Combining Pre-Event Planning and Emergency Response in a Simulation Model to Increase the Resilience in Public Transit Networks

Daniel Lückerath, Oliver Ullrich

Fraunhofer Institute for intelligent Analysis and Information Systems IAIS, Schloss Birlinghoven, 53757 Sankt Augustin, Germany; *daniel.lueckerath@iais.fraunhofer.de; oliver.ullrich@iais.fraunhofer.de*

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Abstract. With increasing pressure from the impact of climate change, urban transit operators aim to improve their networks' resilience against both small disturbances and larger disruptions and outages. To be applicable in pre-planning or emergency response, such measures and strategies have to be thoroughly evaluated. To aid this evaluation process, this paper presents different operational strategies – and their systematic evaluation using a bi-modal transit simulation model – designed to increase the resilience of urban transit networks against the impact of climate change. To illustrate the application of such a system, the paper examines the strategies, including both delay management and disruption management measures based on a simulation model of the urban transit network of the city of Cologne, Germany.

Introduction

Urban transit infrastructure is increasingly put under pressure by the impact of climate change [1]. In general, there are two types of strains: Continuous, slowly increasing stress, which creates more and more small disturbances, and extreme events that lead to larger outages. Out of the latter category, most relevant for European urban centers are coastal, fluvial, and pluvial flooding, flash floods caused by heavy precipitation, rockslides and landslides, temperature extremes, thunderstorms and tornados, winter storms, and rising sea levels [2]. For the former category, the specific impact and its cost are complex to measure exactly.

However, it is being estimated that on average 30% to 50% of current road maintenance cost is already seen as consequences of climate change [3].

To be resilient against both types of stress infrastructure, including urban transit networks, needs a combination of disaster risk management and resilience-increasing strategies, i.e., a combination of good planning in the strategic timeframe and good emergency management in the operational timeframe. To be effective and efficient, both short-term and long-term activities have to be able to rely on well-evaluated operational strategies, i.e., well-tested combinations of measures to mitigate and adapt to the impact of climate change.

Here, simulation can help: 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 pre-planned 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 operational strageties, thereby contributing to increase the resilience of the transit system. The same simulation model can be used for ‘what-if’ analysis in the context of strategic planning of adaptation strategies against the slowly increasing impact of climate change.

This paper presents the application of a bi-modal transit simulation framework to evaluate different operational strategies – both in pre-planning and in emergency response – designed to increase the resilience of urban transit networks against the impact of climate change in general, and of extreme weather events more specifically.

Instead of looking at purely artificial use cases, the paper examines the strategies and their combinations based on a simulation model of the urban transit network of the city of Cologne, Germany.

The paper continues with sharing some background on different concepts of resilience in a public transit concept and on operational strategies aimed at increasing transit resilience (Section 1). It then describes public transit modeling in general and the applied transit simulation model (Section 2). The main part begins with a short description of Cologne's public transit network and continues with the test and evaluation of several operational strategies aimed at combining pre-event planning and emergency response in the context of that transit network (Section 3 and Section 4). The paper concludes with a short discussion of the lessons learned and an outlook to further research (Section 5).

1 Resilience in Public Transit

1.1 Urban Transit Resilience

In the urban transit context, two different understandings of 'resilience' are relevant: engineering (or 'narrow') resilience and multi-equilibria resilience [4][5][6]. 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., [7]). Subsequently, the concept of engineering resilience is static and does not take the need for flexibility and adaptation into account. Multi-equilibria resilience [5] 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 [8]), 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).

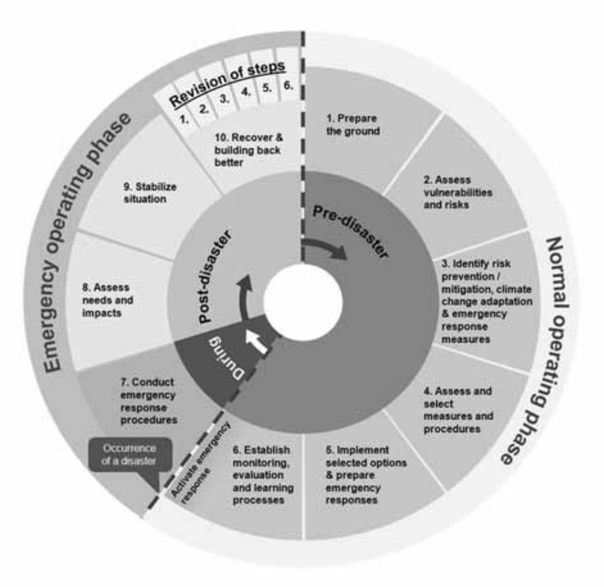

Figure 1: The combined Disaster Risk Management and Resilience Improvement Cycle (Source: [11][12]).

