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rescuePY

Simulation-based Emergency Service Impact Assessment

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Abstract: Mobility in metropolitan regions is changing. The distribution of space in cities, the design of transport modes, and the organization of mobility are being rethought. However, no matter the changes and innovations on the way to a more sustainable future, essential constants must be upheld: In the event of minor, regionally limited emergencies, medical assistance must reach those in need quickly. When dealing with large-scale emergencies, the ability to evacuate the area promptly must be ensured. The impact analysis of mobility innovations on emergency services within urban areas so far has been based purely on empirical observations using existing data. Currently, it is only possible to analyze what-if considerations in a limited way. Nevertheless, due to the increasingly rapid changes in mobility, a comprehensive and interlinked analysis will be necessary. This is the key contribution of rescuePY: rescuePY is a simulation suite based on the mesoscopic and microscopic simulation environment hybridPY. It allows holistic and microscopic transport modeling of rescue infrastructure to quantify the impact of the mobility transition towards higher sustainability on the performance of rescue services.

The main features of this software are:

- Rescue system assessment for strategic, long-term planning
- Mobility-influence studies for operative, mid-term planning
- Activity-based urban evacuation modeling

The capabilities of rescuePY are demonstrated by two applications: a simulation-based, mesoscopic system analysis of emergency services in Munich compared to real-world data and microscopic modeling of emergency vehicles (EMVs) in different road architectures. Ongoing developments aim to improve the evaluation methodology for the aggregated impact analysis of mobility innovations on rescue response services.

Keywords: Simulation, Emergency Service, Mobility Changes

1 Introduction

The reorganization of urban transport to meet the requirements of sustainable mobility has far-reaching effects on various aspects of urban life. Measures that are already being implemented, e.g. [1], or medium-term visions, e.g. [2], envisage significant changes to the urban system.

In particular, it is critical to assess the impact of such changes on the operational effectiveness and capability of emergency services and fire departments. Figure 1 shows the simplified sequence of actions for a regular rescue operation.

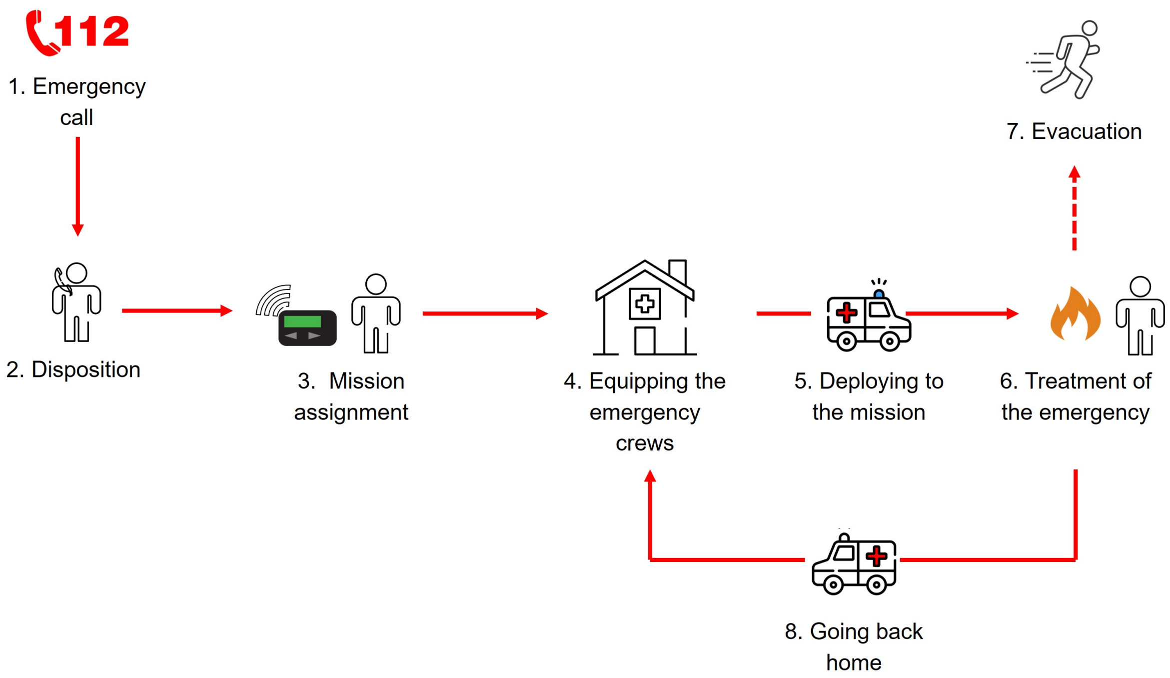

Figure 1. *Sequence of actions for a regular rescue operation.*

Mainly, the journey to the site (step 5) as well as the the ability to treat the emergency (step 6) are influenced by mobility innovations. More than anything, the fire and emergency services require the accessibility of buildings for fire and rescue vehicles, the use of aerial ladder vehicles to ensure the second rescue route, and the response time according to the legal requirements [3].

The emergency service report shows a Bavaria-wide increase in pure travel time by 1 minute and 31 seconds across all types of cities and municipalities from 2013 to 2022. Delays on the journey (e.g., due to traffic jams) were the third most common cause of emergency service response times exceeding the legal requirements, accounting for 13 percent of all delays [4]. In the case of large-scale area emergencies that require an evacuation of the affected area, mobility behavior, the availability of mobility options, and the changed transport network influence the course of the measure [5].

Integrating the requirements of emergency services as critical stakeholders into transport planning is crucial to ensuring that emergency services can continue to operate efficiently. Likewise, it guarantees that the city's residents receive appropriate assistance as quickly as possible in the event of an emergency. On the one hand, the specific requirements of emergency services must be considered in the transport planning process. On the other hand, appropriate measures must be taken by the emergency services, such as the use of optimized vehicles, the relocation of fire stations or the creation of updated plans for the implementation of evacuation measures. These measures are necessary to ensure a safe and well-functioning urban environment [6].

rescuePY is the first step towards a simulation suite, enabling local authorities in charge of emergency planning and disaster control to run easy-to-use emergency simulations which consider changing transportation systems. rescuePY sets itself apart from other simulation software by covering the topics of strategic planning, the long-term rescue system planning, operative planning, the detailed and microscopic analysis of changes to the transportation system in the context of preventive fire protection, and evacuation planning.

The following part is structured as follows: Chapter 2 discusses state-of-the-art system simulations of rescue services, individual vehicle modeling of rescue vehicles, and evacuation models. Afterward, in chapter 3, the implementation inside the rescuePY framework is presented. Finally, two use cases demonstrate the capabilities of rescuePY in chapter 4.

2 State of the Art

The following section provides a brief overview of the state of the art of simulation-based rescue service modeling. At the beginning of this section, the state of traffic simulation-based emergency service modeling is given. The second part examines the current state of microscopic EMV modeling. Finally, a brief overview of simulation-based evacuation modeling will be given.

2.1 Emergency Service System Assessment

Several models, like event-based simulations, hyper-cube models or optimization frameworks, exist for analyzing emergency services. In contrast, traffic simulation-based emergency service modeling on a city-scale level is rare in literature.

