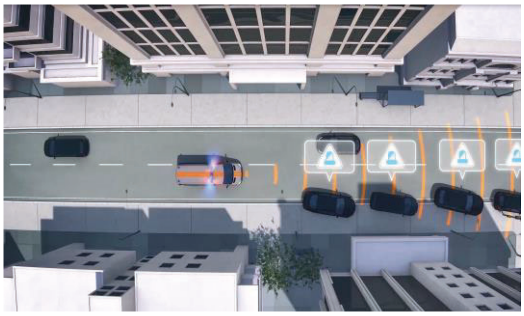
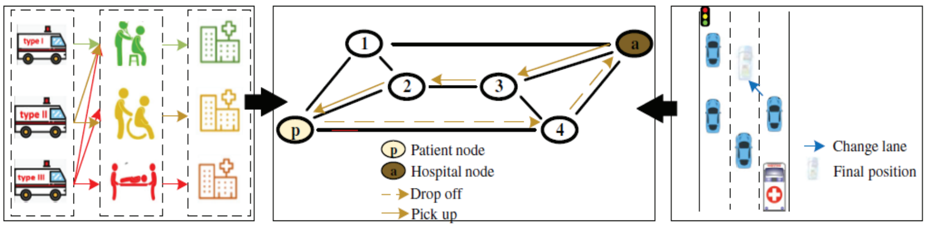
System-Of-Systems for efficient Emergency Response and Urban Mobility (SoSER)

Publik rapport





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FFI Fordonsstrategisk Forskning och Innovation

Innehållsförteckning

1 Sammanfattning

Nödhjälp i en stad är en av samhällets kärnfunktioner och är också en traditionell tillämpning med många års erfarenhet och kunskap. Systemet för insatser vid nödsituationer är ett typiskt system av system (SoS). Det omfattar många oberoende system och kräver ett nära samspel mellan intressenterna både på teknisk och organisatorisk nivå för att uppnå ett gemensamt mål. Det uppfyller SoS:s egenskaper och bör behandlas utifrån SoS-perspektivet när det gäller arkitektur, modellering och simulering, integrering och användning. Detta projekt syftar till att generera kunskap om systemteknik och tillämpning av SoS teknik (SoSE) på nödåtgärder efter olyckor, vilket bidrar till att ytterligare minska antalet dödsfall i vägtrafiken och på så sätt bidra till Nollvisionen.

Med tanke på att räddningshantering är ett komplext system för samhällsskydd har projektet undersökt utvecklingen av systemet och teknik för samhällsskydd och dess tillämpningar inom mobilitet i städer och räddningsinsatser. Katastrofinsatskedjan har betraktats ur ett SoS-perspektiv som omfattar olika aspekter, däribland intressenter, lagar och förordningar samt räddningsfaser. Ny teknik som ger nya möjligheter har beaktats både när det gäller algoritmutveckling som är inriktad på enskilda ämnen och holistisk systemdesign.

Projektet har genomfört en grundlig litteraturstudie om SoS, inklusive definitioner, kategoriseringar, projekt och tillämpningar, tekniska metoder och arkitektur. Urban mobilitet har betraktats som ett socialt system med kombinationer av begreppet koreografier för tjänsteinnovation. Den har också betraktats med uppkopplade automatiserade fordon och molnbaserad trafikstyrning för att påskynda införandet av tjänster och för att möjliggöra interaktion mellan utryckningsfordon och CAV:er. För att stödja samarbetsintelligens har man övervägt federerat inlärning för att möjliggöra samarbete utan datadelning. När det gäller de olika fasen i räddningsinsatserna har algoritmer för lokalisering av anläggningar, förröjning av räddningsfordonens körfält och dirigering utvecklats. Med tanke på konvergensen av arkitekturramar har den framväxande enhetliga arkitekturramen (UAF) utvärderats med den senaste tekniska processen. Praktiken för att utforma arkitekturen för nödsystem rapporteras och omfattar aspekter på hög nivå. Ett specifikt fall av integrering av uppkopplade automatiserade fordon i insatser vid nödsituationer behandlas.

Från SoSE-perspektivet bidrar detta projekt till att visa hur långt man kommit i fråga om SoSE, teknikmetoder för SoSE och erfarenheterna av SoSE inom urban mobilitet genom praxis för insatser vid nödsituationer. På SoSER:s makroskopiska nivå utvärderas i detta projekt SoSE metodik för att förbättra den nuvarande praktiken för hantering av nödsituationer genom samordning och kommunikation mellan olika intressenter. På den mikroskopiska nivån utnyttjar projektet industripartnernas kompetens och utvecklar utrustning och modeller för att förbättra responstiden genom att dra nytta av den senaste tidens framgångar inom artificiell intelligens, kommunikation i fordon och intelligent trafikstyrning och hantering av trafikstockningar.

2 Executive summary in English

Emergency response in a city is one of the core functions of the society and is also a traditional application with many years of experience and knowledge. The emergency response system is a typical system of systems (SoS). It involves many independent systems and requires close interaction between the stakeholders both from the technology level and the organizational level to achieve a common goal. It satisfies the properties of SoS and should be approached from the SoS perspective in architecture, modelling and simulation, integration, as well as deployment. This project aims to generate knowledge on system of system engineering (SoSE) and the application of SoSE methodologies in post-crash emergency response, which help to further reduce the fatalities of road traffic, thus contributing to Vision Zero.

Considering emergency management as a complex SoS, this project has investigated the SoS development, SoS engineering, and its applications in urban mobility and emergency response. The emergency response chain has been considered from a SoS perspective which covers different aspects including stakeholders, laws and regulations, and rescue phases. Emerging technologies that introduce new opportunities have been considered for both algorithm development targeting individual topics, and holistic system design.

The project has conducted a thorough literature study on SoS including the definitions, the categorizations, projects and applications, the engineering practices, and the architecture.

Urban mobility has been considered as a SoS with combinations of the concept of Choreographies for service innovation. It has also been considered with connected automated vehicles (CAVs) and cloud-based traffic control for accelerating service introduction, and for enabling interaction between emergency vehicles and CAVs. For supporting collaborative intelligence, federated learning has been considered to enable collaboration without data sharing. Regarding different stages of emergency response, algorithms for facility location, emergency vehicle lane pre-clearing, and routing have been developed. Given the convergence of architecture frameworks, the emerging unified architecture framework (UAF) has been evaluated with the latest engineering process. The practice of architecting the emergency system is reported which covers the high-level aspects. A specific case of integrating connected automated vehicles into the response process is considered.

From the SoSE perspective, this project contributes with the state of the art of SoSE, engineering methodologies of SoSE, and the application experiences of SoSE in the urban transportation domain through practices in emergency response. At the macroscopic level of SoSER, this project investigated theSoSE methodological framework to improve the current practice of emergency management through multi-stakeholder coordination and communication. At the microscopic level, this project leverages the competencies of industry partners and develops equipment and models in order to improve response time by taking advantage of the recent prosperous artificial intelligence, vehicular communication, and intelligent traffic control and congestion management technologies.

3 Bakgrund

Emergency response in a city is one of the core functions of the society and is also a traditional application with many years of experience and knowledge. Traffic planning and optimization are also the core city functions and traditional research areas closely related to citizens' mobility. All the accumulated knowledge provides valuable input for this project. However, to integrate the traditional traffic planning and the emergency response methods enabled by the emerging connected vehicles and infrastructure, advanced medical devices requires the implementation of existing knowledge under new contexts. To be more specific, emergency vehicles (EVs) now are able to take advantage of real-time traffic information and routing to minimize the time to reach the target hospital; the public safety answering points (PSAPs) now are able to take advantage of on-board pre-hospital assessment and send the patient to the most appropriate hospital; transport operators now are able to prioritize the EVs through connected vehicle and infrastructure; infrastructure planners should now consider emergency management when planning and designing the transport infrastructure and intelligent traffic flow management; drivers of other vehicles are able to give way to EVs through clear interaction enabled by connected vehicle application. This essentially leads to a type of SoS that consists of both existing systems and new systems. In addition, the application of SoS methodologies in emergency response is new and novel, partially because the SoS engineering is not well-established, and also that technologies of connectivity, automation, and AI are evolving. The development of SoS engineering will need a thorough investigation of international efforts such as those that have been done under IEEE, INCOSE – the International Council on Systems Engineering, as well as results from EU-financed projects.