Considering accelerating climate change, the associated increase in frequency and intensity of natural disasters, and the subsequent increase in impacts to (urban transit) infrastructure [9][10], it becomes paramount to design new schedules and networks in a resilient and sustainable way, and to address both types of resilience. From a procedural point of view transit providers can accomplish resilience improvement by adopting a combined disaster risk management and climate change adaptation cycle [11], encompassing both long-term planning of services during normal operations and short-term disaster management during emergencies (see Figure 1).

1.2 Operational Measures to Increase Resilience

Operators can apply a variety of strategies to increase both engineering and multi-equilibria resilience. These measures generally fall into one of two categories: *Delay management measures* are designed to increase service regularity and vehicle punctuality by applying timetable- and rule-based holding strategies. *Disruption management measures* apply more comprehensive interventions that change line routes and schedules of multiple vehicles to mitigate the impact of larger disruptions of the network.

The following paragraphs give brief introductions on delay management and disruption management measures, with a more detailed discussion found in [13].

Delay management strategies. In day-to-day operations, significant effort is made to ensure service quality by avoiding vehicle bunching. Vehicle bunching describes the phenomenon of public transit vehicles to form pairs due to a preceding delayed vehicle taking on more passengers as originally planned and the on-time succeeding vehicle subsequently taking on fewer passengers as originally planned. Thus, without intervention the preceding vehicle gets further delayed while the succeeding vehicle catches up to it [14]. Basic *bunching mitigation measures* hold back a vehicle at a time control point if it is too early by a certain threshold. A more complex version of that strategy also considers a vehicle's estimated punctuality at its next scheduled stops down the line [15]).

The other major category of delay management strategies are *synchronization assurance measures*, aimed at ensuring transfers from one line to another. Usually, these transfers are either rendezvous connections, where a number of vehicles serving different lines wait at the same station to enable passengers to transfer to each other, or directed transfer connections, where a vehicle serving a line waits for a feeder vehicle serving a different line, and thus enables transfer from the second line to the first. To assure these transfer connections, one or more vehicles might have to be kept at a station to wait for a delayed vehicle.

Disruption management strategies. Disruption management measures are usually much more comprehensive and more incisive than delay management strategies. They cover rerouting, short-turning, stop skipping, and route separation. Typically, the measures are ordered by their degree of intervention to form an overall disruption management strategy.

If a disruption occurs that cannot be migitated by delay management, first rerouting of vehicles is considered: sets of potential alternative routes for each line affected by the disruption are constructed using a pathfinding algorithm. Once all potential alternative routes are determined, the method picks – depending on the operator's preferences – either the route with the least traversal time or the most punctual route.

If no alternative route covering all regular stops can be found, short-turning, i.e. ending the trip before reaching the disrupted network section, is considered. Such an action has an impact on the executing vehicle's next trip that has to be mitigated as well:

- Either the vehicle has to make a deadheading trip to the first stop of its next trip,
- or the next trip of the vehicle has to be short-turned as well to start from the vehicle's current position.

A potential disadvantage of the described short-turning method is that it does not guarantee the reachability of all stops further down the route. Sometimes that can be remedied by skipping a part of the stops on the original route.

If all these measures fail, an operator will, where possible, separate all affected routes in the disrupted network section. This can be viewed as a two-sided short-turning strategy, where vehicles stuck on either side of the disrupted network section service as much of their originally scheduled trips as possible. In addition to just short-turning affected trips, route separation generally also requires adjustments to the timetable and the vehicle schedule.

2 Modeling Urban Transit

2.1 Urban Public Transit Modeling

Urban transit consists of a number of interacting networks, e.g., a light rail system, express and community bus networks. Such a network is based on 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 by following pre-defined routes through the network. During the operational day each individual vehicle executes a sequence of service trips, interspersed with deadheads, that is called a rotation. 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. 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. Access to individual segments is controlled by signals, usually at junctions. Often, two or more signals constitute a signal group with a common scheduling strategy.

Typically, daily operations are managed by an operations center, with dispatcher personnel managing procedures for the mitigation of small disturbances and larger outages. In case of any disturbances or outages, transit operators have several 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.

