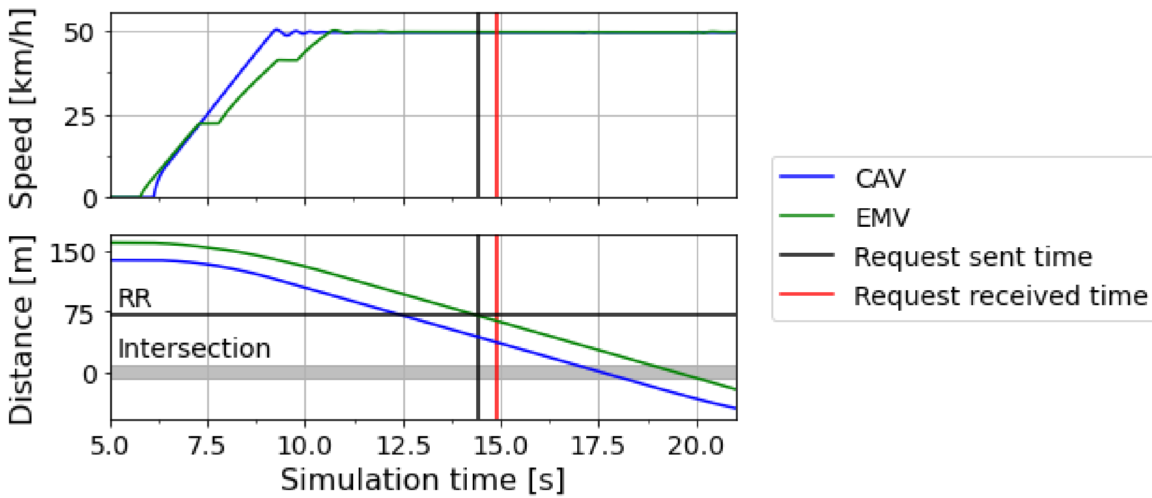


Figure 12: Evolution of the speeds of the vehicles and their distance with respect to the intersection in a passage scenario. The Request Range (RR) is indicated by the horizontal black line, while the grey area represents the intersection.

During this scenario, the vehicles are never found to be on a collision course with each other, so neither the TTC nor the DRAC can be calculated. The time between the CAV leaving the conflict zone and the EMV entering it was measured to be 1.41 s and can be considered safe. However, a potentially hazardous situation could arise in this scenario when this value further decreases, that is to say, if the actual PET becomes smaller than one second. Moreover, if the Request Range is not appropriately tailored to the specific situation at the intersection, the encounter could turn into a side collision, as will be further explored in the next sections.

3.3.2 Varying Request Range

As discussed in section 3.2.4, the Request Range of the service is vital to ensure safety in a passage scenario. Through equation (13) a Request Range can be determined such that the minimum actual PET is larger than PET_{safe}. The importance of the Request Range is shown through the execution of a suite of simulations where the location of the CAV, when the priority request is processed by the MCS (t_{req}), is varied in the vicinity of the separation line (X_{stop}) between Zone 1 and Zone 2. In these simulations, three values for the

