Towards Increasing Resilience of Public Transit Infrastructure – A Bi-Modal Simulation Model

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Abstract. With the impact of climate change increasing, public service infrastructure has to become more resilient against extreme weather events as well as human-made disasters. Public transit is a central part of urban infrastructure, often mainly consisting of interacting light-rail as well as express and community bus networks and connected to national rail and individual traffic systems. To increase such a system's resilience against small disturbances and larger outages – as they might result from climate change – service providers need a toolbox of potential measures to mitigate such incidents' impact and to re-establish services as soon as possible after an outage. This paper presents thoughts towards a bi-modal urban transit simulation system covering both light rail and (express and community) bus networks. Important aims of the system are a) to enable operators to evaluate measures against small disturbances and larger outages as they happen, and b) to evaluate what combination of disaster risk management and resilience-building strategies shows most potential to help increasing the resilience of urban transit systems against extreme weather events resulting from climate change as well as other disasters.

Introduction

Urban infrastructure systems are critical for everyday life, their functions serve both the social and economic well-being of urban residents and commuters. Infrastructure is defined as including all types of publicly and privately operated communication, electricity, and water networks, food production, waste treatment, industrial facilities, as well as urban transportation.

Over the last decades, infrastructure systems that were perceived up until then as isolated services have transformed to connected ecosystems; tightly organised networks provided by a multitude of actors, involving a myriad of physical and digital structures, and offering services to society through all sorts of physical and digital channels. That includes the different modes of urban transit, including light rail systems, express and community buses, and at least partially integrated individual transportation services like taxi cabs, Uber, and Lyft. Out of all commonly available public transit modes, light rail and bus transit have the highest transit performance [1].

To protect their long-term utility, those integrated transit infrastructure components must be resilient against the increasing impact of climate change on urban spaces and systems, including pluvial and fluvial flooding, heat waves, droughts, and windstorms [2].

In case of sudden disasters impacting transit systems, including extreme weather and human-made events, operators have to be able to make decisions fast to a) transfer the infrastructure components into a preplanned disaster mode and b) to be able to re-establish services as soon as the immediate event has passed. These operators can be assisted with a simulation application covering both light rail and bus transit that executes simulation runs sufficiently fast to enable evaluation and comparison of potential decisions and strageties, thereby contributing to increase the resilience of the transit system.

This paper presents steps towards the design of a bimodal simulation model representing an urban area's light rail and bus transit network, designed to assist with increasing the transit infrastructure system's resilience againt extreme weather events and human-made distasters. A specific focus is put on a) fast execution and b) the representation of operating decisions necessary in disaster risk management situations.

Many models representing urban transit are developed as an extension of already established models of individual traffic [3][4][5]. Generally, many of the more recent simulation models including bus transit use microscopic agent-based modeling approaches

[3][4][6][7], the mesoscopic approach to bus transit simulation proposed by Toledo et al. [5] extends a mesoscopic simulation model for individual traffic based on queuing theory proposed by Burghout [8], which represents the street network as a graph of interconnected queues and vehicles as individual entities traversing these queues based on speed/density functions.

Especially models utilizing a fine-grained modeling approach generally necessitate the availability of an extensive data basis, including detailed information on origin-destination matrices, vehicular dynamics, signaling strategies, and lane changing rules [9], and include many components which are not immediately interesting for public transit resilience management. This often leads to long runtimes [10][11], thereby rendering those models inadequate for the use case described above. Therefore, this paper builds upon the work presented in [12] by extending a runtime-efficient bus transit model to include light rail transit.

The paper continues by sharing some background on the core components and concepts of urban transit systems and urban transit resilience (Section 1) and then introduces design decisions for a fast bi-modal transit simulation model (Section 2). It concludes with an outlook on necessary further research steps (Section 3).

1 Urban Transit

1.1 Urban Transit Components

Urban transit usually consists of a number of interacting networks, e.g. a light rail system, express and community bus networks, often connected at specific hubs to national rail systems as well as to individual transit systems like taxi cabs, Uber, or Lyft. For the presented model individual transit as well as national rail stations/airports are parameterized and not part of the core model itself.