Zade et. al. [7] present a MATSim-based modeling of emergency response times in crisis scenarios. This approach provides a first test bed for analyzing emergency strategies. The study simulates a single ambulance station in New Windsor, NY. The researchers incorporate background traffic into their modeling and use synthetic incident data, assuming 100 emergency calls per day in a ten-day scenario. Their model is validated using averaged numbers. Yaneza [8] uses MATSim-based modeling to assist planning agencies of the Philippines in determining routes for disaster response vehicles in crises or disasters and validates the model using expert discussions. Their study focuses entirely on modeling disaster situations and neglects the daily operations. Muzzini [9],[10], and Li et. al. [11] are two modeling approaches for modeling emergency services responding to car accidents inside a road network. The first approach is implemented in MATSim and the second in SUMO; both allow time analysis but only represent a small part of the alarm spectrum and neglect the system level of emergency service systems. In both approaches, the utilization of the rescue system is not validated or discussed. Additionally, there exists the tool CIS-KOSMAS [12]. Despite modeling approaches based on open-source software, it is a piece of commercial software for simulating and analyzing emergency services. The tool is based on a simplified transport network and allows dynamic simulation of emergency service systems. Nevertheless, the software lacks flexibility in terms of scenario building.

In summary, current approaches based on open-source frameworks represent only parts of the emergency service system or neglect daily operations. They are not sufficient for simulating emergency services on a city-wide scale.

2.2 Microscopic Simulation of EMVs

A detailed behavioral model of EMVs and their interaction with the environment is required if one wishes to develop a form of operative planning and infrastructure design which conforms to the needs of emergency services. Likewise, in recent years, there has been a great interest in improving the modeling of EMVs in microscopic traffic simulation software. Table 1 provides an overview of recent research projects and the primary topics covered by each.

In the available literature, the most common topic is modeling the priority of EMVs at intersections, be it through exploring the possibilities of V2X communication, e.g. through traffic light signal preemption for EMVs in [13]–[17], through the coordinated behavior of a system of connected, highly automated vehicles in [17] and [18] or through accurately representing current real-world intersections in papers [16] and [19] . Among the papers above, [17] took a unique angle by developing an algorithm that can handle several tiers of EMV priority. [13], [16], [18] and [19] analyzed the driving behavior of EMVs outside of intersections by comparing car-following or lane-changing models. Furthermore, the reaction of normal, non-emergency vehicles (NVs) to an approaching EMV outside of intersections was modeled in papers [16]–[20]. In particular, [20] specifically analyzed the reaction of autonomous NVs using deep reinforcement learning. Other projects investigated allowing NVs to drive onto the shoulder lane [17] or the sidewalk [19] to form a wider rescue lane for the EMV to pass by. Except for papers [17] and [19], there is no preexisting research on the simulation of motor vehicles using infrastructure not intended for motorized traffic in emergency service applications.

Table 1. *Recent Papers on Microscopic Modeling of Emergency Vehicles.*

Paper Year	[13] 2020	[14] 2020	[15] 2021	[16] 2021	[17] 2022	[18] 2023	[19] 2023	[20] 2021
Traffic simulators	VISSIM	VISSIM	VISSIM	SUMO	-	SUMO, CARLA	Paramics	SUMO
Covered topics:								
- several EMV priority tiers	✗	✗	✗	✗	✓	✗	✗	✗
- EMV intersection priority	✓	✓	✓	✓	✓	✓	✓	✗
- EMV driving behavior	✓	✗	✗	✓	✗	✓	✓	✗
- EMV V2X communication	✓	✓	✓	✓	✓	✓	✗	✗
- automated EMVs	✓	✗	✗	✗	✓	✓	✗	✗
- automated NVs	✗	✗	✗	✗	✗	✓	✗	✓
- reaction of NVs to EMVs	✗	✗	✗	✓	✓	✓	✓	✓
- NVs use areas not intended for motorized traffic to form rescue lane	✗	✗	✗	✗	✓	✗	✓	✗
- EMVs may drive on shoulder, bike lane, etc.	✗	✗	✗	✗	✗	✗	✗	✗
- varying size of EMVs	✗	✗	✗	✗	✗	✗	✗	✗
- varying lane count/width	✗	✗	✗	✗	✗	✗	✗	✗
- protected bike lanes	✗	✗	✗	✗	✗	✗	✗	✗
- modal shift	✗	✗	✗	✗	✗	✗	✗	✗

2.2.1 SUMO Emergency Vehicle Implementation

Due to its open-source nature and the preexisting implementation of EMVs, the software SUMO has been selected as the microscopic simulator within the rescuePY project. Release 1.19.0 of SUMO is used as the baseline for all SUMO-related development within this paper.

In SUMO 1.19.0, the standard implementation of EMVs is based on the work of [16]. EMVs can be defined in the configuration file by giving them the vehicle class emergency and equipping them with a blue light device. Vehicles defined this way will disregard the right of way and red lights, they are allowed to surpass the speed limit, and they can be given the right to drive on dedicated bus lanes or cycle paths. Additionally, they are more likely to drive on the opposite roadside even when they must overtake a long column of vehicles.

Surrounding Vehicles within 25 meters of an EMV will try to form a rescue lane. Vehicles react with a certain probability depending on the distance to the EMV (further away vehicles are less likely to form the rescue lane). All vehicles on the leftmost lane form the rescue lane by changing into the left sub-lane, and all vehicles on all other lanes change into the right sub-lane. The vehicles forming the rescue lane are not allowed to make lane changes to prevent them from using the rescue lane themselves. When driving into the rescue lane, the EMV slows to a maximum of 20 km/h.

When EMVs drive slower than half the maximum allowed road speed, the strategic lane changing gets deactivated, meaning they will use any lane that allows them to advance faster. Hence, the EMV may arrive at an intersection in the wrong turning lane. In such a case, it will be teleported to the closest lane which allows it to continue its route.

2.3 Evacuation Modeling

Understanding the type of event that necessitates an evacuation proved to be crucial for the development of evacuation models. In literature, the reasons for evacuation range from natural disasters, such as tsunamis [21], [22] or floods [23], to other types of situations, such as the discovery of explosive material in the middle of a city [24]. These diverse scenarios underline the need for adaptability and customization in evacuation models to address various scenarios.

Trip-based models and activity-based models are the two primary methodologies that travel demand models can be divided in. Trip-based models, alternatively referred to as the four-step models, forecast travel demand by estimating the number of trips that commence and conclude in designated locations, choosing appropriate modes of transportation, and allocating trips to specific routes. In contrast, activity-based models simulate a person’s daily activities and travel choices while considering time and space constraints and the connections between people, activities, and family members. Activity-based models allow for a more precise and comprehensive estimation of evacuation requirements.

Dynamic simulation is crucial to understanding and optimizing the evacuation process itself. The interactions between people and vehicles, the routes chosen, the traffic congestion, and the evacuation time can all be realistically reflected by these modeling techniques. Various simulation tools are employed, encompassing microscopic, mesoscopic, and macroscopic approaches. Notable among these tools were MATSim, EXODUS, SUMO, and others.

The choice of the modeling methodology depends upon the particular objectives and requirements of the evacuation plan. Systematic reviews, which provide a comprehensive overview of the evacuation modeling methodologies, can be found in [25]–[27].