The project focuses on the application of SoS engineering to emergency response. Essentially, this project investigates methodologies to integrate all relevant stakeholders under the SoS engineering framework for a holistic and integrated SoS that is able to simultaneously make optimal decisions of hospital selection, routing, vehicle cooperation, traffic control and congestion management for transport infrastructure with different levels of intelligent transportation systems, for the purpose of fast emergency response and smart urban mobility. In the meanwhile, by utilizing SoS engineering and catching the emergent behaviors of SoS, we gain a better and more comprehensive understanding of the evolution of such an emergency response system and then optimize its behavior in a highly connected and automated city transport system.

4 Syfte, forskningsfrågor och metod

The emergency response system is a typical SoS. It involves many independent systems and requires close interaction between the stakeholders both from the technology level and the organizational level to achieve a common goal. It satisfies the properties of SoS and should be approached from the SoS perspective in architecture, modelling and simulation, integration, as well as deployment. This proposal focuses on approaching the emergency response system from a SoS perspective and aims at developing an optimal system of systems for emergency response (SoSER).

This project aims to generate knowledge on SoSE and the application of SoSE methodologies to post-crash emergency response, which helps to further reduce the fatalities of road traffic, thus contributing to Vision Zero. From the SoSE perspective, this project contributes with the state of the art of SoSE, engineering methodologies of SoSE, and the application experiences of SoSE in the urban transportation domain through practices in emergency response. At the macroscopic level of SoSER, this project investigates the application of SoSE methodological framework to improve the current practice of emergency management through multi-stakeholder coordination and communication. At the microscopic level, this project leverages the competencies of industry partners and develops equipment and models in order to improve response time by taking advantage of the recent prosperous artificial intelligence, vehicular communication, and intelligent traffic control and congestion management technologies.

The methods used in this project include a literature review and state-of-art analysis of SoSE. This project arranges workshops with industry partners, as well as participates in national and international conferences. Afterward, this project applies the appropriate architecting methodologies identified for urban transportation with a focus on emergency response. The process has a close engagement of different stakeholders so that their concerns are addressed during architecting and that each stakeholder also has a broad view beyond their own domain.

A prehospital screening equipment based on diagnostic microwave technology has been developed. This technology is based on the dielectrical properties of the investigated human matter, e.g., brain tissue.

For routing of EVs and managing the ambulance fleet properly, a mixed-integer linear programming (MIP) model is proposed to assign vehicles to the injured and plan routes with the shortest travel time. A semisoft time window constraint is incorporated to reflect the late arrival penalty onsite and at hospitals.

For utilizing intelligent transport infrastructure adaptation to prioritize EVs, an EV lane pre-clearing strategy to prioritize EVs on such roads through cooperative driving with surrounding connected vehicles (CVs). The cooperative driving problem is formulated as a mixed-integer nonlinear programming (MINP) problem aiming at (i) guaranteeing the desired speed of EVs, and (ii) minimizing the disturbances on CVs. To tackle this NP-hard MINP problem, we formulate the model in a bi-level optimization manner to address these two objectives, respectively.

For the simulation of SoSER, this project has developed simulation tools and platforms based on virtual reality. It includes a micro-scope simulation that addresses e.g., vehicle coordination, vehicle-infrastructure coordination, macro-scope effects on traffic flow, as well as other social-technological systems.

5 Mål

The main goals of this project can be summarized as follows:

- Generating comprehensive knowledge and contributing to the SoS engineering in the urban transportation domain

- Verifying and validating the impact of SoSE for fast emergency response and smart urban mobility
- Improving the current practice of emergency management through multi-stakeholder coordination and communication
- Robust methods for improving emergency response time by taking advantage of the recent advanced technologies such as AI, vehicular communication, and intelligent traffic control and congestion management technologies
- Facilitating cross-industry cooperation, covering system engineering, SoSE, vehicle industry, medical industry, road infrastructure industry, ICT, and safety
- Contributing to creating a strong and competitive Swedish SoS community that has close connections with global SoSE communities

6 Resultat och måluppfyllelse

6.1 SoS engineering review and architecture

The project conducts a thorough literature study on SoS including the definitions, the categorizations, projects and applications, the engineering practices, and the architecture. Urban mobility has been considered as a SoS with combinations of the concept of Choreographies for service innovation. It has also been considered with connected automated vehicles (CAVs) and cloud-based traffic control for accelerating service introduction, and for enabling interaction between emergency vehicles and CAVs. For supporting collaborative intelligence, federated learning has been considered to enable collaboration without data sharing. Algorithms for facility location, emergency vehicle lane pre-clearing leveraging V2X, and routing based on operation research have been developed collectively to improve different stages of emergency response and reach holistic emergency management. Given the convergence of architecture frameworks, the emerging unified architecture framework (UAF) has been evaluated with the latest engineering process. The practice of architecting the emergency system is reported which covers the high-level aspects as modelled by the following views and summarized in Figure 1.

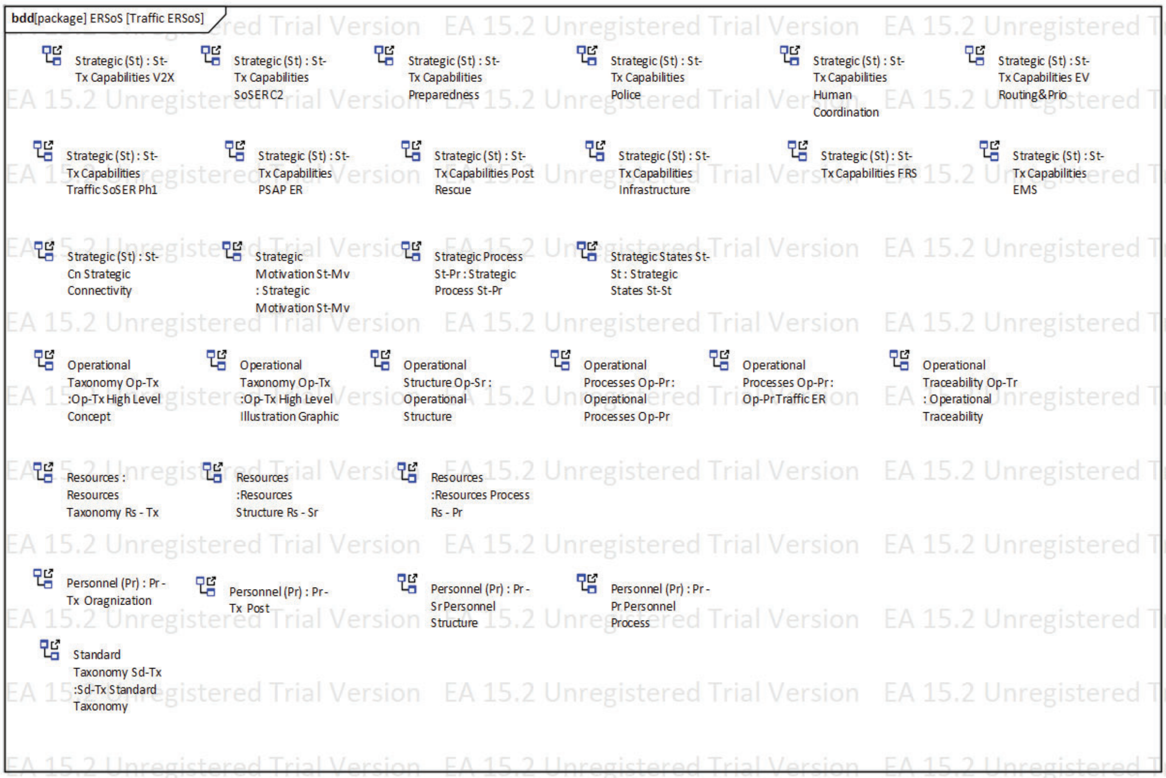


Figure 1 The architecture models of the emergency system of systems - preliminary

A specific case of integrating connected automated vehicles into the response process is considered and the capabilities are moded as shown in Figure 2.