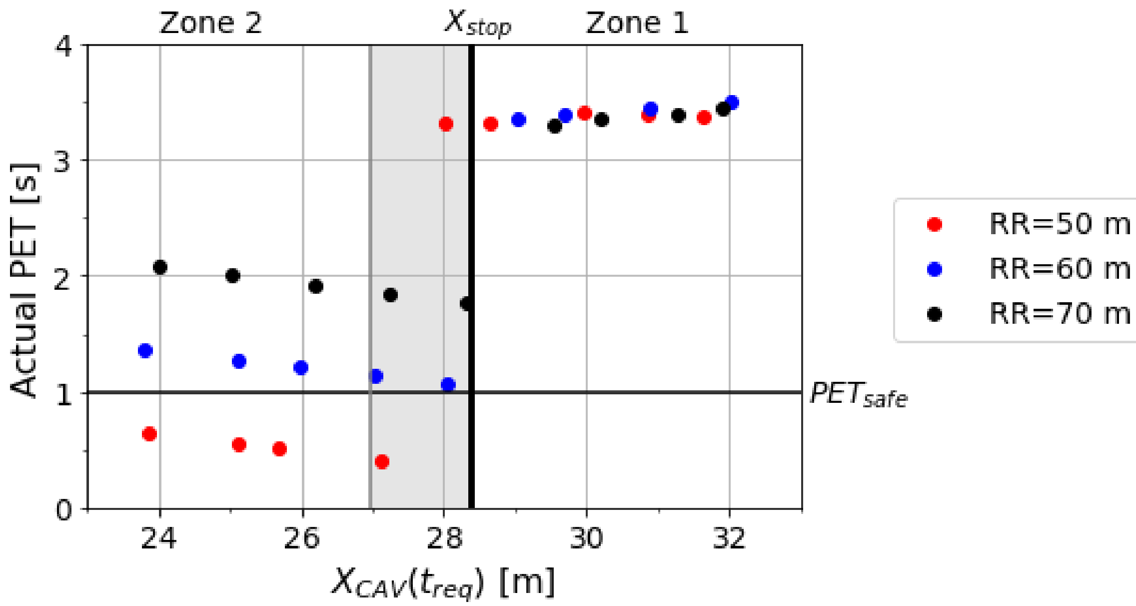


Figure 13: Overview of simulations with varying Request Range (RR). Both vehicles approach the intersection at a speed of 50 km/h and no latency in the communication is simulated.

Request Range are considered: 50 m, 60 m, and 70 m. When the RR is varied, the initial position of the CAV is adjusted accordingly to ensure that it is still close to X_{stop} at t_{req}. The speed limit is kept at 50 km/h, but, for the sake of simplicity, no message latency is taken into account.

The results of the simulations are summarized in Fig. 13. Every dot in the graph corresponds to the output of one simulation. The red, blue, and black dots are associated with a RR of 50 m, 60 m, and 70 m, respectively. The horizontal axis indicates the distance of the CAV with respect to the intersection at t_{req}, i.e. $X_{\text{CAV}}(t_{\text{req}})$. The vertical black line signifies the minimum distance at which the CAV can perform a comfortable safe stop (X_{stop}). The actual PET measured during the simulation is listed on the vertical axis, while the minimum safe PET value PET_{safe} is marked by the horizontal black line.

The dots positioned to the right of X_{stop}, i.e. in Zone 1, correspond to simulations of stopping scenarios. In these scenarios, the service considers the CAV to be located sufficiently distant from the intersection. The MCS advises the CAV to stop at an appointed safe spot in front of the crossing. The actual PET results from the restarting of the CAV after the EMV has left the intersection. As expected, neither the Request Range nor a slight variation in $X_{\text{CAV}}(t_{\text{req}})$ has a significant effect on the PET in these scenarios. With a PET of circa 3.5 s, they can be considered safe.

The dots in Zone 2 correspond to simulations of passage scenarios. Here, the Request Range clearly has a large effect on the minimum observed PET. This can simply be explained by the fact that at t_{req}, the distance of the EMV with respect to the intersection has changed while this distance is kept the same for the CAV (by changing its initial position). Additionally, for a fixed RR, the actual PET decreases with increasing $X_{\text{CAV}}(t_{\text{req}})$. This is the anticipated behavior, as the increased distance causes a delay in its leaving time, while the subsequent entrance time of the EMV remains unchanged. Both effects are in agreement with equation (13).

There is one red dot, however, that seems to defy the separation between Zone 1 and Zone 2. At $X_{\text{CAV}}(t_{\text{req}}) \approx 28$ m, the simulation is expected to result in a passage scenario. Nevertheless, its PET clearly indicates that the CAV made a stop and gave way to the EMV. This perverse behavior stems from a slightly outdated CAV location that the coordination service uses to determine its advice. As the CAV transmits its MCMs with a frequency of 10 Hz, the service could be using the CAV's position of up to 100 ms earlier. At 50 km/h, this corresponds to a potential overestimation of $X_{\text{CAV}}(t_{\text{req}})$ up to 1.39 m, marked by the grey area.