Various studies, see table 2, have utilized diverse combinations to meet the specific requirements. [21] and [23] implemented evacuation plans utilizing trip-based models via MATSim. ABMs were employed to model travel demand in [21]-[23]. When examining both inside and outdoor building evacuation, EXODUS was determined to be more suitable [28][29][30]. Using SUMO's rerouter, [22][31][24] concentrated on dynamic route adjustment in evacuation scenarios.

Summarizing, although studies address the influence of future climate and economic-demographic changes on evacuation modeling [32], the impact of trends in mobility on urban evacuation scenarios has not yet been analyzed. This gap in the literature highlights the need to explore and understand how transformations in mobility affect the effectiveness of urban evacuation plans and models.The use of a modeling framework offers the simple possibility to model different changes in urban mobility and analyse their effects on urban evacuation planning.

[33] and [34] present simulation pipelines for modeling evacuation scenarios. Nevertheless, their frameworks focus only on city-wide evacuations and do not provide any user interface.

Table 2. *Overview of selected simulation based evacuation models.*

Paper Year	[21] 2020	[22] 2023	[28] 2020	[31] 2020	[29] 2018	[30] 2018	[24] 2018	[23] 2016
Urban Environment	×	✓	×	✓	✓	✓	×	✓
Multimodal Simulation	×	×	✓	×	✓	×	×	✓
Pedestrianns	✓	✓	✓	×	✓	✓	×	✓
Vehicles	×	✓	✓	✓	✓	×	✓	✓
Microscopic Simulation	×	✓	✓	✓	×	✓	✓	✓
Validation with Real data	×	×	×	✓	×	×	×	×
Implemented in SUMO	×	✓	✓	✓	×	×	✓	×
Modeling Future Mobility Trends	×	×	×	×	×	×	×	×

3 Methodology

The following section describes the implemented methods behind the rescuePY framework. rescuePY is developed as plugin for hybridPY, a scenario management tool for SUMO and MATSim. The framework is available in python 3.9.

3.1 Strategic Planning

3.1.1 Objectives

The strategic planning module considers the entire emergency service system or a defined sub-area, such as the fire department. The module makes it possible to calculate an assignment of a-priori-defined incidents to the available emergency response infrastructure, taking into account the transport infrastructure. Calculating the assignment allows to quantify changes originating from changes in the emergency service, the volume of incidents, or the underlying transport infrastructure at an early stage far before realization.

In order to quantify the changes and assess the quality of incident coverage, the planning module determines the average travel time until the (first) EMV arrives at the scene or carries out a duplication analysis. In this context, the term duplication is used if the nearest EMV (defined by the routed distance between the emergency location and the ambulance or fire station) is already tied up with an incident, and a more distant EMV has to be used.

The module is shown in Figure 2. The required input parameters are defined on the left-hand side of the picture. To calculate the assignment, first the available infrastructure must be defined. To do this, it is necessary to define the emergency stations with their location and their respective entry to the transport system. This represents the start of the respective deployment trip. For each emergency station, the available emergency infrastructure also has to be defined, e.g., EMVs, aerial ladder vehicles, or ambulances.

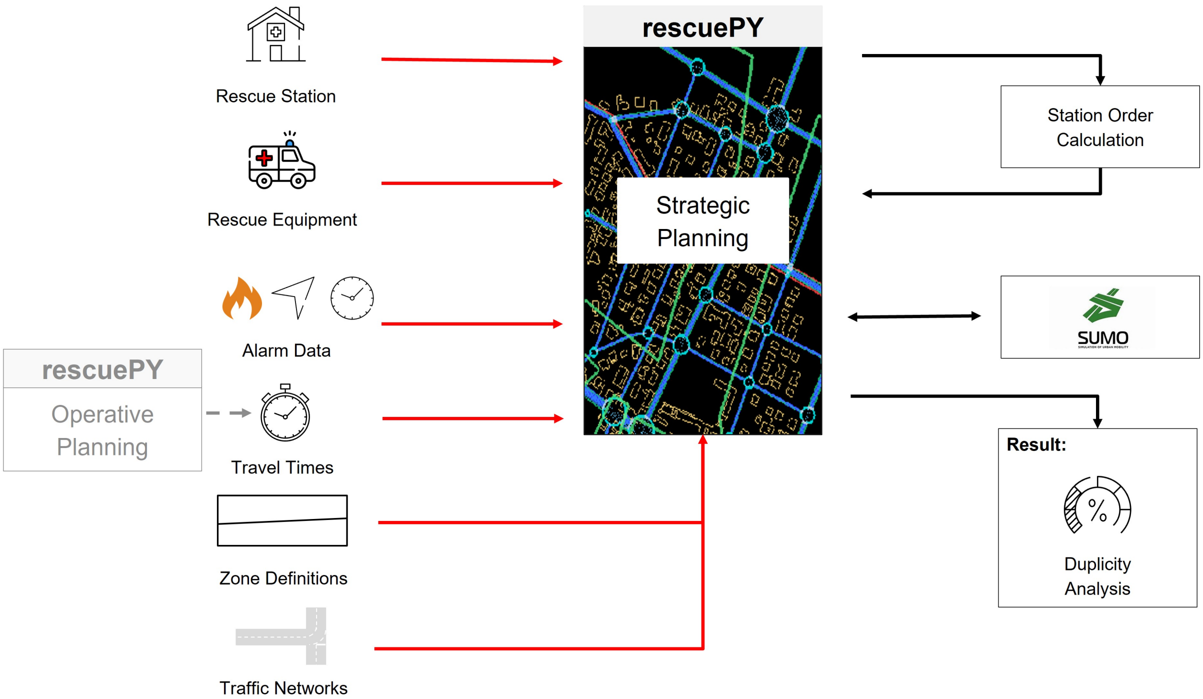

Figure 2. *Structure of the simulation based strategic planning.*

The road network can be imported from OSM using the standard function of [35]. The application makes it possible to specify expected average speeds for EMVs, taking into account special rights and rights of way. The expected travel times can be derived from literature or can be determined by the operative planning module, see Figure 2. Finally, shape files can be used to import zones which represent the basis for the sequential deployment order of the stations to an incident.

The demand that will be assigned to the infrastructure is specified by the incident data. An incident is specified by the time, the location, and the required resources. The data can be imported using generic '.csv' files. Thus, the incident data can directly be imported from existing and compulsary operations management system.

3.1.2 Implementation

Considering the strategic level makes it necessary to look at long-term time horizons, for example, months, quarters, or even years. Once the scenario has been created in recuePY and the input data for the traffic simulation has been provided by the application, the simulation is carried out in the mesoscopic version of SUMO. The mesoscopic simulation network, in which EMVs are only inserted in the event of an incident, allows the application to be more tolerant of network modeling errors. The tour-based simulation logic without simulation of background traffic combined with the insertion in case of need makes it possible to save computing time, especially in periods without any incidents, compared to modeling with parking spaces, for example. The graphic animation of the simulation is done with the help of polygons. This enables user-friendly verification of the data entered.

The simulation is implemented as a TraCI application and is depicted in a simplified form in algorithm 1. The current vehicle status is realized by numeric numbers. The numbering here is equivalent to reality. The EMVs can be dispatched on the basis of a static definition, whereby it is precisely defined which EMV from which station approaches which incident. Alternatively a precalculated zone based sequence defined with rescuePY can be used. Doing so, the closest available vehicle, measured on the basis of the routed distance, is selected.

