Future traffic control beyond modes

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1. Executive summary

Future traffic control beyond modes aims to study the benefits of a nationwide integrated multimodal traffic management system. To do so, first, we review the most recent academic research performed under the topic of multimodal transportation systems in both passenger and freight transportation. For both passenger and freight, we categorize the academic articles based on the decision horizon of the management problems. We start with strategic management articles, which consider the long-term decisions, usually in a time frame of five to ten years. Strategic management addresses solutions for large investments on the infrastructure of the transport network and discusses the maximization of the utility of multimodal transportation networks. Second, we discuss the literature considering the tactical management issues and the proposed solutions. At the tactical level, management decisions in a shorter time scope in comparison to the strategic level are addressed. The tactical decisions are usually made for one or two years' time scope. And finally, the operational management level solutions will be discussed, focusing on short-term solutions, i.e., daily, hourly, or even more frequent. The conclusion that we achieve considering the academic state-of-the-art is that most of the recent academic studies focus on determining the optimal solution to balance the strengths of different modes and their reaction to variable demand. The goal is to compute a system optimum, which minimizes externalities, or travel times, assuming specific controllability of the different modes. The focus of the academic approaches is on relatively small problems, for instance, in terms of links, alternative routes, amount of passengers, or vehicles. Moreover, some practical aspects of organizational or infrastructure requirements are based on assumptions, and rarely discuss all the required steps for implementation, including cost-benefit analysis. The behavioral response of travelers is often based on assumptions that might have a limited realism. Approaches that consider a multi-layer, nationwide multimodal management as a whole integrated system are still not in the focus of researchers. However, one could consider that a nationwide management center is a combination of small actions in different criteria.

To find out whether there has been any practical approach regarding a multimodal management center in different countries, we investigated the state-of-practice mainly based on interviews with academic and industrial experts currently working in the transportation field in selected countries. The countries selection is based on our discussion with SBB colleagues and their interests. The interviews and reports of the ongoing projects cover experts from the following countries: Austria, Hong Kong, Japan, Luxembourg, Netherlands, Sweden, Switzerland, and the United States. The results, in general, show that in the given countries, from a practical point of view, multiple projects, pilots, and implementations, aim to address some aspects of multimodal traffic management. Most of those approaches identify data collection and integration; and definition of standards and exchange format, as prerequisites for any further decision support—for example, SIMsystem (WEF, 2018). A SIMSystem is a “system of systems” that moves people and goods more efficiently by creating interoperability across physical assets like cars and buses, digital technologies like dynamic pricing and shared data exchanges, and the governance structures, standards, and rules by which they operate. Furthermore, there are guidelines provided by Commission Delegated Regulation (EU) 2017/1926, which focuses on the priority action and provision of Union-wide multimodal travel information services for the development and use of specifications and standards. Also, Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010: Framework for ITS road transport and interfaces with other modes, which focuses on Intelligent Transport Systems (ITS) and its advanced applications to provide innovative services relating to different modes of transport and traffic management. Under the guidelines in the European Union level, FRAME NEXT is a project that extends the European ITS Framework Architecture, in short FRAME, with the activities of the different member states in Europe. Moreover, projects that focus on a city, such as Maastricht Bereikbaar 2019: integrated mobility management targeting employers and commuters aims at demand management towards reducing congestion. Finally, Integrated Corridor Management (ICM) project focusing on a corridor in the United States. The vision of ICM is to achieve significant improvements in the efficient movement of people and goods on transportation networks through cooperative, proactive integration of existing infrastructure along major corridors. In conclusion, some systems have been implemented in multiple cases, though no test case reaching the size of a country like Switzerland, explicitly including long-distance train, is known.

Furthermore, we attempt to evaluate the benefits of an integrated multimodal management in different case studies. In the first case study, we focus on freight transport and the benefit of such a system in case of a disruption. Freight transport disruptions in recent years have caused production shutdowns in the industry, supply shortages, and serious economic damage around the world. Contingency strategies from transport operators are often inefficient, and disruption management fails to handle the situation sufficiently. Chapter 6 investigates on mode shift as a disruption response tool. Thereby disrupted transportation links or nodes are avoided by loading goods on another mode of transport for the complete distance or just to bypass disrupted infrastructures. Multimodal management is then the tradeoff between costs for delay versus costs for mode shift. With a qualitative approach consisting of a literature review, expert interviews, and a case study analysis on four events affecting different modes, the study aims at assessing the efficiency of mode shift, building a conceptual mode shift model, and developing recommendations for involved actors to better facilitate mode shift in disruptions. It is found that mode shift as a disruption response tool is generally considered as suitable to reduce disruption costs, whereas its efficiency depends on multiple technical as well as organizational factors, constraints and requirements. These factors are conceptualized in a qualitative model which summarizes recommendations for policymakers, infrastructure providers, as well as managers, transport operators, and the industry. The most common constraints are related to information shortages could be dealt with by digitalization of relevant information as well as real-time data gathering and evaluation with models allowing to assess different contingency strategies. Organizational, regulations and legal frameworks play an important role in implementing such policies.

In the second case study, the focus is on major bottlenecks in Switzerland; the objective is to study the benefits of a multimodal management center in interurban context and to find out what strategies can be implemented in a multimodal management concept and what are their benefits. To do so, we assume an extreme situation as the best approach to evaluate the benefit of such a system. Therefore, disruption scenarios on three major bottlenecks in Switzerland are considered, including Geneva-Lausanne, Zurich-Bern, and Gotthard tunnel. Disruption is defined as bottleneck closure for the time of the study, and evaluations are done based on demand data provided by the National Passenger Transport Model for two different time periods, 2010 and 2040. The methodology applied in Chapter 7 focuses on the multimodal network design problem, quantifying the potential between a user equilibrium and a multimodal system optimum solution, in case of a disruption. Travel time and delay are the performance indicators considered in this approach. For the bottlenecks of Geneva-Lausanne and Zurich-Bern, in case of railway disruption, strategies allowing a system optimum solution would save a lot of delays compared to the user equilibrium It is important to mention that here we have only considered the (annual) average of one hour of demand and one hour of disruption in only one direction. If we scale up the demand and disruption in more hours, the numbers will increase significantly. Also, if the disruption happens during the peak hours, the resulting numbers are much larger comparing to the provided average results. Furthermore, when trying to assess the overall impact in monetary or environmental terms, we should also consider the reoccurrence of such disruptions in a year.

The third case study is dedicated to evaluating the benefits of multi-modal management actions in the management of disruption in an urban context. The simulation of the impacts and dynamics of a real-life disruption in our study is performed by (a) agent-based simulation, and (b) microscopic traffic simulation, in Chapter 8. To mitigate the negative impact of disruptions, transportation operators can implement disruption management actions, such as informing passengers about the disruption, assigning more capacity/frequency to the running services, temporarily altering the functionality of the lanes in roads, etc. The benefits of providing updated information to mitigate the downside of the disruption, are large and include all the modes which can be used as an alternative. The issue time of information is the crucial aspect: if passengers become aware of the disruption at its Start time, instead of when they want to start their trip, the delay that passengers experience decreases considerably. Public transport is especially benefitting from sharing updated and relevant information for passengers to adjust their plans. For a typical disruption, providing information to passengers at the start time of the disruption can reduce the delay as much as increasing the capacity/frequency of some public transport line, which indeed requires enormous investment. Moreover, increasing the capacity/frequency of lines is most effective only when targeting the specific disruption. An overall increase in capacity of the public transport network leads to more passengers performing more transport stages in public transport, while fewer passengers are willing to use car-mode. Such generalized improvement might anyway have little impact to the specific disruption, unless the public transport line is identified, which is the most critical for the passengers directly affected, and then its capacity increased. This results in significantly less delay for the passengers directly affected by the disruption. Even for a road disruption scenario, implementing multi-modal management actions and increasing the capacity of public transport vehicles during in the disrupted period, the amount of delay that passengers experience decreases significantly, and even some passengers experience earlier arrivals. Transport authorities can make a more efficient decision in managing an urban disruption by means of multimodal traffic management, when the travel behavior of affected passengers is modelled; information can be collected, shared, and used for updated routing information; and operation of the public transport lines can be adjusted.

In conclusion, all our case studies investigate the potential gains of multi-modal management solutions in cases of network disruptions, and exemplary actions and information, and ideal system optimum solutions. In those approaches, we assume the realism of current transport models plus available data, which requires well-established standardizations, communication protocols, and authorities initiatives. In reality, operators currently base their decisions on experience and intuition, and most often are able to manage complexity only for a single mode, or even a selection of possibilities within a single mode. An implementation of multimodal traffic management would require as a prerequisite a more systematic and generic approach, also based on technological advancements now available, and information sharing and exchange platforms, for which technical specifications exist or are being defined. A final aspect would require changes and support within organizations, and seek for consensus from different jurisdictional parties.

2. Introduction

Future developments of mobility go strongly through complementarity and blending of modes. From this point of view, the potential benefits (i.e., societal, monetary) of mobility management beyond modes is very interesting to study. Integrated multimodal traffic management refers to the coordination of individual network operations to create an interconnected mobility management system. In many networks across the world, there has been a considerable investment in communication and sensing technologies along major corridors. An integrated multimodal traffic management system aims at exploiting the full potential of deployed intelligent transport technologies to improve not only the operation and performance of the network but also the demand traveling in the network, influence the mode choice, travel time, delay, fuel consumption, and emissions. Moreover, it should increase the reliability and predictability of travel in the network. Commuters consider and plan their mobility comprehensively; they have access to multimodal information and routing (i.e., apps); the same should hold in the infrastructure supply side (i.e., traffic network operators). Future mobility management systems should consider inter-layer communication and their complementarity and collaboration. Currently, we are limited to a lack of communication and/or cooperation between inter-modal infrastructures. Each operator makes decisions independently, and thus, may negatively affect users' mobility. For instance, railway and road traffic optimize their performance separately, but an integrated framework could be beneficial.

Essentially, modes are complementary, in terms of speed, accessibility, and capacity: while trains can achieve a high capacity for a restricted set of nodes (stations), cars can connect almost any two points; furthermore, in urban areas, active modes such as walking or cycling enable accessing (almost) all places. Multimodal traffic management in this regard can be defined as enabling the control of different modes, considering all transport infrastructure in a network (i.e., road, rail,…), in an integrated system to reach an optimum level of service according to the demand by different control strategies. Especially the multimodal management can response to different events, also known as incidents in the network, with collaborative solutions between different modes. The success of a multimodal traffic management system depends on careful planning on the one hand, and on the other hand, on an integrated system-level perspective among the network operators, which calls for advanced transportation analysis tools to estimate and predict network performance under different strategies and analyze the network for different tactical purposes.

Future traffic control beyond modes aims to study the benefits of a nationwide integrated multimodal traffic management system. In this respect, the current report, as the final report provides detailed insight about the whole project and consists of the following chapters: In chapter 3, we define our objective and the proposed research questions. Further on in chapter 4, we gain an insight into the state of the art of multimodal management systems by reviewing the most recent related literature. In chapter 5, we focus on the state of practice based on the interviews with transport experts from different countries. In the next chapters, we study the benefit of multimodal management in three different case studies. In chapter 6, the focus is on freight transport, where qualitative research is done in case of a disruption in the freight network and shows how different multimodal management strategies can be beneficial. In chapter 7, the case studies focus on major interurban bottlenecks. Geneva-Lausanne, Zurich-Bern, and Gotthard tunnel are the studied bottlenecks, methodology provided in this chapter focuses on Wardrop's principles of user equilibrium and system optimum, and the results show in monetary terms how different approaches can be beneficial. In chapter 8, an urban case study is considered, the city of Zurich, as the largest city in Switzerland, is studied under a disruption. Based on two different simulation approaches, different multimodal management strategies are implemented and studied. Finally, in chapter 9, the general conclusions achieved in this project are provided.

3. Research questions and objectives

The overall multi-modal system architecture is complex and interconnecting multiple stakeholders and decision making processes. Its design is a challenge that directly influences operations and mobility services, in both planning, construction, and management of operations. We target more this latter case, for which very limited understanding and realistic assessment of control techniques of a fully developed and interconnected multimodal market exist. We refer to a multi-layer multi-modal hierarchical traffic control scheme, with the flow of information across the layers (vertical system design). Potential collaboration between the operators/managers/stakeholders of different modes (railway and road) can lead to concrete benefits for the overall mobility market.

The research questions tackled by this work pertain to the area of controllability of networks, under multiple modes, and in particular, establishing upper/lower bounds of the potential benefits of multi-modal mobility control. In particular, the questions we aim to answer are the following:

- What systems and technologies exist that can model multimodal traffic control?
- Which approaches have been designed in academia that can tackle control in a multi-modal environment?
- Which technologies and potential futures can be determined in a medium to long time horizon?
- Which possible test cases can be defined that are able to characterize possible different futures?
- What benefits can be defined and quantified that exist in such test cases?

4. State of the art

In this chapter, we review the most recent scientific and academic research performed under the topic of multimodal transportation systems in both passenger and freight transportation. The chapter is organized as follows. In the first section, we focus on passenger traffic and define the multimodal traveling for passenger traffic; next, we review the academic articles studying this subject.

In the second section, our focus is on multimodal freight transport systems. Similarly to the previous section, we begin with a definition of the concept, and we continue with reviewing the state of the art in the academic literature.

4.1. *Passenger traffic*

4.1.1. Definitions of a multimodal trip in passenger traffic

To have a better understanding of the topic, we shortly define the multimodal trip. In this document, we define a multimodal trip as a combination of two or more different forms of transport within a single trip from an origin to a destination. This trip consists of different vehicles, for instance, car, bicycle, tram, bus or train, or different services such as mobility-on-demand services, car sharing, taxis, and other express services. We use the term mode to address the form of the transportation unit in a functional or vehicular sense. Therefore, a multimodal trip always consists of two or more legs with different modes, between which a transfer by foot is necessary. Typical examples of multimodal trips are chains such as walk-bus-train-walk, or bicycle-train-walk, car-train-walk or walk-tram-bus-walk. Moreover, the trip chain walk-city bus-regional bus-walk is also considered as a multimodal trip. We should notice that single-mode trips such as walk-bus-walk or walk-car-walk or walk-tram-walk are defined as unimodal since the transfer process to another mode of vehicular transportation is absent. Thus, a multimodal transportation system is a system that offers different transportation modes connected by interfaces (e.g., stations) that facilitate transfers between the various mobility services defined as modes (in a functional or vehicular sense). (Nes and H. L. Bovy, 2004)

4.1.2. Literature review

To have a structured review of the literature on this subject, we categorize the most recent articles based on the decision horizon of the management problems. Here we start with strategic management articles, which consider the long-term decisions, usually in a time frame of five to ten years. Strategic management addresses solutions by large investments on the infrastructure of the transport network and discusses the maximization of the utility of multimodal transportation networks. Second, we discuss the literature considering the tactical management issues and the proposed solutions. At the tactical level, management decisions in a shorter time scope in comparison to the strategic level are addressed. The tactical decisions are usually made by one or two years time scope. And finally, the operational management level solutions will be discussed, In which we discuss short-term solutions, i.e., daily, hourly. It is worth noting that the different levels of management are highly dependent on the network size and the hierarchy of decision making in a network.

4.1.2.1. Strategic management

A review of the strategic management literature shows that the main contribution is to look at the optimization of the network structure and consider a redesign of urban traffic networks. For instance, in (Nes and H. L. Bovy, 2004) the researchers investigate how changing the strategic characteristics of the urban transit network, such as line density and stop density, and on top of that how adding more frequency or adopting the frequencies between different modes in the network can contribute to the higher rate of multimodal journeys. Their result shows that multimodal access does not improve with alternative network structures. Especially in the case of hierarchical networks, it is highly dependent on the adaptation of the network structure with the hierarchy in the demand densities. Another research (Zheng, Rérat and Geroliminis, 2016) focuses on the distribution of urban road space for a multimodal network and answers the question of how space distribution for modes and interactions among modes affect network traffic performance; the multimodal fundamental diagram is used as a performance indicator of traffic dynamics. They focus on optimizing the network with the objective of minimizing the total passenger hours traveled (PHT), i.e. to serve the total demand optimally by redistributing road space among modes. Moreover, they have investigated different pricing strategies to provide a higher demand shift to more efficient modes. They have mainly concluded that by an application to a bi-modal two-region city (i) the proposed model captures the operational characteristics of each mode, and (ii) optimal dynamic space allocation strategies can be developed. In practice, the approach can serve as a dynamic model to assess space distribution strategies for policymakers with different goals of mobility.

Another group of researchers (Udomwannakh*et et al.*, 2018) have focused on analyzing and reviewing all the existing optimization models for managing multimodal transport networks in a more efficient way. The Discussion in this work focuses on the fact that in most of the models, the cost functions are the basis of all the multimodal routing alternatives in a network, and different factors for each route, transport mode, and risk factors are also considered in the cost functions. It is worth mentioning that the cost function in these studies is the objective function of the optimization model.

The fact that one needs to study the whole network for application of different management strategies for multimodal transport management leads to a lot of computational time and effort. Many researchers have considered analyzing only a corridor in the network for investigating different multimodal management strategies.

For example, the work in (Dawson *et al.*, 2014) investigates a futuristic approach for new active traffic management consisting of different modes for a corridor in Illinois. In this study, the authors focus on the potential support of connected vehicles for smartly controlling the corridor traffic. They show how congestion and delays are affected by the alteration of different penetration rates of connected vehicles in the corridor. Besides, they illustrate that improved roadway and a smart management system accommodate as many as 30,000 more vehicles per day and could save drivers 440 million dollars annually due to reduced congestion and delays.

Similarly, in the framework of Integrated Corridors Management (ICM) (Kurzhanskiy and Varaiya, 2015), the researchers in California are developing a multimodal traffic management system for a corridor near Los Angeles by applying different management strategies. ICM aims at deploying the strategies listed in Table 1 ICM Strategies to reduce congestion and improve mobility along the corridor. It is worth mentioning that the decision towards having integrated corridor management is a strategic management approach, which means it needs a longterm investment; however, the strategies within this structure can be categorized in tactical and operational management levels.

Furthermore, on top of all these technological solutions, they are building a community of stakeholders who can address corridor needs in a collaborative way in order to have a cohesive management system. The stakeholders are mainly Freeway management (Caltrans), city traffic management, and all the agencies involved in rail lines, bus services, and parking facilities (Berkeley Univesity of California, 2014).

Table 1 ICM Strategies (Berkeley Univesity of California, 2014)

Strategy	Benefits
Coordination of freeway ramp meters and arterial signal systems	Leverage the capacity of both freeway and arterials to help traffic around congestion or incidents
Arterial signal synchronization	Optimize traffic flow along arterial streets
Dynamic route guidance and flow rerouting	Offer alternative routes around congested areas
Transit signal priority	Accelerate transit service by giving buses priority on arterials and on-ramps
Real-time travel demand monitoring	Enable transportation managers to see the actual extent and locations of traffic demand on the corridor
Smart parking	Locate available parking spaces at transit stations and private parking garages
Traveler communication	Provide information on traffic conditions, transit services, parking, alternate route/trip/mode options
Mode and time shift incentivisation	Motivate travelers to change how (car, bus, bicycle, etc.) and when they travel

Another approach to discussing the benefits of multimodal management systems is to investigate it in an extreme situation (floods, hurricanes, snow, etc.) and see how the coordination of different transport operators can contribute to better management of the whole network. Researchers in the UK have applied this methodology to analyze the system's criticality of Britain's multi-modal transport network (*Pant et al.*, 2015). They suggest a multi-dimensional metric set for assessing the relative criticality of different nodes and edges in the network based on (i) traffic flows, (ii) traffic disruptions, (iii) rerouting capabilities, and (iv) multi-modal impacts. Initial analysis for Great Britain's multi-modal transport systems demonstrates how criticality assessment can identify single key points of the multi-modal transport networks, which are potentially the most critical to maintaining a good level of national mobility. The paper concludes by considering the implications of this analysis for risk management and the potential for developing and transferring this methodology to other spatial or economic contexts.

In the related academic literature, there are review papers concentrating on the future of multimodal transport network management. For instance, researchers from Austria (Emberger, 2017) have conducted a review of the previous and current approaches towards an integrated multi-modal, demand-management-driven transport strategy, including some environmental aspects. Further, an outlook is provided regarding in which direction the national transport planning strategies should be developed to be able to tackle future challenges such as economic, social, and ecologic sustainability.

Similarly, the researchers from Russia (Nesterov*a et al.*, 2016) give a brief overview of works on the development of transport infrastructure for multimodal transportation and integration of the Russian transport system into the international transport corridors. The technology of the control strategy, which changes the shape and capacity of Multi-modal Transport Network (MTN), is considered as part of the methodology for designing and development of MTN. This technology allows us to carry out strategic and operational management of the strategy implementation based on the use of the balanced scorecard. In the framework of this research project, another group of researchers from Russia (Malygin, Komashinsky, and Tsyganov, 2017) has focused on the creation of multimodal intelligent transportation systems (MITS) for the coordinated use of various types of transport-road, rail, sea, and aviation. The newest generation of MITS architecture is proposed based on the information and network technologies combined with artificial intelligence.

4.1.2.2. Tactical management

tactical management deals with optimally utilizing the given infrastructure by choosing services and associated transportation modes and managing their itineraries and frequency. The tactical decisions are usually made by one or two years time scope.

The literature reviewed on the tactical management level focuses on modeling and optimizing tactical solutions and prove the showcase in a simulation environment. For instance, the work in (Meng *et al.*, 2012) deals with the modeling of the traffic assignment problem in a multimodal network and applies the solution in a mesoscopic simulation tool. The mode choice is considered simultaneously with the route choice based on the improved C-Logit model. The traffic assignment procedure is implemented by a time-dependent shortest path (TDSP) algorithm in which travelers choose their modes and routes based on a range of choice criteria. The model is particularly suited for appraising a variety of transportation management measures, especially for the application of Intelligent Transport Systems (ITS). Five example cases, including OD demand level, bus frequency, parking fee, information supply, and car ownership rate, are designed to test the proposed approach in a simulation model through a medium-scale case study in a district in Beijing, China.

Another group of researchers (Zhu and Zhang, 2013) have developed a path optimization algorithm for a multimodal combined transport network based on a linear programming method, in which they claim to achieve improvement in the transportation service level, strengthen competition ability, and improve comprehensive social benefit. This article provides an example from Liuzhou to Guangzhou with further details.

Considering the environmental benefits of a multimodal management system, there are many researchers working on the optimization of traffic with the objective of minimizing co2 emissions. In particular, the work presented in (Meng, Chunfu, and Xin, 2012) proposes a traffic structure optimization model with low carbon emission constraints under the environmental policy of developing public transportation. Furthermore, by incorporating the limitation of private cars through management measures, they have developed the user equilibrium assignment model and the multimodal user equilibrium assignment model and then solve the models by using a genetic algorithm. Research of traffic assignment models with low carbon emissions constraints can provide theoretical support for reducing greenhouse gas emissions in traffic systems, easing traffic congestion, and lessening traffic pollution effectively.

Another approach at a tactical level for the management of a multimodal transport system is to deploy pricing schemes. In work presented in (Zheng, Rérat and Geroliminis, 2016) the authors investigate an area-based pricing scheme for congested multimodal urban networks with the consideration of user heterogeneity. The pricing scheme is time-dependent, and the tolls are iteratively adjusted through a proportional-integral type feedback controller, based on the level of vehicular traffic congestion and traveler's behavioral adaptation to the cost of pricing. Within this dynamic congestion pricing scheme, they differentiate two groups of users with respect to their value-of-time (related to income levels). They integrate incentives, such as improving public transport services in tactical decisions or return part of the toll to some users, to motivate mode shift and increase the efficiency of pricing and to attain equitable savings for all users. The results are also applied in a medium-size network using an agent-based simulator.

Other approaches that consider the economic benefits of a multimodal real-time traffic management system are introduced in (Bond and Kanaan, 2015). The study focuses on an innovative business model called MassDOT that provides real-time travel time information to the public using dedicated highway signs covering over 700 miles of state highway and encompassing the entire metropolitan area of Boston. This investment in infrastructure means that MassDOT owns and archives these data, maintains and controls their quality, and freely provides them to third party developers in real-time. The development and operation of this Real-Time Traffic Management (RTTM) system has resulted in a shift towards new measures of system performance and has triggered the production of new strategies for multi-modal transportation system management, all in a manner directly supportive of emerging trends: open public data, big data and the development of smart cities.

Another approach benefiting from transferring real-time information between local authorities and transport systems users are introduced in work by Sierpiński and Staniek, 2017. In this approach, individual user route planning should consent to the general traffic flow management system. They introduce a web-based travel planner called Green Travelling (GT) planning with four optimization criteria: quicker, shorter, cheaper, and greener using one of the eleven travel modes, including multimodal combinations. The heuristic approach, which is implemented in the GT planner, makes it possible to support urban traffic management by adding specified factors as attributes of links in the graph of a transport network. This solution can also be used to optimize transport systems and public transport planning based on actual travel needs collected as Big Data that the GT Planner is using as a basis.

In the work of (Dotoli, Epicoco and Falagario, 2017) a technique for efficient multimodal transport planning is provided, which considers conflicting objectives of stakeholders under uncertainty. In this article, a fuzzy cross-efficiency Data Envelopment Analysis (DEA) technique is introduced, and with the help of case studies, the authors demonstrate its effectiveness in determining the most efficient transport planning. Moreover, they identify the optimal trip distance for which multimodal traveling is more efficient than all-road transport.

Another group of researchers developed a network equilibrium model based on a new park and ride system *(Liu et al.*, 2018). The Remote Park and Ride (RPR) suggests a feeder express system from the parking to the closest train station. This system is applied when the cost of construction and operation of parking near a train station is very high. To quantitatively evaluate the impacts of Remote Park and Ride on the network flows, a combined modal split and traffic assignment model (CMSTA) is developed, where a cross-nested logit (CNL) model is adopted to cope with the mode similarity. Numerical examples demonstrate that the RPR services can significantly influence network users' travel decisions, promote the usage of public transportation, and mitigate traffic congestion in the congested areas of metropolitan cities.

4.1.2.3. Operational management

On the operational management level, we look for the best choice of services and associated transportation modes, best itineraries, and allocation of resources to the demand. However, we need to respond to the real-time requirements of all multimodal operators. Operational management deals with dynamicity and stochasticity that are not explicitly addressed at strategic and tactical levels. These characteristics make operational planning problems remarkably complex. Hence, the design of accurate and fast solutions is essential. In this part, we review the literature addressing operational management problems.