In practice, this means that the required deceleration rate of the CAV slightly increases above the a_{comf} used by the service. The service could be adapted to incorporate this effect by either using a slightly lower value for a_{comf} or by deducing the CAV's current position from its planned trajectory.

Finally, Fig. 13 shows that when the service operates with a RR of 60 m, it ensures that the actual PET stays above one second, assuming that the vehicles strictly stick to the speed limit and there is no latency on the exchanged messages.

3.3.3 Varying Speed

When all vehicles in the traffic system are connected and automated, deliberate speeding is expected to be a thing of the past. Nevertheless, slight deviations from the speed limit might still occur and it is important to investigate their impact on the operation of the coordination service. Equation (4) shows that the CAV's stopping distance increases quadratically with increasing speed. The service will thus extend the range for which this CAV is allowed to pass the crossing before the EMV arrives. This range, for CAVs travelling at 50 km/h (X_{stop50}) and 55 km/h (X_{stop55}), is indicated by the vertical black lines in Fig. 14.

In a passage scenario, a faster CAV might thus have to travel a longer distance (quadratic with speed) and arrive later at the intersection. Conversely, its time to pass the crossing decreases. Meanwhile, a faster EMV simply causes it to arrive earlier at the intersection. These three effects are captured in equation (8) and indicated in practice by the results of different simulations shown in Fig. 14. First of all, comparing the blue ($V_{\text{CAV}} = V_{\text{EMV}}$=55 km/h) and the red ($V_{\text{CAV}} = V_{\text{EMV}}$=50 km/h) dots on the left, a very slight decrease of the actual PET is observed, mainly due to the earlier arrival of the EMV. More importantly, however,

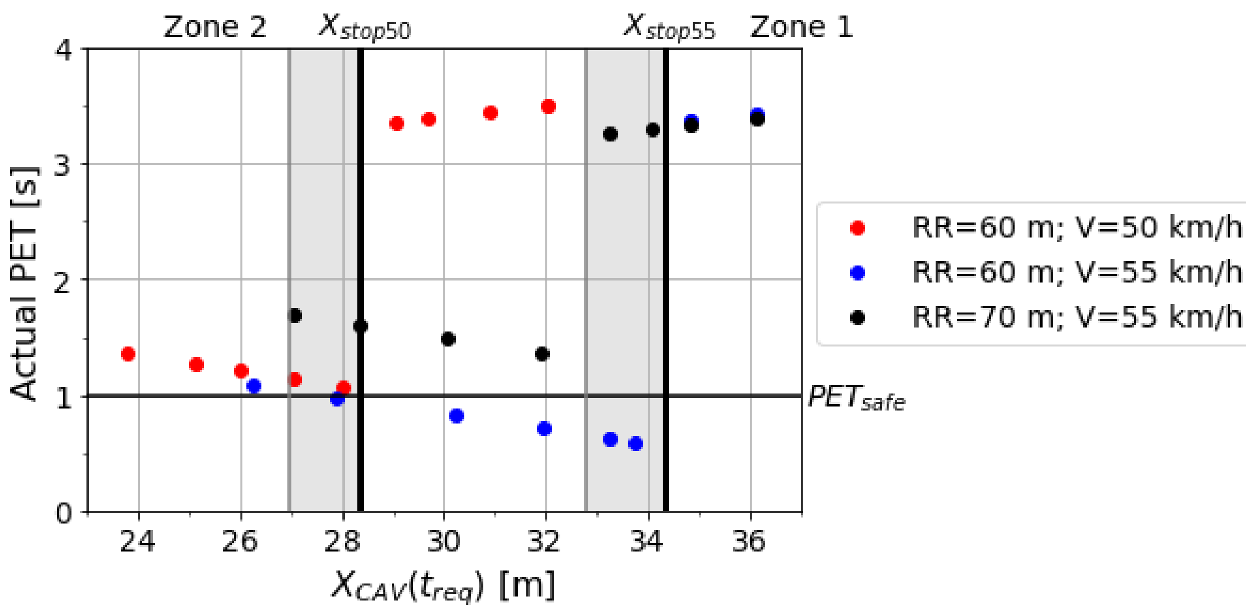


Figure 14: Overview of simulations with varying speed (V) and Request Range (RR). Both vehicles approach the intersection at the same speed and no latency in the communication is simulated.