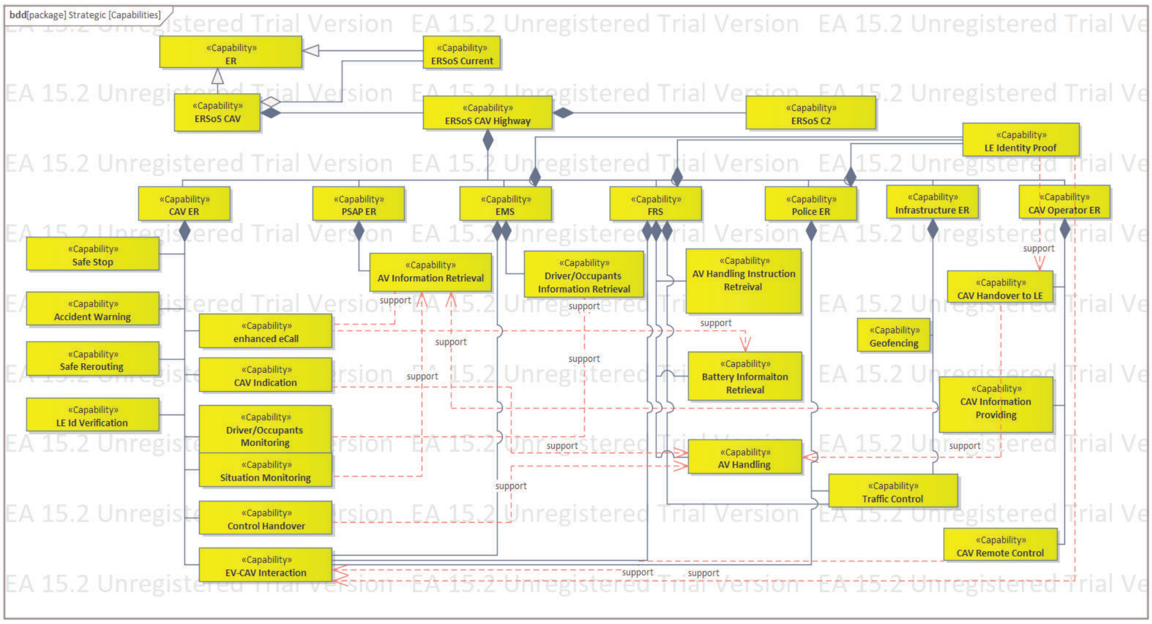


Figure 2 The Strategic (Capability) diagram for handling connected autonomous vehicles in emergency SoS

6.2 A prehospital screening device

Medfield Diagnostics proposes the first unique medical device capable of enabling a truly mobile, prehospital-centred differential stroke and TBI (Traumatic Brain Injury) diagnosis

decision tool. The potential of this device to capture the existing, unpenetrated market space lies in the combination of its diagnostic accuracy and enhanced mobility/low cost. The market entry will be facilitated by measurable health-economic gains. This has already been indicated in initial health-economic assessment.
MD100 is intended to move diagnosis and treatment from the major hospitals all the way to the scene of the incident assisting in shortening the time from "door to needle". This would:

- Dramatically shorten the latency from stroke alarm to thrombolytic therapy, which in itself is of great importance as 2 million brain cells are lost every minute at the beginning of a stroke.
- Increase the number of stroke patients eligible for thrombolytic treatment (within 4.5 h but moving) which is the most effective therapy for ischemic stroke.
- Dramatically shorten the time from door to needle for Traumatic brain Injuries by accurately sending the ambulance to the hospital possible to give the appropriate treatment.

Figure 3. MD 100 prehospital screening device

In this project, several MD100 product development activities have been performed in different areas. These activities are briefly summarized below:

- An update of the mechanical design is conducted for simplifications and cost reductions in volume production. It also improves quality and reduces production variability. The redesign has come quite far and some parts are already completed.
- Considerable effort has been spent in improving the security aspects of MD100 system. The major reason for the upgrade is to protect patient integrity and minimize the risk of malicious attempts to manipulate the device. These aspects are particularly important to address for a portable device used in a prehospital environment since many persons will have physical access to the instrument. It is going to be even more important when the device will be able to connect with other devices and systems for the transfer of results.
- An effort has been done to enable remote software (SW) upgrades. This simplifies the handling of SW releases and upgrades drastically since travelling to instrument sites for upgrading is avoided. This is particularly important for bug fixes that potentially could cause problems for users. Since this will enable remote access to the devices, it is extremely important to ensure that security aspects according to the section above are maintained.
- Algorithm development is key to the performance of MD100 system as is thus a continuous focus area for Medfield Diagnostics AB. Algorithm development and verification are critically dependent on access to relevant clinical data. The more data that is available, the more advanced and well-performing algorithms can be developed. The algorithm development effort is therefore performed in close collaboration with clinical study collaborators. During the reporting period, a master thesis project on algorithm

development has been completed and a large number of alternative algorithms and data processing methods have been explored. Some important improvements in performance have as a result of these efforts been achieved.

From the business point of view, MD100 system has the potential to fill a clearly defined market gap – there is presently no commercially available product on the market enabling fast, prehospital diagnosis of stroke.

To date, the key approach to filling this gap has been based on transferring the existing complex, high-cost diagnostic infrastructure and associated medical competence to ambulance settings through Mobile Stroke Units (MSU) equipped with CT scans. This approach has demonstrated feasibility in densely populated areas with well-developed traffic and telecommunication infrastructure, coupled with well-organised and financed health care systems. However, the broad-scale deployment of MSU is currently not feasible from a financial and operational point of view.

MD100 has the potential to leverage the reported successes and the increasing interest in MSU and fill that existing market gap. MD100 can be fitted into all ambulances and its machine learning capabilities will enable quick and reliable interpretation of the diagnostic results, even by regular ambulance staff (paramedics).

From the technological point of view, there are presently no strong challenges to the microwave technology. The possible alternative solutions include Computer Tomography (CT), Ultrasound, Impedance Measurements and Near-Infrared Spectroscopy. Several different technologies have been researched with the aim to develop a compact system that can be used to distinguish ischemic from haemorrhagic stroke in a prehospital setting.

All the alternative technologies compare unfavourably with MD100 technology in terms of mobility and long-term cost-efficiency. This is explained by the fact that the costs of microwave technology components used in the MD100 system are continuously being prised down by the developments in the telecom industry where they have their origin.

Moreover, microwave propagation in human tissues has an advantage over both impedance, ultrasound and near-infrared technologies via the easy penetration of the human skull. This is the fundamental basis for the novelty and market potential claims of MD100.

Moreover, a microwave-based system has the advantage of being completely safe and without side effects. Therefore, it could potentially also be used as a monitoring device during thrombolytic treatment and thereby avoid complications in the form of intracranial bleeding, which is a known risk of the treatment.

The market segments and customers for MD100 system could be a quite long list of places where a stroke or TBI can occur (remote ski areas, big airports, sport arenas, cruisers, etc.) and potentially all of these sites are qualified to host an instrument such as MD100, but those who ultimately need to care for and treat these patients (i.e. EMS and health care professionals) must be involved and have experience of the instrument before it can be expanded into a wider environment. Consequently, the initial market area focuses are health care professionals and EMS.

6.2 EVAM Transmit communication device

Evam Transmit, developed by H&E Solution, is a digitalized version of warning lights and sirens, that enable emergency vehicles to give nearby motorists an early warning. The warning message is played through the sound system and a warning message is displayed in the sound system display. Nothing needs to be installed in civil cars, instead already built-in functions are used. Through early warnings, Evam Transmit allows a safe and fast passage for the emergency vehicle. This can improve traffic safety, safer working environment for first responders, and shortened response times. Furthermore, Evam Transmit is beneficially used at traffic accident scenes to improve safety for the emergency crew ultimately saving lives.

Figure 4 Evam Transmit

During the project period, Evam has made great progress where most milestones have been met. The first larger zero-series production of the product Evam transmit has been finished with an extremely challenging hardware design. This had its challenges, but all were successfully solved, and 160 units were successfully produced. Evam Transmit devices have been implemented in one country. Approximately 150 vehicles in Doha, Qatar were equipped with EVAM Transmit as a preparation for the 2022 World Cup. The system is now live and successful in Doha, Qatar. Furthermore, several trials have been done, where for example Ambulances in Barcelona, Spain have been equipped with Evam Transmit. These trials further evaluate the effects of Evam Transmit.

The project period has also been filled with work to gain regulatory approval for the usage of the Evam Transmit technology in several European countries but has been lined with problems. In Sweden, the Swedish Radio (SR) has been very negative about the implementation of the technology. This has therefore become a political question where several members of the parliament supported the implementation of Evam Transmit. On the technical sidewe have made several big breakthroughs in radio sending technology which significantly improves the performance of the Evam Transmit technology. This has led to one PCT-approved patent.