One of the simplest operational management policies that make multimodality more attractive and effective depends largely on the ability to integrate real-time information from diverse sources, as well as the suitability of this information for each user. In work presented in (Moreno *et al.*, 2015) a new approach for the management and exchange of information related to multimodal transportation is provided. In this approach, particular emphasis is on the design of the data model and the enablement of services for information retrieval, thereby obtaining a semantic model for the representation of transport information. With this method, the adequacy of the information generated in regard to the specific user's context is also addressed. In another work presented in (Cascajo *et al.*, 2019) the results show that real-time information can significantly help positively perceive transfers and induce more multimodal trips. In addition, the authors suggest that the operators can invest in designing more attractive transfer areas to ensure continuity between transport modes and between information and communication systems to shift the demand towards more multimodal journeys.

Many sophisticated information systems focusing on management and supervision problems in the transportation area exist in the contemporary world. Road traffic management systems, as well as many more, are here to face everyday challenges. However, in spite of considerable progress in this area, systems that combine multiple transport modes for management purposes are very few. The work in (Zaiat, Rossetti and Coelho, 2014) proposes a solution for the monitoring of the operational state of multimodal transportation systems in a single dashboard. The problem they have studied includes such major components such as (i) input information and its sources, (ii) model (metrics, calculation algorithms), and (iii) visualization metaphors. The proposed solution is a dashboard that provides a comprehensive view of the operational state, or Level of Service (LOS), of transportation systems of different modes. Such a system is expected to become an essential tool for transport system monitoring and management, supplying the necessary information in the long term for strategic and for short term emergency planning to the authorities and other decision-makers in the sector.

In another work presented in (Denia*ud et al.*, 2012) the authors focus on interoperability for a coordinated management system as a major aspect that has to be addressed to make sure operators can interact. It is worth to mention that most of the operational management problems in a general concept are studied in (Hammadi and Ksouri, 2013). This book consists of the state-of-the-art on innovative transport systems as well as the possibility of coordinating with the current public transport system, and the authors clearly illustrate this coordination within the framework of an intelligent transport system.

Similarly, the work presented in (Boschian *et al.*, 2011) specifies an integrated system (IS) devoted to the management of Multimodal Transportation Networks (MTNs) to take both tactical decisions, i.e., in an offline mode, and operational decisions, i.e., in real-time. Both IS structures rely on a closed-loop approach that is able to tune the decisions with the current system conditions. In either case, the core of the presented IS consists of a reference model and a simulation module. In particular, the reference model uses information from the real system, obtained by modern Information and Communication Technologies (ICTs), and the simulation module evaluates the impact of the management decisions. In order to obtain a systematic model suitable to describe a generic ITN, the paper proposes a metamodeling approach that describes in a thorough and detailed way the structure and behavior of ITNs. Moreover, the metamodeling procedure is a top-down technique based on the well-known Unified Modeling Language (UML), a graphic and textual formalism able to describe systems from structural and behavioral viewpoints.

Another multimodal traffic management system called VAMOS is presented in (Kretschmer and Krimmling, 2012). Nowadays, this complex system contains different task-specific control and processing subsystems. Key features of the VAMOS system are improved data acquisition, simulation-based traffic modeling, and the automated strategic overall coordination of the subsystems. The VAMOS system also supports multimodal traffic management decisions and traffic control measures taking into account the traffic conditions of both public transport as well as individual traffic.

In a similar approach, the work in (Sumalee, Uchida and Lam, 2011) proposes a multi-modal transport network assignment model considering uncertainties in both the demand and supply sides of the network. These uncertainties are due to adverse weather conditions with different degrees of impact on different modes. The paper provides the derivations of mean and variance-covariance of the stochastic passenger flows, and dis-utility terms are involved in the route/mode choice model under the common-line framework. The risk-averse travelers are assumed to consider both the mean and variance of the random perceived travel time on each multi-modal path in their path choice decisions. The model also considers travelers' perception errors by using a probit stochastic user equilibrium framework, which is formulated as a fixed point problem; a heuristic solution algorithm is proposed to solve the fixed point problem. Numerical examples are presented to illustrate the applications of the proposed model.

On a smaller scale, some approaches, such as the one provided in (Bouattoura, Plesko, and Miller, 2014) focus on multimodal integrated corridor management (ICM) systems. The purpose of the Dallas ICM System is to implement a multi-modal operations decision support tool enabled by real-time data and pertaining to the operation of freeways, arterials, and public transit. One of the primary goals of this deployment was to provide wide-ranging, accurate, and complete data sets, including traffic, transit, parking management, and weather information to operators and the decision support systems. This project included data sources from multiple public agencies and third-party providers, which provided some unique challenges in data management and integration. This paper explores the need for fusing and integrating data by developing common structures, a data dictionary, as well as fusion and validation rules for managing both the static and real-time data content.

In a similar approach, the work presented in (Zhou, Mahmassani and Zhang, 2008) focuses on the development and analysis of demand management strategies for integrated multimodal urban corridor management and proposes a new generation of demand modeling and network analysis tools. In this article, the authors describe the development of a dynamic trip micro-assignment and (meso) simulation system that incorporates individual trip maker choices of travel mode, departure time, and route in multimodal urban transportation networks (with different travel modes such as drive alone, shared ride, bus rapid transit, and metro rail). These travel choice dimensions are integrated into a stochastic utility maximization framework that considers multiple user decision criteria such as travel time, travel cost, schedule delay, as well as travel time reliability. A variational inequality model is first proposed to describe the general stochastic dynamic traffic user equilibrium problem. For a typical case that assumes the logit-based alternative choice model, this paper develops an equivalent gap function-based optimization formulation and a heuristic iterative solution procedure. Based on a multi-dimensional network representation, and efficient time-dependent least-cost path algorithm is embedded to generate an intermodal route choice set that recognizes time-dependent mode transfer costs and feasible mode transfer sequences. A two-stage estimation procedure that can systematically utilize historical static demand information, time-dependent link counts, as well as empirically calibrated stochastic departure time choice models is proposed to infer commuters' preferred arrival time distribution, which is important in modeling departure time choice dynamics. A case study based on a large-scale multimodal transportation network adapted from the Baltimore-Washington corridor is presented to illustrate the capabilities of the methodology and provide insights about the potential benefit of integrated multimodal corridor management.

In a new approach proposed in (Sousa and Mendes-Moreira, 2015) the researchers try to integrate urban logistics in a multimodal mobility system. They envisage the dissemination of sufficient information for the correct decision of every citizen between several mobility options in real-time (especially with the support of mobile technology); they propose that new tools are needed to help the design of innovative business models and policies, and the change of habits and behaviors in the long term. They visualize urban logistics as a multi-stakeholder, multi-criteria, and multimodal dynamic mobility system.

In the last few decades, the rapid evolution of information and communication technologies (ICT) has promoted new methods for daily mobility planning. In the meanwhile, beyond the performance and sustainability enhancement of transportation systems, the promotion of modal shift from private vehicles towards more sustainable modes still remains a major target of transportation systems management, especially in urban areas. In this framework, car sharing and ride sharing appear to be two of the most promising approaches for reducing the number of circulating cars; however, their performance is usually optimized separately. The aim of the work presented in (Cangialosi, Di Febbraro and Sacco, 2016) is to introduce a generalized ride-sharing system consisting of an integrated multimodal transport system that virtualizes already available different modes allowing users to schedule multimodal trips in a single task.

In networks that mobility is mainly based on private cars, it is worth to focus on shifting the demand towards more sustainable modes. In the approach presented in (Zhou, 2012) the researchers investigate the factors that can increase the odds of alternative modes, and based on that, they propose a comprehensive travel demand management program to better promote an alternative mode of transport among commuters. In another study (Harris, 2011) the focus is on the business drivers behind increased cooperation and the development of multimodal transport. The authors have set out the policy objectives and describe the latest operational initiatives across Europe and beyond, considering the operational framework requirements for accelerated deployment and cooperation.

If we consider that the smallest elements in multimodal network management are the intersections, it is worth mentioning the recent literature about the management of multimodal intersections. Considering the recent technologies and the emerging vehicle to infrastructure (V2I) communication, the researchers in (Muralidharan *et al.*, 2016) propose a high-resolution (HR) data system for an intersection that collects the location (lane), speed, and turn the movement of every vehicle as it enters an intersection, together with the associated signal phase. It also provides video monitoring, measures pedestrian and bicycle movements, and has V2I communication capability. The data are available in real-time and archived for later use. Real-time data are used to implement multimodal signal control, e.g. giving priority to public transport. Archived data are used to evaluate intersection, corridor, and network performance for higher-level policies.

Similarly, the research proposed in (He, Head and Ding, 2014) addresses the conflicting issues between actuated-coordination and multi-modal priority control. Enabled by V2I communication in Connected Vehicle Systems, priority eligible vehicles, such as emergency vehicles, transit buses, commercial trucks, and pedestrians, are able to send request messages for priority to a traffic signal controller when approaching a signalized intersection. It is likely that multiple vehicles and pedestrians will send requests such that there may be multiple active requests at the same time. A request-based mixed-integer linear program (MILP) is formulated that explicitly accommodates multiple priority requests from different modes of vehicles and pedestrians, while simultaneously considering coordination and vehicle actuation. A penalty is added to the objective function when the signal coordination is not fulfilled. This "soft" signal coordination allows the signal plan to adjust itself to serve multiple priority requests that may be from different modes. The priority-optimal signal timing is responsive to real-time actualizations of non-priority demand by allowing phases to extend and gap out using traditional vehicle actuation logic. The proposed control method is compared with state-of-practice transit signal priority (TSP), both under the optimized signal timing plans using microscopic traffic simulation. The simulation experiments show that the proposed control model is able to reduce average bus delay, average pedestrian delay, and average car passenger delay, especially for highly congested conditions with a high frequency of transit vehicle priority requests.

4.2. *Freight transportation*

4.2.1. Definitions of multimodal freight transportation systems

In the research area of freight transportation, over the years, different terminologies are used in literature and also in the industry: multimodal, intermodal, co-modal, and the most recent one synchromodal. We briefly give a definition for the multimodal, and we refer an interested reader to find more explanations in (Steadiesei*fi et al.*, 2014). The term multimodal is explained in the context of passenger traffic in section 4.1. In freight transportation, however, the term intermodal is used more frequently, especially in the context of containerization of freight. Many researchers propose the term multimodal as a better substitute because it encompasses all the modes and information for a shipment (Dewitt, Clinger and Group). For the purpose of this document, multimodal freight transportation is defined as the use of two or more modes to move a shipment from origin to destination. The concept of multimodality in freight transport is centuries old (Muller and Mahoney, 1989). However, the integrated management of freight transport and passenger traffic in different time scopes is a relatively new topic. In the following section, we review the literature related to this topic.

4.2.2. Literature review

In order to have a structured review of articles, we follow the same structure as used in the previous section; we divide the research into three time-related subsections: strategic management, tactical and operational management approaches.

4.2.2.1. Strategic management

Strategic management approaches focus on investment decisions on the present infrastructure (networks). Most of the approaches are based on consolidation, which means instead of delivering each cargo in a separate shipment, low volume cargo will be bundled in a larger unit. These services have lower prices and can be transported by higher frequency and high-capacity multimodal services.

In the literature, various groups of researchers have focused on models for structuring the network, and in particular, how changes in the network topology can contribute towards an optimal system. For instance, in (Meyer, Ernst and Krishnamoorthy, 2009) the hub location is studied, and the main objective of this study is to minimize the total cost of transportation. On the contrary, the objective of serving more nodes by adding a new hub is studied by many researchers as well (Alumur and Kara, 2008).

In addition to the topology discussions, the allocation of the spoke nodes to hubs plays a major role in hub location problems. There are different allocation policies of spoke nodes to the located hubs: single, multi-, k-, and hierarchical allocation. In single allocation problems, the flow of spoke nodes can be assigned to only one hub, while in multi-allocation problems, the flow of spoke nodes is allowed to be assigned to more than one hub nodes. In k-allocation problems, spoke nodes are allocated to at most k hubs. Finally, in hierarchical allocation, the interhub network, connecting only pairs of hubs, has two levels. Spoke nodes are allocated to the first level hubs, and these hubs are then allocated to second level larger hubs. These problems are studied by (Alumur and Kara, 2008), (Yaman, 2011), (Wagner, 2008), (Alumur, Kara and Karasan, 2012), (Alumur, Yaman and Kara, 2012). The described models in this literature are solved using a variety of solution methodologies. Decomposition and relaxation approaches have been widely used and demonstrate promising results. To evaluate the performance of the solution algorithms designed in the literature, mostly the standard Australian Post (AP) data sets are used. However, in practice, in a multimodal package delivery system, for example, the number of served nodes and hubs are much more than the standard AP instances. Therefore, designing more robust and efficient solution algorithms are needed (Steadiesei*fi et al.*, 2014).

In addition to all these issues, the research in the field of intelligent transport systems seeks ways to organize transports and their communications more efficient and sustainable. An emerging idea in this context is the more efficient configuration and coordination of multimodal transports. In projects studied in (Föhring and Zelewski, 2015) the authors have prototype an agent-based online rail freight exchange, which can be very useful for multimodal transports.

4.2.2.2. Tactical management

Tactical management deals with optimally utilizing the given infrastructure by choosing services and associated transportation modes, allocating their capacities to orders, and planning their itineraries and frequencies. Deciding whether to send cargo direct or through a consolidation system involves a trade-off influenced by system costs, operation times, network structure, and customer requirements.

The literature covering the tactical aspect of multimodal freight management is studying mainly two groups of models. The first group is named network flow management; it relates to the flow management and addresses the movement of orders in the network. The second group, called service network management, involves the service decisions, including all choices on the transportation services and the modes to move the commodities. Service network management problems are furthermore partitioned into static and dynamic. While in both groups, one determines the frequency of the service, the capacity allocation, the equipment planning, and the routing and flow of commodities, in the former it is assumed that all problem aspects are static over the time horizon, and in the latter, at least one feature (e.g. demand) varies over time. Solving network flow management and service network management problems is difficult due to their large set of variables. The solution methodologies used, shows that due to complexity of these problems, heuristic and metaheuristic solution methods are the prime choice. Among them, Tabu Search (TS) seems to be a popular metaheuristic algorithm: (B*ai et al.*, 2012), (Pedersen, Crainic and Madsen, 2009), (Crainic, Li and Toulouse, 2006), (Duc Minh, Crainic and Toulouse, 2013), (Verma, Verter and Zufferey, 2012).

Moreover, one of the goals of a reliable transportation network is a network that can recover from any disruption by preventing, absorbing, or mitigating its effects. Unexpected incidents like traffic jams, accidents, storms, hurricanes, etc., can cause disruption on a link or in a terminal. In multimodal transportation planning, providing reliable, but at the same time, cost-efficient services is a hard task. If the designed network is flexible enough, disruption might be absorbed by the normal plans, but if this flexibility has not been deliberated, recovery plans are required to revive the system and keep the promised service levels. In multimodal transportation, such recovery plans usually involve service and modal change. Disruptions can be divided into three levels: link, node, and network. The proper strategy needs to be executed to face each type of disruption. Steps that are undertaken in transportation planning include risk mitigation (estimation of probable economic effect), preparedness (estimation of effect on deviation level of network performance), as well as stabilization and recovery (proposing effective, efficient, and flexible recovery strategies). Some strategies used in the literature are alternative route, mode, depot, and departure schedule determination. Some literature also utilizes the concept of buffer capacity and inventory, as well as location and allocation determination strategies. Coordination strategies between the modes and different operators need to be developed and studied further on this topic of disruption in the tactical management level (Agamez-Arias and Moyano-Fuentes, 2017), (Rosyida, Santosa and Pujawan, 2018).

From a futuristic point of view and motivated by various wireless technologies including radio frequency identification (RFID), Bluetooth, cellular networks, and dedicated short-range communications (DSRC), the performance of a futuristic, intelligent wireless transport system for multimodal logistics applications are studied in (Coronado Mondrag*on et al.*, 2012). This study considers mainly two issues: First, in wireless networks, reliable data transfer transport layer services are affected where there is an apparent increase in mobility. In this case, the access point coverage areas are reduced to counter the effects of the path loss in the physical layer. Second, a service provisioning protocol intended for the vehicle to infrastructure (V2I) data transfer is proposed to illustrate the importance of cumulative costs in wireless networks used for logistics applications. The analysis covers the average response time for requesting on-demand services within the considered portside network. The results of the analysis confirm the suitability of the used approach to provide a logistics network capable of meeting the requirements demanded in multimodal logistics.

In conclusion, multimodal transportation service network management is, in practice, a complex problem with thousands of variables and constraints. With a better study of the problem structure and design of smarter solution algorithms, it should be possible to derive more accurate solutions in less computational time.

4.2.2.3. Operational management

On the operational management level, we still look for the best choice of services and associated transportation modes, as well as the best itineraries and allocation of resources to the demand. However, we need to answer the real-time requirements of all multimodal operators, carriers, and shippers. Operational management deals with dynamicity and stochasticity that are not explicitly addressed at strategic and tactical levels. These characteristics make operational management problems remarkably complex. Hence, designing accurate and fast solution algorithms is then essential.

These problems relate to real-time planning for orders, and reaction and adjustment to any kind of disturbance (e.g., accidents, weather changes, or equipment breakdowns). Most of these system elements vary with time and show a non-deterministic behavior. Current decisions depend on both the present information and an estimation of the future, and the objective is not only to minimize the costs but also to maximize the reliability of the system to serve the demand in a satisfactory way.

In order to discuss the different problems, we group the operational management literature into two main topics: resource management and itinerary replanning. Resource Management problems deal with the distribution of all resources e.g., trains, trucks, and containers throughout the network: positioning, repositioning, storing, and allocating them to customer orders. In the literature, for instance (Erera, Morales and Savelsbergh, 2005) compare a base repositioning strategy (a current state-of-the-practice) with three alternative strategies that integrate the repositioning and routing of the containers simultaneously. These three strategies are weekly, bounded daily, and unbounded daily repositioning. They show that the proper timing of repositioning is more important than deciding on the number of containers to be repositioned, and unbounded daily repositioning is overall the best strategy.

Itinerary Replanning problems focus on real-time optimization of schedules, multimodal routes, and relevant response to operational disturbances. The itinerary replanning problems are concerned with optimally responding to real-time system evolution to maximize the service quality and, therefore, the marginal profit. Here, the notion of a planned solution does not make sense, and the whole operation should continuously react and adapt in real-time (Hammadi and Ksouri, 2013). The updating procedure, accuracy, and speed have a major influence on efficient performance. Moreover, a single model or a solution approach is no longer capable of handling these complex problems. As such, there is a need to employ combinations of approaches, not only from the Operation Research area but also from decision-making and computational sciences. There is no doubt that ICT, as well as tracking technologies such as RFID opened up many opportunities for carriers and shippers for better trade. The work in (Crainic, Gendreau and Potvin, 2009) gives an overview of different developments and current technological challenges in Intelligent Transportation Systems (ITS), both in hardware and software platforms. ITS delivers precise information in a matter of seconds, hence significantly reduces the uncertainty at the terminals and for the next carriers of the loads. Most of the developments in this regard have been hardware-driven, and more efforts are still needed to model and solve multimodal transportation planning problems under real-time information in an integrated chain (Crainic, Gendreau and Potvin, 2009).

Resource management and itinerary replanning problems are in practice intertwined and act as two components of a bigger operational management problem. There is wide literature covering similar problems with different solutions. A structured review of these articles and the applied solution methodologies are provided in (Steadieseifi *et al.*, 2014) and (Agamez-Arias and Moyano-Fuentes, 2017).

The role of information and communication technologies (ICTs) in freight transport as key enabler is well recognized. However, the uptake of recent ICT advances for multimodal freight transport provisions has been slow. In (Harris, Wang and Wang, 2015) the researchers aim to explore the potential reasons for such a slow adoption and assess how recent technological advances such as cloud computing and the Internet of Things might have changed the landscape and thus help to overcome these barriers. Resolutions were then explored by reviewing four key ICT development trends emerging recently and evaluating their potential impact in reducing such barriers for deployments. Their main contributions are two-fold: (i) advance current knowledge by presenting an up-to-date overview of existing and emerging ICT applications in the field of multimodal transport and barriers to e-enabled multimodal transport; and (ii) they also capture some of the best practices in industry and aim to provoke a debate among practitioners and academics via the analysis of how innovative use of recent technological developments could potentially lower the barriers to multimodal ICT adoption and lead to a more integrated freight transport network.

The only concept which provides a different view on the management of multimodal freight and passenger transport at the operational level is the work presented in (Engl*er et al.*, 2018). They have defined the trajectory of each commodity as core elements of the transportation process, which should be managed in time and space. The proposed trajectory-based concept is considered as a suitable approach performing the smart and adaptable planning, operation, and management of systems with dissimilar structures, a wide diversity of actors, and distributed responsibilities. It is therefore expected that it will be especially well-suited to facilitate multimodal transport management for future ITS. Based on the introduction of the “transport trajectory” formulation, they show that a trajectory-based status description is generally possible for all transport-relevant components and processes. The expected benefit of trajectory-based transport management is illustrated by means of selected transportation scenarios.

In general, there are very few works in the literature combining the management of multimodal freight transport and passenger transport at the operational level. A key prerequisite for the realization of this ambitious goal is the development of national and international co-modal transport systems that are based on the interoperability of different transport modes. Interoperability itself is also hard to implement without a proper arrangement of a legal framework, organizational measures, and, finally, interconnected transport infrastructures of different transport modes (common multimodal transport network). Currently, differences with regard to the used technical equipment and available infrastructural facilities, as well as administrative and public organizational structures in place, are the major obstacles to comprehensive multimodal transport management.

4.3. *Conclusions*

Considering the academic state of the art, most of the recent academic studies focus on determining the optimal solution to the balancing of the strength of different modes in their reaction to variable demand. The goal is to compute a system optimum, which minimizes externalities, or travel times, assuming specific controllability of the different modes. The focus of the academic approach is on relatively small problems, for instance, in terms of links, alternative routes, amount of passengers, or vehicles. Moreover, some practical aspect of organizational or infrastructure requirements are based on assumptions, and rarely discuss all the required steps for implementation, including costs. The behavioral response of travelers is often based on assumptions that might have a limited realism.

By reviewing the academic articles studying multimodal management and control, we can conclude that the fact that one needs to study the whole network for application of different management strategies for multimodal transport management leads to a lot of computational time and effort. Many researchers have considered analyzing only a corridor in the network for investigating different multimodal management strategies. Furthermore, most of the management strategies in different levels of strategical, tactical, and operational are studied separately. Therefore developing research topics to study an integrated system that considers all the infrastructure in a transport network and considering different management strategies at the same time will contribute to a better understanding of the benefits of a nationwide integrated multimodal traffic management system.

5. State of Practice

The approach to investigating the state of practice is based on interviews with academic and industrial experts currently working in the transportation industry in selected countries. The countries selection is based on the discussion with SBB colleagues and their interests. From all the interviews, we got answers from experts from the following countries: Austria, Hong Kong, Japan, Luxembourg, Netherlands, Sweden, and Switzerland. Unfortunately, we did not get any responses from colleagues in the United States; instead, we have included some relevant parts of the very recent report of Planning and Implementing Multimodal, Integrated Corridor Management. Furthermore, we have mentioned some similar projects in which the objectives are in line with the objectives of an integrated multimodal management system in other countries around the world.

5.1. *Interviews*

The interview questionnaire consist of the following questions:

Table 2 State of practice questionnaire

1. Is there an integrated control center between roads, rail currently available in your country? If not is there cooperation between the control centers for each mode?
2. In the short-term or long-term plan of traffic control center development, is it planned to have an integrated system between road and rail? (please explain if it is short term or long term)
3. In the city you are currently living, is there an integration for traffic control between public and personal transportation? If yes, please explain the relation.
4. What does the planned integrated traffic center offer in case of a disruption considering the multimodality in cities, interurban, or even freight transport?
5. If there are no future plans about the integration of traffic control between modes. What is your opinion about such a control system?
6. As a transport expert, how would you measure the benefit of an integrated traffic control center in an urban or interurban context?
7. If you are aware of projects regarding this topic in your country, please share with us some information/links.

The summary of answers are provided in Table 3 in the following pages.

Table 3 Answers of State of Practice questionnaire

Question Country	1. Is there an integrated control center between roads, rail currently available in your country? If not, is there cooperation between the control centers for each mode?
Austria	Only in terms of Cooperation
Hong Kong	Roads and rail transport systems are monitored by the central government (transport department) in Hong Kong. However, the rail system here is operated by MTR Corporation, and the transport department has no direct authority manipulating that.
Japan	With so many different rail operators as well as, for example, expressway companies and road authorities that is a difficult question. In general, I would say no, but coordination protocols are in place, in particular for earthquake handling.
Luxembourg	Very little cooperation. Roadway control is done by Ponts et Chaussees, City signal control by the municipalities (company HiTec as a subcontractor), Rail control by CFL, bus control by Verkehrsverbund. And they don't have a clear cooperation framework.
Netherlands	No, but there is a discussion between Rail and Road authorities about traffic control at intersections. Also, for intersections, bridge openings and road traffic are tuned. And public transport is tuned (e.g., bus and train schedules).
Sweden	No, not a "control" center in that sense. However, in terms of traffic information (especially disruptions), Stockholm has some integration between the public transport system and the roads. In general, little cooperation also within each mode.
Switzerland	The highway control center in Emmen by ASTRA, SBB, and PostAuto have the so-called "system leadership" and run their own operation control centers, but very close and alignment is in place. Regarding urban public transport in Zurich, there are first ideas that strategically, such a center should be the goal. However, road traffic and public transport are assigned to different city departments. On the operational and planning levels, there is cooperation on an as-needed base with only limited special, dedicated channels. On the strategic level, one is in continuous exchange and coordination, but a variety of stakeholders are to be considered. There is a “Regionale Verkehrsleitzentrale Verkehrsraum Zürich RL-VRZ» in Zürich, by Kanton Zürich and the cities of Zürich and Winterthur as have some cities like Basel traffic control center as well. SBB and BLS have an operation control center.

Question Country	2. In the short-term or long-term plan of traffic control center development, is it planned to have an integrated system between road and rail? (please explain if it is short term or long term)
Austria	Unsure
Hong Kong	There will be any change in the current arrangement in the short- or long-term future.
Japan	I am not sure I have all the information to answer this question. My guess is: no maybe because all rails are run by private companies, whereas the road is mainly managed by the municipality.
Luxembourg	At the company level, yes for sure but not at state level.
Netherlands	About intersection control: in future (long term) roads are planned in such a way that train traffic and road traffic do no longer have conflict, e.g. by tunnels. Other types of control: in logistics the tuning of different modes for transport from origin to destination is considered.
Sweden	No. First of all, road traffic *control* (real time) is relatively little developed compared to railways. Railway traffic control is obviously a necessary, integrated part of the railway system, just like air traffic control. Road traffic control consists of traffic signals, which are mostly autonomous, controlled by some combination of preset schemes and real-time sensors, but very little manual control. In addition, there are some variable message signs, tunnel entry control systems and the like, but not nearly as detailed or "powerful" control mechanisms as for railways or public transport (buses, commuter trains etc.). There have been short-term plans to co-locate road and rail traffic planning in Stockholm.
Switzerland	There are tendencies or plans in this direction. Certainly also driven by the automation in the automotive sector. But These plans are rather long-term. There are plans of the federal offices to improve the efficiency and resilience of the traffic system in total with management as can be found in the “UVEK-Orientierungsrahmen 2040 Zukunft Mobilität Schweiz”, the strategic planning of the federal offices for transport, for roads and for energy and in the “Sachplan Verkehr” as well as stakeholder organizations for the cities in Switzerland are forcing a more integrated traffic management.