Simulation models that represent the described entities and behavior are often extensions of already established models of individual traffic [16][17][18]. Generally, many of the more recent simulation models including bus transit use microscopic agent-based modeling approaches [16][17][19][20][21], the mesoscopic approach to bus transit simulation proposed by Toledo et al. [18] extends a mesoscopic simulation model for individual traffic based on queuing theory proposed by Burghout [21], 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 [22], and include many components which are not immediately interesting for public transit resilience management. This often leads to long runtimes [23][24], thereby rendering those models inadequate for short-term disaster management. Therefore, this paper applies the fast mesoscopic transit simulation model described by Ullrich and Lückerath [25] and [26].

2.2 A Mesoscopic Model of Multi-Modal Public Transit

To examine cost and benefits of different resilience-increasing strategies a mesoscopic urban transit simulation model has been developed based on the event-based approach [27]. Described in detail by Ullrich and Lückerath [25] we now only give a short overview of its characteristics.

At the center of the model lies 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.

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. 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.

Each node represents an entity in the sense of the event-based simulation paradigm, i.e., it can be producer and consumer of events. Thus, temporary changes of attribute characteristics, e.g., for modeling disruptions, can be mapped in a simple way via events and activities.

Vehicles are represented as transient entities 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. In the model, vehicles are classified according to their transit mode, their vehicle type, and their individual vehicle characteristics.

In addition to the physical network components and vehicle behavior presented so far, concepts such as lines, trips and timetables also are represented in the model.

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) [28] 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 [29] and [26].

2.3 Generating Regular Timetables Adhering to Planning Requirements

Transit timetable generation is a well-researched complex optimization problem [30], too complex to describe here in detail. Generally, to accomplish resilience against small disturbances optimization models often aim for s*ervice regularity* [31][32][33][8], a measure of the equability of headways that can be used for static evaluation of a timetable during the planning phase as well as for dynamic assessment of operational performance.

In addition to being resilience against small disturbances, a feasible schedule also has to adhere to other planning requirements – that includes specific departure sequences to accommodate frequent transfer connections or deliberately short headways to reduce the passenger load of follow-up vehicles.

This study applies a disjunctive program formulation producing regular timetables for multi-modal public transit systems adhering to planning requirements given by transit operators. That program was first introduced by Lückerath, Ullrich, Rishe, and Speckenmeyer [33] and allows for the consideration of feasibility constraints from daily operations as well as for the consideration of simultaneous departures for transfer connections, an objective traditionally opposed to regularity.

3 Cologne's Bi-Modal Urban Transit Network

The city of Cologne's urban transit service is organized as a combined bus and light-rail network. Generally, the light-rail lines transport residents and commuters inside the densely populated inner city, as well as connects the inner city to suburban outskirts and neighboring towns. Both functions are highly relevant for daily commuters.

Parts of the light-rail network run overground, in some parts light rail cars share the roadway with car traffic, in others they have exclusive rights of way as well as signal precedence compared to individual traffic. Other light-rail segments run underground. In contrast to many other European cities, above- and below-ground railroads are not separated; instead, the Cologne subway behaves more like an underground streetcar than a typical subway – it does not use specific underground engines or passenger cars with their wide aisles and comparatively few seats for the typically short subway journeys, no turnstiles exist at the platforms.

The bus network includes both express buses on their own right of way and relatively slow community buses that connect neighboring districts as well as provide intra-district connections.

Bus and light-rail network have in common strategic nodes that allow for transfer between the networks, including the stations Barbarossaplatz, Ebertplatz, and Neumarkt. These nodes are usually time control points.

Additionally, at some nodes the urban transit network is connected to national rail, that includes the stations Deutz Bf, Ehrenfeld Bf, Hansaring Bf, Hauptbahnhof, and Mülheim Bf.

In total, the Cologne urban transit network consists of 1,770 stops, of which 1,242 are serviced by buses and 528 by light-rail trains of the types Vossloh Kiepe K4000 [34], K4500 [35], and K5000 [36]. The vehicles service 68 bus and 30 light-rail routes. The light rail part of the network covers 407 kilometers and includes 178 vehicles that execute 2,814 trips per operational day.

Figure 2 depicts an overview of the south-western portion of the network. The complete network is described in detail in [37].

4 Validating Operational Strategies

For the overall validation of the described approaches for operational resilience strategies three sets of simulation experiments are conducted:

1) Basic verification of bunching mitigation measures for delay management on an artificial transport network;
2) validation of synchronization assurance measures for delay management on the bi-modal public transit network of Cologne; and
3) validation of disruption management measures via a simulated disruption of Cologne's light-rail network, as described in summary in [13].

If not specified otherwise, all results are averaged over 100 simulation runs, with statistics being collected – after a stabilization phase – between 8am and 6pm of simulation time.