The parameters *meso-minor-penalty, meso-tls-penalty, max-speed, speed-factor*, which define the time loss at intersections and the maximum speed, can be used to set the individual characteristic values for emergency journeys. The time difference at junctions between a journey with special rights and rights of way and without is neglected here. The presented algorithm uses open-source data and data from the operations

Algorithm 1 Strategic Simulation Logic

Require: $vehicle$, $alarm\_data$, $firestations$
  while $sim\_time < end\_time$ **do**
    if $vehicle@alarm\_data[location]$ and $sim\_step >= alarm\_data[end]$ **then**
      # Going back home
      setstatus(1)
      back_to_firestation($vehicle$,$firestations$)
    end if
    if $vehicle@alarm\_data[location]$ **then**
      # Treatment of the emergency
      setstatus(4)
    end if
    if $vehicle@firestations$ **then**
      setstatus(2)
      remove($vehicle$)
    end if
    if $alarm\_data[simstep] \neq \emptyset$ **then**
      # Deploying to the mission
      $vehicle$ = disposition($firestations$,$alarm\_data[simstep]$)
      send_to_alarm($vehicle$,$alarm\_data[location]$)
      setstatus(3)
    end if
  end while

management system of local emergency services. Using this algorithm, rescuePY is the first open-source framework that enables the flexible simulation of daily operations of rescue services on a city-wide scale.

3.2 Operative Planning

3.2.1 Objectives

The strategic planning is based on average time losses at junctions and on-road sections. The values assumed can be determined for existing infrastructure, e.g., with the help of data recordings or derived from literature values [16]. Future infrastructure concepts or changes in transport demand require a simulative determination of (average) time losses due to the lack of measurability. The objective of the operative planning module, see Figure 3, is the detailed and microscopic analysis of changes to the transportation system and their influence on rescue vehicles in the context of preventive fire protection.

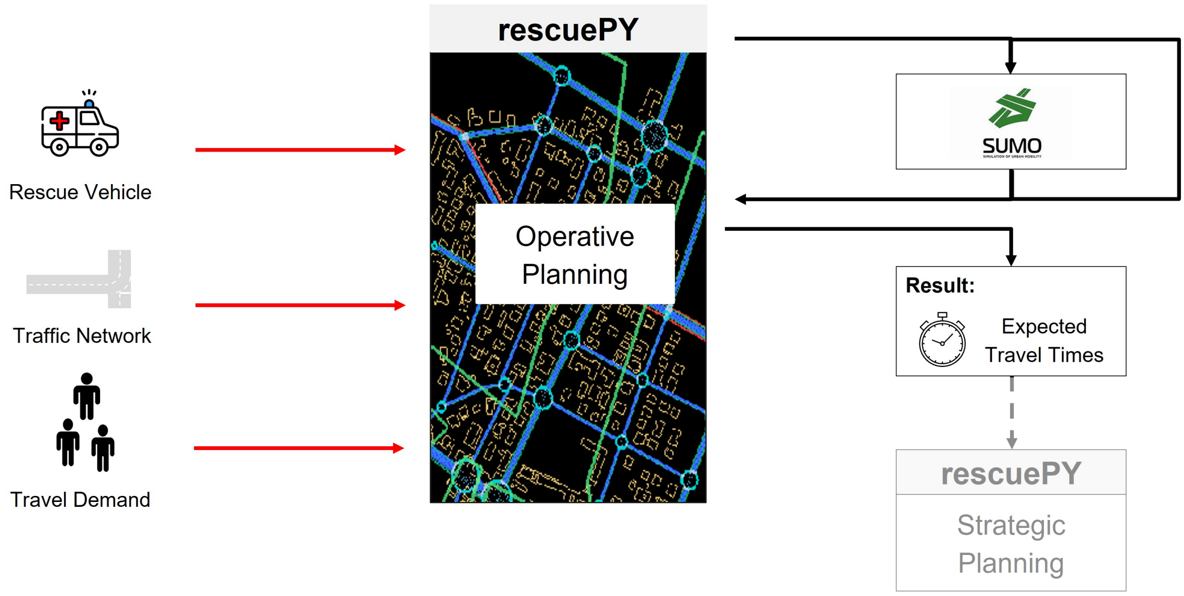

Figure 3. *Structure of the simulation based operative planning.*

Since travel times largely depend on microscopic influences, such as traffic light controls, microscopic modeling is required to determine them. The operative planning module of rescuePY, therefore, relies on the microscopic behavior model of EMVs, which will be presented in the following.

The vehicle specifications of the EMV, including the route to be considered, the traffic infrastructure, and the expected traffic demand, for example, are derived with the help of the hybridPY framework, serve as input parameters. The simulation is carried out iteratively and on the basis of varied random numbers. The result of the simulation is then the average travel time.

The following sections describe the testing methodology as well as the microscopic vehicle model. Based on [19] and expert discussions, the microscopic model was extended within the framework of rescuePY.

3.2.2 Testing Methodology

Within the operative planning module, a testing scenario represents an EMV deployment at a certain time of the day. Inside this scenario, constant vehicle flows are used for evaluation. This is based on the presumption that passing a street or a smaller urban district only takes the EMV a few minutes. During this brief travel time, the effects of temporal variability in demand are presumed to be so minuscule that they can be ignored. Demand variability of EMV deployments at varying times of the day is taken into account through the use of various scenarios. To diminish the effects of randomness each scenario is executed multiple times, with each run using a unique random seed for the SUMO simulation. This process continues until scenario has gone through the desired number of simulation runs.

During the warm-up phase of each simulation, as congestion is still increasing, the travel time of an EMV is overwhelmingly dependent on its departure time, not on other input parameters. After a certain minimum threshold simulation time, the simulation runs develop a stationary traffic situation, meaning that the departure time is no longer the dominant factor determining the travel time. As travel times are only documented if the trip has been finished before the end of the simulation, there is an increasing survivorship bias for EMVs with later departure times. Therefore, only data from vehicles with departure times between a minimum and maximum simulation time threshold is considered significant for the travel time analysis. The thresholds for the minimum and maximum departure times can be determined via regression analysis.

3.2.3 Vehicle Implementation

Our EMV model was built upon the already existing SUMO EMV implementation described in section 2.2.1. The core features of our model are depicted in Figure 4.