A mixed light-rail and bus network consists of a network of street and rail segments as well as stops and stations where passenger exchanges take place. These stops and stations are served by a set of transit vehicles executing service trips, i.e., pairings of starting times and sequences of stops, according to a timetable. Each individual vehicle executes several service trips, interspersed with deadheads, over the course of an operational day, which is called a rotation. Such a rotation usually begins with a deadhead from the vehicle's depot to the first stop of its first service trip and, after a number of service trips, ends with a returning deadhead to the depot. The rotation schedule defines the assignment of specific vehicles to rotations.

While some stops, mainly bus stops, include a bay with capacity for more than one vehicle, many other stops can contain only one vehicle at any given time. Some stops are marked as control points, i.e., locations in the network where control strategies may be employed, e.g., purposely delaying early vehicles until the scheduled departure time is reached. At other stops, vehicles depart as soon as the passenger exchange is completed. Each stop belongs to exactly one station, i.e., a geographically grouped collection of stops which usually share a common name.

Directed paths through the network, connecting two successive stops are called connections. They usually consist of several street and/or rail segments, junctions, and signals, that in turn can be shared by several connections.

Signals control access to individual segments, usually at junctions. Often, two or more signals constitute a signal group with a common scheduling strategy.

Urban transit vehicles generally follow pre-defined line routes, consisting of sequences of stops to be serviced. Often, a line consists of a number of line variants: while a main variant might be served by a majority of vehicles, some variants might contain only stops in the city center but not in the suburbs, others might branch off the trunk route to connect to an outlying commercial area or business park.

In most public transit systems, daily operations are managed by an operations center, with dispatcher personnel managing procedures for the mitigation of small disturbances and larger outages. While the number and intensity of the smaller disturbances might increase from the impacts of climate change, e.g., changing precipitation patterns, many will originate from everyday incidents, like street segments blocked by accidents, or failing transit vehicle doors. Larger outages might result from extreme weather events like pluvial or fluvial flooding, high storms, or excessive heat waves – or from human-caused events like protests or terrorist attacks. In case of any of these events, transit operators have a number of remedies at their disposal to keep services running as long as possible, and to restore them as soon as possible. These include the authority to short-turn or cancel trips, to re-route vehicles, and to deploy extra vehicles.

1.2 Urban Transit Resilience

In the urban transit context, two different understandings of ‘resilience’ are relevant: engineering (or ‘narrow’) resilience and multi-equilibria resilience [13][14][15]. Engineering resilience aims at stability and control, i.e., to withstand shocks and to return to the stable pre-disaster state as fast as possible (‘bouncing back’, see e.g., [16]). Subsequently, the concept of engineering resilience is static and does not take the need for flexibility and adaptation into account. Multi-equilibria resilience [14] on the other hand acknowledges that a disturbed system might not always return to the same stable pre-disaster state and aims at adapting the system to better cope with the disaster (‘bouncing forward’).

For urban transit systems to withstand different types of disasters, transit operators need to design schedules and networks with both resilience concepts in mind. While engineering resilience is useful for mitigating small to medium disturbances that inevitably happen during an operational day (e.g., passengers holding open doors for other passengers), multi-equilibira resilience becomes relevant when addressing medium to large disturbances that might require extensive (temporary) modifications of schedules and vehicle routes. Engineering resilience is usually addressed as part of the medium- to long-term planning (e.g. by designing schedules with high regularity of departure times [17]), multi-equilibria resilience can additionally be addressed in the short- to medium-term planning (e.g. by rerouting vehicles or purposely delaying departure times to keep transfer connections between different transit modes).

Considering accelerating climate change, the associated increase in frequency and intensity of natural disasters, and the subsequent increase in impacts to (urban transit) infrastructure [18][19], it becomes paramount to design new schedules and networks in a resilient and sustainable way, and support operators of existing networks in adapting their services to be more resilient and sustainable.

Simulation models can support this process by enabling decision-makers to assess the implications of alternative decisions faster.

2 Modelling Urban Transit

To represent the described entities and behavior that constitute urban light-rail and bus networks, a bi-modal simulation model based on the event-based approach [20] is being designed. Thoughts on its design and mechanics are shared in the following sections, highlighting partial models representing physical network components, the logical network, vehicle behavior, operational management, and the necessary randomization. All of these partial models are based on the bus transit model described by Lückerath and Ullrich [12].

2.1 Physical Network Model

The basis of the model is the representation of the physical transit network as a directed graph. Stops, connections and segments are modeled as nodes of this graph, with their neighborhood relations modeled as edges. Each node has a geographic position, identifying attributes, and a maximum vehicle capacity.