4.1 Verification of Bunching Mitigation Measures

The anti-bunching strategy is influenced by three parameters:

1) the selection of stops defined as control points;
2) the information about vehicle deviation used for decision making; and
3) the maximum permissible departure time deviation a_{max}^{Diff}.

To verify the approach, these parameters are systematically varied and the resulting combinations are compared with each other and with the null case that uses no bunching mitigation strategy. The observed bunching effects as well as the average and maximum delay, earliness, and waiting time measured over the stops of the network are used as key performance indicators.

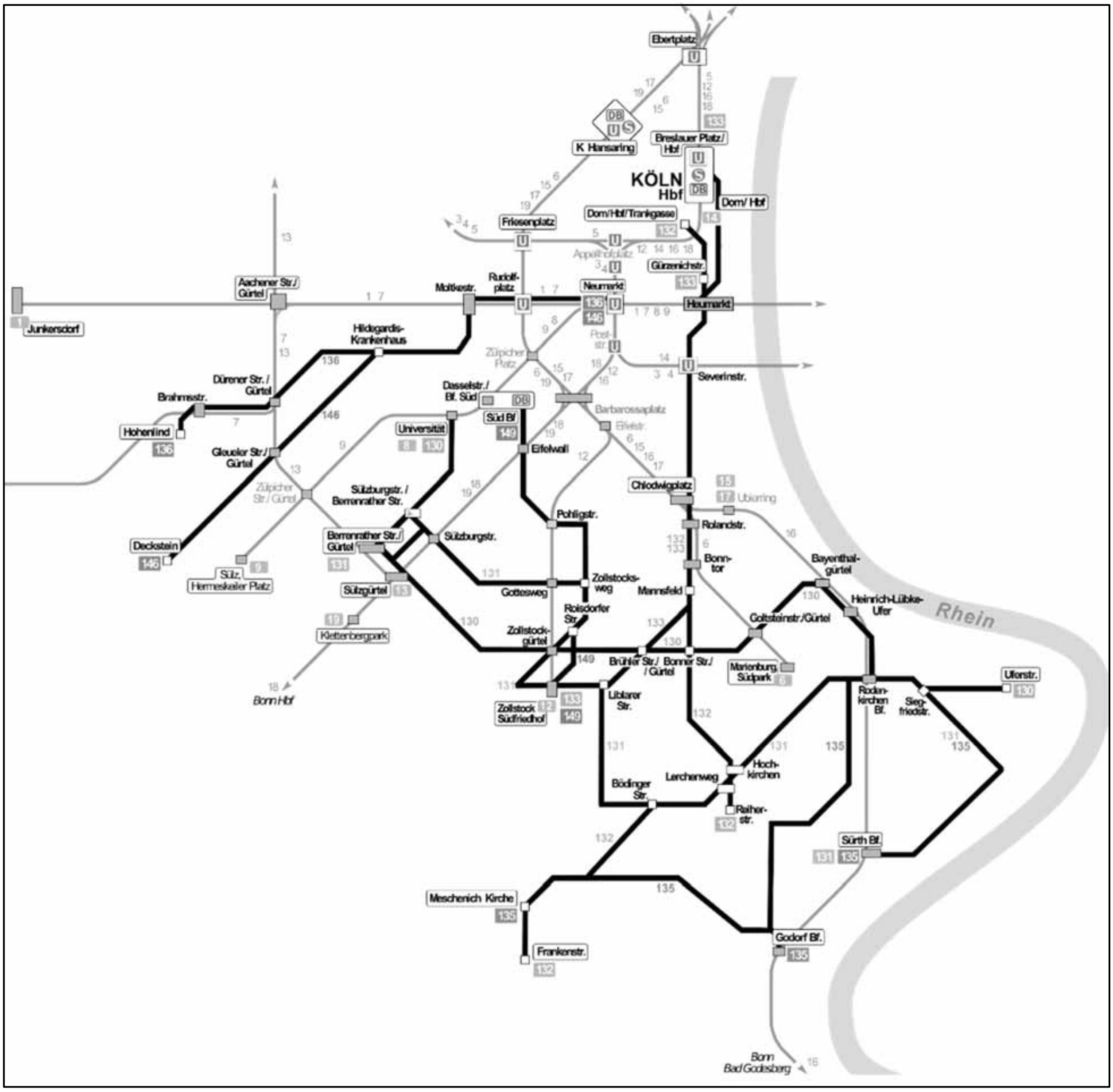

Figure 2: The southwestern part of Cologne's combined bus and light-rail network (Source: [37]).

Due to the complexity of the Cologne network and the combinatorial impracticability of comparing all potentially possible combinations of the relevant parameters, the anti-bunching strategy is verified via simulation runs on the artificial transit network first described in [26].