Question Country	3. In the city you are currently living, is there an integration for traffic control between public and personal transportation? If yes, please explain the relation.
Austria	No. Although they do share information and have multimodal data in the wayfinding apps.
Hong Kong	Again, private and public transport are both monitored by the transport department in Hong Kong. Public transport in Hong Kong mainly consists of rail, buses, minibuses, ferries, and trams. The public transport services are managed and operated by independent operators commissioned by the transport department in Hong Kong. However, the transport department has no direct authority manipulating the management and operations of the local public transport services.
Japan	In normal circumstances, the different rail lines, bus lines, and traffic is controlled separately, as noted in previous question, there is though a control room for emergency control. Also Some places with 'Park and Rail/bus ride', or 'cycle and rail/bus ride'. We are now discussing how we can link new Maglev station with other existing transport systems.
Luxembourg	For the city of Luxembourg, the only form of integration is a few basic signals providing early or late green to PT, and the tram has unconditional priority on all intersections except one (where the cycling path has priority). Public transport is free (bus, train, tramway), and everybody can use all modes of transport and plan its trip through an app. But cars are definitely out of scope.
Netherlands	Again narrowing it down to intersection control: separate bus/tram lanes are controlled separately from the other traffic and often have (conditional) priority over other modes.
Sweden	The transit control system for Stockholm is integrated (metro, buses, commuter trains etc), but they don't control road transport. The bus operators have observatory rights in the road traffic control center and are informed of actions taken etc. I don't think they can influence the decisions, and I don't think any integration goes in the other direction (i.e. from public transport traffic control to road traffic control).
Switzerland	The first steps are towards a mobility platform. Here, only gentle steering is possible, but not control. In Zurich, there is a supervising traffic center (mainly cameras) and a strict prioritization of public traffic. In Basel, the head of the respective department coordinates the evolution of both public transport and road capacity

Question / Country	4. What does the planned integrated traffic center offer in case of a disruption considering the multimodality in cities, interurban, or even freight transport.
Austria	-
Hong Kong	The transport department will communicate with the local public transport operators in case of disruptions. However, it is up to the transit operators to carry out corresponding actions.
Japan	In case of emergency, information provision via app and webpages, in case of large emergency, in collaboration with mobile phone providers.
Luxembourg	Alternative bus lines are set when rail is disrupted (planned works).Less saturation of the different networks. Better organize commuting over the day and the week.
Netherlands	-
Sweden	-
Switzerland	Information about the latest situation and developments. It offers various transport options (PT & sharing offers) regarding travel time and travel expenses. Multimodal is thinkable if within the same company and can provide an easier rerouting of passengers in case of disruption. If more than one company are involved, then ticketing has to be solved in advance.

Question Country	5. If there are no future plans about the integration of traffic control between modes. What is your opinion about such a control system?
Austria	It's a good idea. Especially interesting would be how it could be used to provide priority to sustainable modes, for example by facilitating a bus bridge between two railway stations in case of a disruption - providing strong PT priority to the buses over cars.
Hong Kong	Such control system can certainly improve the effectiveness and resilience of the city's transport from a holistic perspective, however it would be hindered by various administrative difficulties.
Japan	Integration between different PT operators should be clearly better but they are competitors. Road and rail: There is some discussion to promote more park and ride for tourists (Kyoto is tourist city) for that it would be useful - in particular during peak tourist seasons, otherwise road congestion in Kyoto is at a relatively low level.
Luxembourg	It is a necessary step for future traffic and transport management. It might face the issue of data privacy.
Netherlands	Does it have to be control? It can also be: information exchange or reservations for multiple modes when travelling. For instance, information about delays in the train schedule, information where I can park my bicycle at the station, a hired car waiting for me at the arrival train station, so the Mobility As A Service (MAAS) idea rather than control. MAAS is in the upswing in the Netherlands.
Sweden	Better integration between different modes in urban traffic control would be beneficial. The available capacity in the transport system could be utilized more efficiently. The traffic controllers could get a wider palette of possible actions to manage a certain traffic scenario. Sustainable transport modes such as public transport could get higher prioritization in traffic control.
Switzerland	It is a necessary control instrument for the development of a sustainable transport system. This will become even more important in the future as overall transport demand is very likely to grow. However an overall system might be too difficult (too many resources), maybe systems for specific purposes more feasible. In operational level intermodal apps are more important than control centers nowadays. Considering the developing technologies of connected and autonomous cars we will likely be able to influence traffic much more and much quicker than today, especially by direct influencing of individual cars. also it should be combined with financial measures (e.g. road pricing, mobility pricing)

Question Country	6. As a transport expert, how would you measure the benefit of integrated traffic control center in urban or interurban context?
Austria	Typical measures such as mode split, person km travelled, accidents, air quality
Hong Kong	Measure the system in terms of improvement in travel time and travel reliability, as well as travelers' satisfaction (collected through surveys).
Japan	road network speed but also passenger crowding and modal split; parking search traffic reduction
Luxembourg	By increased throughput, reduced travel times, robustness towards incidents.
Netherlands	As a measurement variable, probably the delay. But the benefits are more on policy level rather than on the level of the control itself. The benefit will be: better tuning and understanding between what are now separate parties. This will save a huge amount of time in issuing new policies and integrating new types of control.
Sweden	Integrating bus control with road transport control might be a good idea. But traffic signals are mostly controlled by the city and public transport by the region, so it's not on the table to let the region control the city's traffic signals! highlighting examples of traffic management strategies that would not have been possible without the integration.
Switzerland	The two main outputs where you can measure the benefit of such a control center are flow of traffic and the handling of disruptions: * Flow of traffic: Such a center should be able to increase the flow by being able to accommodate more traveling persons/goods on the roads at the same speed, or by letting the same number of people/goods travel at a higher speed. considering people and goods instead of vehicles, as the main goal of any transport control should not be to move vehicles, but to move people and goods. * Handling of disruptions (planned, e.g. events, or unplanned, e.g. road accidents): Optimizing the flow of traffic is only half the job of a control center. The other half is dealing as quickly and as efficiently as possible with disruptions. How much can the overall flow of traffic be maintained if individual road segments are (partially) blocked? Maintaining the flow better in such situations as well as increasing the flow of traffic in normal situations compared to mode separated control centers. Also utilization of modes considering the spare capacity. An integrated traffic control center should be evaluated, for both, urban and interurban contexts.

Question / Country	7. If you are aware of projects regarding this topic in your country, please share with us some information/link.
Austria	-
Hong Kong	-
Japan	https://www.meti.go.jp/english/press/2019/0408_007.html
Luxembourg	Ramp metering is considered for some ramps on the A6 from Belgium, but nothing has been published yet.
Netherlands	-
Sweden	-
Switzerland	https://www.stadt-zuerich.ch/vbz/de/index/mobilitaet-der-zukunft/mobilitaetsplattform.html Mobility Pricing (Switzerland): https://www.uvek.admin.ch/uvek/de/home/verkehr/mobility-pricing.html

5.2. *Relevant projects*

In this chapter, we briefly mention the projects that their objectives are in line with the objectives of a nationwide integrated multimodal management and control center. A very similar approach is provided in a white paper by the World Economic Forum called SIMSystem (WEF, 2018). A SIMSystem is a “system of systems” that moves people and goods more efficiently by creating interoperability across physical assets like cars and buses, digital technologies like dynamic pricing and shared data exchanges, and the governance structures, standards, and rules by which they operate. At a SIMSystem’s core is a digital platform that overlays on to existing physical assets to provide a holistic, real-time picture of mobility supply and demand as well as the conditions of the overall system (e.g., traffic, infrastructure, weather). When realized, a SIMSystem seamlessly integrates disparate modes of transport for more efficient use of those assets and the infrastructure that supports them (e.g., roads, bike lanes, rail networks, ports). By removing the friction caused by incongruous components, a SIMSystem can enable mobility that is faster, cheaper, safer, cleaner, and more efficient than today. As they note in the white paper, the provided manifesto is meant to be a catalyst and a working guide to help advance the collective understanding of key stakeholders and maximize the benefits of the future of mobility to improve the state of the world.

Similar to SIMsystem as a guideline, there are guidelines provided by Commission Delegated Regulation (EU) 2017/1926, which focuses on the priority action and the provision of Union-wide multimodal travel information services for the development and use of specifications and standards. Also, Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010: Framework for ITS road transport and interfaces with other modes, which focuses on Intelligent Transport Systems (ITS) and its advanced applications to provide innovative services relating to different modes of transport and traffic management and enable various users to be better informed and make safer, more coordinated and ‘smarter’ use of transport networks. These two guidelines, however are the very base of a multimodal management center in any geography, and they do not focus on actions about multimodal management or control. Under the guidelines in the European Union, level FRAME NEXT is a project that extends the European ITS Framework Architecture, in short FRAME, with the activities of the different member states in Europe, with the priority areas concerned by the ITS directive and with the methodologies and tools that make a modern ITS architecture attractive and appealing for its users. This project can be considered as a very first basis of a multimodal and integrated management system at the EU level.

Projects that focus on a city such as Maastricht Bereikbaar 2019: integrated mobility management targeting employers and commuters aim at demand management towards reducing congestion by 20% and door-to-door journey times by 10% by promoting the smarter, more efficient use of transport infrastructure. At the same time, measures were implemented to reduce emissions and help maintain a healthy living and working environment in the region. It is worth mentioning that there are other projects that their objectives are similar to our approach but focusing, for instance, only on the road such as TEN-T policy.

As mentioned at the beginning of this chapter, our attempt to get information about the state of practice in the United States was unsuccessful, but useful and very recent information is provided by the latest report from the Integrated Corridor Management project by the National Academies of Sciences, Engineering, and Medicine 2020. Which is worth to summarize in here:

The vision of ICM is to achieve significant improvements in the efficient movement of people and goods on transportation networks through aggressive, proactive integration of existing infrastructure along major corridors. Table 4 maps example objectives to each of the general ICM goal areas.

Table 4 ICM Goals and Objectives

ICM Goal	ICM Objectives
Improving travel time	• Provide alternative route and mode options • Enhance ITS (e.g., dynamic lane management, adaptive traffic signal control) • Reduce impacts of roadway incidents
Increasing corridor throughput	• Add capacity during periods of severe congestion • Coordinate signal control systems
Improving travel time reliability	• Allow people and goods to move with minimal congestion and time delay, and greater predictability • Promote ride sharing, such as carpool, vanpool, and park and ride • Enhance ITS (e.g., dynamic signal phasing and vehicle detection systems)
Improving incident management	• Reduce incident response times • Reduce secondary crash rate • Improve decision support systems and response plan coordination
Enabling intermodal travel decisions	• Enhance transit services, amenities, and facilities • Improve bicycle and pedestrian facilities • Increase use of affordable non-auto travel modes • Support the development of new transit options (e.g., passenger rail)
Improving safety for all travelers	• Reduce injuries and fatalities • Inform travelers of stop-and-go traffic • Increase detection systems for all travel modes (including bicyclists and pedestrians)

Furthermore, they state that to achieve these objectives, a time dynamic view of the network is a fundamental element of transportation system management, regarding the fact that A busy modern transportation system is inherently a dynamic entity. It never exists in pure equilibrium and is in a state of perpetual change at multiple temporal wavelengths: minute-to-minute, hour-to-hour, peak-to-non-peak, day-to-day, seasonally, and year-to-year. Therefore, system management is essentially a task of managing change.

With the advent of more continuous data available, the ability to characterize dynamic corridor performance has improved. These conditions can be within a day (e.g., the rise and fall of congestion in a peak period) or over many days (e.g., the variation in travel times between a specific origin and destination departing at a specific time each day over a full year). Likewise, there is a fundamental need to develop more effective condition-specific corridor management responses. For ICM to be successful, vague notions of recurrent and nonrecurrent congestion (convenient in a relatively data-scarce environment) are giving way to a more informed, data-driven approach that systematically classifies a wide range of operational conditions based on underlying causes (e.g., weather, incident, and demand patterns) as well as profiles of system performance (e.g., travel time, bottleneck throughput, and delay patterns).

Current ICM best practices use a data-driven method to identify multiple distinct operational conditions to better characterize transportation system dynamics. This set of operational conditions is a more effective and useful basis for the comparison of potential ICM response plans and is a foundational element of any effort aimed at improving corridor performance.

Focusing on the benefits, in specific, they summarize the benefit of stakeholders being involved in the ICM as follows:

- Improved situational awareness of corridor conditions
- Enhanced customer service
- Reduced incident response times
- Improve safety and equity in transportation operations
- Improved mode-specific diversion routes
- Enhanced data and information sharing
- Forum for collaboration
- Increased monitoring capabilities and assets
- Eliminate redundancies in infrastructure investments

Finally, the benefits of selected different potential strategies are listed in the following table.

Table 5 Potential ICM Strategies

ICM Strategy	Description	Potential Benefits
Improved Dynamic Corridor Ramp Metering	Dynamic adjustment (up or down) of metering rates based on current facility conditions and remaining available capacity of the facility/system.	• Increased throughput • Decreased vehicle hours traveled • Decreased primary incidents • Increased speeds • Decreased travel times • Decreased delay
Queue Warning	Inform travelers of the presence of downstream stop-and-go traffic based on real-time traffic detection using warning signs and flashing lights.	• Decreased primary and secondary incidents • Decreased speed variability
Improved Decision Support Systems (DSS)/Incident Response Plans	DSSs use real-time data and knowledge of the current state/conditions of the network to provide appropriate alternate routes to TMC operators as they respond to incidents (e.g., traffic collisions, severe weather, evacuations).	• Reduced response time • Reduced negative impacts on network performance
Media and Social Media Alerts	Mobile alerts for real-time traveler information such as congestion hot spots and locations of	• Decreased primary and secondary incidents

	incidents, lane closures, and construction events can provide roadway users with actionable information.	• Decreased delay
Dynamic HOV Lane Conversion	When congestion is light, the HOV lane can be operated as a general-purpose lane, and when congestion is severe, access can be limited to transit vehicles only. For facilities that lack dedicated HOV lanes, hard shoulder running can be used to add a general-purpose lane to the freeway, while the median lane is simultaneously converted into an HOV lane.	• Increased transit ridership • Increased transit on-time performance
Speed Harmonization/ Variable Speed Limits (VSL)	VSL is used to gradually slow traffic down ahead of a congested area to reduce the occurrence of traffic collisions, and attempts to set speed limits appropriately in the congested regions so that traffic continues to flow smoothly rather than deteriorating to less efficient stop and-go conditions.	• Increased capacity • Decreased primary and secondary incidents • Increased average speed • Decreased peak period duration • Decreased emissions • Decreased fuel consumption
Dynamic Rerouting	Alternate route guidance is provided to drivers heading for designated destinations when conditions on the primary route have deteriorated below a prescribed threshold due to congestion, weather conditions, or other situations. This strategy is closely supported by effective DSSs.	• Decreased travel time • Increased average speed • Decreased speed variability
Lane Use Signals/Dynamic Lane Management	Opening and closing of lanes on a facility in response to real-time conditions. Congested conditions may result in the opening of additional lanes (such as reversible or shoulder lanes) to traffic. When closures occur, lane use signals provide drivers warning ahead of the closure so that they may anticipate the merge ahead.	• Increased throughput • Increased capacity • Decreased primary and secondary incidents • Decreased emissions
Dynamic Pricing	Uses tolls to manage supply during periods of high demand. Prices are set to maintain a prescribed level of performance on the facility, such as a minimum acceptable speed. Provisions are sometimes enacted that allow HOVs and transit vehicles to receive discounted toll rates.	• Increased transit ridership • Increased transit on-time performance
Automated Work Zone Information System (AWIS)	The AWIS system uses a Central System Controller, highway advisory radios (HAR), traffic sensors, CMSs, and speed stations to calculate and report delay times to travelers via CMSs. The public is provided with general work zone and delay information via various traveler information sources (e.g., 511, HAR system).	• Decreased fatal crash rate • Decreased rear-end crash rate
Predictive Traveler Information	Travel time estimates are generated based on predicted (as opposed to recently observed) performance of the system, using models, expected incident clearance times, schedules of regional special events, etc. and are expected to be more reliable and accurate than those based on past data.	• Increased on-time performance

Increased Transit and Parking Capacity	New parking spots planned within the corridor can be used to attract single occupancy vehicle (SOV) trips to transit. Additional buses or light rail vehicles can be added as necessary to accommodate increases in demand. Financial incentives such as reduction in fees for transit and parking may be incorporated into this strategy.	• Increased transit ridership • Decreased freeway and arterial travel time • Increased capacity
Dynamic Lane Reversal	A specialized and common form of dynamic lane management, this strategy involves the designation of a specialized lane (or lanes) on a facility to the direction of travel that would most benefit from its capacity according to current conditions. Some reversible lane facilities follow preset time of day schedules.	• Decreased travel time • Increased capacity • Decreased delay
Coordination of Freeway Ramp Metering and Arterial Signal Control	Ramp metering and arterial signal control systems that are operated in isolation can lead to excess congestion. In a coordinated system, ramp metering rates are generally used to inform signal operations on nearby arterials, so that their operations complement – rather than conflict with – each other.	• Decreased delays • Decreased travel time • Reduced emissions • Increased throughput
Adaptive Traffic Signal Control	Operating a signalized intersection, corridor, or network of arterials such that the timing parameters are set based on current traffic conditions. These systems can respond reactively to atypical traffic conditions (e.g., high demands caused by special events), or proactively to anticipated recurrent congestion based on historical data.	• Decreased travel time • Decreased delay • Decreased number of stops
Traffic Information for Route Planning	Through close system integration with real-time traffic condition data sources, freight dispatchers and fleet managers can more effectively route their vehicles around anticipated congestion and modify driver departure times to minimize overall vehicle hours traveled and optimize delivery times.	• Travel time reliability • Economic efficiency
Maintenance and Construction Planning	Planned events, such as anticipated lane and roadway closures for scheduled maintenance, can be considered by freight dispatchers and fleet managers when driver plans are developed each day, such that the trip performance and delivery impacts of those closures can be minimized. Long-term freight planning data can also be used as inputs for optimizing maintenance schedules, so that closures on peak freight routes and travel days can be minimized or anticipated and mitigated.	• Travel time reliability • Economic productivity • Quality customer service
Dynamic Routing around Active Incidents	Truck alternative routes are limited and can be challenging to locate during incident situations. With ICM, integration between truck operators and traveler information systems becomes possible, allowing specific truck route detour guidance to be directed toward relevant freight vehicle operators only. Additionally, integration between DOTs and local agencies helps ensure that the active detour truck routes are prepared to handle the rerouted traffic (e.g., through	• Navigability • Travel time reliability

	signal retiming, local traffic control, activation of arterial CMSs for guidance).	
Incident/Operations Management	Many regions have deployed procedures and communication systems to enable transit operators to receive real-time information on traffic congestion or disruptions, enabling them to reroute buses around incidents.	• Travel time reliability • System efficiency • Safety
Coordinated Detour Routing	With an ICM program, a set of approved detour routes for general traffic and for restricted vehicles (e.g., freight) can be determined in advance, along with the criteria and procedures for activating those routes. Doing so allows incident responders to quickly evaluate whether a detour route is warranted, and to efficiently activate suitable detour routes as needed. With appropriate ICM detour route procedures, incident responders can be confident that detour routes will be capable of handling the diverted traffic.	• Responder safety • Safe, quick incident clearance • Prompt, reliable, interoperable communication

5.3. *Conclusions*

The results, in general, show that in the given countries, from a practical point of view, multiple projects, pilots, and implementations, aim to address some aspects of multimodal traffic management. Most of those approaches identify data collection and integration; and definition of standards and exchange format, as prerequisites for any further decision support—for example, SIMsystem (WEF, 2018). A SIMSystem is a “system of systems” that moves people and goods more efficiently by creating interoperability across physical assets like cars and buses, digital technologies like dynamic pricing and shared data exchanges, and the governance structures, standards, and rules by which they operate. At a SIMSystem’s core is a digital platform that overlays on to existing physical assets to provide a holistic, real-time picture of mobility supply and demand as well as the conditions of the overall system (e.g., traffic, infrastructure, weather). There are guidelines provided by Commission Delegated Regulation (EU) 2017/1926, which focuses on the priority action and the provision of Union-wide multimodal travel information services for the development and use of specifications and standards. Also, Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010: Framework for ITS road transport and interfaces with other modes, which focuses on Intelligent Transport Systems (ITS) and its advanced applications to provide innovative services relating to different modes of transport and traffic management and enable various users to be better informed and make safer, more coordinated and ‘smarter’ use of transport networks. Under the guidelines in the European Union, level FRAME NEXT is a project that extends the European ITS Framework Architecture, in short FRAME, with the activities of the different member states in Europe. Furthermore, Projects that focus on a city such as Maastricht Bereikbaar 2019: integrated mobility management targeting employers and commuters aim at demand management towards reducing congestion by 20% and door-to-door journey times by 10% by promoting the smarter, more efficient use of transport infrastructure. And the ICM project focusing on a corridor in the United States. The vision of ICM is to achieve significant improvements in the efficient movement of people and goods on transportation networks through aggressive, proactive integration of existing infrastructure along major corridors. Some systems have been implemented in multiple cases, though no test case reaching the size of a country like Switzerland, explicitly including long-distance trains, is known.

6. Case study: Multimodal management during a disruption in freight transport[1]

6.1. *Introduction*

The daily costs of transport disruptions caused by delays or complete cancellations can be massive. These disruptions commonly interrupted or at least diminished the flow of goods and even caused shortages on some consumer products. Hence, minimizing the threat or impacts of such disruptions is a crucial field of action for actors involved in freight transportation. In the transportation context, these disturbances relate to several possible disruption scenarios including, for example, the closure of a railway or motorway link because of natural disaster damage, the inoperability of an intermodal terminal because of staff shortages, infrastructure breakdowns due to lack of maintenance or inoperability of transport units because of environmental conditions (see for example Ludvigsen & Klæboe, 2014).

Disruption is typically unexpected and can be managed at three different stages. Prior to its occurrence, i.e., from a strategic point of view, mitigation of exposure or impact is sought. During its occurrence, at a tactical and operational scope, the impact of the disruption is minimized by means of contingency plans. Finally, after the disruption, actions aimed at restoring full system functionality and analyze best practices. A transport system is resilient during a disruption if the origin and destination of a freight shipment are still connected by a freight transportation service, whether or not infrastructure restorations, rerouting, mode switching, or other response activities are taken. The goal of this section is to study under which conditions large unexpected events such as disruptions can act as triggers for a multimodal shift, in order to keep the resilience of a transport system and investigate which aspects play a role in this direction.

We refer to severe disruptions causing strong negative impacts (limited or no possibility to use some facility or link), large exposure (large volume of freight affected), for a longer amount of time (more than a day) on the freight transport system which requires considerable response activities by transport operators and affected companies. We perform this analysis along with three directions: by means of literature research, by means of interviews with experts (categorized in different groups based on their role and experience). We moreover analyze some test cases; and summarize the finding by a conceptual model reporting the most relevant factors for multimodal control of a transport network, encouraging/ based on multimodal shift.

One contingent strategy of responding to disruptions besides the above-mentioned examples is employing alternative transport modes for shipments (Chen & Miller-Hooks, 2012). Thereby goods are transported by another mode than usually planned from origin to destination on the complete length or just on certain sections, for example, to bypass a closed rail corridor. This includes the replanning of already running services as well as of planned or scheduled but not yet running services. Both response actions are summarized under the term mode shift in this study.

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[1] This chapter is based on : Jan Lordieck, Multimodal Freight Transport Systems under Disruptions Potentials and Requirements of Mode Shift for Disruption Response (supervisor: A. Trivella, F. Corman) Seminar Project, Master in spatial Development and Infrastructure Systems, ETH Zurich 2020

Mode shifting refers to the concept of multi- or intermodality. In contrast to unimodal freight transport, where only one mode is used, multimodal freight transport describes transport chains wherein at least two modes are utilized for shipping the goods from origin to destination (United Nations/Economic Commission for Europe et al., 2001). Intermodal freight transport is a special form of multimodal freight transport because the goods are moved on the entire journey in the same loading unit or road vehicle, which is transported by different modes (United Nations/Economic Commission for Europe et al., 2001). The goods themselves are not handled when changing mode (United Nations/Economic Commission for Europe et al., 2001). A common example of intermodal freight transport in container traffic. Nevertheless, the mode shift in this study also includes switching from unimodal transportation on one mode to unimodal transportation on another mode.

Multiple studies on multimodality in post-disruption situations show that usage of the concept is, in general, beneficial for responding to disruptions. However, most studies simulate disruptions and have several limitations (see, for example, Burgholzer et al., 2013; Chen & Miller-Hooks, 2012; Ishfaq, 2012). Rarely, authors investigate responses in past events (see, for example, Ludvigsen & Klæboe, 2014; Woodburn, 2019). Multiple studies on multimodality in post-disruption situations show that usage of the concept is, in general, beneficial for responding to disruptions; however, most studies simulate disruptions and have several limitations (see, for example, Burgholzer et al., 2013; Chen & Miller-Hooks, 2012; Ishfaq, 2012). Rarely, authors investigate responses in past events (see, for example, Ludvigsen & Klæboe, 2014; Woodburn, 2019).

The concept of synchromodality considered adaptive mode choice based on real-time information about the multi- or intermodal freight transport network is proposed (Reis, 2015). This also includes the avoidance of network disruptions by changing to other modes. However, it does not conceptually include the change from a unimodal freight to another unimodal transportation scheme or to a multimodal strategy in response to disruptions. The largest factors for acceptance of the synchromodal paradigm relate to the readiness of the operators and companies for mode change, legal aspects, and sometimes also capacity or cost constraints.

Disruptions of freight transport systems can have multiple different forms, causes, and severities; affecting node (a terminal, origin or destination), link (railway lines, motorways or inland waterways), and/or network (affecting multiple links/nodes) (Rosyida et al., 2018). Depending on the severity of the disruption, nodes and links can be completely inoperative or operate on lower capacity than without the impact of the disruption. There might be an alternative for transport, either within the same mode; or for different modes.