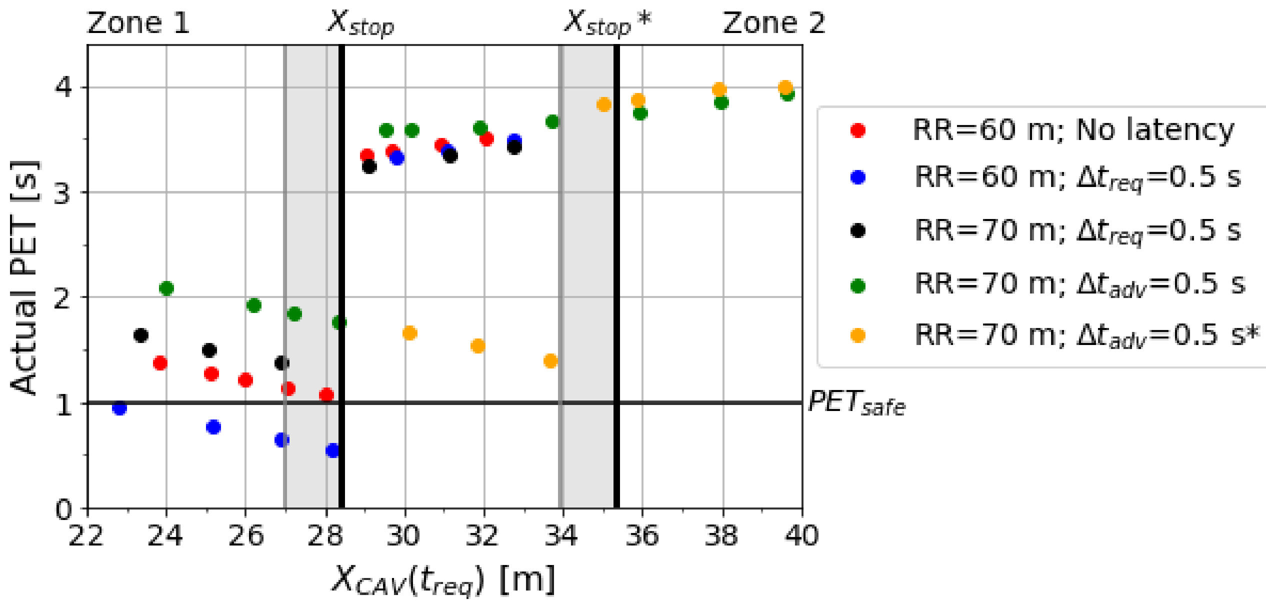


Figure 15: Overview of simulations with varying latency and Request Range (RR). Both vehicles approach the intersection at a speed of 50 km/h. The legend indicates whether the scenario is simulated with latency on the request message (Δt_{req}) or on the advice message (Δt_{adv}).
*Simulations performed with the service adapted to equation (11).

safe stop scenarios are turned into dangerous passage scenarios (PET $<$ 1 s), due to the increased stopping distance.
The black dots prove that this problem can be solved by increasing the Request Range to 70 m, as already suggested by Fig 10. Two anomalous black dots indicate that a stop was performed while the CAV was already located in Zone 2 at t_{req}. As discussed in the previous section, these result from the uncertainty in the timing of the most recent MCM sent by the CAV. Their positions in the grey area show that they fall within the limits of the expected error.

3.3.4 Varying Latency

In the previous sections, no communication latency or other delays were taken into account. However, equation (13) shows that the choice of an appropriate Request Range depends on the anticipated total delay between the transmission of a request/advice MCM and its subsequent processing at the receiver. The impact of time delays on the operation of the coordination service is investigated through several simulations represented by the dots in Fig 15. The speed limit was set to 50 km/h in all these scenarios.
Latency on the priority request message causes all operations of the service to

be delayed, thus effectively reducing the Request Range proportional to the EMV's speed. The blue dots in Fig 15 indicate that leaving the Request Range unchanged, results in a decrease of the actual PET, causing potentially dangerous situations. Simply adjusting the RR from 60 m to 70 m solves this issue, as observed by the black dots.