For this experiment, we decide on using only the starting stops of the individual lines as control points, which translates to applying no correcting measures during the vehicles' trips, versus using all stops as control points.

The threshold value of the departure time deviation a_{max}^{Diff} is varied in ten-second steps between zero and 30 seconds. Additionally, a larger threshold of 60 seconds is investigated. Together with the two options for the information to be used for decision-making (only local deviation or also environmental information, i.e., the punctuality at the next stop), this results in 20 different variations of the anti-bunching strategy. Key results are shown in Table 1.

The comparison of the observed bunching effects verifies the anti-bunching strategy and shows expected patterns: The application of any version of anti-bunching measures leads to a reduction of the fraction of diminished safety distances compared to the null case. The reduction decreases with increasing value of a_{max}^{Diff} and is stronger when all stops act as control points. The former can be explained by the fact that with increasing a_{max}^{Diff} the departure time deviation is no longer limited by this threshold value but by the travel and stop times determined on the basis of the simulation parameters or empirical data, i.e. it approaches the uncontrolled case.

The key performance indicators for delay, earliness, and waiting time from Table 1 confirm the observed patterns. The indicators were calculated by determining the average and maximum delay/earliness/waiting time at each stop of the network over the departures taking place there. These values were then averaged over the simulation runs and stops performed on the network.

As expected, the average and maximum delay increases with decreasing a_{max}^{Diff}, since vehicles are no longer able to form time buffers and thus absorb potential delays. At the same time, earliness and waiting time decrease. It is also plausible that the maximum waiting time is higher when only selected stops are used as control points, since vehicles between them accumulate larger time buffers than when all stops act as control points. Since the time buffers introduced by vehicles in front of control points are directly converted into additional waiting time, the maximum waiting time thus increases.

4.2 Validation of Synchronization Assurance Measures

To validate the synchronization assurance strategies, two different timetables for the bi-modal public transit network of Cologne were generated using the approach from [33] and examined with regard to their suitability for the implementation of directed transfer connections between the two modes of transport. Departing bus vehicles are to wait at selected control points for arriving rail vehicles to allow transferring passengers quickly.

One timetable, designated KVB-BT+, represents the optimal solution for the service regularity of the overall system. The other timetable, denoted KVB-BT-C+, is generated taking into account the transfer specifications and a balanced weighting between service regularity and fulfillment of the specifications.

Establishing transfer connections at all stops of a network is neither possible nor practical. Ideally, the most relevant interchanges should be identified based on information about passenger trips, such as origin-destination matrices, as well as operational and policy considerations, and the overall timetable should be developed with this information in mind. The most interesting potential transfer nodes of the Cologne network are the bus stations Chorweiler, Ostheim, and Porz Markt. The three selected interchanges have dedicated stops for all departing bus lines and – with the exception of the Porz Markt – all departing light-rail lines. At the stop Porz Markt, the light rail lines 7-T01 and 8-T01 as well as 7-T02 and 8-T02 share common stops, but since the variants of line group 8 share a significant part of their route with the corresponding variants of line group 7 and the latter have significantly longer routes, it can be assumed that lines 7-T01 and 7-T02 are more relevant for the establishment of interchange connections.

The three selected stops also represent a cross-section of different possible constellations of start/end or transit stops: The Chorweiler stop is the final/starting stop of the rail lines 18-T01/T02 as well as the bus line 126-B01/B02. In addition, bus lines 120-B01/B02, 121-B01/B02 and 125-B01/B02 leave from here. The Ostheim stop, on the other hand, is a transit stop for the train lines 9-T01/T02 and the bus lines 152-B01/B02, as well as the start/end stop for the bus lines 157-B01/B02. Finally, the stop Porz Markt is the start/end stop for the bus lines 152-B01/B02, 154-B01/B02, 160-B01/B02, 161-B01/B02, 162-B01/B02 and the train lines 8-T02/T01, as well as a through stop for the train lines 7-T01/7-T02.

For the light rail network, we assume a boarding time of three seconds per passenger and a departure interval of ten minutes, the arrival rates of all stops are set such that $T_{f,s}^{Rail} = 20$ seconds. In addition, all stops in the rail network act as control points at which on-time departures are enforced.

An arrival time of three seconds per passenger is also assumed for the bus network and the arrival rates of all stops are set so that $T_{f,s}^{Bus} = 20$ seconds. The connections of the Cologne bus network have an average

planned travel time of about 94 seconds. Accordingly, $\gamma^{Bus} = 1 - (\frac{20}{94}) \approx 0.79$ is set. Since individual traffic is subject to stronger fluctuations in travel time than rail traffic, $\eta^{Bus} = 0.21$ is set following a random sample sensitivity analysis.