Based on the classification by Crainic (2000), response activities can be categorized as:

- Strategic level measures: long-term mitigation activities like securing railway lines from rockfall or preventive usage of less vulnerable routes.
- Tactical planning: medium term changes (from a few days to a few months) of freight transportation, for example the design of service networks, simpler route or mode sequence adaptions in response to disruptions lasting long.
- Operational planning: mode changes of already running services, quick implementation of a computed action based on the prevailing conditions of the network

Freight transport differs from private transport as it has legally identified stakeholders, namely: (1) customers, i.e., industrial clients who order freight transport services, (2) transport operators, which conduct the ordered services, (3) infrastructure managers, which allocate slots and are responsible for network operation as well as (4) authorities and infrastructure owners, which plan and build the infrastructure, most governments.

6.2. *Analysis of literature*

All investigated articles find and agree on that mode shift as a response to disruptions in the multimodal transport system is beneficial in terms of delay reduction as well as cost reduction when considering supply chain disruption costs and delay costs. The other possibilities identified are waiting until the disruption is over and rerouting within the same mode.

Table 6 Analysis of literature

Category	Type	Article	Type of disruption	Characteristics of mode shift for disruption response	Requirements of mode shift / Notes	Notes
Transportation	Case Study	Ludvigsen & Klæboe, 2014	Several multi-day disruptions in the rail network of Norway, Sweden, Switzerland, and Poland, harsh winter 2010	Operators and infrastructure managers unprepared; limited/no preparedness and crisis management measures and skills Lack of backup systems in single modes Rail operators unable to organize mode shift on themselves; shippers, forwarders, and integrators pushed mode shift rail to road	Additional personnel readily available. Crisis management plan and a priori determined measures available	
Transportation	Case Study	Woodburn, 2019	53-days disruption of an important rail link in Great Britain	Schedules for domestic intermodal services lengthened the most; 24h wagon rotation for intermodal services not possible; Response to closure improved over time Challenging fragmentation of rail freight operator market; resource problems; requirement for diesel-locomotives Intermodal terminals have less time for handling delayed arriving trains; a limited number of alternative routes Logistic service providers can switch urgent shipments to the road; Some modal switch from rail to short sea	Contingency plan on strategic and operational level available, continuously updated, especially for intermodal services	

Transportation	Artificial case	DiPietro et al., 2014	Dam failure, closure of a link in the inland waterway (US) Coal transportation.	Coal transport is often based on single-mode (i.e., inland waterway shipping), no rail access, truck capacity too limited, the physical absence of a practical alternative. Access to multiple modes reduces vulnerability to disruptions Mode shift influenced by loading, unloading, storage cost		
Transportation	Disruption Modelling	Ambra et al., 2019	Closures of links of rail lines in the intermodal network of France, Belgium, and Luxembourg	Dynamic mode shifting to barge or truck leads to better distance, costs, and lead-times performance Sometimes cheaper to wait until the disruption is over, due to handling costs, long detours, for long lead-time, long-distance shipments	Disruption duration needs to be known and honestly communicated to avoid unnecessary proactive action	Ignoring terminal capacity, legal or contractual aspects; modeling only rail, assuming complete network information
Transportation	Disruption Modelling	Burgholzer et al., 2013	Closures and capacity reductions for 2,6 and 24h of rail and inland waterway links	Mode and route shift decrease travel time under disruptions; Longer transport times reduce mode switch to inland waterway Transport units change routes/mode in roughly 17% of all cases. Disruption of inland waterways lead to 64% of mode shift		minimizing transport time, ignoring costs, assuming complete network information, unclear how capacity differences of modes are handled

Transportation	Disruption Modelling	Chen & Miller-Hooks, 2012	Different scenarios of failures of nodes and links in road and railway network (US), considering repairing and mode shift	Response activities increase the resilience of an intermodal transportation network Resilient networks are not necessarily reliable but cheaper to implement because of mode shift and other response possibilities Intermodal networks more vulnerable than single-mode networks because of terminals, but with more chances for response actions Complete intermodal networks are very resilient because of high-redundancy due to different modes; Hub networks very resilient during disaster response activities		Capacity assumed to be sufficient to handle all flows; limited consideration of response activity, associated costs, time needed
Transportation	Disruption Modelling	Dong et al., 2015	Disruptions at link level on road, railway and inland waterway (US) for transportation of cereal	Mode shift reduces delay of shipments under disruptions. Waiting for reopening of links sometimes cheaper and faster than changing modes (especially from or to inland waterway) Shifting from rail or inland waterway to road increases costs (500% -1400%, depending on many factors). Rerouting better than mode shift for road disruptions	Availability of infrastructure for changing mode (intermodal terminals), especially crucial in case study for inland waterways	No supply chain disruption costs considered for time loss when waiting (might decrease the cost increase when changing to road)

Transportation	Disruption Modelling	Fialkoff et al., 2017	Closure of deep-sea ports and their access (US)	Short sea shipping could have been an (not considered) alternative; legal restrictions limit possibilities of mode shift	Regulations need to allow quick mode shift under disruptions	
Transportation	Disruption Modelling	Fikar et al., 2016	Capacity reduction or complete closure for 24h/72h of the Brenner Rail Pass Austria-Italy	Very large delays because of missing alternatives; switch from rail to road; overall rail network is less utilised Improving disruption preparedness by reserving transportation capacities for rerouting/ shifting to alternative modes	Operations at intermodal terminals need to be ensured (additional staff, backup equipment etc.)	No costs considered, no legal, managerial or contractual aspects of switching mode/changing terminals
Transportation	Disruption Modelling	MacKenzie et al., 2012	Closure of a major port (US) for 1-2 months	Mode shift is economically more favourable than waiting for the port to reopen because of less supply chain disruption costs	Suppliers or shippers must be penalized for delivering late because mode shift is more expensive for them than waiting	Shifting to road or rail is assumed to be always possible, no capacity constraints of terminals or units considered
Transportation	Disruption Modelling	Ouyang et al., 2015	Closure of long-distance railway stations and airports (China)	Complementary transport systems enable mode shift and decrease system vulnerability	Infrastructures need to be accessible at roughly the same location	No link failures, no details on vehicles or commodities flows, not specific about freight

Transportation	Disruption Modelling	Uddin & Huynh, 2016	Capacity reductions/ closures for nodes and links in road, railway intermodal network (US)	Node and terminal disruptions more severe than link disruptions In link/node disruptions, intermodal road and rail have lower rail costs and redundant network structures; In terminal disruptions road has high redundancy and lower costs		No capacity considerations, no legal, managerial or contractual aspects of switching mode/terminal
Supply Chain Management	Artificial Case	McKinnon, 2006	Multiple days to weeks strike of truck drivers (UK), entire road network	Near monopoly of road transport for finished products to retails Missing rail links to factories, warehouses and shops; freight rail terminals require collection or delivery by road; emergency railway access might take weeks		
Supply Chain Management	Theory model	Ishfaq, 2012	Theoretical failure of shortest path between an OD pair (US), no time horizon given	Second-best routes 3-5% worse than shortest paths Reservation of resources can increase flexibility Including different modes gives more options for alternative routes, at reduced costs compared with road-only unimodal network, overall increasing resilience	Availability of redundant mode access, transportation services and intermodal terminals Efficiency of redundant transportation paths	No capacity considerations, no cost estimation of keeping secondary routes available from a service contract point of view

Freight transport optimized at a strategic level means low redundancy; the second-best option is much worse

From a network perspective, transport systems of different modes might, especially during disruptions, be complementary to each other and provide alternatives for freight transportation if infrastructure and service access are available (Ouyang et al., 2015). Considering that single-mode systems (roads excluded) often do not have many redundancies because they reduce the efficiency of the system by increasing costs for not strictly necessary facilities under normal operation, the existence of multiple different complementary but interconnected transport systems counteracts these redundancy deficiencies

The investigated studies which consider capacities show that exploiting the available slots still provides the opportunity of utilizing complementary systems as redundancies of the disrupted system by shifting mode (see Burgholzer et al., 2013; Fikar et al., 2016; Uddin & Huynh, 2016). In contrast, they also show that the capacity loss cannot be completely compensated by links of other modes and true redundancies in the whole system are still necessary to mitigate the consequences of disruptions (Fikar et al., 2016; Woodburn, 2019).

Strategically, the location and availability of redundant links determines the impact of disruption

DiPietro et al. (2014) show in their study on the supply network of coal power plants that facilities with active access to multiple modes of transport are better positioned if disruptions in one mode occur. Some mines, for example, can shift coal supplies from rail to road, but some power plants do not have the possibility to unload trucks. While the former infrastructure is available at least on a larger geographical level in North America (Chen & Miller-Hooks, 2012; Ishfaq, 2012), Europe (Ambra et al., 2019; Fikar et al., 2016), and China (Ouyang et al., 2015), on a smaller geographical level redundant transport systems are often not available, and mode shift strategies are not applicable (see for example a study from Norway by Husdal & Bråthen, 2010).

In an operational perspective, tradeoff costs for delay/cost for mode shift

Since mode shift always includes additional handling of goods and, in most cases, also switching to a less efficient mode for that particular good, it can be much more expensive than the planned transport chain not considering the disruption (Ambra et al., 2019; DiPietro et al., 2014; MacKenzie et al., 2012). This implies that (1) transport operators might favor waiting if they are not incentivized by delay penalties to take action (Hu et al., 2013; MacKenzie et al., 2012), (2) costs for switching to another less efficient mode can be so high, that waiting to a certain extend is less costly than taking action even if considering potential production losses which are especially the case for bulky goods transported by barge (Ambra et al., 2019; Dong et al., 2015; Pant et al., 2011) and that (3) progressively taking action when a disruption occurs might not be worth it if it is quickly fixed (Ambra et al., 2019). Hence, trading off the costs of waiting and mode shifting is necessary. Properly calculating this trade-off, therefore, requires an honest and reliable estimate of the disruption duration (Ambra et al., 2019).

Operationally, handling costs limit mode shift

Another exception is unimodal road transport. Studies find that shipments that were planned to be transported by road do not switch to another mode even if the road transport network is disrupted on a certain link (Dong et al., 2015). This is caused by interleaving the previously described additional handling costs and the high redundancy of the road or specifically the motorway network. It is cheaper to reroute trucks instead of investing in additional handling because different routes are nearly always available, and detours are relatively small (Dong et al., 2015). This stresses the importance and advantages of mode shift in scarce networks with fewer redundancies like the railways or inland waterways (Burgholzer et al., 2013; DiPietro et al., 2014; Fikar et al., 2016; Woodburn, 2019a). In contrast, transportation by truck is crucial for the whole transportation system as factories, distribution centers, and especially shops lack access by other modes and thus, transportation by road is nearly always required for the first and last mile (McKinnon, 2006). Therefore, a network disruption of the road transportation system due to, for example, truck driver strikes, fuel shortages, or earthquakes threats the functioning of freight transportation as a whole, as shown by McKinnon (2006) in his study on a potential nationwide strike of truck drivers in the UK.

Mode shift identifies other bottlenecks

Especially during disruptions when more mode switching activities are demanded, intermodal terminals form bottlenecks of the system. Woodburn (2019) finds in his study on a rail link closure in Great Britain that during the time of the disruption, intermodal terminals experienced less available handling time per train and issues handling trains arriving out of schedule. Therefore, Fikar et al. (2016) argue that ensuring their operation with, for example, additional staff or backup equipment needs to be ensured. Furthermore, certain links might not be able to handle much additional traffic due to rerouting and mode shifting in case of the disruption of another link.

At operation scale, there is only limited substitutability of modes

Different transport means pose challenges on mode shift responses. This is especially the case when thinking of switching from barge to truck. DiPietro et al. (2014), for example, note that a typical barge in the coal supply chain network has a capacity of 1085t while a truck has only 25t. Further considering that this also requires offloading many more trucks than a single barge, stresses the infeasibility of road transportation substituting inland waterway shipping (DiPietro et al., 2014). Although this issue is also present, while less strong, when switching, for example, from barge to train or from train to truck, it receives only a few attention from the literature.

Strategic readiness for operational adjustments based on online control and synchromodality

Behdani et al. (2014) thereby conclude from their own findings and a literature review that intermodal services organized with a synchromodal concept can handle exceptional situations better than statically booked intermodal services. Ambra et al. (2019) come to the same conclusion in a dedicated study on the topic of disruption response of synchromodally organized transportation services, but also highlight that, as previously described, actively taking action is sometimes more costly than just waiting until the disruption is fixed.

Organizational issues limit theoretical potential

Transport operators and infrastructure managers (in their cases, mostly rail freight operators and railway infrastructure managers) are not prepared for coping with sudden disruptions (Ludvigsen & Klæboe, 2014; Woodburn, 2019). Business contingency plans are not in place, and a-priori determined response or recovery measures are not defined (Ludvigsen & Klæboe, 2014). Especially in the rail sector, risk reduction and disaster management are complexes involving many different stakeholders, often from different countries and jurisdictions (Otto et al., 2019). These results imply that disruption management can be improved if involved entities have updated contingency plans on strategic and operational level ready to act quickly (Woodburn, 2019).

This is an issue often neglected by the investigated studies. However, Fialkoff et al. (2017) show that post-disaster transport operation is not just a technical question but also includes institutional, managerial, readiness, and legal aspects. Such aspects are often ignored in research. It can be assumed that mode shift as a response in real disruption situations is currently much less efficient than the literature indicates.

6.3. *Analysis of interviews*

Questions target on (1) substantiating common findings, (2) finding causes for differences, (3) validating deviations from the literature review but also on (4) getting a personal assessment of multimodality under disruption from the experts acknowledging their experience, and (5) revealing further aspects and requirements of mode shift under disruptions. The appendix 11.1 has more details on the specific items investigated

The interviewed experts report to which extent mode shift is identified as a necessary strategy to cope with disruptions, or where multimodality should be supported because it allows mode shift for crucial goods for the whole society or for specific industries in the private sector.

Table 7 Analysis of interviews

Aspect	Detail	Number of indications
Time	Duration of disruption	8
Space	Scale and Scope (of affected infrastructure)	1
	Distance of shipments	1
Disruption	Type and intensity	2
Mode	Rerouting options on current mode	4
Goods	Type (size, shape, container, etc)	4
	Time sensitivity	2
	Hazardous Material	3
	Value	1
	Sensitivity to damage	1
	Source and potential other sources	1
Costs	Willingness to pay for additional costs of mode shift	3
	Ability to shut down production (e.g. Steel production)	1
Involved Actors	Objectives and preferences	1
	Preparation and readiness	5
Information	Availability of information on disruption, potential alternatives or how to organise new transport chain	3

Duration triggers reaction type, and priority of actions

The most prominent factor is the duration of the disruption. In general, mode shift is considered not efficient for short disruptions lasting only a few hours (Interview T. Ambra, 2020; Interview R. Maggi, 2020), except if the readiness level of the involved actors is high, enabling quick and flexible mode shift (Interview, J. Ernst, 2020). This is especially the case if short notice mode decisions are the normal situation in day-to-day business (Interview J. Ernst, 2020; Interview R. Negenborn, 2020). Most interview partners estimate from a mere duration perspective that mode shift begins to be a sufficient tool if disruptions last between one and three days (for example, Interview T. Ambra, 2020; Interview E. Miller-Hooks, 2020).

While preparation for quickly switching to rail is necessary in any case, a higher degree of readiness is generally beneficial for the efficiency (Interview J. Baeriswyl, 2020; Interview D. Pfister, 2020; Interview T. Schmid, 2020).

Rerouting on the own mode is always considered as the first option, while mode shift is only a backup measure (Interview J. Baeriswyl, 2020; Interview J. Ernst, 2020; Interview D. Pfister, 2020). Furthermore, the type of good is often mentioned by experts directly related to the field. Hereby, especially its suitability for handling is crucial for the efficiency of mode shift (Interview J. Baeriswyl, 2020; Interview D. Bruckman, 2020).

More efficient mode shift under disruptions depends on constraints

Systemic constraints are caused by the current (legal, technical, etc.) system and could be overcome with adaptions of the system or the behavior of actors in it. Inherent constraints represent constraints that are not caused only by external influences but by mode shift as a process itself. Removing those constraints will require major (practically unwished, or impossible) changes in, for example, in the economic system.

While technical constraints are more agreed on by the interview partners, organizational and economic constraints vary, focusing on different points. However, the main organizational issues are information shortages and therein the missing experience with other modes that are required to organize ad hoc mode shift. This is especially the case for rail transports, which pose high entry barriers to new customers.

Table 8 Mode Shift Constraints

Category		Constraint	Number of indications
Systemic constraints	Technical	Availability and capacity of terminals	2
		Handling possibilities for different modes at the goods' sources (e.g. plant, factory)	1
	Organizational	Strict regulation of rail	7
		Human factor in decision process slows down mode shift	1
		Complexity of empty transporting of containers and wagons after mode shift	1
		Information shortages	6
		Uncertainty about terminal capabilities	1
		Necessary information not digitally available	1
		Necessary modelling tools for informed decision making on mode shift not available	1
		IT Systems of different operators not interoperable	1
		Missing experience with other modes	4
		Uncertainty about responsibility for bearing extra costs caused by disruptions	4
	Econ.	High cost of additional mode shift	1
		High cost of having spare capacities to allow mode shift in exceptional cases	3
Inherent Constraints	Technical	Capacity constraints on other modes	7
		Specific goods bound to certain modes (e.g. dangerous goods to rail)	4
		Difference in transport means' capacities	4
		Small scale distribution only possible by road	1
	Organizational	Ability to handle growing complexity of transport chains with additional mode shifts necessary	2
		High coordination effort for switching goods from multiple different customers which were transport in a single transport mean to other modes	1
		Trust issues when sharing information with competitors	1
	Econ.	If mode shift is required, market reacts with higher prices	2

Larger, multimodal transport operators are better able to facilitate mode shift than smaller operators because they have more experience and potentially also better information sources and cooperation with other operators (Interview R. Maggi, 2020; Interview T. Schmid, 2020). This relates to the inherent limitation that companies need to be able to organize the more complex transport chain (Interview D. Bruckman, 2020), which might be especially difficult for smaller companies with less experienced staff.

Another often mentioned limitation of mode shift is the uncertainty about responsibility for disruptions. It is legally difficult to determine responsibility for transport disruptions, and therefore indemnity claims are often undisbursed (Interview J. Baeriswyl, 2020; Interview J. Ernst, 2020; Interview D. Pfister, 2020; Interview P. Buhl, 2020). If, for example, a disruption is caused by force majeure, the customer is most likely fully bearing the financial risk (Interview C. Peter, 2020). Furthermore, freight transportation contracts are often long-lasting and must also be paid under disrupted conditions (Interview J. Baeriswyl, 2020; Interview R. Maggi, 2020). Hence, customers might be afraid of paying twice if they shift mode, and indemnity claims are effectless.

Choosing the most efficient transport solution pushes other alternatives out of the market and leaves fewer options for shifting under disruptions (Interview E. Jenelius, 2020). Capacity constraints are most relevant for link infrastructure and less for node infrastructure. Terminals often have spare capacity available, and moreover, capacity can easily be increased with additional personnel (Interview P. Buhl, 2020).

Node disruptions are irrelevant for the interview partners, which might be caused by a lack of experience due to a few recent events or because enough terminals with sufficient capacity are available. Overall, many different specific requirements are proposed by experts.

Redundancy and balancing modes trade of disruption costs versus nondisrupted performance

More balanced use of modes on freight relations to distribute capacities across different modes (Interview R. Zuidwijk, 2020; Interview R. Negenborn, 2020). Holistic, integrated transport systems are best to tackle disruptions because there are fewer single points of failure, and capacity is distributed on multiple infrastructures (R. Zuidwijk, 2020; Interview R. Negenborn, 2020). Future technologies like truck platooning can introduce further alternatives that are able to support resilience in the transportation system (R. Zuidwijk, 2020).

Many interviewees doubt that resilience and vulnerability are widely acknowledged as important topics in transportation (Interview R. Maggi, 2020; Interview E. Miller-Hooks, 2020).

Service driven companies versus cost-driven companies

As an extreme case, a service-driven company might have to have a vertically integrated structure with its own rail services and access to the Swiss rail network, provides further autonomy and information advantages, not requiring extensive coordination or cooperation with unacquainted partners or competitors, under disrupted conditions.

Good practices include cooperation with large transport operators, which can offer various modes for international transports and also use different infrastructures (e.g., the North Sea and Mediterranean ports) to increase the resilience of their supply chain. All partners in the supply chain have contingency plans, and make them available to the partners, and have special arrangements to be able to quickly request additional capacities if necessary. (Interview J. Ernst, 2020; Interview P. Geiger, 2020)

Goods have different requirement while being transported

Heavy equipment, hazmat, or special cargo prone to damage caused by additional handling might not be easily shifted, or mode, or in general, one tries to avoid additional handling. Another limiting factor for mode shift is that nearly all in- and output products are not transported on or in standardized units. In such cases, waiting and rerouting in case of disruption are preferred options.

Rerouting within, from/ to the rail mode

Rail operators consider rerouting of trains as their first response to disruptions and mode shift only as a second response. If a mode shift is necessary, the process is not organized by the company itself but is in the responsibility of the customer. Switching from another mode to rail is agreed to be hindered by the strict regulation of the rail sector, which poses high entry barriers for inexperienced companies.

If trains are stuck on the tracks, SBB Cargo supports its customers with partner services to transfer goods to trucks. Otherwise, both companies state that their customers are better able to organize a new transport chain by shifting mode than they are because of missing partners and experience. Cooperation under disruptions is common and includes mostly pooling of resources and selling or buying of traction units, respectively.

In the European rail infrastructure, the general concept of network neutrality applies. Hence, no transport operator is privileged, and disruption measures can be coordinated between different operators. The situation is different in, for example, the USA, where the rail networks are privately owned and operated by the railway companies themselves

The political vision of incentives; responsibility on who takes action on critical/ noncritical cases

In general, the goal is to keep as much freight as possible on sustainable modes (rail and inland waterway), because shifting to the road is often not reversed after the disruption is solved. In the swiss case, the Federal Office of National Economic Supply (FONES) is allowed to take measures for the logistics sector, complementing the regulation by the Federal Road Office FEDRO. The measures which can be taken include easing of the night or Sunday ban for heavy truck transport, temporary more flexible working hours for truck and train drivers, temporary use of the maximum technical weight of trucks above legally allowed maximum, prioritization of train paths and terminal slots for scarce goods as well as the extension of customs opening hours at the borders (Interview A. Jeppesen, 2020). However, these measures are only used if a critical supply situation is reached, and the transport system cannot deliver necessary products for the Swiss economy or society anymore (Interview A. Jeppesen, 2020). Until this point is reached, the market system is instead responsible for actions.

Table 9 Requirements for more efficient mode shift

Category	Requirement	Number of indications
Technical	Further standardization (e.g. containerisation)	2
	More and further distributed terminals	2
	More sensors to detect disruptions quickly	1
	More infrastructure redundancy on single modes	1
Organisational	More suppliers of multimodal shipments with open mode	2
Information	Simulation and modelling tools allowing companies to enable evaluating different contingency strategies	1
	More risk analysis and precise estimations of losses due to disruptions in private companies	1
	Legally flexible contracts to allow quick mode shift	3
	Institutional and legal basis for necessary data exchange	1
	Real time information exchange between transport operators	2
	Faster post-disruption decision processes	1
Contingency Planning	Plans for disruption scenarios must be available beforehand	1
	Make issuing of an operating permission dependent on availability of a contingency plan	2
Policy	General support for multimodal transport	2
	Foster more balanced use of modes in normal operation to distribute spare capacity equally among modes	1

6.4. *Analysis of selected cases*

Another empirical method for rare events with limited data available is a case study approach. They allow us to gain insights into specific situations with certain causes for a disruption and taken response measures. Because of the rarity of these events, samples are very small, and cross-contextual predictions are not possible. Nevertheless, case studies allow to specifically compare different situations and get an initial understanding of what differences and patterns may exist (Ludvigsen & Klæboe, 2014). Therefore, the results of the case study analysis can contribute to answering the research questions. To keep the focus wide, two selected case studies, including disruptions of different modes, are investigated. The Rastatt incident in 2017 serves as a case study for a railway disruption of a major freight link, the low water in the Rhine in 2018 for an inland waterway disruption, which directly affects the swiss transport system. These case studies are analyzed by first summarizing the event and second conducting desk research on documents that tackle response actions taken in the freight transport sector. These findings are supplemented by asking interview partners who were involved in or had extensive knowledge about the freight transport management around this disruption or by asking specific questions on mode shift strategies under these disruptions. These results are then also compared between different modes and groups of interview partners. Finally, the results of all methods are synthesized into a conceptual model to answer the research questions and support formulating recommendations for the different actors. A timetable showing the temporal order of the steps can be found in the appendix 11.1.

Rastatt

On the 12th of August 2017, a tunnel collapsed during boring activities beneath the existing Karlsruhe-Basel section of the Rhine-Alpine Rail Freight Corridor caused its complete closure for almost two months until it was reopened on the 2nd of October 2017 (Fender, 2017; Railway Gazette, 2017). The section is one of the busiest railway lines in Europe for the passenger as well as freight trains, of which roughly 200 passes daily (Fender, 2017; Netzwerk Europäischer Eisenbahnen e.V., 2017). Although DB Netze, the infrastructure manager for this section, offered several alternative routes (possibly with reduced capacity and subject to extra constraints), the closure caused € 12 million turnover losses for rail freight operators each week (Netzwerk Europäischer Eisenbahnen e.V., 2017). A later conducted study on the wider economic impacts of the incident estimates losses of the added value of approximately € 2 billion, whereof rail logistic companies and their customers bear 85% (HTC, 2018). These high loss figures were caused because the alternative routes were first not as efficient as the Rhine-Alpine corridor and second, could not offer the necessary conditions (e.g., electrification, allowed train length and weight) as well as the capacity to compensate the closed link (Netzwerk Europäischer Eisenbahnen e.V., 2017; Railway Gazette, 2017). Further managerial and organizational issues, including the lack of cooperation between different infrastructure managers from neighboring countries and rail freight operators or, for example, the difficulty to run freight trains ad hoc through France, further limited response options (Netzwerk Europäischer Eisenbahnen e.V., 2017). Hence, only 40% of the theoretical capacity of the alternative routes could be utilized, and roughly two-thirds of freight trains were canceled (HTC, 2018). The rail freight industry heavily criticizes the missing contingency plans and the poor disruption management of DB Netze as well as the lack of cooperation between different European infrastructure managers and states that the disruption could have been handled much more efficiently (HTC, 2018).