On the other hand, a delay in the advice message, sent by the MCS, causes the CAV to have moved closer to the intersection than anticipated by the MCS. As a result, it will have to brake harder and might be required to exceed the comfortable deceleration limit (a_{comf}) used by the service. This can be prevented by imposing the limit in formula (10) to determine whether the CAV should be advised to stop or not. Furthermore, the Request Range should be adapted according to equation (13) to ensure that the expansion of Zone 2 does not lead to a decreased minimum PET.

The green dots show the results for an MCS that does not impose the new limit on the stopping distance. Although the actual PET always remains above one second, the required deceleration of the CAV at t_{adv} increases to 4.23 m/s^2, which is larger than a_{comf}. The orange dots indicate the simulation results of the adapted service. In this case, the actual PET stays above PET_{safe} and the required deceleration never exceeds a_{comf}.

3.3.5 Multiple Vehicles

Up to this point, only scenarios consisting of two vehicles have been discussed. In practice, of course, multiple vehicles could be simultaneously approaching the intersection with various incoming and outgoing directions. Four distinct categories of scenarios have been identified and are schematically represented in Fig. 16. The operation of the service will be discussed qualitatively in each of these cases.

The first and simplest category consists of scenarios in which maximum one of the approaching CAVs is in Zone 2 at the arrival of the stop advice. In this case, all CAVs but one receive an MCM with an individually appointed safe spot in front of the junction. The one CAV in Zone 2 will pass the crossing well before the EMV arrives, and the others make a safe stop. As such, no conflict situations arise.

In the second category, multiple CAVs are located in Zone 2 at t_{adv}, but none of them have intersecting trajectories. Therefore, they could simply keep their pace and clear the intersection in time.

The third category deals with scenarios in which multiple CAVs with conflicting trajectories can not perform a comfortable stop in front of the crossing. In this situation, one of the vehicles would be required to decelerate and give way. As this CAV would still need to pass the intersection before the EMV arrives, the PET might drop below the safety limit. Therefore, the MCS should advice the EMV to slow down.

In the fourth category, one CAV is located in Zone 2, while another CAV (CAV 2) drives in front of the EMV. As the CAVs have conflicting trajectories, CAV 2 will have to slow down to keep the Post-Enchroachment Time above one