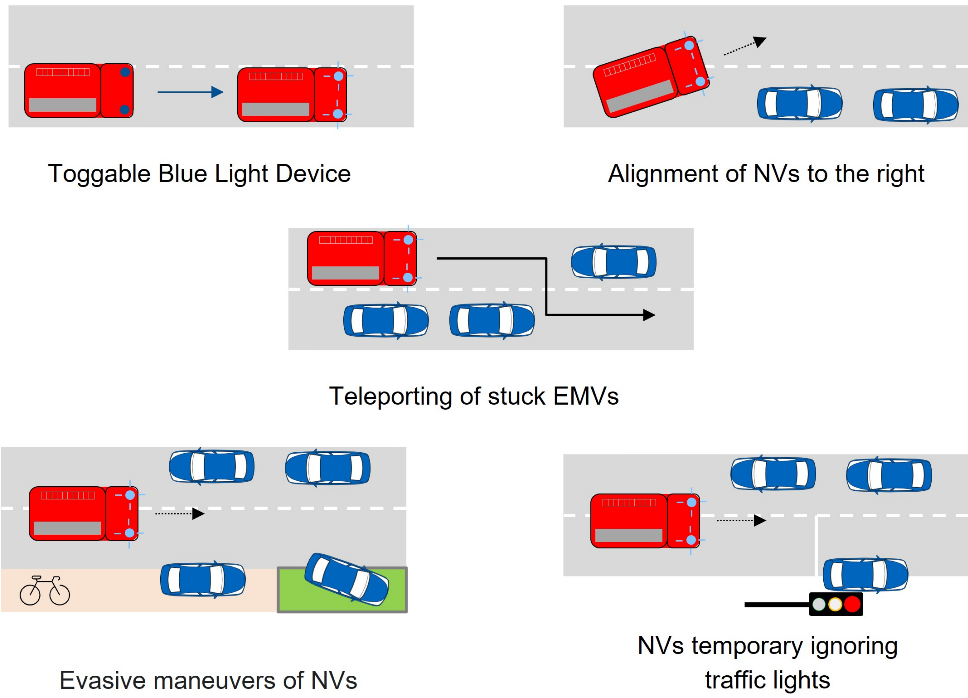

Figure 4. *Core features of the behavioral model.*

In the following, the behavioral adjustments are explained in detail. The first paragraph addresses the alternations made to the C++ source code of SUMO, while later paragraphs describes the behavior enabled through the use of the TraCI API. So far, both approaches have only been optimized for right-handed traffic.

The formation of rescue lanes for multi-lane streets is problematic in the standard EMV model because the vehicles on the leftmost lane would align to the left, with all other vehicles on all remaining lanes aligning to the right. When the EMV is in the rightmost lane, no valid rescue lane is formed because both the vehicles in the rightmost lane as well as the vehicles in the middle lane change into the right sub-lane. With our modified model, the alignment of vehicles in middle lanes depends on the position of the EMV, so a valid rescue lane always gets formed. This change reflects that, in general, forming rescue lanes is neither regulated nor mandatory in urban environments. Additionally, the standard EMV model has NVs align to the left side of the lane on single-lane roads, which does not reflect the reality and makes it harder for the EMV to overtake them on the opposite lane. In our model, vehicles on single-lane roads align to the right to allow the EMV easier overtaking. Furthermore, the blue light device can now be activated and deactivated via TraCI. This device grants any vehicle equipped with it the special driving permissions and behavior of an emergency vehicle. The standard version of SUMO permanently grants special, emergency driving rights to any vehicle with a blue light device. In contrast, our toggleable blue light device allows for the simulation of EMVs before and after being called to an incident. Only when the blue light device is activated does EMV operate with its special driving rights, as described above and in section 2.2.1. When deactivated, the EMV follows all traffic rules like a NV.

For easier adaptation to varying traffic innovations, other features are implemented as a TraCI application. With regards to the EMVs, the TraCI application improves handling of situations in which the EMVs cannot move due to surrounding traffic. Assuming that in real life, the NVs would eventually manage to create a gap large enough for the EMV to pass, this problem is solved by teleporting the EMV to the next edge on its route after a certain amount of time has passed. If the EMV became stuck while passing vehicles on the opposite driving lane, its driving direction must be reversed. Otherwise, it would drive in the wrong direction after teleportation. This direction reversal command is given via TraCI. As this command is non-existent in the standard SUMO release, it can only interpreted by our modified version of SUMO.

While EMVs are only directly affected through the TraCI API in the form of occasional teleports, the moment-to-moment driving behavior of the NVs is heavily influenced using TraCI commands. If the operative simulation algorithm registers an EMV in moderate proximity of an NV, the NV is commanded to keep right. If the EMV is in close proximity of the the NV, the exact behavior of the NV depends on the exact situation. Factors such as the vehicle class, the relative orientation of the EMV to the NV, possible movement-barriers determined by the permissions of the neighboring lanes as well as general simulation parameters affect the exact way an NV responds to an EMV.

With TraCI, when the EMV gets in close proximity of the car, the operative simulation algorithm of rescuePY is able to detect the bike lane next to it. In order to form a rescue lane, it stops the car and moves the car onto the bike lane so the EMV can pass. If there were no bike lane, the algorithm would allow the NV to keep driving and even ignore red lights to get the nearest free junction where it can pull over and let the EMV pass. In case there is no further lane to right, vehicles can still pull over and form a rescue lane by going off road, albeit with an optional time penalty compared to the bike lane scenario. Vehicles in close proximity to an EMV, but not being approached by an EMV from behind, are generally commanded to come to a full stop and may only move laterally to help the EMV pass.

The temporal and spatial parameters for this behavior are highly customizable in the TraCI application, allowing for the adaptation to the local rules and behavior of vehicles in the area one wishes to simulate.

3.3 Evacuation Planning

3.3.1 Objectives

The first two modules of rescuePY make it possible to investigate the question of how help can reach the patient or person in need quickly and what impact mobility innovations have on this. However, certain emergency situations, such as the discovery of a bomb or the release of hazardous substances, make it necessary for the affected people to leave the affected area as quickly as possible.

The evacuation planning of rescuePY is based on the assumption that the area to be evacuated corresponds to a small part of the city, for example, a certain district. After the warning is announced, people within the evacuation area must leave the area to be evacuated immediately, regardless of the activity they are engaged in. The area to be evacuated may no longer be entered by unauthorized persons after the warning has been issued. Persons who are evacuated must go to the specified accommodation.

The procedure is shown in Figure 5. In rescuePY, the population from a defined area is specified, the transport infrastructure is imported and the areas to be evacuated as well as the emergency shelters are defined.

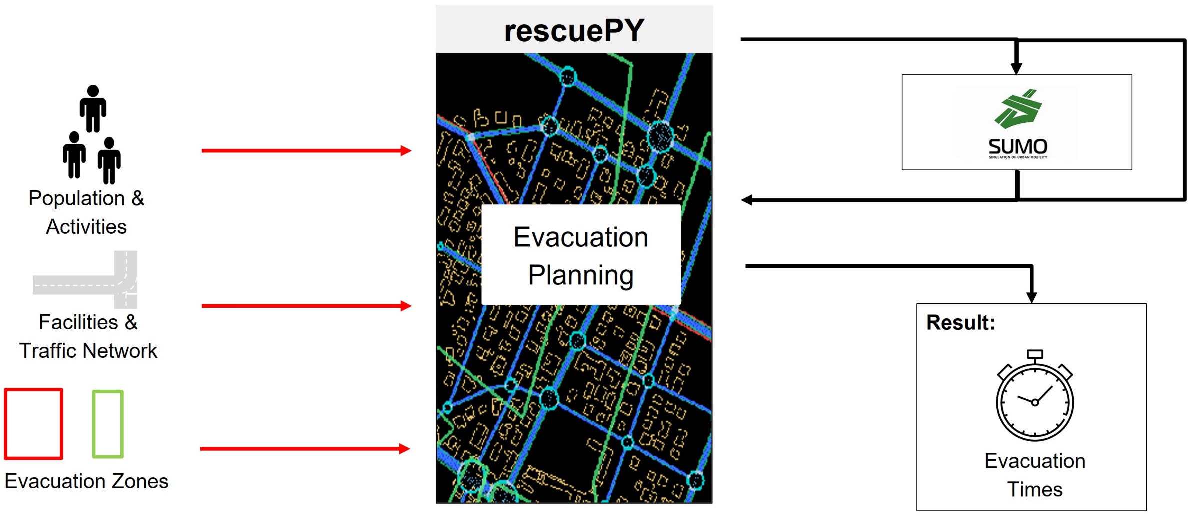

Figure 5. *Structure of the simulation based evacuation planning.*

By using this model, decision-makers gain a comprehensive understanding of all key evacuation parameters, such as the number and location of shelters, the arrangement and timing of vehicles leaving the area, the expected evacuation time and the proportion of people evacuated in a given period.