Due to the regulatory hinders in Europe an alternative approach using cellular (4G/5G) and ITS-G5 has been taken for the European market. The development of the Evam Platform was therefore started and is today being used at several Swedish Emergency services with larger tests ongoing in the scope of Nordic Way 3. The tests focus on the two use-cases “Emergency vehicle approaching” and “Traffic signal priority”.

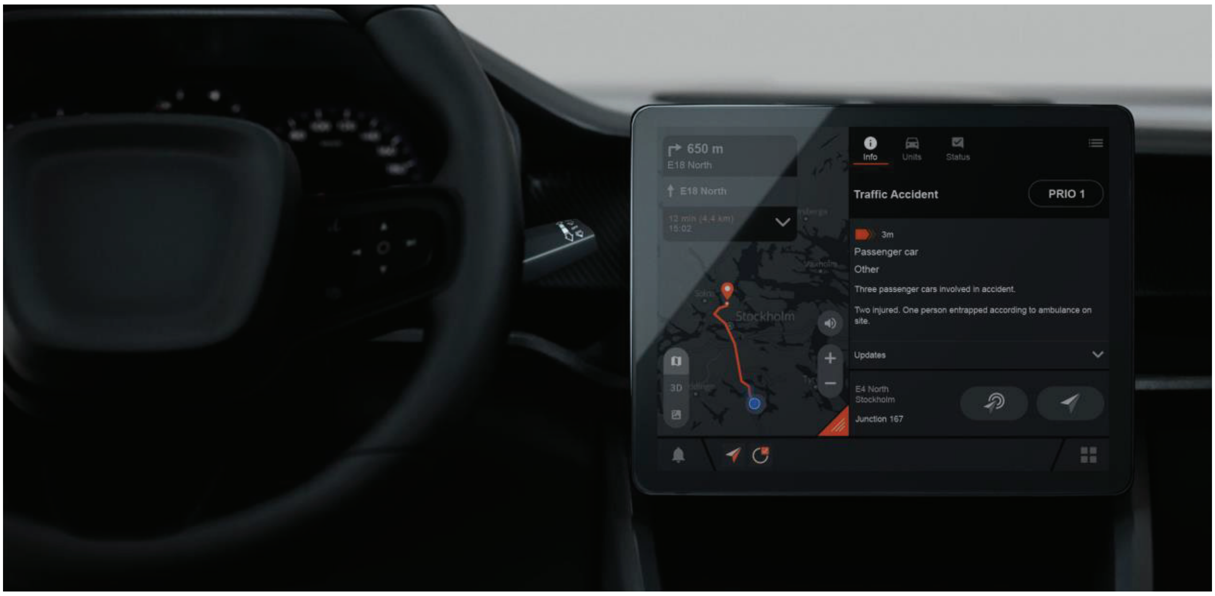
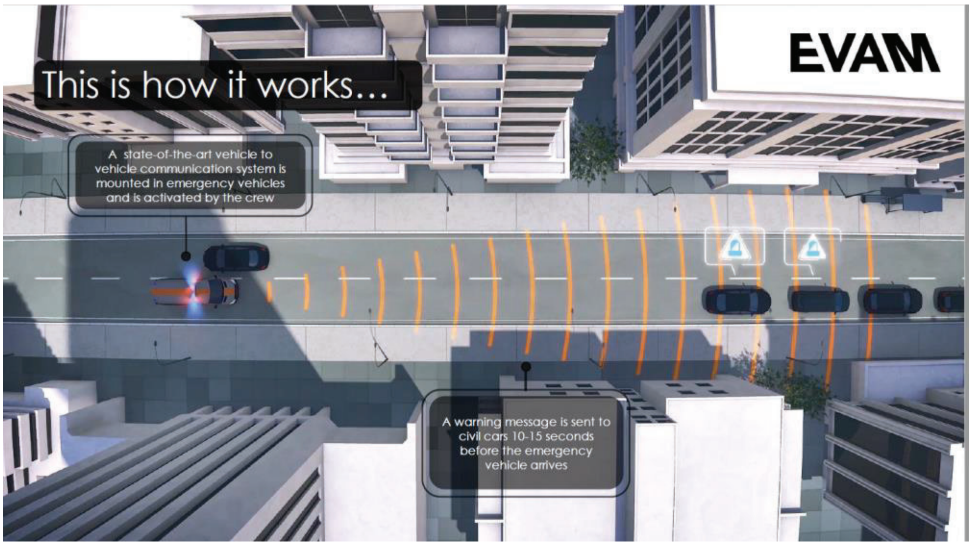


Figure 5 The newly developed Evam Platform



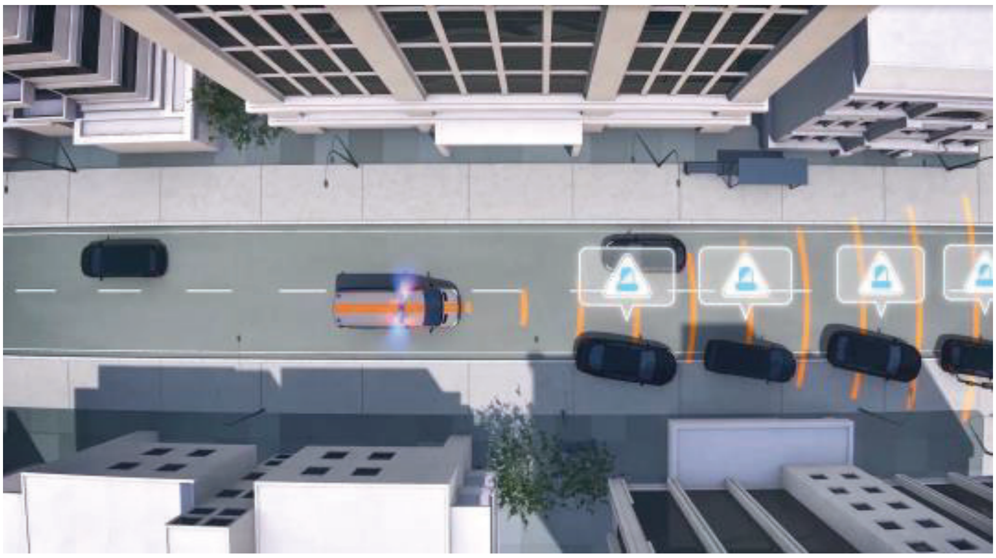


Figure 6 Functions of EVAM Transmit

6.3 An EV routing method considering interactions of multiple stakeholders

The emergency medical services providers (EMSP) have to design a rescue plan to cope with the dynamic traffic condition and the scarce resources, such as hospitals and ambulances while guaranteeing the shortest transport time and proper resource allocation. Thus, traffic operators and hospitals must be involved in the planning process. It offers an underexplored opportunity to consider both hospitals' expertise and traffic conditions in ambulance routing problems (ARP).

The ambulance routing problem aims to plan routes to pick up patients and drop them off at the hospitals. This problem will be fundamentally different from the traditional vehicle routing problem by taking into account two advanced technologies: prehospital screening and lane pre-clearing, as shown in the below figure. Typically, the ambulance routing problem can be categorized into two classes: hospital-based and depot-based. For the depot-based system, ambulances belong to hospitals and are initially located at their hospitals. In some cases, ambulances, together with other emergency vehicles, will be positioned at a depot, which is defined as a depot-based system. In this research, we focus on the hospital-based one. By customizing the initial location for the ambulance fleet, the proposed method can be implemented in depot-based scenarios.