Nearly every interview partner mentioned the Rastatt event as an example of a massive freight transport disruption they were affected by or know about, most of them unquestioned. It is seen as the most massive disruption in the last years and maybe even longer. Responses varied widely across the transportation sector, but the rerouting of freight trains was the immediate reaction by all operators (Interview J. Baeriswyl, 2020; HTC, 2018; Interview D. Pfister, 2020). However, as described above, this was not enough to restore enough capacity. Thus, even DB Netze planned for a mode shift strategy (DB Netze, 2017), whereas it is not clear how it was exactly shaped.

Nevertheless, from traffic counts, it is evident that mode shift to road and inland waterway happened. During the closure period in 2017, the heavy truck traffic between Karlsruhe and Basel increased by around 2,000 vehicles per day, as well as handling of goods at Basel Port increased by roughly 27% compared to figures from 2016 (HTC, 2018). These figures are much greater than usual growth would suggest and hence can be assigned to mode shift (HTC, 2018). The Rastatt case also shows the economic impact of mode shift in disruption response. Although companies using mainly road transportation for their supply chains were not directly affected by the incident, the increase in demand for road transportation led to an increase in prices, and thus these companies were indirectly affected by higher costs for their transports (Interview C. Peter, 2020).

Thereby mode shift is, in most cases, not organized by the rail freight operator but by the customer themselves (Interview J. Baeriswyl, 2020; Interview D. Pfister, 2020). The Migros group, for example, switched all freight, which previously was on the rail to road, which was quickly possible because the alternative was readily available (Interview P. Geiger, 2020). However, in general cases, contractual limitations often challenge the cost-efficient mode shift. Contracts for rail freight often have durations for multiple months or years, for which the costs must also be paid if the offer is not used by the customer (HTC, 2018). Therefore, switching to another mode in such situations causes high additional costs for the customer (HTC, 2018). However, in such a special situation, contracts often get rearranged to compensate for inconvenience and undelivered services (Interview J. Baeriswyl, 2020).

Rastatt made evidently that rail freight operators do not have enough extra rolling stock and staff available to quickly react to massive disruptions and use alternatives with different operation parameters (HTC, 2018). However, as these companies need to operate as efficiently as possible in every-day business, these spare capacities for inefficient routes are not financeable under market conditions (HTC, 2018; Interview D. Pfister, 2020). Moreover, the loss of trust in the rail freight industry was massive and different actors fear that traffic, which shifted to the road, might not shift back to rail (HTC, 2018).

Rhine Low Water

In the second half of 2018, the river Rhine had a long low water period, strongly impacting in-land navigation on the river. Due to less rainfall in central Europe from March to November 2018, the water levels fell below the river specific thresholds from which load draft and maximum loading of barges are limited. Shipping on the river was impacted on 41% of days from June to November on the Upper and Middle Rhine (Measuring Point: Maxau) and 67% on the Lower Rhine (Measuring Point: Duisburg-Ruhrort) (BFG, 2019). Especially severe were the months October and November, when shipping was continuously strongly impacted on the whole river, except a short relief phase at the end of October (BFG, 2019). Sometimes barges could only operate at one-fifth of their capacity (Hannig, 2019). This resulted in fewer trans-ported goods. At Iffezheim (Upper Rhein), 23.6% fewer goods were transported in 13.8% fewer barges than in the previous year, mostly because of the months of October and November (Weinoldt, 2019). In absolute numbers, transported goods dropped from 22.5 million t to 17.2 million t and the number of barges from 29111 to 25100 (Weinoldt, 2019). This outlines, on the one hand, the magnitude of goods transported on the river and, on the other hand, the severity of the impacts due to low water. Especially industries dependent on the delivery of bulky goods, including the chemical industry and steel production but also the provision of fuels for transportation and electricity production in power plants, were strongly impacted (BFG, 2019; Weinoldt, 2019). Only because of the Rhine, industrial production in whole Germany was up to 2% lower during the low water period (Ademmer et al., 2019), as factories upstream had to curb or even stop their production due to supply shortages (BFG, 2019). BASF, a large German chemical producer, for example, had to stop the production of an intermediate product for plastics at the plant in Ludwigshafen (Upper Rhine) because of missing supplies from 5 to 10 barges per day, which could not be fully substituted by other modes (Hanrahan, 2018; Reuters, 2018). Entirely shifting to road transport, for example, would have required up to 1600 large trucks per day, which was not feasible (Hanrahan, 2018).

The low water on the Rhine has two big differences to the other case studies investigated. The first is missing redundancy. While the European motorway system provides in most areas plenty of alternative routes and the railway system at least enables some rerouting, inland waterway transport has no direct redundancy in the system, and hence, the remaining options are mode shift or waiting (Scholten et al., 2011). The second one is that this disruption was not complete closure of the transport infrastructure, as barges were still able to operate, although with limited capacity. In a survey on low and high-water events on the Rhine conducted in 2011, it is found that thereof the first response is distributing the goods on more ships than usual (Scholten et al., 2011). Shifting to rail or road is mostly only named as the second response action (Scholten et al., 2011). This is a similar response as rail freight companies first try to reroute before shifting mode. In this study, it is also found that readiness from the industry along the river dependent on its transport function is limited. Only 25% of the companies had precautionary arrangements in 2011 (Scholten et al., 2011). Furthermore, 15% of the companies have four transport options; 50% have three, and 25% have only two (Scholten et al., 2011). While it is not specified which options are exactly meant, it is stated that companies with three or more options have more possibilities to facilitate mode shift and could cope better with low water.

Although there is no comparable recent study available, the severity of the consequences from the low water period indicates that readiness has not increased much. However, it can be assumed from the available figures that many companies have a rail or road access for delivery, which enables them to respond with mode shift. Therefore, the shift to rail, especially for bulky goods (oil, wheat, etc.) worked well until the capacity limit was reached (Interview J. Baeriswyl, 2020; Interview D. Pfister, 2020). The release of the Swiss national reserve of Oil and other products in response to shortages due to the missing barge capacity (Hauri, 2019) underlines that the railway network was not able to absorb all of the missing capacity from inland waterway transportation. Limiting factors are especially the availability of wagons, traction material, drivers, and paths (Interview J. Baeriswyl, 2020; Interview D. Pfister 2020).

Although trucks have a poor capability for transporting mass or bulky goods (Scholten et al., 2011), some shipments were transferred from the river onto the motorway (Hanrahan, 2018). However, this is often not a viable option due to high unit costs and limited capacity (Hanrahan, 2018). While the capacity of the highway network might be large enough to tolerate some additional traffic jams, the additional number of necessary trucks is not available (Scholten et al., 2011).

6.5. *Conclusions*

We reviewed the potential of mode shift to tackle disruption in the freight transport network. Mode shift can be a sufficient tool under disruptions, and further supporting measures can further increase its efficiency.

Specific sectors/actors have specific requirements on the mode shift. The rail freight operators, for example, are especially concerned about rerouting options on their own mode as well as the strict regulation. Synchromodality researchers point on the information shortages which hinder mode shifting.

Mode shift response is always a question of price and willingness to pay. The constraints identified most often are not hard barriers, but extra costs for mode shifting, for necessary technical and organizational effort. The ratio between the cost of delay and cost of mode shift has a strong influence.

Mode shift is not inherently desirable. Customers and transport operators design/choose the most efficient transport chain for their specific goal; a mode shift always increases costs and complexity from this optimum. Mode shift alone requires equipment and time, thus reducing efficiency. Government's support on combined transport and synchromodal freight transport concepts could include flexibility at a planning stage and counter those efficiency losses.

Being ready and able to implement a mode shift cannot compensate for a limited redundancy in the transport system. Redundant infrastructure/personnel would not be fully used under normal conditions, thereby causing inefficiency and costs, which must be borne by someone (e.g., customers of freight services, taxpayers, etc.). Policies should determine if financing these redundancies against better management of future uncertain disruptions or tolerating cancellations and delays. An honest, quantitative assessment of the consequences of both cases is necessary.

The findings of this research allow the construction of a conceptual model to summarize the conclusions for mode shift, reported in Figure 1. The identified factors describe the likelihood of relations between software and infrastructure resources, as well as organizational aspects, which support an authority/ transport operator/ customer towards a mode shift, as a response to disruption under some systemic conditions. Likelihood can be considered equivalent to efficiency, as both values are proportional to each other, in a profit-driven supply chain. The strength of influence from different factors differs based on the reports; we display general conclusions based on findings from previous research and interviews. The model is structured into categories of components (elements in the process of mode shift, including actors, technical components information, regulations) and their parameters representing their characteristics. The plus and minus signs indicate the direction of influence towards the likelihood that mode shift is performed. Binary parameters indicate just a distinction between *available* or *not available* (for example, availability of loading facilities at origin or destination increases the likelihood of mode shift). Discrete parameters influence the likelihood of more shift in a more continuous manner (for example, a long distance of shipment increases the likelihood of mode shift).

Given that the general focus of current academic research is more on technical aspects rather than policy and regulations, we specifically included components which can be categorized into an organizational nature, rather than only into components of technical nature. Technical components determine mostly the likelihood of mode shift via technical parameters; the influence of organizational components is mostly determined by organizational parameters. From a qualitative point of view, both categories have a similar influence on mode shift likelihood, as the number of entities and parameters is equal and very similar, respectively. Overall, the most influential parameters are of organizational nature and often pertain to information shortages and the capability of customer and transport operators to conduct mode shift.

This model is only conceptual, and cross-dependencies between different parameters are not considered, and relations are only qualitative. Future research might quantify the impacts of single parameters as well as to develop methods to incorporate organizational parameters into the model, as far as they can be modeled, described by existing data, or quantified. Current freight transportation models studying disruption response do not accurately account for mode shift; they especially miss organizational or strongly simplify organizational and technical factors. Research has identified how modeling intermodal freight networks with spatially-explicit characteristics, based on a detailed geographic information system (and not a simplified graph theory model) yields more realistic results (Ambra et al., 2019). Organizational components and their respective parameters would require the fine-grained data to be included in a large-scale freight transportation model. However, the literature review shows how complex building such a model is. This work identifies a starting set of parameters which should improve the modeling of mode shifting activities if those could be accurately described. Agent-based models, if all such data would be available, could simulate/replicate the most important trends and reactions that stakeholders take in their interest.

To support mode shift, a suitable contractual and regulatory environment is required. Industry standards in transportation to simplify quick mode shift, ranging from hardware (containerization or wagons) to software (IT-Systems for data exchange).

Terminals need to have sufficient amount and capacity but also have available contingency strategies to enable quick reaction to the unexpected aftermath of a disruption. Mode shift alone is not able to create full resilience for the freight transportation system as a whole if not accompanied by redundancy building (i.e., sufficient capacity on alternative links). Large scale mode shift under disruptions exploits available spare capacities; different stakeholders (single companies and transport operators) have more options for transporting goods and maintaining supply chains.

Contingency planning needs to encompass technical parameters and organizational parameters. The small sample of interviewed companies seems to be well-prepared for future disruptions, and readiness increased since the last major events.

Political and policy support plays a crucial role. Regulation simplifying processes in exceptional cases allow higher efficiency (see also Fialkoff et al., 2017). Switzerland already has legal tools in place, enabling the Federal Office of National Economic Supply (FONES) to ease freight transport regulation. This, however, requires political support to identify what is an emergency and the price one is willing to pay in either case.

Competition increases the pressure for efficiency, thus resulting in stronger pressure to close inefficient redundant links. Companies focus mostly on a short- or medium-term horizon to maximize profits and tend to not account for rare events. If transportation companies are obliged to keep reserves in units, or spare capacity, the reaction to disruptions could be smoother. An operation permit could, for example, be dependent on the availability of redundant units and a contingency plan. This would reduce the negative effect of competition, but also increases costs for all market participants who have to follow such a rule.

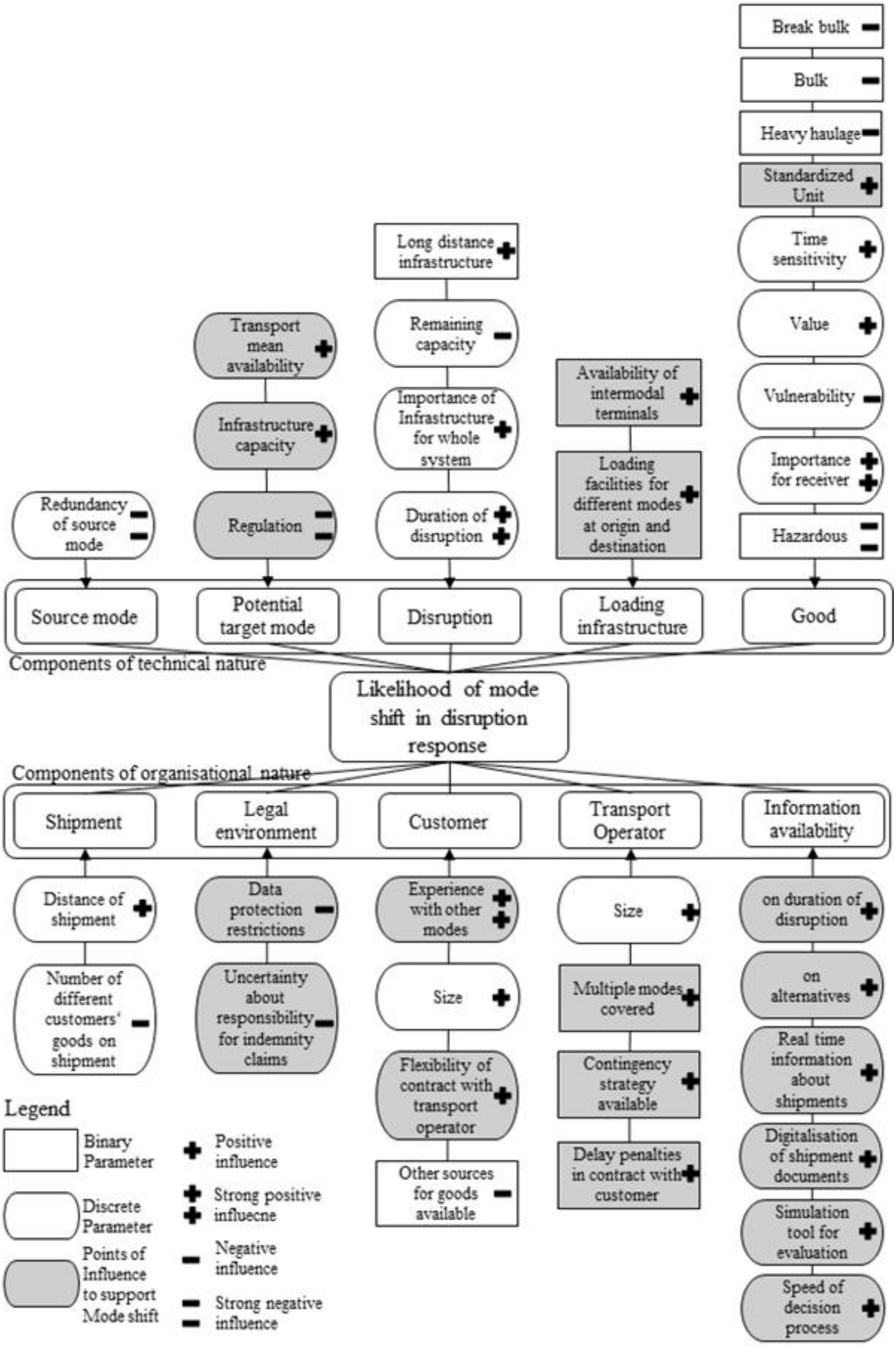

Figure 1 Summary: conceptual model of requirements and actions for mode shift in freight networks

The following Tables reports a categorization of actions which influence mode shift as response to multimodal disruptions, based on their strategic or operational point of view. In a strategic point of view, the following actions would be possible:

Table 10 Summary: Strategic actions

Infrastructure	Goods	Policy, legal, authorities	Transp Operator	Customer	Information
More intermodal terminals, larger capacity Load/unload possibility for transport means of different modes at sites	Increase standardization (e.g. waggons, containers, cranable truck trailers etc.)	Create an institutional and legal basis for real time data exchange in transportation (e.g. amend GDPR) Ease mode restrictions for certain goods (e.g. regulate container for hazardous goods but leave mode open) Have global contingency strategies; evaluate them by simulation or modelling tools Standardize post-disruption decision making processes	Distribute goods on multiple modes already in normal operations; have close partners operating on other modes Increase redundancy on all modes Have contingency strategies for internal processes; evaluate them by simulation or modelling tools More flexible contracts, like shipments with open mode	Distribute goods on multiple modes already in normal operations Have contingency strategies across multiple operators; evaluate them by simulation or modelling tools more flexible contracts with transport operators; include delay penalties	Digital transport documents, real time tracking Publish detailed and freely available information on crucial variables of the infrastructure (e.g. capacities, axle load etc.) Standardize post-disruption decision making processes

From an operational point of view

Table 11 Summary: Operational actions

Infrastructure	Goods	Policy, legal, authorities	Transp Operator	Customer	Information
Load/unload possibility for transport means of different modes at sites	Increase standardization (e.g. waggons, containers, cranable truck trailers etc.)	Clarify legal responsibility for transport disruptions; Ease regulation in disruptions Adjust contingency strategies; evaluate them by simulation or modelling tools Standardize post-disruption decision making processes	Adjust contingency strategies; evaluate them by simulation or modelling tools More flexible contracts, like shipments with open mode	Adjust contingency strategies; evaluate them by simulation or modelling tools	Early and accurate disruptions detection Digital transport documents, real time tracking Publish detailed and freely available information on crucial variables of the infrastructure (e.g. capacities, axle load etc.), specifically updated in the aftermath of a disruption Gather and honestly communicate information on disruptions Standardize post-disruption decision making processes

7. Case study: Multimodal management during a disruption in a major interurban bottleneck[2]

7.1. *Introduction*

In this chapter, we explain the approach to calculate the benefit of a multimodal management and control center in an interurban context. From the interurban bottlenecks of Switzerland, the following bottlenecks are studied: Geneva-Lausanne, Zurich-Bern, and Gotthard tunnel.

This chapter consists of the following sections; first, the detailed objectives of this case study are explained. In the second subsection, the methodology applied to this case study is described, and finally, the results for each bottleneck are provided.

7.2. *Objectives*

The main objective of this chapter is to study the benefits of multimodal management center in the interurban context. In other words, what strategies can be implemented in a multimodal management concept, and what are their benefits? To do so, we assume an extreme situation will be the best approach to evaluate the benefit of such a system. Therefore, disruption scenarios on three major bottlenecks in Switzerland are studied, including Geneva-Lausanne, Zurich-Bern, and Gotthard tunnel. Disruption is defined as bottleneck closure for the time of the study, which is based on the demand data provided by the National Passenger Transport Model. In particular, the study is made on the morning peak hour model from 7:00 to 8:00 in two implementation horizons of 2010 and 2040. For the case of the Gotthard tunnel, the data from 2017 and 2040 is used, which is the first set of data released after the tunnel got in operation. Based on the proposed methodology for the given strategies, two main performance indicators are used in this analysis: travel time and delay. In this study, we have considered only one direction for each bottleneck. Moreover, the monetary values of the delay are also calculated based on the table provided in appendix 0.

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[2] This chapter is based on:
Allegra Romano, A simplified model for transportation equilibrium analysis in case of multimodal networks (supervisors: Zahra Ghandeharioun, Luca D'Acierno) Master's thesis in Hydraulic and Transportation Engineering, Università degli Studi di Napoli Federico II, 2020

7.3. *Methodology*

In this section, the methodology used for analyzing the disruption in major bottlenecks is explained. This methodology aims to calculate the benefit of a multimodal management center in case of a disruption. To do so, first, we explain the multimodal network design problem, and by implementing the equilibrium assignment method, we describe how strategies in both sides of the spectrum of user equilibrium and system optimum can be beneficial in such a system.

7.3.1. Multimodal Networks Design Problem

The design problem of multimodal networks can be formulated through a constrained optimization model in which the proposal is to optimize (maximize or minimize) an objective function Λ, which depends on the design variables y and the flows of users on the transport system f^*:

$$\hat{y} = arg\ min\, Z(y, f^*)$$
$$y \in S_y$$

Equation 1

Subjected to a coherence constraint between supply, performance, demand, and flows and therefore the assignment constraint:

$$f^* = \Lambda(f^*, y)$$

Equation 2

Furthermore, it is subjected to an external constraint of the overall budget:

$$\Gamma(f^*, y) \leq B$$

Equation 3

The variables in the equations are:

$\hat{y}$: optimal value for the decision variable vector y

Z: objective function;

f^*: is the vector or matrix of the descriptive variable

S_y: set of admissible solutions for the decision variable y.

Λ: multimodal assignment or simulation function that links the descriptive variables to the decision variables.

B: budget.

The representation of the system and its variables can be static or dynamic. It is called assignment if it is static; if it is dynamic, it is called simulation. To solve the multimodal assignment problem, Three methodologies can be used :

I. The external approach algorithms: based on the iterative application of rigid demand assignment algorithms and demand models. In particular, each time the assignment models reach convergence, the origin-destination matrices are updated using the demand models. The external approach algorithms stop when between two successive iterations, the percentage variations of the arc flows and the origin-destination flows are below a predetermined threshold.

II. The internal approach algorithms: they have a structure similar to the rigid demand assignment algorithms but update at each iteration the origin-destination matrices using the demand models. The algorithm stops when between two successive iterations, the percentage variations of the arc flows are below a certain predetermined threshold.

III. Hyper-network approach: based on the construction of a particular network model, called hyper network, which implicitly simulates (on the net) the elasticity of the transport demand, through the introduction of fictitious arcs and appropriate cost functions. In this case, the use of a rigid demand assignment algorithm on a hyper-network is equivalent to the implementation of an elastic demand assignment algorithm.

In the current work, a simplified aggregate methodology for the multimodal equilibrium assignment is implemented in order to speed up the intervention procedures in case of extraordinary events. In fact, the problem of traditional methodologies lies in simulating the system as it requires a high computational burden due to the number of iterations required. In fact, to obtain the path costs, it is necessary to calculate the arc costs, which depend on the arc flows, etc. Obviously, this turns out to be time-consuming. Consequently, a simplified model is proposed to manage the multimodal network "in real-time." In particular, there were determined equations that, given the route flows, allow us to calculate the costs directly. Surely, this methodology is not precise as the typical ones but allows them to act promptly.

The general framework for the multimodal network design problem assumes the following configuration:

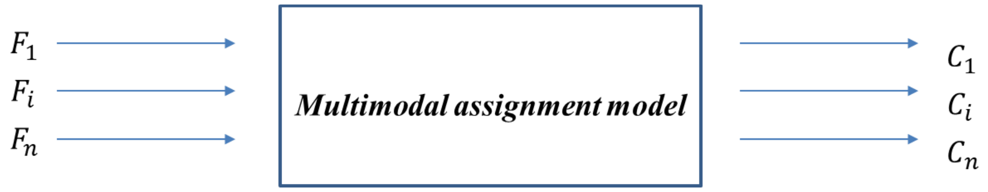


Figure 2 Multimodal assignment model

The path flows are obtained through commercial simulation software. On the market, there are several software that could be used. In particular, PTV Visum software was used in this project.

For the determination of cost functions, usually in the literature, reference is made to artificial neural networks that should be trained. Therefore, our proposal instead is to refer to functions in closed form to have faster optimization models, since by exploiting their mathematical properties, it is possible to reach convergence quickly. In this case, reference is made to multiple linear regressions.

Multiple linear regression analysis is a method used to identify the influence that independent variables have on a dependent variable.

In mathematical terms, multiple linear regression assumes a relation of the following form:

$$\hat{y}_i = \beta_0 + \beta_1 x_{1,i} + \cdots + \beta_{p-1} x_{p-1,i} + \varepsilon$$

Equation 4

where:

$\hat{y}_i$: dependent variable;

β_0: y- intercept (constant term)

β_{p-1}: slope coefficient for each independent variable. Estimated regression coefficients of the model;

$x_{p-1,}$: independent variables of the model.

ε: model's error term, also known as the residual.

p: number of the parameters.

The equation 14 can be expressed in matrix form as:

$$Y = X\beta + \varepsilon$$

Equation 5

where:

$$\mathrm{Y} = \begin{bmatrix} y_1 \\ \vdots \\ y_n \end{bmatrix} \quad n\ is\ the\ number\ of\ observations$$

$$X = \begin{matrix} x_{1,1} & \cdots & x_{p-1,1} \\ \vdots & \vdots & \vdots \\ x_{1,n} & \cdots & x_{p-1,n} \end{matrix}$$

$$\mathrm{\beta} = \begin{bmatrix} \beta_1 \\ \vdots \\ \beta_{p-1} \end{bmatrix}$$

$$\mathrm{\varepsilon} = \begin{bmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_{p-1} \end{bmatrix}$$

The term β in equation 5 can be obtained in closed form as:

$$\beta = (X^T X)^{-1} X^T Y$$

Equation 6

and so, the term ε is equal to:

$$\varepsilon = Y - X\beta$$

Equation 7

The calibration of the coefficient β is obtained by requiring the sum of the residual errors ε to be minimal. The residual error is equal to the difference between the real value and the expected value. This procedure is called the Least Squares method.

The least-squares method approximates the solution of the problem by this way:

$$\min(\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_l)^2)$$

Equation 8

As mentioned before, the input data are given by the National Passenger Transport Model. In particular, reference is made to the morning peak hour model from 7:00 to 8:00 of 2010.

The object of interest of the study is to assess the redistribution of users as a result of extraordinary events affecting infrastructure. This means that the direct consequence will be a variation in demand. Therefore, simulations were implemented in Visum in different flow scenario, the basic one and scenarios in which the demand was increased by 20%, 50%, 100%, 200%, and 400%. The result of these simulations is provided in the result section for each bottleneck.

Road capacity is considered constant in the different simulations.

The variables that have been considered are traffic flow and travel time. It is acceptable to consider only travel time because the aim is to obtain a model that can provide rapid support for the operator's decisions. Considering only travel times as model variables certainly make it less precise, but the goal is not to obtain high precision results but to have a rough estimate of the system's performance.

The demand and travel time observations obtained through the NVPM simulation in Visum are used to calibrate the cost function. The formula to express the relation between the travel time and the flow known as BPR (Bureau of Public Roads) function is used. The equation for the definition of travel times is the following:

$$T_f(f) = T_0\,[1 + \alpha\left(\frac{f}{Cap}\right)^{\beta}]$$

Equation 9

where:

T_f: travel time

T_0: free-flow travel time. It is the travel time of the road under ideal conditions (with zero flow), calculated as the ratio between length and maximum speed on the route:

f: traffic volume (vehicles/h);

Cap: capacity (vehicles/h) of the link, generally estimated according to its physical characteristics (length, number of lanes, etc.);

$\alpha\ and\ \beta$: Characteristic parameters of the link.