Stops are nodes in the model graph where transit vehicle entities – i.e., busses and light rail cars – stop for boarding and disembarking processes. They always belong to exactly one station and have time-of-day and location-specific stopping times. Different capacity or spatial dimensions of stops are modelled by a maximum number of vehicle entities they can service simultaniously.

Stations group together geographically related stops and give them a uniform name.

Connections are directed paths in the model graph that link two stops. They have a specific length as well as time of day and location specific average travel times. In addition, they are assigned a planned travel time by the timetable. Depending on the transit system to be modeled and the level of detail of the available data, connection nodes also manage model components of the segments, switches and signals belonging to their connection.

Segments represent subsections of connections, representing road or rail segments between two road junctions or between two switches of a rail transport system. Consequently, their corresponding model components have a specific length, a scheduled travel time and manage empirical data on their average travel time. In addition, they have an allowed maximum traversal speed, which can be used, e.g., for microscopic simulation of driving behavior.

To represent the driving behavior of different traffic modes, the model distinguishes between two types of segment nodes: roads and tracks. Road nodes are segment nodes that are used by entities of individual traffic, have an unrestricted vehicle capacity, and do not enforce a fixed vehicle sequence. Without (detailed) information about lanes, it is assumed that there is sufficient space for overtaking maneuvers on each road node, i.e., travel times of individual vehicle entities can be calculated without considering other entities traveling on the node.

In contrast to road nodes, track nodes are used exclusively by rail vehicle entities and enforce both compliance with a maximum vehicle capacity as well as a fixed vehicle sequence. The latter prevents inadmissible overtaking maneuvers between vehicle entities traveling on the same track node and is realized via the travel time calculation (see Section 2.5): If available, the entity traveling directly ahead is always considered to determine the travel time of a vehicle entity newly arriving on a track node. The calculated simulation time at which the new vehicle entity arrives at the end of the track node can never be earlier than that of the entity directly in front. Without possibilities for overtaking maneuvers, the formation of backlogs - even across neighboring nodes - is considered in the model using the vehicle capacity of nodes.

Switches are locations in rail-based transit systems where track crossings take place without interrupting the journey, i.e. they have a unique geographical position and are related to at least three tracks – at least one each incoming and outgoing. They are modeled as transfer points without spatial extension and are traversed in zero time. Switches can merge several tracks and must be activated to target the correct incoming/outgoing track before an entity can cross them. This is represented in the model by vehicles reserving switches before crossing them and releasing them after a successful transfer.

Signals represent traffic lights of road traffic as well as light signal systems of rail traffic. They usually form a signal group with other signals and have attributes such as switching time or signal status (e.g. green, yellow, red).

Both switches and signals are modelled as additional information layer and not as nodes of the model graph. They can only be found at start or end positions of segment nodes in the model and can be associated with the corresponding nodes based on these positions.

2.2 Logical Network Model

In addition to the physical network components presented so far, logical components such as lines, trips and timetables have to also be considered to model public transit.

Lines consist of an ordered set of stops, which specifies the route to be followed during regular operation. In the simulation model, this is represented by a reference to a set of corresponding nodes of the model graph. To avoid time-consuming dynamic path finding during the simulation run, lines are additionally supplemented by an ordered set of connection nodes. Furthermore, each line can be assigned to a specific transit mode (e.g., bus or train) and may additionally only be served by vehicle types permitted for it. E.g., a low-floor train may not serve a line whose stops are designed for high-floor trains.

Trips combine ordered sets of stops and connections with a start time and are differentiated into service trips and deadheads. In the model, trips manage references to sets of stop and connection nodes, similar to lines. Service trips additionally refer to the line they serve. Deadheads do not follow a predefined route and therefore do not refer to a line in the model.

2.3 Vehicles

Vehicles are represented as transient entities [20] that encapsulate a significant portion of the event-based simulation logic and move across the model graph during a simulation run. Each vehicle entity has a reference to the trip it is currently serving, i.e., at each simulation time it only has access to the information that is directly relevant for its current activity. All additional information, e.g., about the timetable and the vehicle fleet, is administered by specialized management modules (see Section 2.4).