3.3.2 Implementation

The implementation of the evacuation model is divided into two parts. Firstly, the activity-based prediction model, which is based on [35], must be expanded to include an evacuation activity. Secondly, the route selection of the agents must be manipulated at simulation run time.

Evacuations usually happen during everyday events, disrupting people's routines and requiring them to reorganize their entire day's schedule in compliance with evacuation regulations. As a result, activity-based modeling can capture the effects of these scenarios precisely. The daily travel demand of the area must first be modeled using

[35]. The modeling process can be briefly described: The first step is importing information about the virtual population and households (including gender, occupation, age, income, etc.) and assigning them to facilities based on the capacity of the building. Subsequently, the schedule of activities for the day is determined based on the attributes of the virtual population and predefined sequences. Lastly, based on the characteristics of the virtual population and the time and place of these activities, travel routes and transportation alternatives are generated.

Once the modeling of the basic activities of the day has been completed, it is necessary to take into account the elements of the evacuation model. The evacuation model consists of three crucial components: the time of evacuation, the choice of transportation mode for evacuation, and the choice of evacuation route. For instance, Figure 6 illustrates that around 12 o'clock, an evacuation order is sent. Considering only vp8

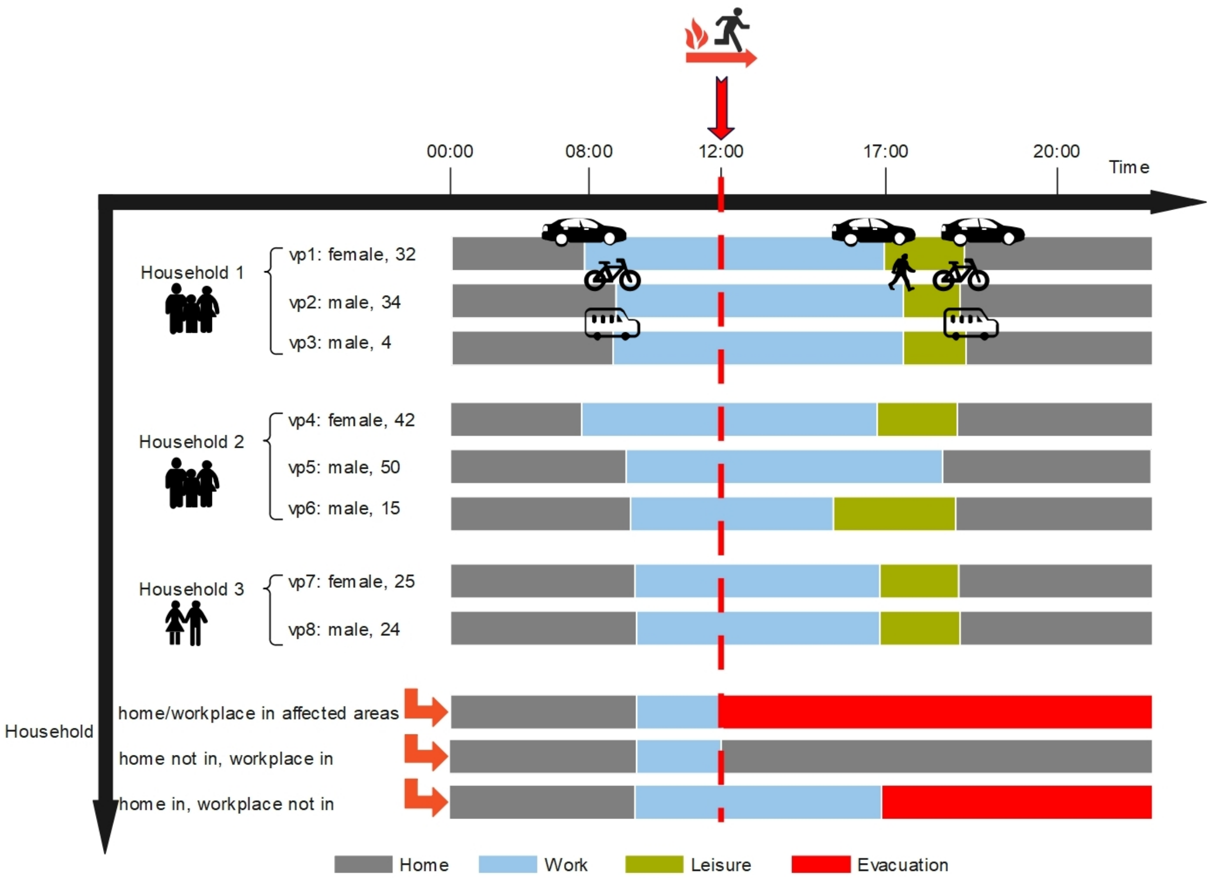

Figure 6. *Activity-based evacuation modeling.*

as an example, he must adjust his plans of action with consideration of the new situation after he receives the order. Here are four possibilities related to the current environment:

- *Case 1:* Neither his home nor his workplace need to be evacuated, then he will continue his normal life.
- *Case 2:* If his home and place of work are in a zone that needs to be evacuated, he will immediately cease working and choose the most effective means of transportation to the nearest shelter based on the situation at that moment.
- *Case 3:* When the workplace is in a location that needs to be evacuated and the home location is not, then he will immediately end his work and return home.

- *Case 4:* When the place where his home is located needs to be evacuated and the place of work does not, then he will continue with his work and when it is over, will go to a shelter.

Once demand has been generated using the rescuePY model, specific adjustments must be made to the routes taken by individuals. Inside the rescuePY tool, the Dijkstra algorithm is utilized to define the route from origin to destination for the evacuees. Nevertheless, the priority for these persons is to leave the risk zone as quickly as possible.

TraCI provides the possibility to reroute vehicles based on the minimization of a cost function that considers different attributes of the network links as weights. During the evacuation, the network links are assigned relatively high-cost values. In this way, when rerouting road users, the new route will prioritize leaving the evacuation zone as soon as possible before heading towards their ultimate destination, be it their home or shelter. Additionally, individuals are prohibited from entering the area.

4 First Results and Discussion

In the following section, the benefits of the rescuePY simulation platform will be discussed using two case studies. Firstly, the strategic planning module will be compared with real data. Secondly, a sensitivity analysis of the operative planning module and the associated enhancements compared to the basic implementation of [16] is conducted.