The parameters of the BPR were obtained through the Least Squares Method.

In the case of road traffic, there is a direct proportionality between users who choose to travel by car and the number of cars. Therefore, an increase in demand implies an increase in travel times. On the railway, the congestion is given by the number of trains. The congestion does not vary with demand. In case of invariant service assumptions, which is a condition where the infrastructure manager does not foresee a change in the number of trains in response to disturbances, an increase of users does not influence the timetable. However, the situation changes when there is a significant increase in passenger demand. In fact, the dwell time at the stops/stations, which is the time a train spends at a scheduled stop without moving, depends mainly on the number of users. If the demand is excessive, some users will be forced to take the next vehicle, and this will lead to an increase in the waiting time and so of the travel time.

In the current work, it will be assumed that the dwell time is invariant in the different flow scenarios.

Therefore, a constant cost function, independent of flow, is defined for rail transport:

$$T = T_0$$

Where T_0 is the calculated travel time.

7.3.2. Model Validation

Once the model is calibrated, it shall be appropriately validated. During the calibration phase, the significance of the estimated parameters must be verified. Significance tests and tests on the goodness of the fit were carried out.

Regarding significance tests, Student's t-test was made for evaluating the significance of each individual coefficient. The t-Student test is based on the t statistic:

$$t = \frac{|\beta_i|}{\sqrt{Var\ |\beta_{i,i}|}}$$

Equation 10

where:

β_i: Estimated regression coefficients of the model;

$\sqrt{Var\ |\beta_{i,i}|}$: Square root of the absolute value of the main diagonal of the variance-covariance matrix.

The t statistic is distributed according to a t-Student variable with a number of degrees of freedom equal to the sample size minus the number of coefficients estimated. This test checks the null hypothesis H_0 that a coefficient β_k is equal to zero and the estimate β_k is different from zero due to sample errors.

The null hypothesis is rejected with an α probability of committing an error of I species (that is to reject a true hypothesis) if the value of the t-statistic is external to the interval of extremes

$[z_{\alpha/2}, z_{1-\alpha/2}]$.

Once the statistical value t has been obtained, this must be compared with the threshold values. These values are found in the table of quantiles of the variable t-Student. This table allows finding directly, depending on the degrees of freedom n and on the probability α, the value of quantile $t_{\alpha;n}$.

Fisher's F test is made in order to evaluate the overall significance of the regression. An F-test, also known as Fisher test, is a test in which the *F* statistic has an F-distribution under the null hypothesis with n-1 and p-1 degrees of freedom:

$$F = \frac{\sum(\hat{Y}_l - \bar{Y})^2}{\sum(Y_i - \hat{Y}_l)^2} \cdot \frac{n-p}{p-1}$$

Equation 11

where:

$\hat{Y}_l$: value obtained from the model;

$\bar{Y} = \frac{1}{n} Y_i$

Y_i : observed value;

n and p are the dimensions of the two samples.

This value must be greater than $F_{\alpha/2}$ with $n-1$ and $m-1$ degree of freedom.

Fisher's test F checks the null hypothesis H_0 that all the coefficients β_k is equal to zero and that at least one of the parameters β_k is different from zero.

In addition, the statistic R^2 was calculated. R^2 is called the regression coefficient. It is a statistic that gives information about the goodness of fit of a model. It is a statistical way of measuring how of the regression predictions approximate the real data points and how much. The regression coefficient assumes values between 0 and 1. If it is equal to 1, the regression predictions perfectly fit the data.

$$R^2 = \frac{\sum(\hat{Y}_l - \bar{Y})^2}{\sum(Y_i - \hat{Y}_l)^2}$$

Equation 12

Moreover, it is also possible to calculate a corrected R^2. It is used for multiple linear regression analysis. It is used to measure the variability of Y due to variable X. As the number of explanatory variables X increases, the value of R^2 also increases.

$$R^2_{corr} = R^2 - \frac{p(1-R^2)}{N-p-1}$$

Equation 13

The results for model validation for the Geneva-Lausanne bottleneck is provided in appendix 11.2.

7.3.3. Equilibrium Assignment

Through this simplified model, the optimal redistribution of flows within the transport infrastructures in two conditions could be found. These conditions are based on Wardrope's first and second principles. The first Wardrop's principle is User Equilibrium, meaning that: The journey times on all routes actually used are equal and are not greater than those who would be experienced by a single vehicle on any unused route. On the other hand, second Wardrop's principle, know as System optimum means: At equilibrium, the journey time is at a minimum. That implies that all users behave cooperatively in choosing their routes to ensure the most efficient use of the whole system. In the transportation network, the User Equilibrium (UE) condition is naturally reached by the interaction between transportation demand and supply, and therefore in the hypothesis of absence of external interventions. On the other hand, the System Optimum (SO) is the best operational condition of the system.

Since the UE condition is not advantageous in economic terms, different strategies and policies could be implemented to manage and then redistribute transport demand. In this way, it is possible to lead the system towards its optimal operating condition, which takes the name of System Optimum (SO). In this context, it is important to emphasize that the user is a rational decision-maker who maximizes its utility. Consequently, it is not possible to act directly on transport demand, but it is possible to direct the transport demand towards the desired condition through actions on the transport demand.

The multimodal assignment is solved both for the user equilibrium and system optimum conditions. There are two assignment models: stochastic or deterministic. The difference, from a modelling point of view, lies in the hypothesis on random residues. In fact, considering the expression of perceived utility U_j^i:

$$U_j^i = V_j^i + \varepsilon_j^i \qquad \forall\, j \,\in\, I^i$$

Equation 14

This is expressed as the sum of two components: a systematic utility and a random residue. Systematic utility V_j^i represents the average perceived utility among all users with the same decision-maker context i. The random residual value ε_j^i represents the deviation of the user's perceived utility i from that value and captures the combined effects of the various factors that introduce uncertainty in the modeling of choices.

In the case of deterministic models, the perceived utility is considered deterministic and, therefore, not random. Therefore, the random residue is zero, and therefore all users choose a minimum cost itinerary:

$$U_j^i = V_j^i \quad \forall\, j \,\in\, I^i$$

Equation 15

The demand flow for each O-D pair is all assigned to the minimum cost path, while the other paths are not assigned any flow.

On the contrary, in probabilistic models, the perceived utility is considered a random variable. In this case, users go on the shortest route but on the basis of their perception of utility. Consequently, the demand will not be assigned only to the minimum cost path and so it is able to reproduce the actual users' behavior.

Both types of assignments are used. In particular, the deterministic method is used in the planning phase, as it tends to enhance the differences. In fact, it loads more the most loaded elements and discharges more the less loaded ones. Loading the most loaded elements, it is useful to design the system in order to cope with the most critical conditions. Unloading the lightly loaded elements is useful when, for economic problems, it is necessary to cut services. So, if an operator has to invest "one euro" more, launching a deterministic assignment, he is able to see which is the most loaded element and to understand which element should invest. If, on the other hand, he has to cut "one euro" launching a deterministic assignment, the most unloaded element is shown, and he understands which element to cut. In conclusion, once the intervention is oriented, indicators (noise pollution, lost time, queue length) must be calculated, and so a stochastic assignment is necessary since it reproduces the real case and makes understand what actually happens.

In the following section, the above-explained methodology is applied to the bottleneck of Geneva-Lausanne with a detailed analysis of the equilibrium assignment. For the other two bottlenecks of Zurich-Bern and Gotthard Tunnel, only the results are provided.

7.4. *Geneva Lausanne*

The model is applied to the link between Geneva and Lausanne, both located in the French-speaking Switzerland, Romandie.

The distance between Geneva and Lausanne is about 60 km. It takes approximately 50 minutes to go from Geneva to Lausanne by car using the Highway and 1 hour and a half using the Main Road. On the other hand, it takes around 35 minutes by train.

Two alternatives for private traffic and a solution for railway traffic is considered. Specifically, for private transport, reference is made to the Highway and the Main Road.

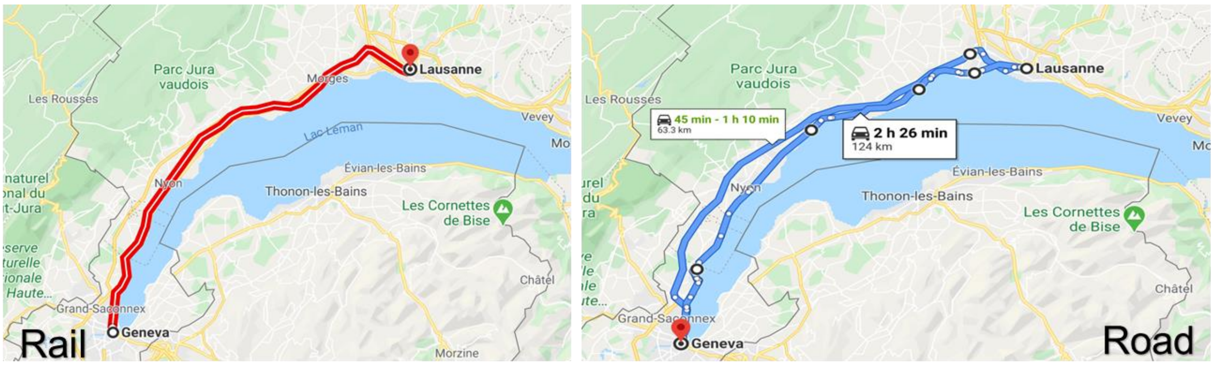


Figure 3 Rail and Road alternative routes between Geneva and Laussane- Image: Google Maps

The additional hypothesis is that the railway is closed for a disruption. Consequently, the objective is to determine the optimal redistribution of the total demand within the other two options.

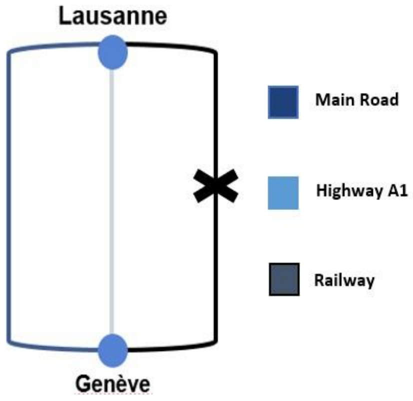


Figure 4 Disruption scenario

In the following tables, the results of the different simulations as the average flow and average travel time of links between Geneva and Lausanne in Visum are shown:

Table 12 Geneva- Lausanne Main road demand and travel time 2010

Origin: Geneva - Destination: Lausanne		
Main Road	Flow	Travel Time
	veh ph pd	h
Current state	569	0.98
plus 25%	726	1.03
plus 50%	869	1.10
plus 100%	1141	1.27
plus 200%	1616	1.73
plus 400%	2563	2.90

Table 13 Geneva- Lausanne Highway demand and travel time 2010

Origin: Geneva - Destination: Lausanne		
Highway	Flow	Travel Time
	veh ph pd	h
Current state	1813	0.83
plus 25%	2157	0.88
plus 50%	2459	0.95
plus 100%	2954	1.12
plus 200%	4056	1.57
plus 400%	6297	2.58

Figure 5 shows the BPR for the highway, for the link from Geneva to Lausanne. The same can be seen in Figure 6 for the main road:

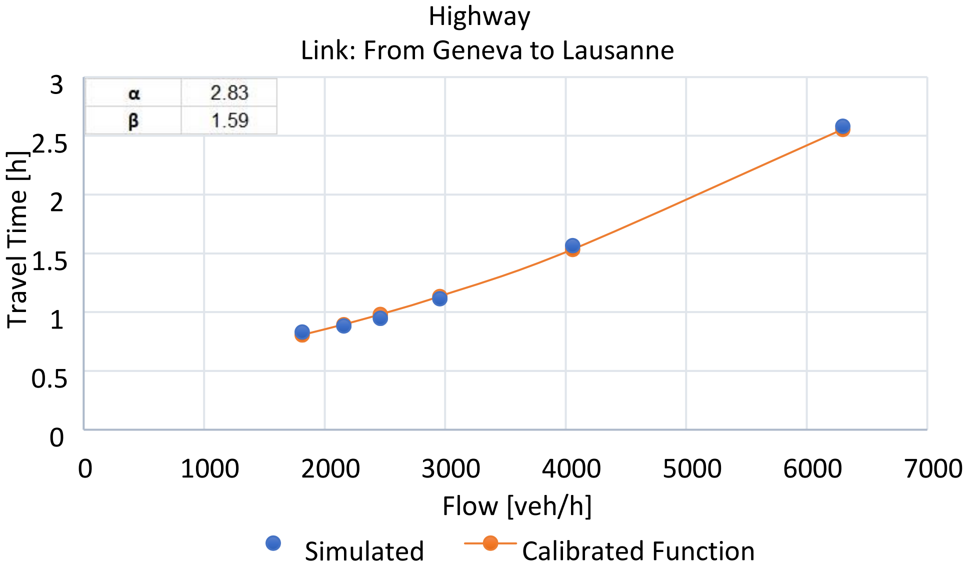


Figure 5 BPR Function Highway- Geneva Lausanne

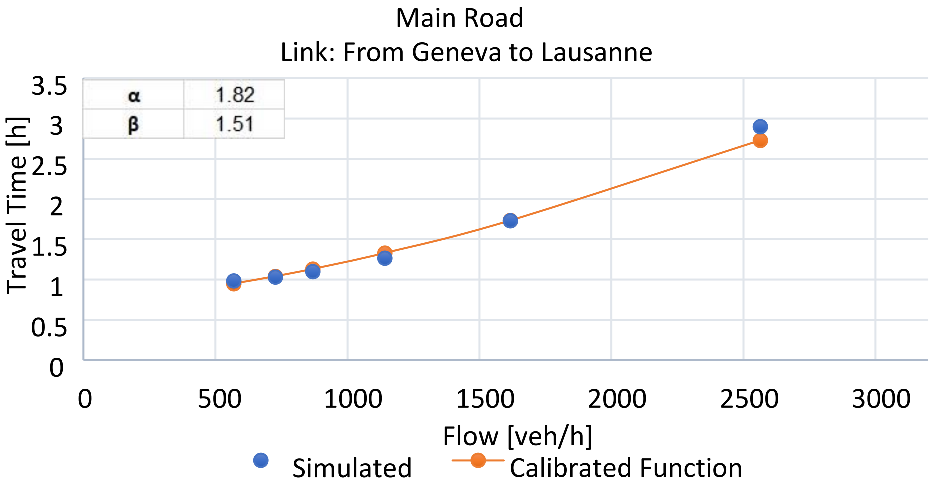


Figure 6 BPR function Main road Geneva Lausanne

The results for model validation for Geneva-Lausanne bottleneck are provided in appendix 11.2.

The same procedure was carried out for railway transport. The demand has been increased by 100 % and by 400%. The results obtained from the simulations were different from the ones for private transport. In fact, Visum is not able to reproduce and increase in travel times due to an increase in the demand on the railway. Reported generalized travel time for rail, considering different demand was always constant and equal to 1.11 hours.

In this perspective, the multimodal assignment has been implemented with a deterministic approach.

The input data are the path flows that have been obtained simulating in Visum the basic scenario:

- Main road flow: 569 veh.ph.pd [3] , Travel time: 0.98 h
- Highway flow: 1813 veh.ph.pd , Travel time: 0.83 h
- Railway flow: 2044 ppl.ph.pd [4] , Generalized Travel time: 1.11 h
- Total demand: 4085 veh.ph.pd

For the *user equilibrium*, the flows x_i on the different alternatives i are searched such that the travel time for the different alternatives i is equal. So, in this case, the equation to be solved is:

$$min|Tt_{MR1}(f_{MR}) - Tt_H(f_H)|$$

Equation 16

For the Main Road:

---

[3] Vehicle per hour per direction.
[4] People per hour per direction.

$$Tt_{MR}(f_{MR}) \; = \; T_{0_{MR}} \, [1 \; + \; \alpha_{MR} \left(\frac{f_{MR}}{Cap_{MR}}\right)^{\beta_{MR}}]$$

Equation 17

where:

$Tt_{MR}(f_{MR})$: travel time for the Main Road;

$T_{0_{MR}}$: free flow travel time, equal to:

$$\frac{L_0}{V_0} = \frac{59.8}{80} \frac{km}{km/_h} = 0.74\,h$$

α_{MR}=1.82;

β_{MR}=1.51;

f_{MR}=569 veh phpd;

Cap_{MR}=2000 veh/h.

On the other hand, the equation of the Highway is:

$$Tt_{H}(f_{H}) \; = \; T_{0_{H}} \, [1 \; + \; \alpha_{H} \left(\frac{f_{H}}{Cap_{H}}\right)^{\beta_{H}}]$$

Equation 18

where:

$Tt_{H}(f_{H})$: travel time for the Highway;

$T_{0_{H}}$: free flow travel time, equal to:

$$\frac{L_0}{V_0} = \frac{63.3}{120} \frac{km}{km/_h} = 0.52\,h$$

α_{H}=2.83;

β_{H}=1.59;

f_{H}=1813 veh phpd;

Cap_{H}=5200 veh/h.

This optimization problem is subjected to:

$$\begin{cases} f_{MR} + \; f_H = F \\ \quad f_{MR} \geq 0 \\ \quad\; f_H \geq 0 \end{cases}$$

Equation 19

f_{MR}: flow on the Main Road

f_H: flow on the Highway

F: total demand, the summation of the flows on the Main Road, on the Highway, and on the Railway, between Geneva and Lausanne.

On the other hand, in the case of *system optimum*, the flows x_i on the different alternatives *i* are searched such that the sum of travel times for the different alternatives *i* is minimal.

$$min[Tt_{MR1}(f_{MR}) + Tt_H(f_H)]$$

Equation 20

where Tt_{MR1} and Tt_H are the same as before.

Also, for the system optimum case, the optimization problem is subjected to:

$$\begin{cases} f_{MR} + f_H = F \\ f_{MR} \geq 0 \\ f_H \geq 0 \end{cases}$$

Equation 21

The optimization problem is solved in Matlab, with the *fmincon* function. Fmincon finds the minimum of a constrained nonlinear multivariable function.

7.4.1. Results based on demand data 2010

The input data are the average path flows that have been obtained by Visum simulation of the basic scenario:

- Main road flow: 569 veh.ph.pd , Travel time: 0.98 h
- Highway flow: 1813 veh.ph.pd , Travel time: 0.83 h
- Railway flow: 2044 ppl.ph.pd , Generalized travel time: 1.11 h
- Total demand: 4085 veh.ph.pd

7.4.1.1. Disruption on the railway

In the following tables, the results of the equilibrium assignment are provided when the disruption happened on the railway, and therefore all the demand shifts to the road.

Table 14 Geneva-Lausanne - User Equilibrium- Disruption on railway

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
User Equilibrium	Highway	3129	1.2	4296	0	0	0.66	2397
	Road	956	1.2	4296			0.44	1605

Monetary Value of delay:

$$0.66 \times 3129 \times 30.64 \times 1.09 + 0.44 \times 956 \times 30.64 \times 1.09 = 83{,}814\ CHF$$

Delay is calculated by subtracting the free-flow travel time from the obtained travel time. Free flow travel time for the Highway equals to 0.52 hours, and free-flow travel time for the main road equals to 0.74 hours. Also, for each vehicle occupancy rate of 1.09 persons per vehicle is used, this rate is based on the study provided by the Swiss Association of the Road and traffic experts VSS in 2007. The complete table is provided in appendix 11.4.

Table 15 Geneva-Lausanne - System Optimum- Disruption on railway

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
System Optimum	Highway	2986	1.14	4124	4847	8114	0.61	2225
	Road	1098	1.29	4671			0.55	1980

Monetary Value of delay :

$0.61 \times 2986 \times 30.64 \times 1.09 + 0.55 \times 1098 \times 30.64 \times 1.09 = 81{,}837\ CHF$.ph.pd

To have a comparison between user equilibrium and system optimum in the following table, the average travel time and delay are calculated for both cases.

Table 16 User Equilibrium and System Optimum Comparison

	Total travel time		Average travel time		Average delay	
	h	s	h	s	h	s
User equilibrium	4874.7	17549160	1.193	4296	0.614	2211
System optimum	4846.9	17449198	1.187	4271	0.600	2159

7.4.1.2. Disruption on the Highway

Highway travel time: 0.83 h and Highway current demand: 1813 veh.ph.pd

Main road travel time: 0.98 h and current demand: 569 veh.ph.pd

Railway generalized travel time: 1.11 h and the current demand on the railway: 2044 ppl

If we assume that after the highway disruption, all the demand will be shifted to rail and the demand on the main road remains the same, we will have:

Main road: 569 veh.ph.pd

Rail: 2044+ 1813x1.09= 4020 ppl

Currently, there are 5 direct trains per hour running between Geneva and Laussane, which can cover the excess demand from the disruption. It should be noted that the offered level of service by the stakeholder plays a role in the coverage of excess demand. For a higher level of service, the extra cost will be the cost of added trains according to excess demand and all the operation and planning and infrastructure costs.

7.4.2. Results based on demand data 2040

The input data are the average path flows that have been obtained by Visum simulation of the basic scenario in 2040:

- Main road flow: 687 veh phpd , Travel time: 1.03 h
- Highway flow: 2130 veh phpd , Travel time: 0.85 h
- Railway flow: 2869 ppl phpd , Generalized Travel time: 1.11 h
- Total demand: = 2130 + 687 + 2869/ 1.03 = 5602 veh.ph.pd

7.4.2.1. Disruption on the railway

In the following tables, the results of the equilibrium assignment are provided when the disruption happened on the railway, and therefore all the demand shifts to the road.

Table 17 Geneva-Lausanne - User Equilibrium- Disruption on railway 2040

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
User Equilibrium	Highway	4317	1.5	5251	0	0	0.93	3352
	Road	1285	1.5	5251			0.71	2560

Monetary Value of delay:

$$0.93 \times 4317 \times 30.64 \times 1.03 + 0.71 \times 1285 \times 30.64 \times 1.03 = 155{,}693\ CHF$$

Delay is calculated by subtracting the free-flow travel time from the obtained travel time. Free flow travel time for the Highway equals to 0.52 hours, and free-flow travel time for the main road equals to 0.74 hours. Also, for each vehicle occupancy rate of 1.03 person per vehicle is used.

Table 18 Geneva-Lausanne - System Optimum- Disruption on railway 2040

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
System Optimum	Highway	4218	1.4	5131	8156	29,361,784	0.89	3231
	Road	1384	1.5	5574			0.80	2883

Monetary Value of delay :

$$0.89 \times 4218 \times 30.64 \times 1.03 + 0.80 \times 1384 \times 30.64 \times 1.03 = 154{,}487\ CHF$$

To have a comparison between user equilibrium and system optimum in the following table, the average travel time and delay are calculated for both cases.

Table 19 User Equilibrium and System Optimum Comparison

	Total travel time		Average travel time		Average delay	
	h	s	h	s	h	s
User equilibrium	8171	29416102	1.458	5251	0.880	3170
System optimum	8154	29356974	1.455	5240	0.873	3145

7.4.2.2. Disruption on the Highway

Highway travel time: 0.85 h and Highway demand in 2040: 2130 veh.ph.pd

Main road travel time 1.03 h and demand in 2040: 687 veh.ph.pd

Railway generalized travel time: 1.11 h and the demand in 2040 on the railway: 2869 ppl

If we assume that after the highway disruption, all the demand will be shifted to rail and the demand on the main road remains the same, we will have:

Main road: 687 veh.ph.pd

Rail: 2869+ 2130x1.03= 5062 ppl

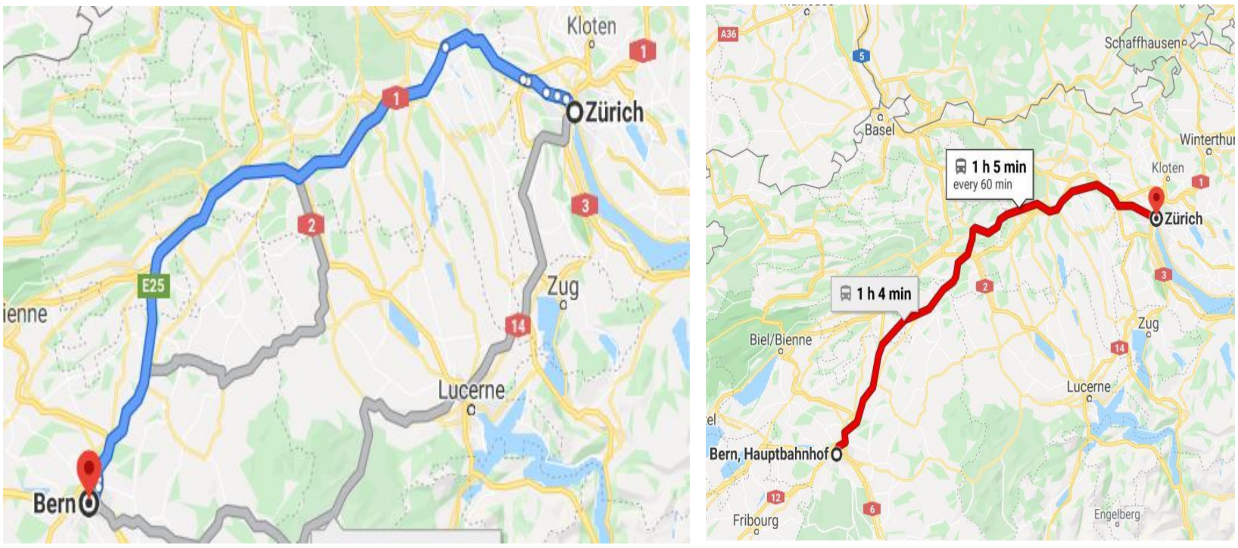
Currently, there are five direct trains per hour running between Geneva and Laussane, which can tightly cover the excess demand from the disruption. It should be noted that the offered level of service by the stakeholder plays a role in the coverage of excess demand. For a higher level of service, the extra cost will be the cost of added trains according to excess demand and all the operation and planning and infrastructure costs. Also, considering the delay for the people shifting from road to rail, dwell time, and shifting procedure should be considered as the delay experienced by the passengers.

7.5. *Zurich Bern*

The model is applied to the link between Zurich and Bern, defined as a major bottleneck in Switzerland.

The distance between Zurich and Bern is about 123 km. It takes approximately based on travel time calculated by google maps 1 hour and 40 minutes to go from Zurich to Bern by car using the Highway A1 and 2 hours and a half using the Highway A1 and A2. On the other hand, it takes around 1 hour and 5 minutes by train.

Two alternatives for private traffic and a solution for railway traffic is considered. Specifically, for private transport, reference is made to the Highway A1 and the Highway A1 and A2.