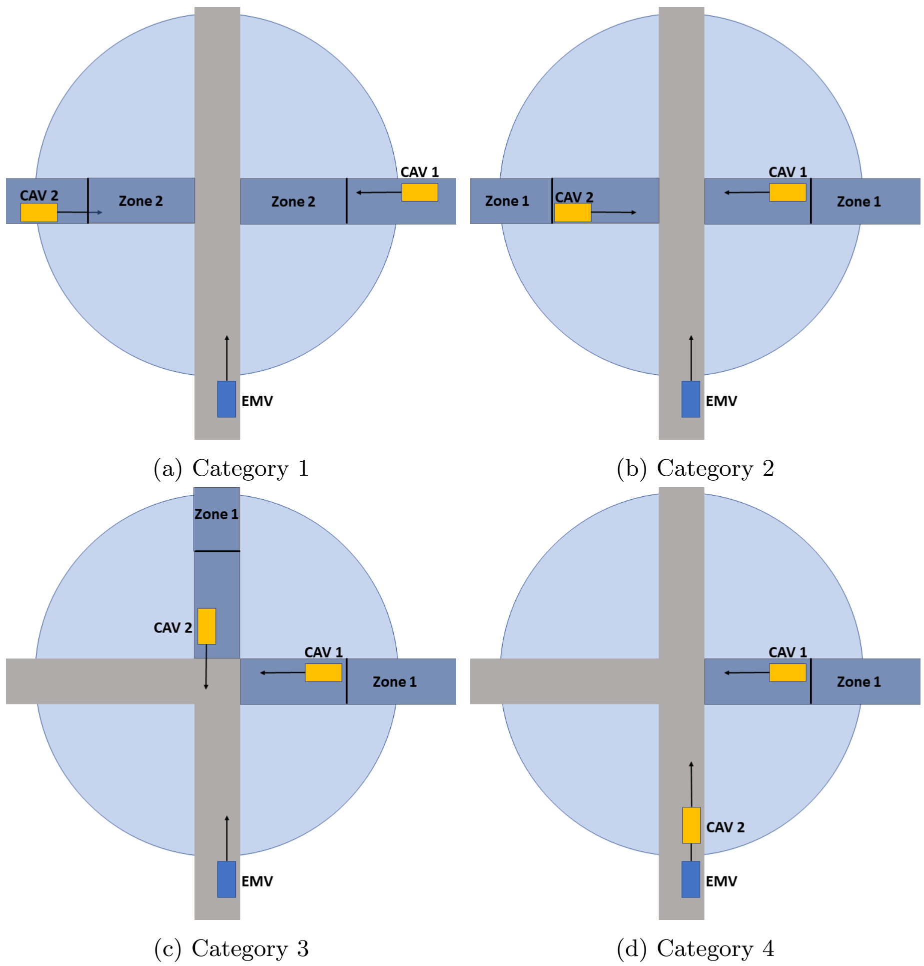


Figure 16: Schematic representation of the multiple vehicle scenario categories.

second. Therefore, the EMV will also be forced to slow down.
The above discussion shows that in specific scenarios, which involve multiple CAVs, the EMV needs to decelerate, regardless of its priority request and the Request Range. The alternative, slowed-down trajectory could be calculated by the MCS and proposed as advice to the EMV in order to ensure safety at the intersection.

3.3.6 Edge Scenarios

Thus far, the centralized coordination service has been examined under normal operating conditions. However, as the MCS could be seen as a safety-critical system, it is vital to investigate its operation in certain edge scenarios. For

instance, it has been stressed that upon receiving a priority request, the MCS advises CAVs that are sufficiently far from the intersection to make a stop at a designated safe spot. The fact that the coordinated maneuver is communicated as advice rather than a command implies that the CAVs have the option to neglect or reject it. As European law is currently not adapted to allow a centralized Maneuver Coordination Service to assume absolute authority over a vehicle in the area of operation.
Every CAV is responsible for its own actions and is equipped with its own sensors and its own perception system. Therefore, the decision to follow up on the advice proposed by the MCS is to be made by every individual CAV. For instance, if the CAV is aware of some malfunction in its braking system, it might not be able to perform the stopping maneuver safely and it could reject the MCS's advice. In turn, the MCS needs to inform the EMV that its priority request has been declined. The EMV will have to decelerate and repeat its request until safe passage is possible.
Furthermore, the CAV could be experiencing issues with its communication device causing it to neglect the advice of the MCS. In order to prevent the coordination service from waiting indefinitely for a reply, a timeout period can be specified, after which it will automatically consider the advice to be rejected. In the worst case, a malevolent CAV could accept the MCS's advice to perform a stop without actually decelerating. In this case, the MCS would notice that the particular CAV does not stick to the proposed trajectory and it could warn other traffic participants.
In conclusion, the safe operation of the coordination service relies on correct and complete information of all the traffic participants at or approaching the intersection. The above examples show that this can never be fully guaranteed and that the advice of the MCS should always be treated with care. While the service can provide very valuable information to perform coordinate maneuvers, the individual CAVs remain responsible for their own actions.

3.4 Conclusion

In this chapter, a Maneuver Coordination Service (MCS) was proposed to facilitate the prioritization of emergency vehicles (EMV) at unsignalized intersections in a connected and automated traffic context. The connected and automated vehicles (CAV) continuously send Maneuver Coordination Messages (MCM) to the MCS via an indirect C-V2X network. When an EMV enters the request range surrounding the intersection, it submits a priority request to the MCS. The MCS then evaluates which CAVs that are able to make a comfortable stop at the intersection and which cannot. The former vehicles receive the advice to stop at a specific location in front of the intersection, while the latter are permitted to pass the crossing before the EMV arrives.
The maximum deceleration required to come to a standstill at the safe spot is limited to 3.4 m/s^2. This ensures that the stop maneuver is safe. For the passage maneuver, formula (13) was derived in section 3.2.4 to determine the minimum Request Range needed to ensure that the Post-Enchroachment Time