Strategy			Delay [sec.]		Earliness [sec.]		Waiting time [sec.]	
Control points	Information	a_{max}^{Diff}	Ø	Max.	Ø	Max.	Ø	Max.
-	-	-	4.4	84.6	14.1	104.8	0.0	0.0
Start	Local	0	8.5	95.6	4.6	61.7	1.5	57.0
Start	Local	10	4.6	85.6	10.7	71.4	0.4	58.2
Start	Local	20	4.4	84.3	12.5	81.3	0.2	55.3
Start	Local	30	4.4	84.1	13.5	88.5	0.1	44.9
Start	Local	60	4.4	82.3	14.1	104.0	0.0	16.9
All	Local	0	10.4	98.4	0.0	0.0	2.6	27.9
All	Local	10	5.4	89.6	5.0	10.0	1.5	27.6
All	Local	20	4.4	82.8	8.8	20.0	0.8	26.7
All	Local	30	4.3	85.4	11.1	30.0	0.5	25.3
All	Local	60	4.4	84.7	13.7	60.0	0.1	20.5
Start	Environment	0	7.1	98.4	5.6	62.4	1.3	58.4
Start	Environment	10	4.6	86.9	10.8	69.9	0.5	57.8
Start	Environment	20	4.3	84.8	12.6	81.0	0.2	56.4
Start	Environment	30	4.3	82.8	13.5	90.3	0.1	47.1
Start	Environment	60	4.4	86.4	14.1	104.3	0.0	15.2
All	Environment	0	8.4	100.4	0.7	13.4	2.4	27.7
All	Environment	10	5.3	89.7	5.2	15.2	1.5	27.6
All	Environment	20	4.4	84.6	8.8	20.0	0.9	26.7
All	Environment	30	4.3	84.6	11.2	30.0	0.5	24.9
All	Environment	60	4.4	83.8	13.7	60.0	0.1	20.4

Table 1: Average delay, earliness, and waiting time of different management strategies; source: [37].

In addition, slight variations in travel time due to traffic signals are mapped – again, following a sensitivity analysis – by setting $\iota = 0.01$, i.e. per traffic signal on a connection the standard deviation of travel time is increased by one percent. Finally, the first stops of all lines as well as the stops that represent connection points to long-distance traffic (i.e., 128 of the 1.242 stops of the bus network) are defined as control points. At these control points, the previously identified most appropriate anti-bunching strategy is implemented: Vehicles are allowed to depart, based on local information, a maximum of ten seconds before their scheduled departure time.

Under these parameters, the suitability of both schedules for the implementation of synchronization assurance measures is tested by means of six experiments. For this purpose, we systematically vary the connection waiting time wt_c and the transfer time t_t to comply with the transfer connections defined for the timetable and the results are compared, as far as possible, with key performance indicators of the base case without transfer connections (marked by the parameter values "-").

The waiting time wt_c is varied in 60-second increments from 0 to 180, since the traffic planning specifications under which schedule KVB-BT-C+ was generated allow bus vehicles to depart as scheduled up to three minutes before the feeder vehicle of the light-rail service. In order to maintain the transfer connection, they must therefore wait up to three minutes for the light-rail vehicle if they arrive on time. In addition, a shorter waiting time of 30 seconds is also tested.

Values of 0 and 30 seconds are used for the transfer time t_t, which indicated how long vehicles wait after completing a transfer connection until their actual departure.

The former is only used together with a waiting time of $wt_c = 0$ to capture the inherent suitability of the schedules to implement transfer connections, i.e. without (significant) intervention of the dispatcher. The value of 30 seconds for t_t was chosen so that any (artificial) delays due to this value would not affect the simulation metrics too much. In the real system, waiting buses would start as soon as all transferring passengers have entered the vehicle. Based on passenger numbers, a plausible (average) value is chosen that should allow the majority of passengers to transfer comfortably. The time t_q, which bus vehicles wait until they are asked again whether the transfer connection is fulfilled, is set to 30 seconds uniformly for all experiments.

Table 2 lists the resulting percentage of connections made by the different bus lines at the three stops during the measurement period under the different timetables and parameters. These are the departures of the bus lines during which the relevant feeder vehicles of the light-rail lines arrive within the specified time interval.

The results show that schedule KVB-BT-C+, as expected, is already better suited for the transfer of transfer connections than schedule KVB-BT+ without significant intervention by the dispatcher.