Road

A1 Highway

A1 and A2 Highway

Railway

Direct link between Zurich and Bern

Figure 7 Rail and Road alternative routes between Zurich and Bern- Image: Google Maps

Similar to the previous case study in the link between Geneva and Lausanne in section 7.4, The additional hypothesis is that the railway is closed for a disruption. Consequently, the objective is to determine the optimal redistribution of the total demand within the other two options.

The input data are also given by the National Passenger Transport Model. In particular, reference is made to the morning peak hour model from 7:00 to 8:00 of 2010.

The object of interest of the study is to assess the redistribution of users as a result of extraordinary events affecting infrastructure. This means that the direct consequence will be a variation in demand. Therefore, simulations were implemented in Visum in different flow scenario, the basic one and scenarios in which the demand was increased by 20%, 50%, 100%, 200%, and 400%. Road capacity is considered constant in the different simulations.

The variables that have been considered are traffic flow and travel time. It is acceptable to consider only travel time because the aim is to obtain a model that can provide rapid support for the operator's decisions. Considering only travel times as model variables certainly make it less precise, but the goal is not to obtain high precision results but to have a rough estimate of the system's performance.

In the following tables, the results of the multimodal assignment are provided.

7.5.1. Results based on demand data 2010

The input data are the average path flows that have been obtained by Visum simulation of the basic scenario:

- Highway A1 flow: 3500 veh.ph.pd ,Travel time: 1.19 h
- Highway A1 and A2 flow: 2577 veh.ph.pd, Travel time: 1.54 h
- Railway flow: 4200 ppl phpd, Travel time: 1.08 h
- Total demand: 9577 veh.ph.pd

7.5.1.1. Disruption on the railway

In the following tables, the results of the equilibrium assignment are provided when the disruption happened on the railway, and therefore all the demand shifts to the road.

Table 20 Zurich-Bern - User Equilibrium- Disruption on railway

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
User Equilibrium	Highway A1	6027	1.92	6914	0	0	0.91	3284
	Highway A1 and A2	3550	1.92	6914			0.89	3194

Monetary Value of delay :

$$0.91 \times 6027 \times 30.64 \times 1.09 + 0.89 \times 3550 \times 30.64 \times 1.09 = \ 288{,}691 \ CHF$$

Delay is calculated by subtracting the free-flow travel time from the obtained travel time. Free flow travel time for highway A1 equals to 1 hour and free-flow travel time for highway A1 and A2 equals to 1.03 hours. Also, for each vehicle occupancy rate of 1.09 person per vehicle is used.

Table 21 Zurich-Bern - System Optimum- Disruption on railway

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
System Optimum	Highway A1	6503	2.10	7578	3.81	13748	1.10	3948
	Highway A1 and A2	3074	1.71	6169			0.68	2449

Monetary Value of delay:

$$1.10 \times 6503 \times 30.64 \times 1.09 + 0.68 \times 3074 \times 30.64 \times 1.09 = 285{,}663 \, CHF$$

To have a comparison between user equilibrium and system optimum in the following table, the average travel time and delay are calculated for both cases.

Table 22User Equilibrium and System Optimum Comparison

	Total travel time		Average travel time		Average delay	
	h	s	h	s	h	s
User equilibrium	18395.08	66222292	1.92	6914	0.90	3250
System optimum	18333.24	65999678	1.91	6890	0.895917	3225

7.5.1.2. Disruption on the Highway

Highway A1 travel time: 1.19 h and Highway current demand: 3500 veh.ph.pd

Highway A1 and A2 travel time: 1.54 h and current demand: 2577 veh.ph.pd

Railway travel time: 1.08 h and the current demand on the railway: 4200 ppl

If we assume that after the partial disruption on highway A1 all the demand will be shifted to rail and the demand on the alternative route od highway A1 and A2 remain the same, we will have:

Highway A1 and A2: 2577 veh.ph.pd

Rail: 4200+ 3500x1.09= 8016 ppl

Currently, there are 6 direct trains per hour running between Zurich and Bern, which can not cover the excess demand from the disruption. The extra cost will be the cost of adding two more trains according to excess demand. It should be noted that the offered level of service by the stakeholder plays a role in the coverage of excess demand. For a higher level of service, the extra cost will be the cost of added trains according to excess demand and all the operation and planning and infrastructure costs. Also, considering the delay for the people shifting from road to rail, dwell time, and shifting procedure should be considered as the delay experienced by the passengers.

7.5.2. Results based on demand data 2040

The input data are the average path flows that have been obtained by Visum simulation of the basic scenario in 2040:

- Highway A1 flow: 4040 veh.ph.pd, Travel time: 1.19 h
- Highway A1 and A2 flow: 3027 veh.ph.pd, Travel time: 1.53 h
- Railway flow: 5895 ppl phpd
- Total demand: 4040+ 3027 + 5895/1.03 = 12790 veh.ph.pd

7.5.2.1. Disruption on the railway

In the following tables, the results of the equilibrium assignment are provided when the disruption happened on the railway, and therefore all the demand shifts to the road.

Table 23 Zurich-Bern - User Equilibrium- Disruption on railway 2040

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
User Equilibrium	Highway A1	7954	2.7	9811	0	0	1.72	6181
	Highway A1 and A2	4836	2.7	9811			1.69	6091

Monetary Value of delay :

$$1.72 \times 7954 \times 30.64 \times 1.03 + 1.69 \times 4836 \times 30.64 \times 1.03 = \ 689{,}215 \ CHF$$

Delay is calculated by subtracting the free-flow travel time from the obtained travel time. Free flow travel time for highway A1 equals to 1 hour and free-flow travel time for highway A1 and A2 equals to 1.03 hours. Also, for each vehicle occupancy rate of 1.03 person per vehicle is used.

Table 24 Zurich-Bern - System Optimum- Disruption on railway 2040

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
System Optimum	Highway A1	7779	2.63	9475	34792	125253765	1.62	5845
	Highway A1 and A2	5011	2.85	10286			1.82	6566

Monetary Value of delay:

$$1.62 \times 7779 \times 30.64 \times 1.03 + 1.82 \times 5011 \times 30.64 \times 1.03 = 687{,}030 \ CHF$$

To have a comparison between user equilibrium and system optimum in the following table the average travel time and delay is calculated for both cases.

Table 25 User Equilibrium and System Optimum Comparison

	Total travel time		Average travel time		Average delay	
	h	s	h	s	h	s
User equilibrium	34856.3	125482690	2.725	9811	1.707	6146
System optimum	34791.44	125249171	2.720	9792	1.702	6127

7.5.2.2. Disruption on the Highway

Highway A1 travel time: 1.19 h and Highway demand in 2040: 4040 veh.ph.pd

Highway A1 and A2 travel time: 1.53 h and demand in 2040: 3027 veh.ph.pd

Railway travel time: 1 h and the demand on the railway in 2040 will be: 5869 ppl

If we assume that after the partial disruption on highway A1 all the demand will be shifted to rail and the demand on the alternative route od highway A1 and A2 remain the same, we will have:

Highway A1 and A2: 3027 veh.ph.pd

Rail: 5869+ 4040x1.03= 10030 ppl

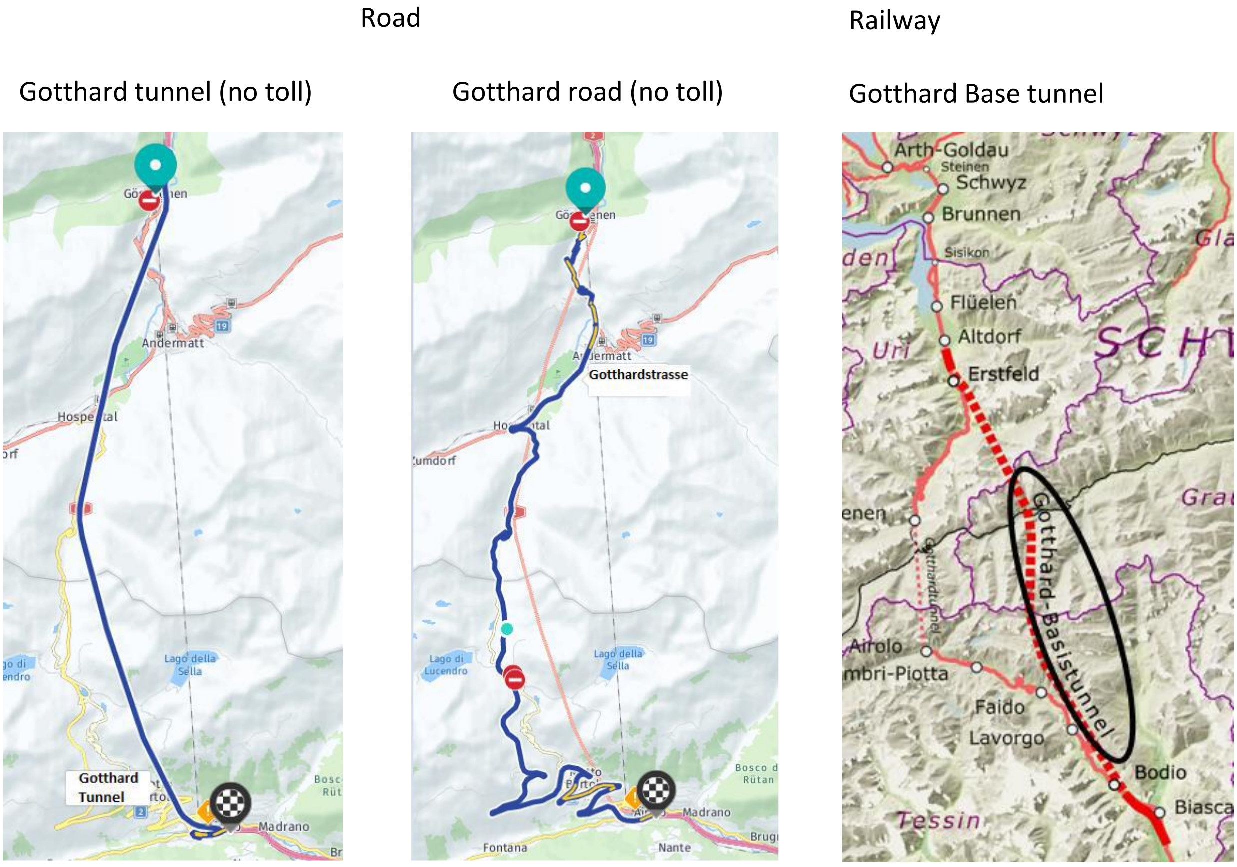
Currently, there are six direct trains per hour running between Zurich and Bern, which can not cover the excess demand from the disruption. The extra cost will be the cost of adding two more trains according to excess demand. It should be noted that the offered level of service by the stakeholder plays a role in the coverage of excess demand. For a higher level of service, the extra cost will be the cost of added trains according to excess demand and all the operation and planning and infrastructure costs. Also, considering the delay for the people shifting from road to rail, dwell time, and shifting procedure should be considered as the delay experienced by the passengers.

7.6. *Gotthard Tunnel*

The same approach studies on the Gotthard tunnel, starting from Erstfeld and ending in Bodio defined as a major bottleneck in Switzerland.

Traveling from north to south along Gotthard tunnel has two alternatives on the road,It takes approximately based on travel time calculated by google maps 40 minutes by car using the Gotthardstrasse and 45 minutes using the Highway to go from Goeschenen to Airolo. On the other hand, it takes around 30 minutes by train from Flüelen to Bellinzona.

Two alternatives for private traffic and a solution for railway traffic is considered. Specifically, for private transport, reference is made to the Highway A2 and the Gotthardstrasse. The difference of starting and ending point for rail and road are not affecting the route choice of the road users.



Road

Railway

Gotthard tunnel (no toll)

Gotthard road (no toll)

Gotthard Base tunnel

Figure 8 Rail and Road alternative routes between Goeschenen and Airolo- Image: Google Maps,wikipedia

Similar to the other case studies. The additional hypothesis is that the railway is closed for a disruption. Consequently, the objective is to determine the optimal redistribution of the total demand within the other two options.

The input data are also given by the National Passenger Transport Model. In particular, reference is made to the morning peak hour model from 7:00 to 8:00 of 2017. This is the very first demand data released by ARE after the opening of the Gotthard tunnel in 2016. This demand does not look particularly realistic, especially considering the induced demand by the new infrastructure.

The objective of the study is to assess the redistribution of users as a result of extraordinary events affecting infrastructure. This means that the direct consequence will be a variation in demand. Therefore, simulations were implemented in Visum in different flow scenario, the basic one and scenarios in which the demand was increased by 20%, 50%, 100%, 200%, and 400%. Road capacity is considered constant in the different simulations.

The variables that have been considered are traffic flow and travel time. It is acceptable to consider only travel time because the aim is to obtain a model that can provide rapid support for the operator's decisions. Considering only travel times as model variables certainly make it less precise, but the goal is not to obtain high precision results but to have a rough estimate of the system's performance.

In the following tables, the results of the multimodal assignment are provided.

7.6.1. Results based on demand data 2017

The input data are the average path flows that have been obtained by Visum simulation of the basic scenario:

- Road Gotthard Tunnel 403 veh.ph.pd, travel time: 0.25 h
- Gotthardstrasse: 15 veh.ph.pd, travel time: 0.4 h
- Railway flow: 70 ppl ph pd, travel time: 0.5 h
- Total demand: 478 veh.ph.pd

7.6.1.1. Disruption on the railway

In the following tables, the results of the equilibrium assignment are provided when the disruption happened on the railway, and therefore all the demand shifts to the road.

Table 26 Gotthard Tunnel north to south - User Equilibrium- Disruption on railway

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
User Equilibrium	Tunnel	478	0.25	905	0.19	697	0.001	5.79
	Road	≅ 0	0.44	1604			0.045	163.3

Monetary Value of delay:

$$0.001 \times 478.33 \times 30.64 \times 1.09 = 15.97\ CHF$$

Delay is calculated by subtracting the free-flow travel time from the obtained travel time. Free flow travel time for Gotthard road tunnel equals 0.25 hours, and free-flow travel time for Gotthardstrasse equals to 0.4 hours. Also, for each vehicle occupancy rate of 1.09 person per vehicle is used.

Table 27 Gotthard Tunnel north to south - System Optimum- Disruption on railway

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
System Optimum	Tunnel	478	0.25	905	120.35	433	0.001	5.97
	Road	≅ 0	0.44	1604			0.062	224.8

Monetary Value of delay:

$$0.001 \times 478.33 \times 30.64 \times 1.09 = 15.97 \ \ CHF$$

To have a comparison between user equilibrium and system optimum in the following table, the average travel time and delay are calculated for both cases.

Table 28 User Equilibrium and System Optimum Comparison

	Total travel time		Average travel time		Average delay	
	h	s	h	s	h	s
User equilibrium	120.3	433271	0.25	905	0.25	905
System optimum	120.3	433271	0.25	905	0.25	905

7.6.1.2. Disruption on the Highway

Gotthard road tunnel travel time: 0.25 h and Highway current demand: 403 veh.ph.pd

Gotthardstrasse: 0.4 h and current demand: 15 veh.ph.pd

Railway travel time: 0.5 h and the current demand on the railway: 70 ppl

If we assume that after the partial disruption on the road tunnel, all the demand will be shifted to rail and the demand on the alternative route of Gotthardstrasse remains the same, we will have:

Gotthardstrasse: 15 veh.ph.pd

Rail: 70+ 403x1.09 = 509 ppl

Currently, there are one direct trains per hour running north to south in the Gotthard tunnel, which can cover the excess demand from the disruption.

7.6.2. Results based on demand data 2040

The input data are the average path flows that have been obtained by Visum simulation of the basic scenario in 2040:

- Road Gotthard Tunnel 384 veh.ph.pd, travel time: 0.25 h
- Gotthardstrasse: 14 veh.ph.pd , travel time: 0.4 h
- Railway flow: 98 ppl.ph.pd , travel time: 0.5 h
- Total demand: 384 +14+ 98/1.03= 493 veh.ph.pd

7.6.2.1. Disruption on the railway

In the following tables, the results of the equilibrium assignment are provided when the disruption happened on the railway, and therefore all the demand shifts to the road.

Table 29 Gotthard Tunnel north to south - User Equilibrium- Disruption on railway 2040

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
User Equilibrium	Tunnel	493	0.25	900	0.15	539	0.000174	0.62
	Road	≅ 0	0.40	1440			≅ 0	0.04

Monetary Value of delay:

$$0.0001 \times 493 \times 30.64 \times 1.03 = 2.70 \ \ CHF$$

Delay is calculated by subtracting the free-flow travel time from the obtained travel time. Free flow travel time for Gotthard road tunnel equals 0.25 hours, and free-flow travel time for Gotthardstrasse equals to 0.4 hours. Also, for each vehicle occupancy rate of 1.03 person per vehicle is used.

Table 30 Gotthard Tunnel north to south - System Optimum- Disruption on railway 2040

		Flow	Travel time		Objective function		Delay	
		Veh.ph.pd	h	s	h	s	h	s
System Optimum	Tunnel	493	0.25	900	123.37	444139	0.000174	0.62
	Road	≅ 0	0.4	1440			≅ 0	0.00014

Monetary Value of delay:

$$0.000174 \times 493 \times 30.64 \times 1.03 = 2.7 \ \ CHF$$

To have a comparison between user equilibrium and system optimum in the following table, the average travel time and delay are calculated for both cases.

Table 31 User Equilibrium and System Optimum Comparison

	Total travel time		Average travel time		Average delay	
	h	s	h	s	h	s
User equilibrium	123.3	444008	0.25	900	≅ 0	0.62
System optimum	123.37	444139	0.25	900	≅ 0	0.62

7.6.2.2. Disruption on the Highway

Gotthard road tunnel travel time: 0.25 h and Highway demand in 2040: 384 veh.ph.pd

Gotthardstrasse: 0.4 h and the demand in 2040: 14 veh.ph.pd

Railway travel time: 0.5 h and the demand on the railway in 2040: 98 ppl

If we assume that after the partial disruption on the road tunnel, all the demand will be shifted to rail and the demand on the alternative route of Gotthardstrasse remains the same, we will have:

Gotthardstrasse: 14 veh.ph.pd

Rail: 98+ 384x1.03 = 493 ppl

Currently, there are 1 direct trains per hour running from north to south in the Gotthard tunnel, which can cover the excess demand from the disruption.

7.7. Conclusions

In this chapter, we aimed at estimating the benefits of a multimodal management center in an interurban context. By means of the National Passenger Transport Model and variation of demand, we could calibrate a BPR function that can provide a travel time for any given demand. We investigated the effect of closure, known as an extreme event in management, based on the BPR function and equilibrium assignment. In the equilibrium assignment, we deployed two Wardrop's principles to estimate the effects of management measures for both user equilibrium and system optimum management strategies. Travel time and delay as performance indicator could show us how much is the benefit of each approach. By translating these indicators into monetary terms, we made it easier to compare the values for further decisions.

By looking at the results in more detail, we learn that in the bottlenecks of Geneva-Lausanne and Zurich-Bern, in case of railway disruption, the system optimum shows better results comparing to user equilibrium. It is important to mention that here we have only considered the average of one hour of demand and an hour of disruption in only one direction. If we scale up the demand and the disruption in more hours, the numbers will increase significantly. Also, if the disruption happens during peak hours, the numbers are much larger compared to these results. Furthermore, we should also consider the reoccurrence of such disruption in a year.

For instance, if we look at the results at section 7.4.1.1, if a disruption occurs on the railway link between Geneva and Lausanne for one hour, and we assume that the commuters will be distributed in a way that the network reaches a user equilibrium state, the monetary value reported for the delay in user equilibrium scenario equals to 83,814 CHF. If we have a management center that can incentivize commuters to the routes and reach a system optimum state in the network, the monetary value of delay achieved at system optimum equals to 81,837 CHF. We can conclude that almost 2000 CHF per hour can be saved when deploying the system optimum management strategies compared to the user equilibrium state that will be achieved without management. It is worth to mention that we are neglecting the propagation of delay on the other parts of the network due to this disruption. In this case study, we only consider the delay that affects the direct demand on this link. It is obvious that replanning and rescheduling and effects on the other parts of the whole network of Switzerland have more costs, and a multimodal management center can be beneficial for such situations.

In the other major bottleneck: Zurich- Bern, the monetary gap between user equilibrium and system optimum is larger. If we compare the values provide in section 7.5.1.1, we can conclude that almost 3000 CHF per hour can be saved when deploying the system optimum management strategies. Both calculated numbers increase in scenarios in 2040 due to the forecasted increase in demand in the future.

In the case of the Gotthard tunnel bottleneck, the demand provided by National Passenger Transport Model is based on the year 2017, only one year after the opening of the Gotthard tunnel, which can explain the low numbers reported as average flow. The demand in 2040 is also estimated based on the demand reported in 2017. In case of a railway disruption, since the travel time on the Gotthard Strasse is larger than the Gotthard road tunnel, all the demand is shifted to the tunnel. Therefore both system optimum and user equilibrium showing the same result. It is important to mention that the demand reported by the National Passenger Transport Model for the Gotthard tunnel is not matching the current demand after the opening of the Gotthard base tunnel.

8. Case Study: Multi-modal management during a disruption in the urban area

8.1. *Introduction*

In this chapter, the benefits of a multi-modal management center in an urban context are evaluated. To do so, we have adopted different approaches based on the available simulation software: MATSim and Vissim. Similar to the previous case study, we mainly focus on a disruption scenario in an urban context to evaluate the benefits.

In the first approach, based on agent-based simulation software MATSim, we evaluate different management strategies based on proposed performance indicators.

In the second approach, by implementing different strategies in the microscopic simulation environment of Vissim, we evaluate the benefit of multi-modal management based on proposed performance indicators in the microscopic approach.

To mitigate the negative impact of disruptions, transportation operators can implement disruption management actions such as informing passengers about the disruption, assigning more capacity/frequency to the running services, temporarily altering the functionally of the lanes in roads, etc. Among the disruption management actions, informing passengers as a solution for mitigating the downsides of disruptions in public transport is very attractive, as it does not need massive investments in the infrastructure, vehicle, or personnel resources.

We show to what extent informing passengers about the disruption can help to minimize the delay. The delay varies according to the time they become aware of the disruption, and by the extent they can replan their desired trips and activities. Moreover, we analyze to what extent higher capacity/frequency of running services can help reduce the delay in the disruption and changing the behavior of passengers through time. Then, we compare the results of various disruption management actions.

In Matsim scenarios, we use a calibrated disaggregated model of demand (already used and tested in (Leng and Corman, 2020), which determines input for the agent-based simulation (also calibrated/ evaluated in many previous studies. Similarly, in Vissim scenarios, we benefit from a calibrated model of the city of Zurich provided by city authorities that are connected to the real signal planning system.

In this chapter, we continue with a more detailed problem description and methodology for each approach, and finally, the results are provided.

8.2. *Problem description and objectives*

The main objective of this study is to explore and evaluate the impacts of traffic management measures on the Zurich network's performance in case of a disrupted link. Particular attention is given to the comparison of optimization measures beyond traffic modes.We assume a disruption is an event, unexpected or unknown until shortly before, or even after its occurrence, which prevents some public transport services, cars to be run/move as planned. Possible disruptions can be related, for instance, to operational limitations, failures, accidents, adverse weather conditions, etc. The impact of disruptions to public transport or road network is large because they affect the network-wide availability of resources and limit the capacity of roads/services offered. For instance, some services cannot run anymore, as the infrastructure, vehicles, or crew required are not available at the right moment, at the right place; some other services will be unable to face greater demands.

We present two disruption scenarios for public transport (pt) and road networks. We analyze the multi-modal management action of disruption, and we evaluate that in the case of a disruption in the road network, to what extent disruption management actions in both road and public transport level can assist in mitigating the downsides of the disrupting in the road network.

In the next sections, we will explain the methodology that we have implemented for our simulation. Then, we define concepts such as disruption, directly affected agents, equilibrium, and within-day replanning.

8.3. *Agent-based simulation approach*

8.3.1. Methodology

The simulation of the impacts and dynamics of a real-life disruption in our study is performed by agent-based simulation. We also propose a state of the art within-day replanning module, which provides us with the possibility of simulating complex scenarios and realistic situations. This section explains some of the basic concepts and terminology of agent-based simulation, including iterative replanning (equilibrium) and within-day replanning.

The agent-based simulation analyzes individual behavior by modeling each traveler as an individual agent who makes their own decisions according to predefined rules. Agents interact with each other in the simulation environment where one agent’s choice affects another agent’s choice and, finally, the whole environment. According to (Russell and Norvig, 2010), an agent is “anything that can be viewed as perceiving its environment through sensors and acting upon that environment through actuators.”

The present research uses the software MATSim, described more in detail in what follows, which required specific extensions to include complex aspects of real-life dynamics and accurate analysis of the agents' behavior. We analyze the effects of multi-modal management actions on the agents' behavior and their travel time.

Equilibrium:

The simulation process of MATSim is an iterative procedure to approximate the day-to-day user equilibrium solution. One loop corresponds to one day. Eventually, an equilibrium is reached where the agents cannot further improve their plans unilaterally. In equilibrium, agents are aware of the information about the network completely.

Daily-plan

A daily-plan is the actual sequence of activities (with location and duration) and trips (with mode chosen, routes, duration). In Figure 9, a simple example of the daily-plan of an agent is illustrated. The agent to reach work from home, to reach the shopping location, and finally come back home at the end of the day. A trip is made up of one or multiple stages (continuous movements with one mode of transport) (Axhausen Kay, 2007), for instance, when agents have to transfer between two public transport vehicles.

As an example, an agent can start in the morning by traveling from Home (Activity1) to Work (Activity2) by bus (Trip 1). The day continues after work by traveling to Shopping (Activity3) by train (Trip 2), and, finally, by returning Home (Activity1) by bus (Trip 3). These concepts are described in Figure 9 (top part), along with the illustrative time (vertical) and space (horizontal) axes. For the sake of simplicity, in this example, just one stage per trip is considered.