(PET), i.e. the time between the CAV leaving the conflict zone and the arrival time of the EMV, stays above the one-second safety limit.
A simulation framework was set up to investigate the operation of the proposed service in different scenarios, including varying request ranges, approaching speeds, and communication latency. The results showed that when a suitable Request Range is set, and only one other CAV is present, the service can ensure safety.
The appropriate Request Range is determined by a combination of factors such as the approaching speeds of the vehicles, the projected maximum communication delays, the topology of the intersection, and the length of the CAV. Since these factors may vary in different situations, a general maximum Request Range should include a margin of safety for each variable.
This shows that the increased latency of using indirect C-V2X instead of ITS-G5 or direct C-V2X communication does not necessarily impact safety. What matters most is the guarantee that the latency will not exceed a specific limit. If the coordination service can schedule the maneuver sufficiently ahead, i.e. if the Request Range is large enough, all vehicles are informed well in time to adapt to the proposed coordinated maneuver.
When using a long-range C-V2X network for the coordination service, the request range would not be limited by the communication range. Another limitation on the request range could result from the limited length of the vehicles' planned trajectories. Moreover, the increase of the request range also increases the probability for unexpected actions, which could pose new challenges to the service.
It is important to note that it is not within the scope of this study to provide an optimized and exhaustive intersection management system. For instance, it would be more fuel and traffic flow efficient to advice the CAVs to gradually decelerate towards the intersection instead of advising them to make a full stop. Additionally, the service is not adapted to deal with scenarios involving multiple CAVs. A qualitative analysis of such scenarios showed that under specific circumstances the EMV will be required to decelerate in order to ensure safety at the intersection. For these scenarios, the MCS could be extended to propose the optimal decelerating trajectory to the EMV.
Finally, some edge scenarios, such as rejection of the proposed stop advice or communication issues, were taken into consideration. From these adverse cases, it becomes clear that the vehicles should not rely solely on the proper operation of the coordination service. Even when the communication breaks down, or when the MCS fails to provide an appropriately coordinated maneuver, the autonomous vehicles should be able to perform safe maneuvers based on their own perception and planning systems.

4 Conclusion and Discussion

4.1 Conclusion

The increasing integration of digital technologies is transforming our society in the most profound ways. In the coming years, it will change the area of road traffic by adopting connectivity and automation. Vehicles will gather and exchange large amounts of data on their environment, enabling the deployment of an increasing level of automated systems.
Digitization is expected to lead to more efficient and safer road transportation. However, the specific effects it will have on all stakeholders are not yet clear. This work focused on the potential impact of emerging connectivity and automation of road traffic on the operation of emergency services.
The first objective was to quantify and evaluate the impact of connected traffic services that improve the speed and safety of emergency vehicles in urban traffic. Two services were implemented in the microscopic traffic simulator SUMO, the Traffic Signal Priority Service (TSPS) and the Vehicle Rerouting Service (VRS). The services were evaluated in realistic morning and evening traffic scenarios in the city center of Eindhoven.
In the TSPS, the emergency vehicle (EMV) notifies the intelligent Traffic Light Controller of its approach and requests priority at the intersection. It was found that the radius at which the priority request is transmitted can significantly impact the time gain of the emergency vehicle. At a radius of 800 m the queues at the intersection have generally dissolved by the time the EMV arrives. With this implementation, a reduction in response time of around thirty seconds was achieved for a trip inside the city center, while the average speed of other vehicles decreased by 0.7%.
The VRS reroutes other traffic participants away from the route of the emergency services once an emergency call is made. The resulting gain in response time was found to be similar to the TSPS. However, the activation of the VRS lead to a 13.8% decrease in the average speed of the other vehicles.
The combination of both services resulted in a decrease of 30.2% and an increase of 14.4% in the travel times of the emergency vehicle and the other vehicles, respectively.
The societal gain of the services was evaluated based on the value of qualitative life-years saved by the reduced emergency response time. This gain was balanced with the societal cost of the delayed traffic to determine the societal value of the services. In this rudimentary evaluation, the TSPS clearly outperformed the VRS.
The second objective of this work was to investigate the prioritization of emergency vehicles by a centralized maneuver coordination service at unsignalized intersections in connected and automated traffic. The maneuver Coordination Service was implemented as a ROS2 node and tested in a simulation framework combining the CARLA simulation environment and the Autoware.auto autonomous driving stack.
When an emergency vehicle approaches the intersection, the MCS gets notified