In the model, vehicles are classified according to their transit mode, their vehicle type, and their individual vehicle characteristics. While transit mode discerns light-rail and bus vehicles, the vehicle type is used for a more detailed subdivision. For example, various types of Vossloh Kiepe GmbH vehicles are in use in the Cologne light rail network, including low-floor vehicles of type K4000 [21] and K4500 [22] and high-floor vehicles of type K5000 [23]. The most detailed classification is based on individual vehicle characteristics. They encapsulate attributes such as passenger capacity, vehicle length, maximum speed, minimum stopping time or boarding rate.

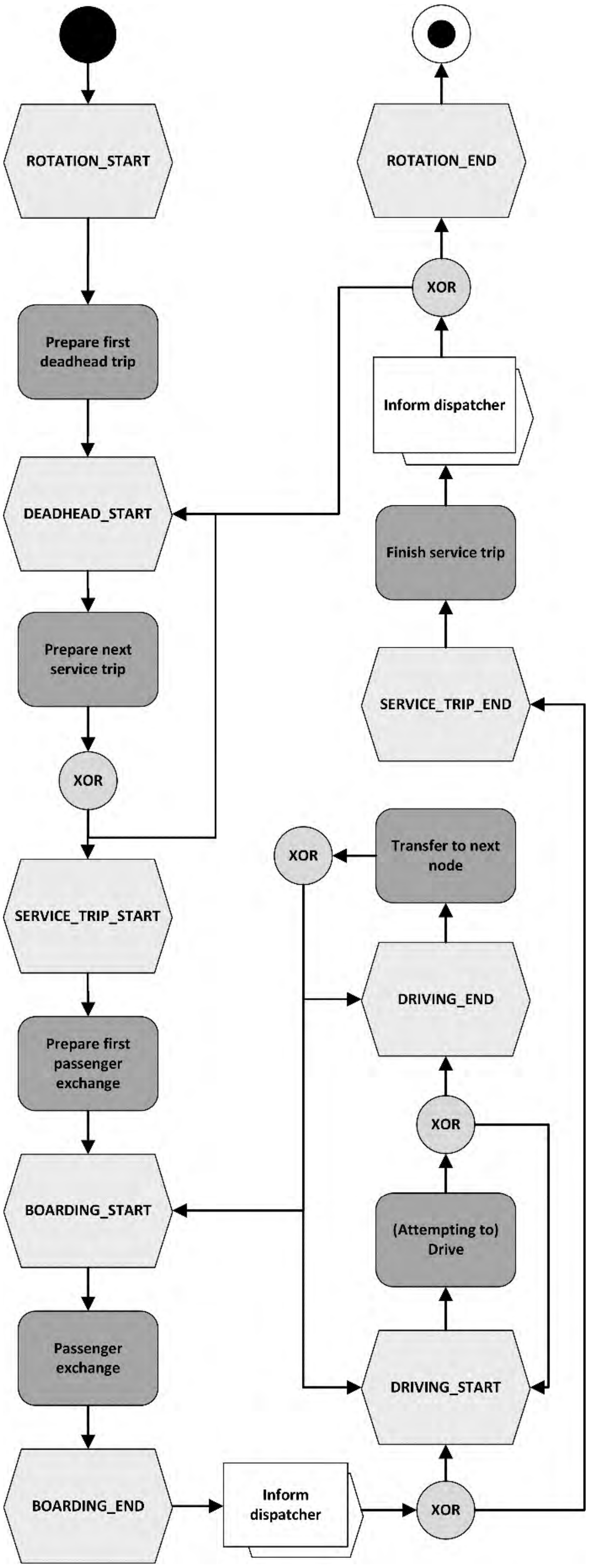

Figure 1: Simulation event types for the light rail and bus vehicles.

Nine simulation event types represent the behavior of bus and light rail vehicles (see Table 1). For a detailed description of the bus-related simulation events see [12]. Figure 1 shows the relationships between the individual event and activity types for light-rail vehicles, based on the associated event process chains. For a detailed discussion of the bus model behavior, see [12].

Simulation event type
ROTATION_START
ROTATION_END
DEADHEAD_TRIP_START
SERVICE_TRIP_START
TRIP_END
BOARDING_START
BOARDING_END
DRIVING_START
DRIVING_END

Table 1: Simulation event types for the light rail and bus vehicles.