4.1 Strategic Planning

The strategic planning module aims to simulate the city-wide emergency response using a mesoscopic network. The mesoscopic network promises a simple and, at the same time, versatile use of the simulation due to its robustness against network errors. In order to check the validity of the approach, the travel times from the fire station inside the simulation are compared with the actual deployment data.

The study is based on actual incident data from March 2013 from the Munich Fire Department. This data set contains the incident location, the time of the alarm, the alerted vehicles, and the associated status changes. A status change occurs when a vehicle departs for an emergency (from the station), arrives at the scene, starts driving back to the station, and arrives at the station. The status is reported by manually pressing the respective number on the vehicle radio device.

The current road network of the city of Munich, based on OSM data, is used as the basis for the simulation. The road network was not adjusted or adapted. The parameters used for the simulation are depicted in table 3. Parameters v_{over} and Δt_{minor}

Table 3. *Overview of used simulation parameters.*

variable	value
v_{max}	90 km/h
v_{over}	1.28
Δt_{tls}	0.1
Δt_{minor}	3.5s
Δt_{sim}	10s

were measured by [16]. The other two parameters are based on expert discussions user-selected. The time step of the simulation Δt_{sim} is defined as 10 seconds.

The simulation was executed on a standard laptop and consumed 10 minutes of calculation time. The results of the respective run are depicted in Figure 7 exemplary for Munich fire station 2.

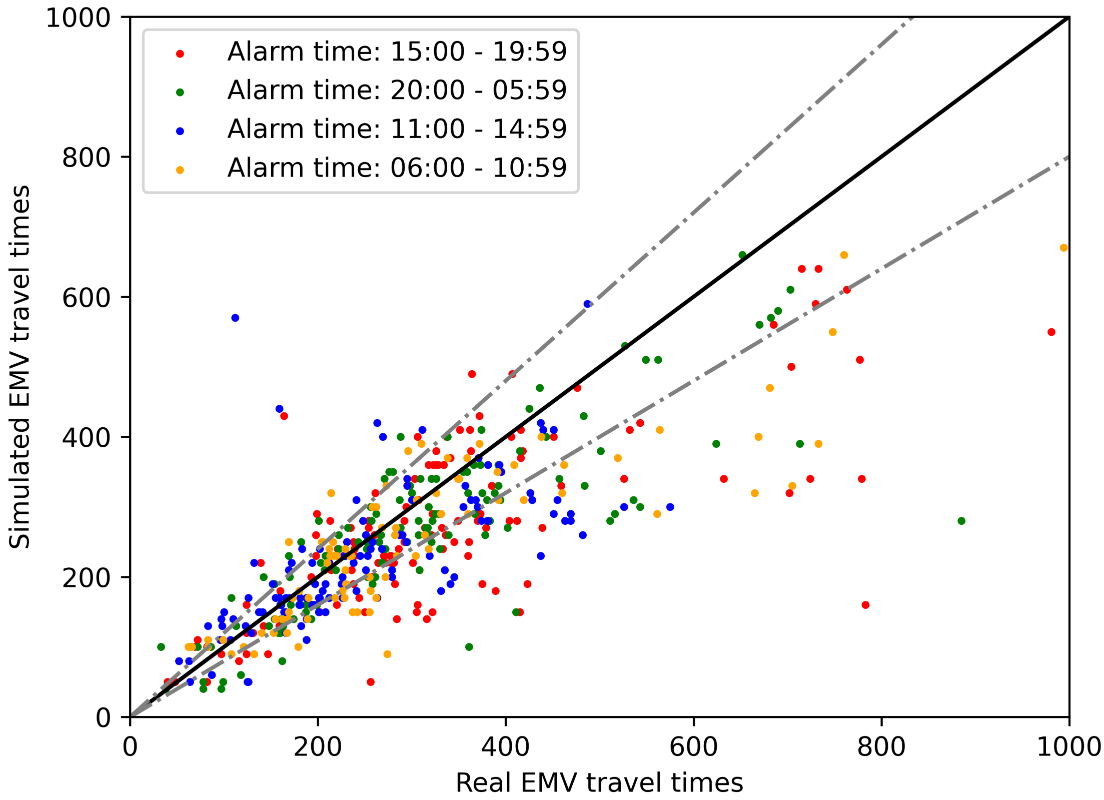

Figure 7. *Comparison of the strategic panning results with real world data.*

The figure shows the simulated EMV travel times for the journey from station to site over the reported EMV travel times. The color of the point indicates the time of the alarm. The calculated average travel time for station 2 is $300s$, the mean absolute percentage error is 24%, and the mean absolute error is $-43s$. The results are comparable for other fire stations.The mean absolute error varies from $-3s$ to $-45s$.

As it can be seen in Figure 7, the simulated times differ heavily from the actual values during peak hours and night. Whereas the first point indicates the missing traffic adjustments, the second category can be explained by data errors.

4.2 Operative Planning

In the following section, the sensitivity of the microscopic EMV behavior modeling to changes in transport infrastructure and demand will be examined, and the observed behavior will be discussed.

The street selected for testing is the Schellingstraße in Munich, Germany, ranging from the intersection with the Ludwigstraße to the intersection with the Luisenstraße. The street has one driving lane and one parking lane in each direction. Given the location near the city center and the high number of passing and parking cars, we can assume the parking lane to be nearly completely occupied for most of the day. As the occupied parking lane is not usable by moving traffic, only one driving lane per driving direction is modeled in our base scenario. There is a sidewalk on either side of the street but pedestrians are not simulated. All non-pedestrians must share the single driving lane per direction. The parked vehicles are taken into account as an impenetrable barrier in the base scenario, preventing vehicles from moving to the right of their lane towards the sidewalk.

The case study is conducted using four different scenarios on the Schellingstraße, shown in Figure 8:

- *Base scenario as described above.*
- *Base scenario with off-road:* The lane of parked cars is replaced with a widened side-walk or green space separated from the steet by a curb. Using TraCI, NVs may mount the curb and go off-road to form a rescue lane.
- *Scenario with unprotected bike lanes:* The lane of parked cars is replaced with a normal, unprotected bike lane. Using TraCI, motorized NVs may move onto the bikelane to form a rescue lane.
- *Scenario with protected bike lanes:* The lane of parked cars is replaced with a protected bike lane: a bike lane separated from motorized traffic by a physical barrier, modeled as a separate edge in the network. This bike lane is just wide enough for the EMVs used in this scenario to drive on. While EMVs can only drive there with a reduced maximum speed, taking the protected bike lane may still be faster than being stuck in the congested motorized traffic lane. Using a rerouting device, an EMV can adapt its route during run-time to find the quickest lanes. Due to the physical barrier, an EMV can only change between the protected bike lane and the motor vehicle lane at junctions. As the simulated section of the Schellingstraße is completely straight, it is assumed that real-life EMV drivers would be able to properly judge the traffic level up to the following intersection, too. Using TraCI, bicycles can move over to the sidewalk to form a rescue lane.