and determines a suitable maneuver for all other connected and automated vehicles (CAV). Based on their location with respect to the intersection and their current speed, the CAVs will either be advised to stop in front of the intersection or pass before the EMV arrives.
Simulation tests involving one CAV showed that when the range at which the priority request is transmitted is sufficiently large, the MCS can maintain safety. In scenarios with higher vehicle speeds and increased latency, this request range needs to be extended accordingly.
Qualitative analysis of scenarios involving multiple CAVs indicates that in specific circumstances the MCS should advise the EMV to slow down in order to ensure safety. Moreover, all autonomous vehicles should be able to rely on their own safety systems in case of communication failures.
In conclusion, emergency services can definitely benefit from connectivity in road traffic. As simulations of the Traffic Signal Priority Service showed, the response time can be significantly reduced by prioritizing emergency vehicles. Moreover, it could drastically reduce the risk emergency services face when violating red lights. However, as the Vehicle Rerouting Service showed, some applications also have significant adverse effects on other stakeholders. Therefore, it is important to investigate the potential impact of connected services before implementing them on a large scale.
In addition, the combination of connectivity and automation could greatly enhance the operation of emergency services. Not only would it remove the distress for the human drivers, and for the driver of the emergency vehicle in particular, but the automated interaction would also streamline maneuver negotiations, resulting in a shorter response time. However, as the investigation of the MCS showed, full automation requires comprehensive consideration of all possible scenarios and the assurance of safety in even the most adverse circumstances.

4.2 Discussion

In 2014, ETSI and CEN completed their first release on standardization of C-ITS [5]. At that time, the European Commission anticipated the deployment of the first connected cars on European roads in 2015 [81]. By 2021 still, only 24% of the total European car fleet was connected [82]. Despite projections that by 2035, 93% of the vehicles will be connected, the adoption has been slow. Meanwhile, the potential benefits of connected services depend on the number of users.
At the same time, almost every Original Equipment Manufacturer (OEM) is developing its own automated systems with their own Operational Design Domains (ODD). In order for these systems to benefit from communication with other vehicles, it is vital that the received information is reliable and accurate. Solving these trust issues could significantly increase the benefits of connectivity and support its uptake.
On the other hand, government bodies could impose regulations to stimulate OEMs with the adoption of safety-related systems. Similar, to what the European Union has recently done with the Intelligent Speed Assistance system [83].

Governments should promote standardization without limiting innovation. This is in agreement with the technology-neutrality stance of the European Commission, which allows for the coexistence of ITS-G5 and C-V2X in the 5.9 GHz frequency band. Stimulation of innovation also takes place through the funding of research and pilot projects. Another important role of governments is to protect road users' data. For example, on European roads, the General Data Protection Regulation (GDPR) requires the use of variable pseudonyms to identify vehicles in C-ITS applications [84].
Road operators are usually related to governmental entities but have a more specific role in the digitization of road traffic. Road operators already use variable-message signs to warn travelers about congestion, road works, and accidents. The installation of intelligent traffic light controllers enables them to prioritize specific vehicles and transport modes. Additionally, road operators can support the introduction of autonomous vehicles by providing services that help them in mixed-traffic conditions, as proposed in the TransAID project [85]. When the penetration of autonomous vehicles increases, they could facilitate maneuver coordination services such as the one proposed in this work.
Telecommunication operators can play an important role by providing a long-range C-V2X network. This would require an extensive network to cover the entire road network. Moreover, currently, telecommunication operators provide a so-called 'best effort' quality of service, which does not promise a specific maximum communication latency. Especially for safety-related applications, telecommunication operators need to guarantee a specific network quality. The operator should, for instance, be able to guarantee that 99.9% of the messages are delivered with a latency below X ms, depending on the specific application.

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