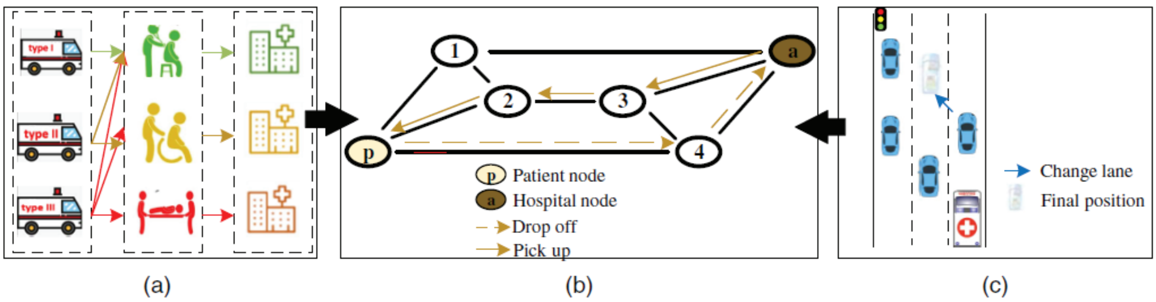
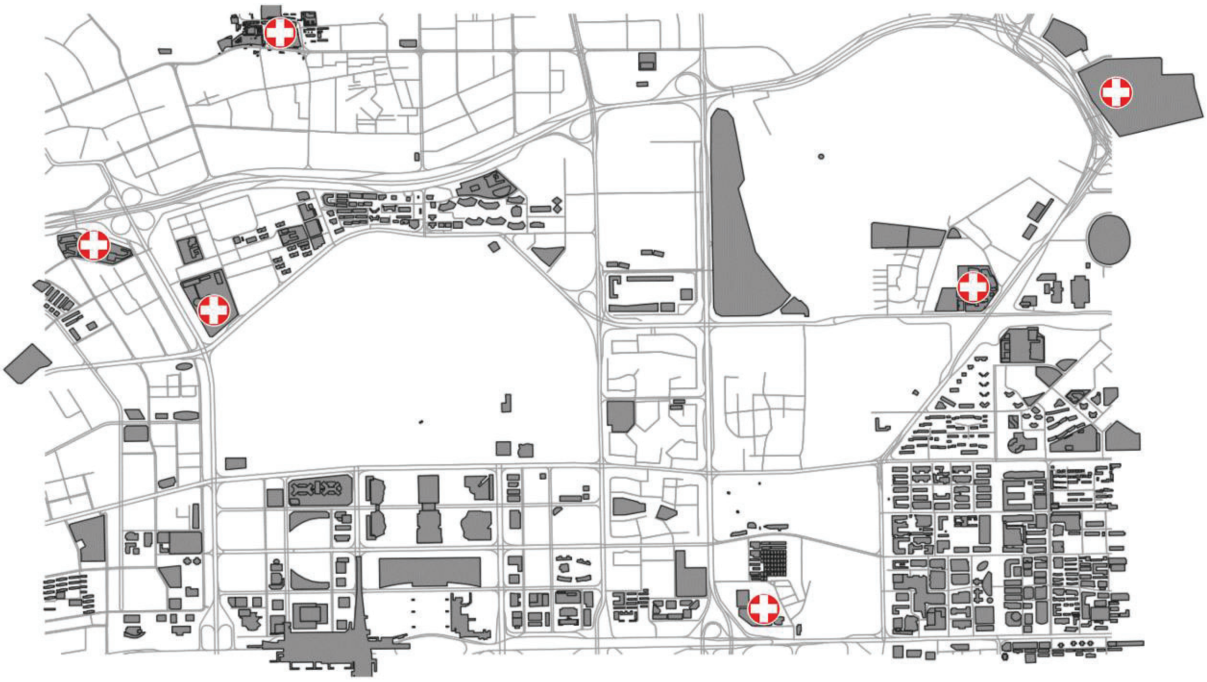
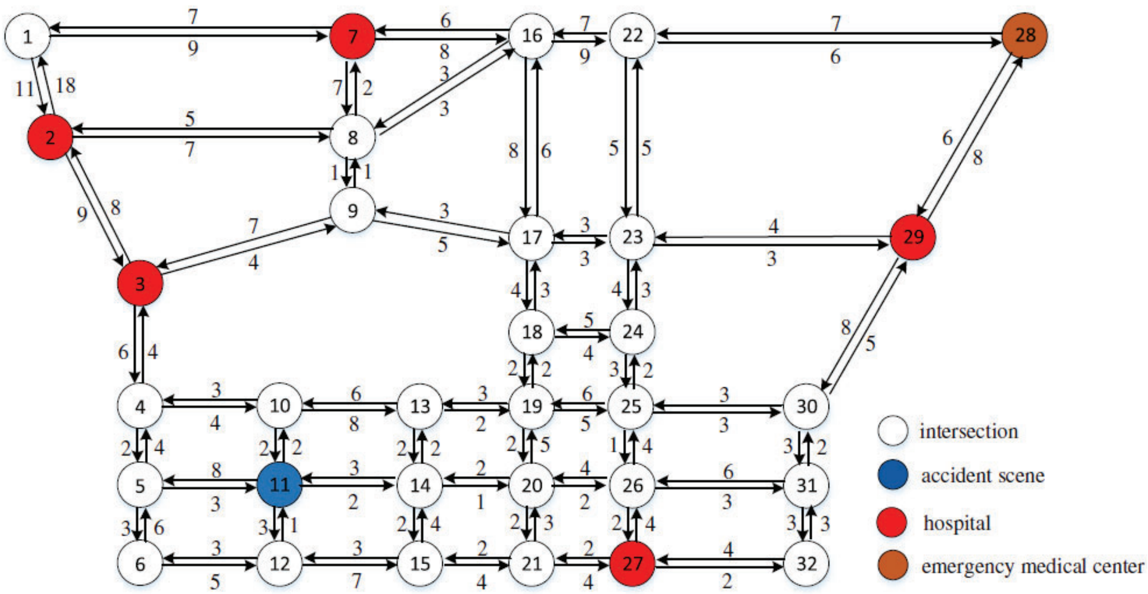


Figure 7 Ambulance routing process: (a) prehospital screening; (b) ambulance routing; and (c) lane preclearing

In this project, we focus on the ambulance routing problem, which strives to involve EMSP, traffic operators, and hospitals in the planning process. In detail, the prehospital screening and lane precleaning are implemented as input to speed up the first aid and avoid inefficient delivery. The Mixed-integer Program (MIP) optimization model is proposed for ambulance dispatching and vehicle routing based on a high-spatial-resolution network to reduce the transport time, the dispatching cost, and the late arrival penalty. Patients with different severities will be allocated to the hospital with the proper expertise, while ambulance allocation to patients depends on travel time after lane clearing. The semisoft time windows constraint is formulated to reflect the urgency of rescue, and a late arrival penalty on scene and at hospitals is introduced in the objective function. A real-world case in Shenzhen, China (Figure 8), is studied to validate the efficiency in rescue time and computational time. The exact optimal solution can be generated within a short computational time by commercial solvers. The comparison with cases with inactive stakeholders is made to verify the resulting efficiency.





Node ID	Ambulance fleet		
	Type I	Type II	Type III
2	0	0	1
3	1	1	1
7	0	1	1
27	1	1	1
28	0	1	1
29	3	4	3

Patient list	Patient number	Accident scene	Level	Hospital
1	2	11	1	3
2	1	11	2	27
3	2	11	3	7
4	1	11	4	29

Figure 8 Case study in Shenzhen

To validate the efficiency of multistakeholder consideration, we take Patient list 3 as an example of 2 patients waiting to be treated. We compare the generated result with cases that have inactive hospitals and traffic operators, respectively. In the first case, traffic operators are involved in decision-making. Thus, the real-time traffic condition could be included in route choice. For the hospital involvement, each patient's destination is precisely determined by prehospital screening equipment, and the nearest qualified hospital will be assigned to the patient. In two cases, we assume that the proper type of ambulance will be assigned to serve the patients. The route plans are illustrated in Figure 9.

When the hospitals are excluded in route planning, EMS will assign patients to the nearest hospital regardless of its expertise, as shown in the left part of Figure. 9. If the assigned hospital is a comprehensive one with diverse expertise, there will be little difference between active and inactive hospital involvement. But suppose this hospital is not qualified for providing a specific treatment. In that case, it takes several minutes (e.g., 5 min in this case) to figure out that the patient should be transferred and costs more than 25 min for the additional transport.