Several runs with varying random seeds were conducted for each simulation configuration. The resulting median travel times of the EMVs are depicted in Figure 9. The baseline travel demand, depicted as the 100% demand level, is based on the measured peak hour demand on 21.07.2022 from 12:11 - 13:11, from the detector data in the Mobilithek [1]. The EMVs are assumed to drive from the real location of the fire station in the west to an emergency situation in the east, each traveling a route length

[1] https://mobilithek.info/

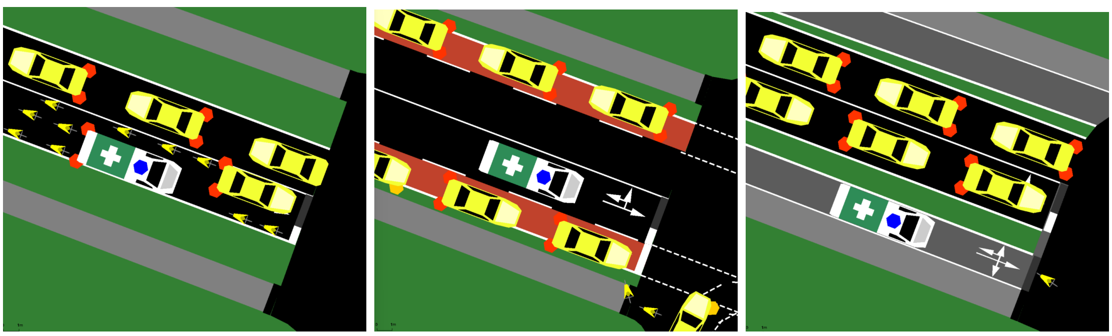

Figure 8. *Scenario infrastructure: base (left), base with off-road (no image shown, but uses same infrastructure as base), unprotected bike lanes (center) and protected bike lanes (right).*

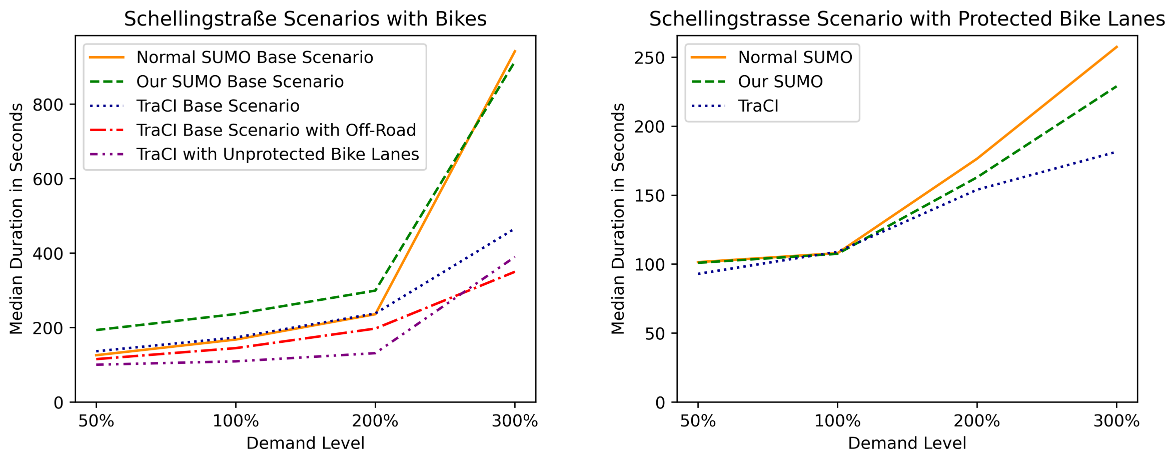

Figure 9. *Comparison of median travel times.*

of circa 1.1 km. A new EMV starts every 1200 seconds. The interval is chosen so that traffic may return to a stationary state before the appearance of the next EMV. In Figure 9, graphs labeled with "Normal SUMO" refer to simulations run with the standard 1.19.0 release of SUMO. "Our SUMO" refers to simulations executed with our modified version of SUMO 1.19.0, while the label "TraCI" means the simulations were performed with our TraCI algorithm in combination with our modified version of SUMO 1.19.0.

As can be seen in the left chart of Figure 9, for lower demand levels, the base scenario simulations shows lower travel times with normal SUMO than with our SUMO. This stems from cyclists unrealistically moving to the center of the road to form a rescue lane, leaving just enough enough space for the EMV to pass them on the right. In our SUMO, despite the cyclists correctly move to the right to form the rescue lane, the EMV does not appear to have enough room to pass on left. This leads to slower travel times, as the EMV is rather hesitant to overtake vehicles and follows behind cyclists for extended periods of time. Under high levels of demand, our TraCI algorithm displays lower travel times even for the identical network. This can likely be attributed to NVs directly in front of the EMV running red lights and pulling over in junctions, as well as to the EMV being able to teleport after being stuck for a significant amount of time. When going off-road is enabled using TraCI, a much wider rescue lane can be formed, leading to lower EMV travel times. Travel times for most demand levels are reduced even further with TraCI when unprotected bike lanes are added to the network, as the time penalty for motor vehicles moving onto the unprotected bike lane is set to be lower than the penalty for mounting a curb to go off-road. Without the TraCI algorithm, motor vehicles are not be able to move over to the bike lane to form a recue lane.

The right chart of Figure 9 shows the results when using the network with protected bike lanes. Due to this change in the network, all EMV algorithms display greatly reduced travel times compared to the base scenario. Nonetheless, the improvements made to our SUMO, e.g. more aggressive behavior of EMVs in junctions, help reduce travel times. The travel times are shortened once more when TraCI is used, as bicycles can now move over to the sidewalk to let the EMV pass more easily.

Overall, it could be shown that the EMVs model generates a plausible behavior in urban traffic and consideres neccessary effects in the interaction between EMVs and surrounding vehicles. Nevertheless, in future work the model needs to be calibrated (e.g., regarding reaction and teleportation times) using observations and trajectories and validated against the system travel times.

5 Conclusion and Outlook

This paper presents a modeling suite for creating a digital twin of the emergency service system. The strength of the framework is the combination of modeling the emergency service system alongside the detailed modeling of transport infrastructure. Although it is crucial to ensure the effective operation of emergency services, it is an often neglected aspect in transport planning. The presented framework allows local authorities in charge of emergency planning and disaster control to easily conduct simulation-based strategic, operative emergency, and evacuation planning.

The applicability of the simulation environment was demonstrated by comparing the times of simulated journeys with real journeys. With the help of freely available map data and incident documentation data, strategic questions can be easily answered. In order to make more accurate predictions in the future, the presented microscopic vehicle modeling will be calibrated with trajectory data from actual EMVs. In addition, the robustness of the microscopic model w.r.t a greater variety of vehicle and infrastructure designs will be improved. Furthermore, it is planned to couple the microscopic and mesoscopic levels of the simulation suite in an automated way to enhance its usability.

Data Availability

The underlying SUMO networks originate from freely accessible and usable OpenStreetMap data extracts. The historic incident data used in this study is coming from the City of Munich and is currently (Februar 2024) not freely-accessible.

Author contributions

Fabian Schuhmann contributed to the paper in the following ways: conceptualization, methodology, data curation, formal analysis, visualization, software, and writing the original draft. Maximilian Sievers, Stefan Schrott, Ivan Kapovich, Lijie Feng, contributed in the following ways: methodology, visualization, software and reviewing and editing the manuscript. Markus Lienkamp contributed in the following ways: supervision and reviewing and editing the manuscript.

Competing interests

The authors declare that they have no competing interests.

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