2.4 Operational Management

The model components presented so far are sufficient for the representation of elementary functions of public transit systems, but they neglect all higher-level management activities that contribute to the functioning and resilience of transit systems. To allow for management on a higher level than individual trips, the timetable must be supplemented by a rotation schedule, which combines trips into groups (so called rotations) [24] that can be executed by individual vehicles within an operating day. These and other management activities are encapsulated in three management modules: the fleet manager, the line manager, and the dispatcher. Thus, changes to the modeling of individual administrative activities do not affect the modeling of other areas of the simulation model. Work in progress on these modules has been reported in [25].

Fleet manager

The fleet manager administrates the vehicle fleet and allows other components of the simulation model to access the vehicle fleet via defined interfaces, manages which vehicles are currently in use, and is responsible for generating and managing the initial rotation schedule. If no rotation schedule is specified by the user, the fleet manager uses a rotation schedule generator to create an (artificial) rotation schedule.

Line manager

The line manager administrates the lines served as part of a timetable and associates their outward and return directions with each other. In addition, it provides uniform interfaces for accessing individual lines as well as sets of lines. This allows, for example, access to all lines serving a specific stop or a specific connection.

Dispatcher

The dispatcher is the most important and comprehensive management module and can be understood as a model of the operator's decision processes. It holds all the data required for the operational process, such as the current timetables and rotation schedules at a specific point in time. In addition to managing regular operations, the dispatcher also includes the simulation logic required for traffic management. Four different event types address the module's behavior during regular operation (see Table 2).

Simulation event type
OPERATIONAL_DAY_START
OPERATIONAL_DAY_END
BOARDING_END
SERVICE_TRIP_END

Table 2: Simulation event types concerning the dispatcher module.

The event type OPERATIONAL_DAY_START models the start of the operating day. As a result of this event type, the dispatcher assigns to the vehicle entities of the vehicle fleet, based on the rotation schedule, the first trip to be served by them. A subsequent event of the type ROTATION_START is sent to each assigned vehicle entity.

The end of the operating day is modeled by the event type OPERATIONAL_DAY_END. It signals that all service trips have been performed and all vehicle entities have returned to the depot.

Vehicle entities send events of the type BOARDING_END, which signal the end of the pure boarding process, to the dispatcher during the simulated operating day. The dispatcher then makes further decisions on traffic management measures based on this information. For this purpose, the dispatcher can resort to different strategies (see [12] and [25] for detailed descriptions of different statregies). For determining the departure time of a vehicle during regular operations, a location-based departure strategy is employed. Under this strategy, selected stops are defined as control stops at which vehicles always have to wait until their planned departure time, as defined by the timetable, has been reached (e.g., to allow transfers between bus and light rail systems). At all other stops of the network vehicles always depart as soon as the boarding process has been completed, regardless of whether the planned departure time has already been reached or not. If the dispatcher receives an event of the type BOARDING_END, it checks whether traffic management measures are to be applied or not. Depending on the result of this check, the waiting time to be added to the entry/exit time is determined. This waiting time is communicated to the affected vehicle entity by sending it a subsequent event corresponding to the end of the waiting time. This subsequent event can be either of the type SERVICE_TRIP_END or DRIVING_START. The former is the case when the vehicle entity is at the last stop of its current trip. The latter is sent to tell the entity to move to the next node specified in the line route. In addition to traffic management used under 'normal operating conditions', the dispatcher also contains an arsenal of 'emergency traffic management strategies' (as described in [25]), e.g. dynamic rerouting of vehicles in case of blocked segments, shortturning of trips in case of high delay, or temporary splitting of routes.

The last event type relevant for regular operation is SERVICE_TRIP_END. It represents the end of a service trip and the subsequent signaling of the control center. As a result of this event, the dispatcher assigns the next service trip to the vehicle entity according to the current schedule and initiates the previously required deadhead. It is ensured that the minimum turnaround time specified by the user is observed between the end of one service trip and the start of the next one. If the finished service trip was the last planned trip of the vehicle entity for the simulated operational day, the dispatcher instructs it to end its rotation. If all trips to be performed on this operating day are completed at the end of the service trip, the dispatcher ends the operating day by scheduling an event of type OPERATIONAL_DAY_END.

2.5 Randomization

Two randomized elements are part of the proposed model: the vehicle's traversal time for connections, and the passenger exchange times at stops. Both are directly adapted from [12] with only slight adaptation.