Figure. 10 compares the breakdown cost in each case. The scenario in which hospitals are excluded expenses the most, followed by the cases with inactive traffic operators, which is three times the baseline cost. Because we assume the proper ambulance allocation, the dispatch fee remains the same for three cases. The largest difference derives from the arrival delay due to the high penalty cost. The onsite delay under the three strategies are 0, 0, and 1 min, respectively, and the hospital arrival delay is 4, 21, and 17 min, respectively. A few minutes of arrival delay has a tremendous difference in the treatment effect that determines life or death for the wounded. Therefore, the comparative analysis of the three cases fully illustrates the huge advantages of collaboration among EMSP, the hospital, and the traffic operator in planning and dispatching. If the traffic operators are excluded from route planning, empirical-based travel time will be adapted for the route choice. As prehospital screening is considered, the destination for the ambulance is determined. Intuitively, there are two differences from the baseline. First, the ambulance cannot travel at the predefined speed for the entire journey because the operators do not coordinate the lane preclearing. If some road sections are congested, the travel time will accordingly increase. Second, the exact shortest

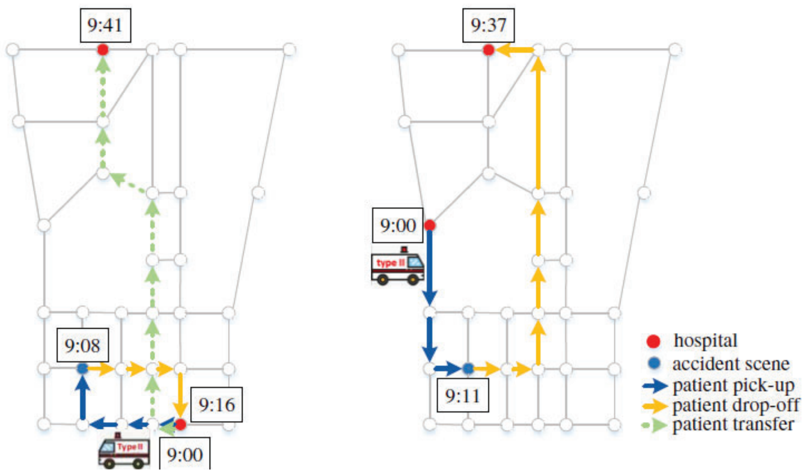


Figure 9 Ambulance routing under different strategies

path may not be assigned to the ambulance based on empirical data, as shown in the right side of Figure. 9. The dynamic traffic conditions will largely influence the travel time.

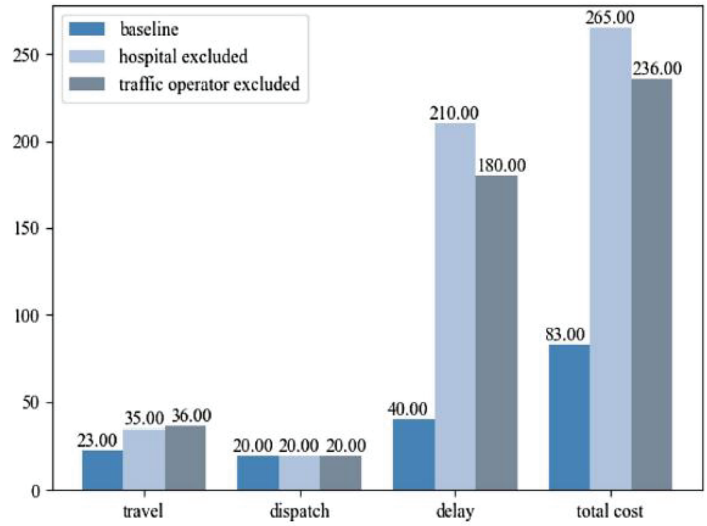


Figure 10 Breakdown cost under different strategies

6.4 An emergency vehicle lane pre-clearing strategy and control under V2X

Reducing and guaranteeing the response time of EVs has become one of the main goals in developing emergency management systems. The task of vehicles prioritizing emergency vehicles on highway segments can be considered as a vehicular reorganization problem, with the objective of one cleared lane. An orderly fulfillment of such reorganizations entails high-level cooperation between drivers that are only feasible nowadays through multiple sets of coordinated traffic signals. The difficulties of such self-organization of drivers are partially due to the lack of communication and the absence of a centralized control algorithm. Considering the promising development of connected vehicles, what is missing is an efficient control algorithm for EV lane pre-clearing that could give explicit orders and optimal trajectories for CVs to follow. Note that in the present paper, we assume that all drivers would comply with such trajectories and prioritize EVs based on emergency protocols.

In this project, we propose a cooperative control strategy for EV prioritization at highway segments in connected environments. Specifically, we intend to design optimal trajectories for both EVs and surrounding vehicles, so that EVs could drive with the desired speed uninterruptedly as well as minimize the influence on normal traffic. This work contributes to the state-of-the-art in the following aspects: (i) explicit EV priority solutions on highway segments are proposed that do not entail pull-over; (ii) The proposed method is able to guarantee the desired speed of emergency vehicles in various traffic conditions ; (iii) The influence of EVs on the normal traffic flow is minimized; (iv) The proposed method could also help in EV routing problems by identifying and suggesting better paths with higher operational EV speed, with only aggregated traffic density data.

We seek to find the optimal trajectories for normal vehicles to clear one lane for one emergency vehicle on highway segments, given the desired speed of the EV, the locations and speed of normal vehicles. A typical scenario is illustrated in Figure 11, where an EV is driving toward a vehicle fleet. Instead of the pull-over approach, we propose that the EV could also maintain its desired speed if surrounding normal vehicles drive cooperatively and follow the scheduled trajectories.

In the proposed model, normal vehicles in the target road section are firstly divided into several blocks. For each block, we develop a searching and integer linear programming based algorithm, entitled EV sorting algorithm, to optimally clear one lane for the approaching emergency vehicle. With the resultant local sorting plan, a constrained optimization problem is then formulated to determine when to conduct the sorting trajectories for each block. Case studies indicate that with the proposed algorithm, emergency vehicles are able to proceed with a desired speed, and also minimize the disturbance on normal traffic flows. In addition, simulation analysis is conducted to examine the relationship between optimal solutions and influencing variables. It is found that the optimal solution mainly depends on traffic density. Simulation results also indicate a linear relationship between the optimal control solution and road density, which helps EVs to make better routing decisions.