Under the latter, inherently only an average of 14.05 percent of all potential transfer connections are fulfilled, while under schedule KVB-BT-C+ an average of 42.20 percent of all transfer connections are fulfilled.

If the dispatcher is prompted to intervene more strongly by increasing the maximum waiting time wt_c, the proportion of fulfilled transfer connections can be increased to an average of up to 29.63 percent under schedule KVB-BT+. Under timetable KVB-BT-C+, on the other hand, the average share of fulfilled transfer connections can be increased to up to 87.49 percent. This effect is to be expected because under the KVB-BT-C+ timetable the bus lines are forced to depart from the three interchanges within three minutes of the departure times of the light-rail lines concerned.

By deliberately delaying the vehicles of the bus lines by up to three minutes during the simulation, the probability that the interchange connections will be fulfilled in regular operation must therefore be increased. Under the KVB-BT+ timetable, however, the application of this strategy does not have such a pronounced effect since the synchronizations between the departures of the bus and light-rail lines are largely random without taking traffic planning requirements into account.

Time table		KVB-BT+					KVB-BT-C$^+$				
	wt_c [sec.]	0	30	60	120	180	0	30	60	120	180
	t_t [sec.]	0	30	30	30	30	0	30	30	30	30
Chorweiler	**120-B01**	0.00	0.00	0.00	0.00	0.00	0.00	97.38	**98.33**	**98.33**	**98.33**
	120-B02	0.77	0.72	0.92	0.82	0.73	63.37	63.48	63.78	63.48	**64.32**
	121-B01	0.00	0.00	0.00	0.00	0.00	69.97	**70.53**	68.56	68.30	68.23
	121-B02	0.00	0.00	0.00	0.00	0.00	0.07	97.38	**98.33**	**98.33**	**98.33**
	125-B01	13.44	12.57	12.05	98.28	98.06	0.00	0.00	0.00	0.00	**98.32**
	125-B02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	**98.33**	**98.33**
	126-B02	96.67	96.67	96.67	96.67	96.67	0.00	0.00	0.02	**98.33**	**98.33**
Ostheim	**152-B01**	49.88	48.91	37.50	0.88	0.00	**99.95**	98.78	49.13	46.86	5.22
	152-B02	0.00	0.00	0.00	0.00	0.00	99.98	**100.00**	99.99	**100.00**	**100.00**
	157-B01	0.00	0.00	0.00	49.92	49.03	99.70	**99.80**	99.73	95.96	83.00
Porz Markt	**152-B01**	50.00	50.00	50.00	50.00	50.00	0.00	26.26	**100.00**	**100.00**	**100.00**
	154-B01	0.00	0.00	0.00	0.00	50.00	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
	160-B01	0.00	30.36	50.00	50.00	50.00	0.00	0.00	0.00	**100.00**	**100.00**
	161-B01	0.00	0.00	0.00	0.00	0,00	**100.00**	**100.00**	**100.00**	**100.00**	**100.00**
	162-B01	0.00	0.00	0.00	0.00	50.00	0.00	0.00	0.00	0.00	**100.00**
	Ø	14.05	15.95	16.48	23.10	29.63	42.20	56.91	58.53	77.86	**87.49**

Table 2: Average ratio of kept transfer connections at core stops examined with different combinations of timetables and transfer times; source: [37].

The fact that even under the KVB-BT-C+ timetable not all transfer connections can be fulfilled can also be explained by the fluctuating travel and stop times due to the dynamic conditions.

However, the effects induced by the synchronization strategy are not limited to the interchanges and the directly affected lines. Delays and associated bunching effects are often carried over the entire remaining route and are also transferred to the reverse directions of the line groups, in some cases in the form of increased delay and/or earliness.

4.3 Validation of Disruption Management Measures

To validate disruption management measures, a disruption in the Cologne light-rail network is simulated (as already briefly discussed in [26]). All simulation parameters described in the previous section are retained, as is the stopping strategy used, where early *vehicles* are forced to depart on time at each stop.

The simulated disruption is the one-sided blockade of the connection between the Neumarkt (NEU) and Heumarkt (HEU) stops in the city center between nine and ten in the morning. As a result, no operations can take place on the connection during this period.

Without explicitly addressing the disruption, services are extremely disrupted in their operations, with average delays of between about one and two hours. If, on the other hand, the disruption is responded to by splitting the route, its effects cannot be completely eliminated, but they have a much more moderate impact on the operating schedule, with line delays of no more than approx. 44 seconds.