A lognormal distribution is assumed for the **traversal times** for a connection c [26]. Lacking detailed data, the parameters of this distribution, i.e. expectancy value and standard deviation, have to be approximated from the planned traversal times $t_p(c)$. These traversal times usually comprise the planned driving time $t_d(c)$ and the planned passenger exchange time $t_b(c)$, which in turn are comprised of average observed driving/passenger exchange times, standard deviations, and unknown terms (see Equation 1).

$$\begin{aligned} \mathrm{t_p}(c) &= t_d(c) + t_b(c) \\ &= (\mu_c^d + \sigma_c^d + \epsilon_c^d) \\ &+ (\mu_c^b + \sigma_c^b + \epsilon_c^b) \end{aligned} \tag{1}$$

It can be assumed that the planned traversal time $t_p(c)$ is greater than the average observed traversal time μ_c^d to avoid systematic delays. The average traversal time can then be roughly approximated as follows:

$$\hat{\mu}_c^d = t_p(c) * \gamma, \forall c \in C, 0 < \gamma < 1 \tag{2}$$

The ratio γ has to be determined by the user. The standard deviation σ_c^d can be approximated in the same way. It can be assumed that the standard deviation is only a small fraction of the planned traversal time. This yields Equation 3.

$$\hat{\sigma}_c^d = t_p(c) * \eta, \forall c \in C, 0 < \eta < 1, \eta \ll \gamma \tag{3}$$

The **passenger exchange times** for busses and light-rail vehicles can be modeled following the method first proposed in [27]. This method is suitable for high frequency transit systems like urban light-rail and bus transit, where it can be assumed that passengers arrive randomly during the inter-arrival time of two successive vehicles, instead of arriving in bulk shortly before the planned departure time. Furthermore, the method facilitates the modeling of vehicle bunching, i.e. the effect that two vehicles form an undesired platoon because the vehicle in front takes on more passengers than planned and subsequently suffers longer passenger exchange times, while the rear vehicle takes on fewer passengers as planned and thus catches up to the vehicle in front.

If the number $N_{b,s}$ of passengers entering a vehicle b at a stop s, and the average time I_b a passenger takes to enter vehicle b are known, the passenger exchange time $T_{b,s}$ can be determined as follows:

$$T_{b,s} = T_b^{min} + I_b + N_{b,s} \tag{4}$$

Here T_b^{min} describes a vehicle specific minimum time, e.g. for opening and closing the vehicle's doors. If the passenger arrival rate a_s at stop s is known, $N_{b,s}$ can be modeled dependent on the basic interval $T_{L(b)}$ of line $L(b)$ currently served by vehicle b. With $N_{b,s} = T_{L(b)} * a_s$ the passenger exchange time can then be approximated as shown in Equation 5.

$$T_{b,s} = T_b^{min} + I_b + T_{L(b)} * a_s \tag{5}$$

If instead of the basic interval between vehicles of the same line, simulated headways between successive vehicles servicing the same stop are used, the model becomes dynamic and thus suitable for a simulation model. If $t_{dep}(b-1, s)$ describes the time a vehicle b's predecessor has serviced the stop, the passenger exchange time $T_{b,s}(t_{sim})$ can be determined as in shown in Equation 6.

$$\begin{aligned} &T_{b,s}(t_{sim}) \\ &= \begin{cases} T_b^{min}, & b\ is\ first\ vehicle\ at\ s \\ T_b^{min} + \left(t_{sim} - t_{dep}(b-1, s)\right) * a_s * I_b, & else \end{cases} \end{aligned} \tag{6}$$

3 Further Research

This paper introduced steps towards increasing the resilience of public transit infrastructure with a focus on designing and developing a fast bi-modal simulation model covering both light-rail and (express and community) bus transit. For that purpose, the components of public transit infrastructure systems were discussed, followed by a short introduction of resilience concepts and frameworks. Then, thoughts on the development of a bi-modal simulation model were shared, focusing on modelling physical components, the logical network, vehicle behavior, operational decisions, and the necessary randomization.

To complete the project, further research steps are necessary: As a next step, the simulation model and application have to be completed, tested, and validated. An additional goal for that step is to evaluate the model’s execution speed – to be useful in real-world applications, development has to focus on fast execution of individual simulation runs. Then, the validated model will be applied to evaluate what combination of disaster risk management and resilience-building strategies shows most potential to help increasing the resilience of urban transit systems against extreme weather events resulting from climate change as well as other disasters.

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