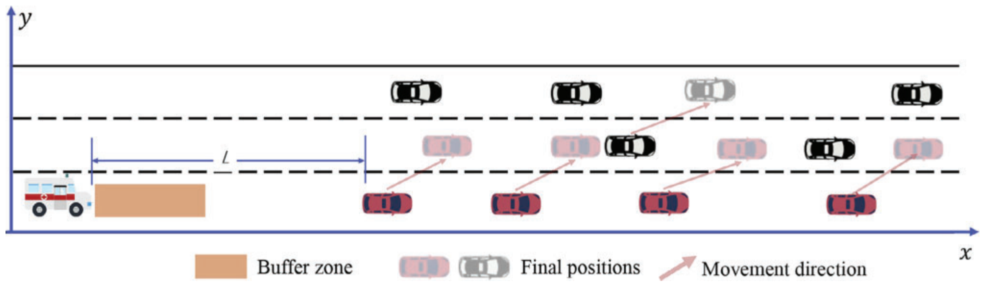


Figure 11 An illustration of the EV lane pre-clearing problem

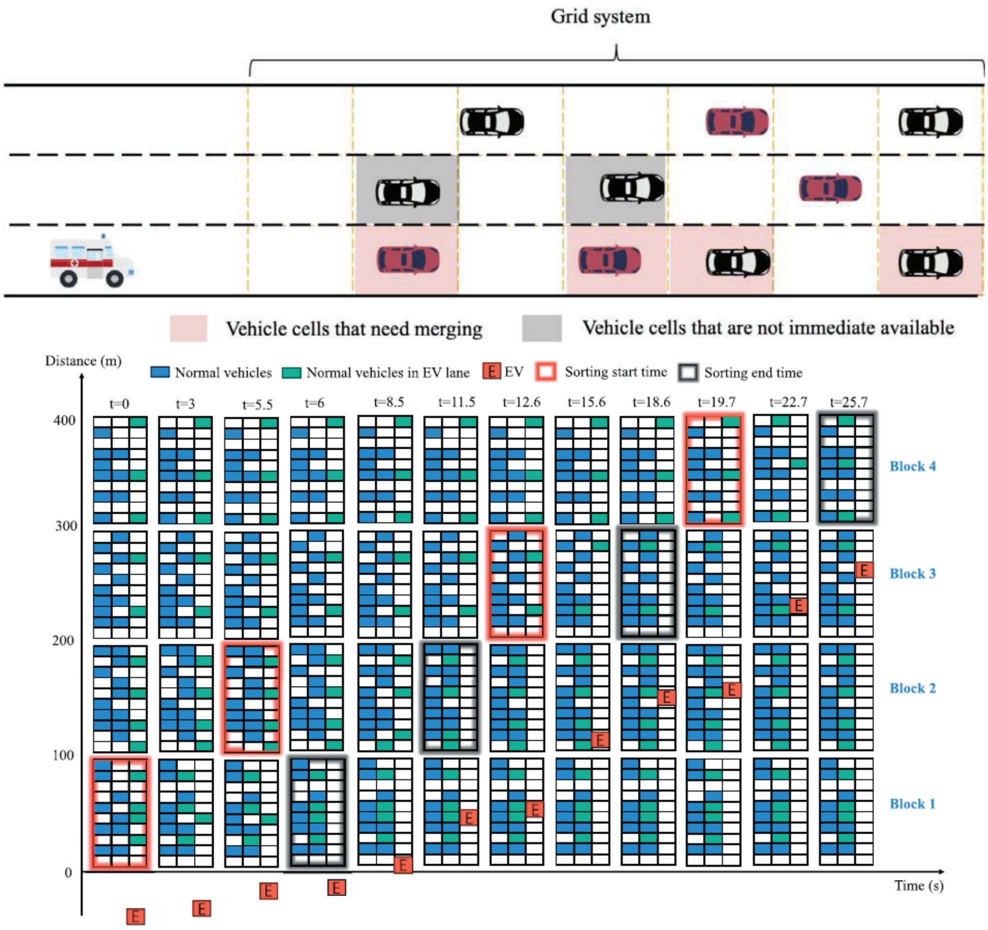


Figure 12 The result of the EV lane pre-clearing algorithm with the HighD Sample

6.5 A platoon regulation algorithm to improve traffic performance in the accident site

In this project, we propose a cooperative control strategy for work zones (e.g., accident sites), aiming to improve the traffic performance in such areas through proactive regulations and cooperative driving in a connected environment. Figure 13 illustrates the technical scheme of the present study, which can be applied to typical work zones as illustrated in Figure 14. For convenience, the blocked lane in work zones or crash sites will be referred to as the blocked lane and other lanes as the normal lanes. The gaps mentioned in this research indicate distance headway. The proposed control strategy includes two stages, that is, the regulation stage and the merging stage. In the regulation stage, a nonlinear programming model is developed to adjust the longitudinal positions of vehicles on the normal lanes with the purpose of accommodating more merging vehicles.

Specially, we notice the fact that vehicles driving in platoons usually result in a smaller average gap, indicating that a large vehicle gap on normal lanes is more efficient in accommodating merging vehicles than several small and scattered gaps with the same total length. In other words, we seek to moderately reform several small gaps into large gaps so that vehicles could naturally drive with smaller gaps due to platooning, instead of directly controlling headways. We propose a regulation longitudinal position (RLP) model to adjust vehicular positions on normal lanes to create larger gaps for merging as well as minimizing the introduced disturbance on those vehicles. Subsequently, with the regulated gaps, we develop an optimal control strategy in the merging stage to design optimal merging trajectories for all vehicles.

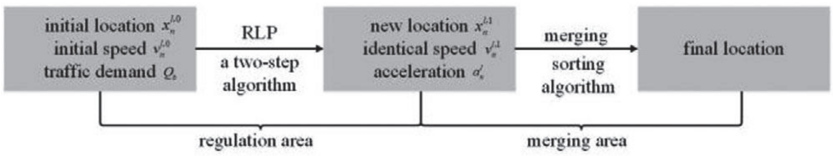


Figure 13 The technical scheme of the method

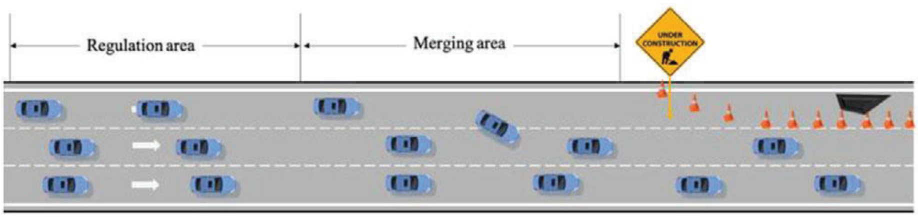


Figure 14 Schematic layout of the emergency area

We explore how the proposed method performs, compared with the traffic condition without control in different traffic volumes, which is completed by the state-of-the-art traffic simulation software Paramics. We also compare our results with the basic scenario without control created in Paramics. In the experiments, the input volume varies from 1800 to 3000 vehicles per hour (vph) with an increment of 600 vph on a three-lane highway with a closed work zone occupying the left, middle, and right lanes, respectively. To make the analysis realistic, 70% cars and 30% trucks are considered in the simulation. The speed is limited to 105 km/h. A notable thing is that in various traffic scenarios, the total length (TTL) of the regulation area and the sorting area is different. The ATS is selected as the measurement of performance, and the results are shown in Table 6. To avoid confusion, here the platoon regulation (denoted as “platoon” in Tables 1 and 2) indicates a control scenario with our proposed method, and the Paramics represent the scenario without control.

As shown in Table 1, in low traffic volume scenarios, the no-control group performs slightly better than the platoon regulation algorithm. A major reason is that, in the low traffic volume, vehicles are encouraged to accelerate to free-flow speed in the simulation software and are able to smoothly perform lane changing in a natural way. While our method constrains that all vehicles need to follow the identical optimal speed. In the high traffic volume, the proposed algorithm presents improved efficiency compared with the no-control group due to cooperative driving. When the high traffic density exceeds the one that achieves capacity, traffic flows become unstable and congested, leading to queueing upstream without control (Gartner et al., 2001). With different initial traffic conditions, T_{max} may vary from nearly 10s to 50s. In order to meet all merging demands, in each scenario, we choose the maximum T_{max} to facilitate the regulation. In the table, it can be found that the ATS in the control group does not change as dramatically as those in the no-control group. The reason is that vehicles are driving cooperatively and thus largely able to maintain the identical optimal speed.

TABLE 1. Comparison of ATS with and without control

Volume (vph)	Blocked lane	ATS (m/s)	
		Platoon	Paramics
1800	Left	23.07	25.60
2400	Left	21.02	19.84
3000	Left	18.29	6.67
1800	Middle	18.87	22.19
2400	Middle	16.38	7.65
3000	Middle	13.53	5.74
1800	Right	25.03	26.36
2400	Right	24.35	25.75
3000	Right	18.52	15.77

TABLE 2. Comparison of different control methods

Volume (vph)	MTT (s)				
	Platoon	Paramics	EM	LM	NEM
1200	100.4	101.2	115	112.1	114.2
1600	109.1	188.4	231.4	174.3	118.5
2000	112.7	252.7	484	482	189.8

A comparative study is also conducted to show the performance of different ideas on regulating vehicles upstream of the work zone. The Early merge strategy (EM), Late merge strategy (LM), and New England Merge strategy (NEM) are considered under different density, which varies from 1200 vph to 2000 vph with an increment of 400 vph.

Similar to the present paper, NEM also investigates the problem of setting some areas upstream of the work zone with different objectives. However, the fundamental ideas of the two studies are different. In their study, before entering the merging area, vehicles in both lanes are projected onto a single virtual lane, and all the distance headways are expected to be close to but greater than the safe distance. On the contrary, in our research, vehicles adjusted their positions according to the optimal solution with the purpose of making full use of spatial gaps. Here, we use the same setups as those in Ren, Xie, & Jiang (2020), where a work zone on a two-lane highway is considered with the right lane blocked. 70% of cars and 30% of trucks are considered in the platoon. The speed limit is set as 70 km/h. Notably, in their research, the mean travel time (MTT) is selected as the measurement of effectiveness measured from 1720 meters upstream of the work zone. The results are presented in Table 7. The proposed platoon regulation algorithm shows the minimum MTT in all considered scenarios.

Compared with the NEM strategy, in the low or medium traffic volume environment (take 1200 vph and 1600 vph as examples), though the platoon regulation performs the best, the performance of the two strategies is quite similar. In the high traffic volume environment (take 2000 vph as an example), the proposed method in this paper outperforms other groups. As aforementioned, in the low or medium traffic volume environments, vehicles have more opportunities to naturally complete lane changing, while in the high traffic volume traffic environments, it may cause congestion spread upstream of the work zone without a proper control method, leading to decreased speed.

6.6 A VR Simulator for emergency management

FellowBot's VR traffic simulator aims to increase traffic safety in future scenarios with autonomous vehicles by closing the gap between traffic planning authorities and regular citizens. A common problem is that available traffic data often is unnecessarily abstract and valuable input from regular road users can be missed out. Data visualization is therefore the first step to engage citizens into the planning process and new traffic safety norms regarding emerging electric, connected and autonomous vehicles.