Figures 3 and 4 show as an example the departure times of all simulated trips of the line 1-T01 during the of the line 1-T01 at all stops of the route during the measurement period are plotted. First of all, before the onset of the disruption (upper dashed line), the behavior is the same both with and without incident management: Vehicles are able to travel without further complications from their starting stop at Junkersdorf (platform #1243) to their final stop at Bensberg (platform #1274). As soon as the fault becomes active, however, the resulting system behavior differs however, differs significantly.

Without incident management, all trips that reach the Neumarkt stop (platform #1254) during the incident are delayed there until the incident is cleared (lower dashed line).

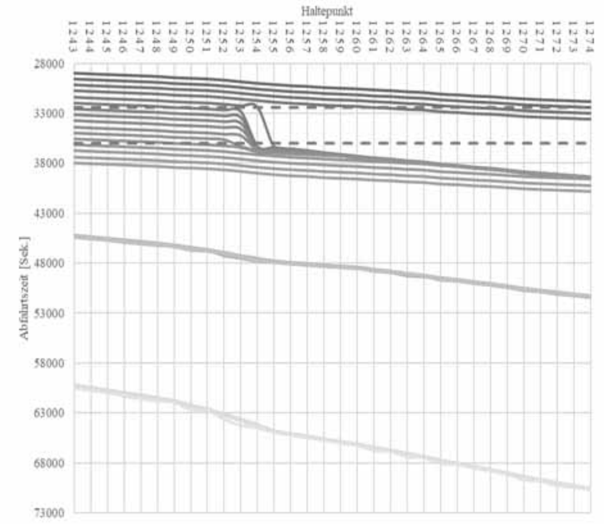

Figure 3: Impact of a 60-minute outage on a light-rail line without mitigation strategy: Most vehicles servicing the line wait at the blocked location for the outage to be repaired; after that the vehicle bunching effect [14] causes the service to be unusable for the rest of the operational day. (Source: [37]).

The vehicles then continue their journeys as a convoy, without even spacing. Since the vehicles cannot make up for their delay, also due to the unintentional column movement, it is transferred to the subsequent journeys in the opposite direction, where the same phenomenon can be observed. Without external intervention, this effect cannot be broken, so that the regular service breaks down and only sporadically a single column of delayed trains serves the stops.

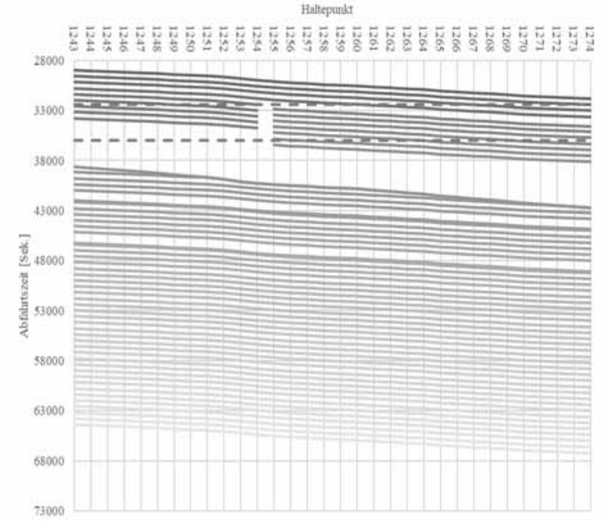

Figure 4: Impact of a 60-minute outage on a light-rail line with an effective mitigation strategy: The service level bounces back to almost normal half an hour after the outage has been repaired. (Source: [37]).

With disruption management, however, regular operations can be maintained to a large extent. As shown in Figure 4, the trips that would reach the Neumarkt stop during the disruption are shortened at this stop. The service of the stops behind the disruption, on the other hand, is taken over by the vehicles that travel in the opposite direction only to the stop Heumarkt (platform #1255). After the end of the disruption and after the vehicles have arrived at the Junkersdorf stop by means of a regular trip in the opposite direction, regular service is resumed.

5 Conclusion

This paper described the application of a bi-modal, mesoscopic simulation model in the test and evaluation process of measures and strategies aimed at increasing the resilience of urban transit networks against the impact of climate change. The paper provided an introduction to transit resilience as well as delay management and disruption management measures, described urban transit modeling, simulation, and timetable generation. As a main part, the paper examined the evaluation of measures and strategies based on a simulation model of the urban transit network of the city of Cologne, Germany.

As described, the research indicate that the delay and disruption management strategies increase the resilience of transit networks as expected. Additionally, the results also indicate that the described evaluation process indeed is applicable to test and evaluate both pre-planned and emergency response strategies.

In further research steps, the described strategies will first be refined using the model of another urban transit network, and then carefully transitioned to the application in a real-world transit network.

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