The demos already at hand display scenarios when an emergency vehicle passes by, disturbing the normal flow of traffic. As examples, we have used an ambulance and a police car passing by the 'player' at high speed. The VR simulator is developed in Unreal Engine and is using CARLA and SUMO for traffic simulation.

Figure 15 A demo of the VR simulator

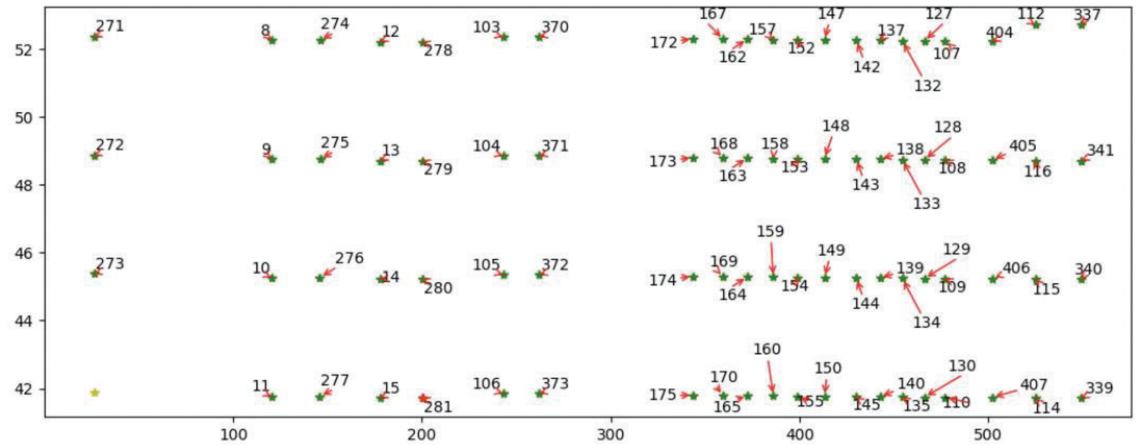
Unreal Engine 4

Unreal Engine (UE) is a game engine developed by Epic Games, initially developed for PC first-person shooters, it has since been used in a variety of genres of three-dimensional (3D) games and has seen adoption by other industries, most notably the film and television industry. Written in C++, the Unreal Engine features a high degree of portability, supporting a wide range of desktop, mobile, console and virtual reality platforms.

CARLA

CARLA is an open-source autonomous driving simulator. It was built from scratch to serve as a modular and flexible API to address a range of tasks involved in the problem of autonomous driving. CARLA is built over a client-server architecture and the server runs the simulation. The client retrieves information, and demands for changes in the world. This section deals with communication between client and server. By default, CARLA runs in asynchronous mode. The server runs the simulation as fast as possible, without waiting for the client. In synchronous mode, the server waits for a client tick, a "ready to go" message, before updating to the following simulation step. Our simulation runs in a synchronous mode because the client is processing the images from the cameras, therefore the server needs to wait for the client.

Vehicles that are to be controlled by the Python API need to be spawned by the Python API (the same goes for other objects like cameras). The spawn points for the cars don't correspond by ID or location coordinates to those in the UE4 editor and therefore have to be found within the python API (for example by plotting them with their Python API IDs.)



SUMO
SUMO is another package that is used as a Traffic manager. It manages the traffic on a bigger scale than in Carla, and is possible to have much bigger control. With SUMO you can also modify the waypoints and spawning points. This package is a must for our project.

CARLA is grounded on Unreal Engine to run the simulation and uses the OpenDRIVE standard (1.4 as of today) to define roads and urban settings. Control over the simulation is granted through an API handled in Python and C++ that is constantly growing as the project does. Our ambulance project script contains code to plot spawn points, spawn cars (based on manually selected spawn points), spawn cameras, save videos from the cameras, and to specify the behavior of the cars in the scenario.

7 Spridning och publicering

7.1 Kunskaps- och resultatspridning

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	X	Outcomes are disseminated via publication, workshops and meetings with stakeholders.
Föras vidare till andra avancerade tekniska utvecklingsprojekt	X	One VINNOVA project is funded based on extensive collaboration and research from this project.
Föras vidare till produktutvecklingsprojekt	X	Two products have been developed and improved
Introduceras på marknaden	X	Two products have been introduced into the market
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut	X	The outcomes provide scientific evidence and support for the regulations about emergency management

7.2 Publikationer

Wang, W., Wu, S., Wang, S., Zhen, L., Qu, X., 2021. Emergency facility location problems in logistics: Status and perspectives. Transportation research part E: logistics and transportation review 154: 102465.

Wu, J., Kulcsár, B., Ahn, S., Qu, X., 2020. Emergency vehicle lane pre-clearing: from microscopic cooperation to routing decision making. Transportation research part B: methodological 141: 223-239.

Zeng, Z., Yi, W., Wang, S., Qu, X., 2021. Emergency vehicle routing in urban road networks with multistakeholder cooperation. Journal of transportation engineering, Part A: Systems 147(10): 04021064.
Cao, D., Wu, J., Wu, J., Kulcsár, B., Qu, X., 2021. A platoon regulation algorithm to improve the traffic performance of highway work zones. Computer‐Aided Civil and Infrastructure Engineering 36(7): 941-956.

Chen, L., Habibovic, A., Gråsjö, M., Adebahr, M., King, P., 2020. Cloud-based traffic control: a system of systems for accelerating C-ITS deployment and autonomous vehicle integration. Virtual ITS European Congress, 9-10 November 2020.

Kong, X., Wu, J., Qu, X., 2021. An Online Processing Method for the Cooperative Control of Connected and Automated Vehicle Platoons. Smart Transportation Systems 2021, Springer: 133-139.

Autili, M., Chen, L., Englund, C., Pompilio, C., & Tivoli, M. (2021). Cooperative Intelligent Transport Systems: Choreography-Based Urban Traffic Coordination. IEEE Transactions on Intelligent Transportation Systems, 22(4), 2088–2099. https://doi.org/10.1109/TITS.2021.3059394

Habibovic, A., & Chen, L. (2021). Connected Automated Vehicles: Technologies, Developments, and Trends. In International Encyclopedia of Transportation (pp. 180–188). Elsevier. https://doi.org/10.1016/B978-0-08-102671-7.10110-1

Chen, L., Torstensson, M., & Englund, C. (2020). Federated Learning to Enable Automotive Collaborative Ecosystem: Opportunities and Challenges. 27th ITS World Congress, 1–10.

Chen, L., Torstensson, M., & Habibovic, A. (2022). System of Systems for emergency response: the case with CAVs on highways. 25th IEEE International Conference on Intelligent Transportation Systems, submitted.

8 Slutsatser och fortsatt forskning

The project has conducted a thorough literature study on SoS including the definitions, the categorizations, projects and applications, the engineering practices, and the architecture. Urban mobility has been considered as a SoS with combinations of the concept of Choreographies for service innovation. It has also been considered with connected automated vehicles (CAVs) and cloud-based traffic control for accelerating service introduction, and for enabling interaction between emergency vehicles and CAVs. For supporting collaborative intelligence, federated learning has been considered to enable collaboration without data sharing. Given the convergence of architecture frameworks, the emerging unified architecture framework (UAF) has been evaluated with the latest engineering process. The practice of architecting the emergency system is reported which covers the high-level aspects. A specific case of integrating connected automated vehicles into the response process is considered.

Regarding different stages of emergency response, a prehospital screening product, a V2X communication device, algorithms for facility location, emergency vehicle lane pre-clearing, and routing have been developed. These include a pre-hospital screening device MD100 with data-driven evaluation algorithms and a V2X-oriented EVAM transmit device, a robust EV lane pre-clearing strategy to prioritize EVs, traffic flow coordination models in various traffic conditions, a robust EV routing model, and simulation methods and tools for system demonstrations and pilots.

From the SoSE perspective, this project contributes with the state of the art of SoSE, engineering methodologies of SoSE, and the application experiences of SoSE in the urban transportation domain through practices in emergency response. At the macroscopic level of SoSER, this project investigated the application of SoSE methodological framework to improve the current practice of emergency management through multi-stakeholder coordination and communication. At the microscopic level, this project leverages the competencies of industry partners and develops equipment and models in order to improve response time by taking advantage of the recent prosperous artificial intelligence, vehicular communication, and intelligent traffic control and congestion management technologies.

9 Deltagande parter och kontaktpersoner

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