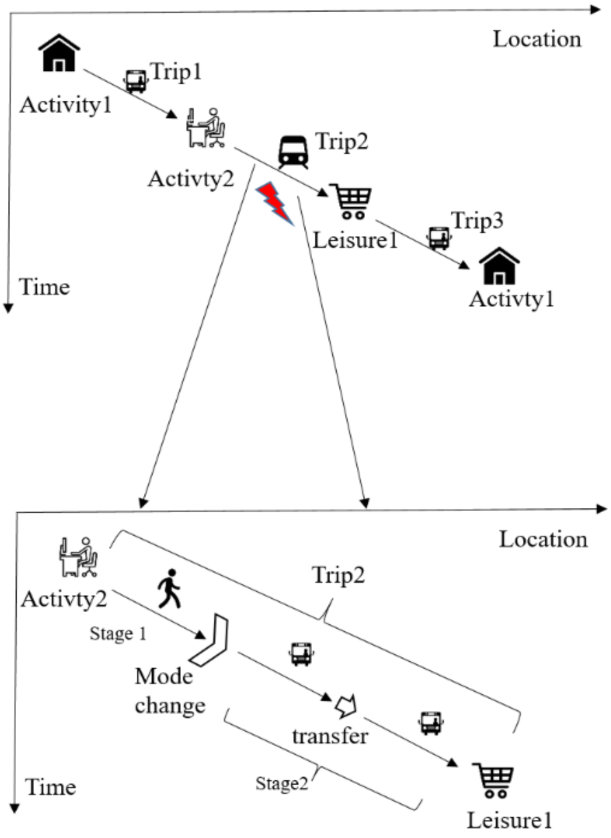


Figure 9: an explanation of traveling in agent-based simulation (top: planned; bottom: replanning in disruption)

8.3.1.1. Within-day replanning approach

An iterative (day-to-day) replanning approach is valid as long as the scenario describes a typical situation or day. However, if unexpected events happen, agents cannot anticipate. Therefore, in such a situation, a user equilibrium (and iterative approach used for a day-to-day process to find it) is not a logical choice, as it is far from reality: agents face disruptions only once; and have no information on beforehand on the alternatives (Dobler and Nagel, 2016).

A clear solution to preventing such problems is using an alternative simulation approach which does not work based on the iterative optimization process. To this end, a within-day replanning approach simulates only a single iteration, preventing problems resulting from an iterative simulation process (Dobler and Nagel, 2016).

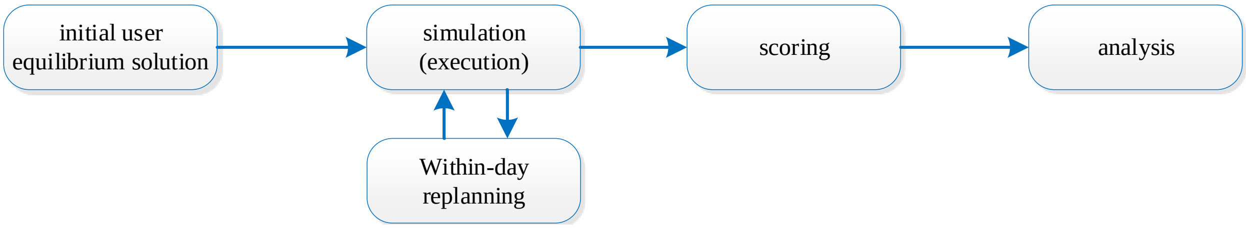


Figure 10: The agent-based simulation approach (within-day replanning)

Figure 10 shows how such a situation can be simulated. Each agent adjusts their daily-plan by means of the within-day replanning module, which is called for each agent, at a specific time, triggered when the agents become aware of the disruption (we call $T_{\text{info, a}}$ the time at which agent *a* becomes aware of the disruption).

The within-day replanning module (WR) returns as output a complete daily-plan, in which the part of being replanned is adjusted. We call this output an *adjusted daily plan*. For instance, in Figure 9, the bottom part shows how a replanning replaces the planned trip during a disruption, with a different trip involving two stages, walking, and buses, keeping the same activities, possibly facing some delay.

(Leng and Corman, 2020) develop a first within-day replanning module for public transport in MATSim. In our research, we have developed an extension to the MATSim by considering the capacity as a critical aspect of management actions in our scenarios and develop our state-of-art module to MATSim. Next, we describe the case study that we chose to test our methodology in the case of disruption in public transportation, and the management actions considered.

8.3.2. Public transport (PT) disruption: a case study of Zurich city

8.3.2.1. Case study for public transport

To test our methodology and evaluate the effects of disruption on a large multi-modal network, we chose Zürich and its public transportation system. However, the proposed methodology is not limited to any particular geographical situation and can be applied universally. We represent the population of Zürich utilizing agents, at a 1% sampling rate, that is, each agent represents 100 persons in real life; capacities of road links and vehicles are scaled accordingly. This results in 12'072 agents (it is the number of agents who commute in a day in Zurich, it is necessary means that they live in the Zurich city). We refer to a disruption affecting the core of the public transport network, namely affecting Zürich HB, which is the central rail station in Zürich, and Zürich Oerlikon, the second-largest nodal point. Between those two stations, three alternative rail infrastructure connections are running via Zürich Hardbrücke, via Zürich Wipkingen, and via the Zürich cross-city link (DML) tunnel. Services at Zürich Hardbrücke station are operated by six train lines: S6, S7, S9, S15, S16, S21. Services at Zürich Wipkingen station are also operated by six train lines: S24, RE, IC4, IR75, IR37, and IR70. The tunneled line (undisrupted) is used by eight train lines: S2, S8, S19, S14, IR36, IC8, IC5, and IC1.

A schematic view of the public transport disrupted lines and stations is illustrated in Figure 11. The disruptions are confined to geographical and time dimensions. The disruption starts at 16:00 o'clock and ends at 19:00. The dotted lines in Figure 11 represent the disrupted sections of the rail lines, while the solid lines are those sections of the rail lines, which are always available for trains to run.

Referring to this disruption, we identify agents affected by the disruption as those running at the disrupted time, on a disrupted vehicle, between the disrupted stations, in the normal day. In other words, the agents in a normal day would use any Disrupted Lines (S15, S9, S16, S6, S7, S21, S24, RE, IC4, IR75, IR37, and IR70) during the Disruption Time to travel between the Disrupted Stations (Zürich Hardbrücke, Zürich Wipkingen, Zürich HB, and Zürich Oerlikon - for IC4 Schaffhausen and finally Zürich Flughafen for lines IR75 and IR37), or traveling further, but requiring to pass over the disrupted lines. In the simulated test case, 140 agents (therefore corresponding to 14'000 people in real life) cannot perform their usual trip. These agents are called "directly affected agents", and we analyze their delay and mode choice in detail.

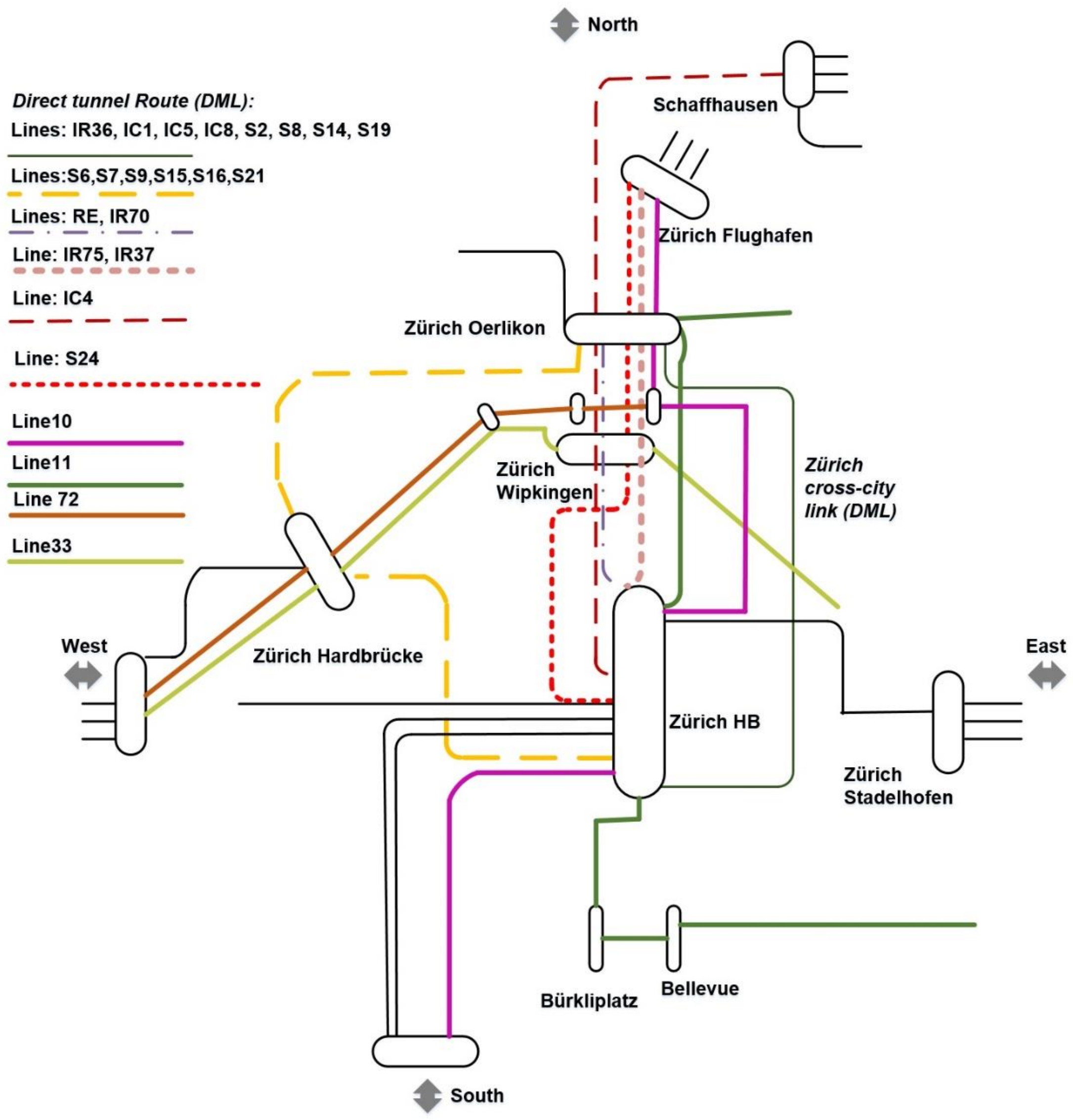


Figure 11: Details of rail elements in Zürich scenario for the considered scenario

Understanding the number of directly affected agents is essential for having a more precise delay and mode choice analysis. We should consider that disruption occurred in a specific part of the Zürich network, and therefore not all the agents experience the disruption and its consequences in the whole Zürich network. If the analysis considers all the agents, the effect will be relatively small. This is essential, especially for the delay analysis, as directly affected agents will suffer from a few minutes to hours delay time, depending on the circumstances of the scenario that we simulate. Whereas if we consider 140 agents with all the rest of 11’932 agents (all together 12'072), then the total delay will fade among the whole population of Zürich; therefore, in the delay analysis, we only consider the delay for the directly affected agents. However, a comparison in the big picture considers the whole Zürich public transport network. Furthermore, we present mode choice analysis for both categories of whole agents and directly affected agents.

8.3.2.2. Disruption management actions in public transport (PT)

In the disruption situations, management of the disruption plays a significant role in reducing the inconvenience of the passengers. We simulate scenarios based on three disruption management actions: information management, capacity management, and infrastructure management (in our case is adding to the frequency of running services). The target of this section is to expand each type of disruption management action simulated in this research and clarify in more detail.

8.3.2.2.1. Information management action

In an unexpected disruption, the behavior of the passengers is heavily reliant on the information they receive, in content and time. Having no information, passengers might be stranded at stops, wait for a public transport service which is not running, or not running on time, resulting in large delays. A disruption might also result in cancellation of activities due to a too-late arrival (i.e., arrival at work with multiple hours of delay). We consider those delays as direct effects of the disruption.

Having some information available, travelers can react accordingly, specifically adjust their travel plan to the newly implemented disposition timetable, to maximize their utility of traveling, notwithstanding the disruption. Having information available very early can be assumed to result in fewer delays, as the set of alternative choices is larger and allows for pro-active actions. Having information very late might result in larger delays, as there are little actions left to do. Therefore, the time at which travelers receive information is crucial. We identify a few relevant cases of the timing of information dissemination, which we will investigate in detail in this research that we explain as scenarios.

We assume when travelers know about the disruption, they look for adjusting at best their behavior. In general, the earlier the time at which agents would receive information, the better the reaction will be. In the case of a completely unexpected disruption, the best situation is to receive information right at the moment the disruption begins. We assume travelers can react in the following ways:

- They can become aware of the disruption at a specific time, equal for everybody (i.e., once an announcement is broadcasted to everybody at a given time).
- The time the travelers become aware of the disruption can be different for everybody, based on their time plan: think about when they finish their workday, they look for their public transport trip in a routing planner service (in this case, the time would be different for any different traveler, according to when they would finish work).
- The time the travelers become aware of the disruption can be different for everybody, based on their location: they can become aware of the disruption, for instance, once they reach a station with a display.
- Special cases also include travelers who experience the disruption on-board a disrupted vehicle and thus are forced to exit the current trip and find another way of moving forward.

We explain the related scenarios for information management and define each one based on their criteria in the simulation in MATSim in the following.

1 Scenario "Equilibrium without the disruption" is a normal day (basic scenario) without any disruption. This corresponds to a normal daily routine for the passengers. This is the base behavior, the "Equilibrium without the disruption" for the agent that is approximated through the iterative process of day-to-day replanning in the agent-based simulation. Equilibrium means that the information is fully available for the agents, and they can see anticipative network effects.

2 Scenario “Equilibrium+disruption" is the equilibrium scenario with disruption. In this scenario, the information is fully available for the agents. Agents have complete information about the

disruption, for instance, the location and the start and end time of the disruption, and about the network so they can see anticipative network effects. We discover by a day-to-day iterative approach the reaction of the other agents to the disruption. Agents adapt their travel plans through the iterations.

3 Scenario "start of the disruption" is a scenario in which agents have information about the disruption at a specific time. Agents become aware of the disruption exactly when disruption starts through the within-day replanning module in MATSim.

4 Scenario "Start of the trip" is a scenario in which agents have information about the disruption at a specific time. Agents become aware of the disruption at different times in relation to the time they intend to perform their trip, which is actually disrupted. Specifically, agents affected by the disruption have, by definition, one or more trips in their daily-plan, which cannot be performed. When the first disrupted trip is attempted to be performed, the agent becomes aware of the disruption and asks for a replanning through the within-day replanning module.

5 Scenario "None". Agents do not have any information about the disruption, specifically on their location, affected lines, and the start and end time of the disruption. Their reaction consists of waiting at the train station until the arrival of the next vehicle, of the public transport line they intended to take.

8.3.2.2.2. Vehicle capacity management action

In order to mitigate the downsides of the disruption on agents, we simulate four scenarios in which the vehicle capacity of a specific public transport line is increased to serve the agents in the disrupted public transport network. We chose tram10 that connect the Zürich HB to Zürich Oerlikon, line72 that connect Zürich Hardbrücke to the century of Zürich city, and line33, which connect Zürich Hardbrücke to Zürich Wipkingen. We have chosen those three mentioned public transport lines by using the focus group method based on the transport experts' point of view.

Therefore, we have the following scenarios:

6 Scenario "Line10-Large-Capacity-Increased" is a disruption scenario equivalent to the "start of the disruption" plus increasing the vehicle capacity (maximum number of passengers on board) of line10 for double. Line10 is a "Tram" in the network of the Zürich and has the capacity of 2 agents (each agent equals 1% of the population) in MATSim simulation, which equals to 200 passengers. On the other side, line10 has in total 289 departures in the normal day, each departure 2 agent-capacity. Therefore, a total of 2*289=578 agents/day. By simulating the "Line10-Large-Capacity-Increased" in which the vehicle capacity of line10 is increased to double, means it serves 2*578=1156 agents on a disrupted day.

7 Scenario "Line72-Large-Capacity-Increased" is a disruption scenario equivalent to the "start of the disruption" plus increasing the vehicle capacity (maximum number of passengers on board) of line72 for double. Line72 is a "Bus" in the network of the Zürich and has the capacity of 1 agent (each agent equals to 1% of the population) in MATSim simulation, which equals to 100 passengers. On the other hand, line72 has 305 departures on a normal day, each departure 1 agent-capacity. Therefore, a total of 1*305=305 agents/day. By simulating the "Line72-Large-Capacity-Increased" in which the vehicle capacity of line72 is increased to double, it means that it serves 2*305=610 agents/disrupted day.

8 Scenario "Line33-Large-Capacity-Increased" is a disruption scenario equivalent to the "start of the disruption" plus increasing the vehicle capacity (maximum number of passengers on board) of line33 for double. Line33 is a "Bus" in the network of the Zürich and has the capacity of 1 agent

(each agent equals 1% of the population) in MATSim simulation, which equals to 100 passengers. On the other hand, line33 has in total 322 departures in the normal day, each departure 1 agent-capacity. Therefore, a total of 1*322=322 agents/day. By simulating the "Line33-Large-Capacity-Increased" in which the capacity of line33 is increased to double, it means that it serves 2*322=644 agents/disrupted day.

In order to have a more precise evaluation, by the simulation, we identify which public transport line is mostly used by directly affected agents. Based on our results, 140 directly affected agents travel mostly with line11, after those disrupted lines. Therefore, we add another scenario as:

9 Scenario "Line11-Large-Capacity-Increased" is a disruption scenario equivalent to the "start of the disruption" plus increasing the vehicle capacity (maximum number of passengers on board) of line11 for double. Line11 is a "Tram" in the network of the Zürich and has the capacity of 2 agents (each agent equals 1% of the population) in MATSim simulation, which equals to 200 passengers. On the other side, line11 has in total 299 departures in the normal day, each departure 2 agent-capacity. Therefore, a total of 2*299=598 agents/day. By simulating the "Line11-Large-Capacity-Increased" in which the capacity of line11 is increased to double, it means that it serves 2*598=1196 agents/disrupted day.

For a summary of the discussed data, Table 32 illustrates the statics data of the mentioned lines, their capacity, and the changes over the management actions.

Table 32: Summary of simulated lines' data, their capacity, and the changes over the management actions

line id	Number of Transit routes	Number of Departures Per each transit line	Capacity on a normal day, agent(s)/day	Large increased capacity in a disruption day agent(s)/ disruption-day
Line10	7	11	2 per vehicle	4 per vehicle
		128		
		9		
		9		
		127		
		2		
		3		
In total: Line10	7	289	578	1156
Line72-Large-Capacity-Increased	8	3	1 per vehicle	2 per vehicle
		7		
		4		
		2		
		139		
		4		
		6		
		140		
In total: Line72-Large-Capacity-Increased	8	305	305	610
Line33-Large-Capacity-Increased	10	21	1 per vehicle	2 per vehicle
		138		
		5		
		3		
		3		
		6		
		5		
		136		
		3		
		2		
In total: Line33-Large-Capacity-Increased	10	322	322	644
Line11-Large-Capacity-Increased	11	1	2 per vehicle	4 per vehicle
		1		
		4		
		3		
		9		
		3		
		139		
		138		
		1		
		2		
		7		
In total: Line11-Large-Capacity-Increased	11	299	598	1196

For further analysis, we increase the vehicle capacity of the whole network, with three criteria: increasing the vehicle capacity for the whole day, increasing the vehicle capacity after the disruption is started, and increasing the vehicle capacity and simulate the equilibrium (day-to-day) situation.

We simulate two levels of increase (again, in vehicle capacity for the running services) for the Zürich city network. Increasing the vehicle capacity of the whole network by 100%, the Large (L) increase, and increasing the vehicle capacity of the network by 39.67%, the Medium (M) increase, which is the minimum meaningful for this sampling rate of population.

A large increase in the vehicle capacity of the whole transport network requires a huge investment. However, we have mentioned it as illustrating an optimum solution comparing with our other scenarios. Increasing the vehicle capacity of the network of Zürich to a Medium increase of 39.67% is the minimum meaningful amount for our sampling rate of population.

10 Scenario "Medium-Capacity-Increased-allDay" is a disruption scenario equivalent to the "start of the disruption" plus increasing the vehicle capacity of the whole network by 39.67% (medium increase) during the whole day. By increasing the vehicle capacity of the whole transport system by medium for the whole day, the transport system can serve 233'608 agents/disruption-day.

11 Scenario "Medium-Capacity-Increased-PostDisr" is a disruption scenario equivalent to the "start of the disruption" plus increasing the vehicle capacity of the whole network by 39.67% for after the disruption starts, which in our case is after 16 o'clock. By increasing the vehicle capacity of the whole transport system by medium after the disruption started, the transport system can serve 195'446 agents/disruption-day.

12 Scenario "Equilibrium+Medium-Increase-Capacity" is an equilibrium scenario equivalent to “Medium-Capacity-Increased-allDay" plus running through the day-to-day iterations. In this scenario, we have increased the vehicle capacity of the whole transport system by 39.67% for the whole day and running through the equilibrium; therefore, the transport system serves 233'608 agents/disruption-day.

13 Scenario “Large-Capacity-Increased-allDay” is a disruption scenario equivalent to the "start of the disruption" plus considering a large increase (100%) in the vehicle capacity of the whole network for the whole day. In the disruption day, the public transport of Zürich has the capacity to serve 167'257 agents per day. In this scenario, we have increased the vehicle capacity of the whole transport system by 100% for the whole day; therefore, the transport system serves 334'514 agents/disruption-day.

14 Scenario “Large-Capacity-Increased-PostDisr” is a disruption scenario equivalent to the "start of the disruption" plus increasing the vehicle capacity of the whole network to 100% for after the disruption starts, which in our case is after 16 o'clock. In the disruption day, the public transport of Zürich has the vehicle capacity to serve 167'257 agents/day. In this scenario, we have increased the vehicle capacity of the whole transport system by 100%after the disruption starts; therefore, the transport system serves 239'722 agents/disruption-day.

15 Scenario “Equilibrium+Large-Increase-Capacity” is an equilibrium scenario equivalent to “Large-Capacity-Increased-allDay” plus running through the day-to-day iterations. In the disruption day, the public transport of Zürich has the vehicle capacity to serve 167'257 agents/day. In this scenario, we have increased the vehicle capacity of the whole transport system by 100% for the whole day and running through the equilibrium; therefore, the transport system serves 334'514 agents/disruption-day.

For a summary of the discussed data, Table 33 illustrates the statics data for the capacity of the Zürich public transportation network and the changes over the management actions.

Table 33: Zürich public transportation network vehicle capacity and the changes over the management actions

Network	Total Zürich network of public transport
Zurich-Network-Capacity (agents/allDay)	167,257
Zurich-Network-Large-Capacity-Increased (agents/allDay)	334'514
Zurich-Network-Large-Capacity-Increased (agents/PostDisruption)	239'722
Zurich-Network-Medium-Capacity-Increased (agents/allDay)	233'608
Zurich-Network-Medium-Capacity-Increased (agents/PostDisruption)	195'446

Table 33 shows that the network of Zürich can serve 167,257 agents on a normal day. In the case of medium increase in the network, the number of agents whom the public transport of Zürich can serve them is 39.67% more than the normal day, by comparing the value in Scenarios "Zurich-Network-Medium-Capacity-Increased(agents/allDay)“ and "Zurich-Network-Capacity(agents/allDay)". Such a medium increase is the minimum meaningful for this sampling rate of population.

8.3.2.2.3. Frequency management action

Although both increasing frequency and capacity of vehicles impose extra operational costs in the public transport network, the former needs the reallocation of drivers and rolling stock, whereas the latter needs altering in rolling stock composition and assignment of drivers.

From the passengers’ point of view, more frequency is preferred over larger vehicles. Although they both frequency and vehicle capacity management actions mitigate the on-board crowding problem resulting from the disruption situations, the higher frequency also leads to shorter delay, compared to increasing vehicle capacity scenario.

The objective of this section is to test our mentioned statement to determine whether higher frequency in the public transport network yields to the better impact of service variations considering agents' delay. Besides, determining to what extent higher frequency impacts agents' delay compared with the increasing capacity of vehicles. To this end, we propose the following scenario:

16 Scenario "Line10-Frequency-Increased". For line10, we simulate a situation in which the frequency of the line10 is increased by double. Line10 has 289 departure-vehicle/day. As each vehicle from line10 has the capacity of 2 agents, therefore in total, line10 has the vehicle capacity of 578 agents/day. By increasing the frequency of line10 to 100%, then the number of frequencies increased to 578 departure-vehicle/day, and therefore it has the capacity of 1156 agents/disruption-day.

A higher frequency of running services must be assigned in the appropriate interval between the original-departures according to the timetable. Besides, it should be expanded throughout the day to serve agents effectively. Line10 runs every 7 minutes in peak hours. However, the frequency in other parts of the day is extremely varied. In our simulation, because Line10’s frequency varies based on the time of the day, we add the extra frequency of line10, five minutes after each original-departure results for PT.

8.3.2.3. Results for PT disruption

8.3.2.3.1. Delay analysis for public transport (PT) disruption

Now that the disruption management actions and scenarios are explained, we can compare the delay that directly affected agents' experience in each scenario in Table 34. Activity-delay is the difference between the arrival time at activities in the "Equilibrium without the disruption" scenario and the arrival time at activities, in each disrupted scenario, for all directly affected agents. Considering the delay for each activity per agent compare to the "Equilibrium without the disruption" after the disruption start time (after 16 o'clock) until the end of the day. This delay is labeled as activity-delay. As the "Equilibrium without the disruption" is the reference for the activity delay; therefore, the amount of activity-delay is zero for this scenario. By having the total delays (sum) for agents, and the value of time (please refer to

Value of Time in appendix 11.3), we can compute the monetary value. Monetary value is presented for activity-delay. The results of the monetary value of time for the delay that agents experienced can be found in Table 34.

By comparing the monetary value in the scenario "Medium-Capacity-Increased-PostDisr " with the scenario "Start of disruption" in Table 34, we can conclude that if increase the capacity of pt in the disruption situation after the disruption occurred by medium-range, the average delay directly affected agents experience reduced by 15.7% and therefore, yields to save 11486 CHF monetary value time of agents

Table 34: Delay analysis for the disruption in Zürich comparing in scenarios for 140 affected agents

Scenarios	**Activity-delay (minutes)**								**Monetary value of time (CHF)**	**Monetary value percentage compared with Start of disruption**
	average	min	25%	50%	75%	90%	max	Total delay		
None	92.85	0	38.62	88.6	125	180	300	10677	602503	723.9%
Start of trip	14.73	0	1.98	10.4	23.45	33.8	76.13	2062	95582	30.7%
Start of disruption	11.27	0	0.02	6.39	15.51	30.39	76.13	1577	73131	0.0%
Equilibrium+ disruption	5.3	-52.74	-0.01	0.83	7.55	26.13	93.52	742	34391	-53.0%
Line10-Large-Capacity-Increased	11.16	0	0.02	6.36	15.02	30.39	76.13	1562	72417	-1.0%
Line10-Frequency-Increased	11.11	0	0.02	6.39	15	30.04	76.13	1555	72092	-1.4%
Line72-Large-Capacity-Increased	11.37	0	0.02	6.08	17.74	31.63	76.13	1591	73779	0.9%
Line33-Large-Capacity-Increased	11.34	0	0.02	6.39	15.51	30.39	76.13	1587	73585	0.6%
Line11-Large-Capacity-Increased	9.43	0	0.02	4.05	12.16	27.89	76.13	1320	61191	-16.3%
Medium-Capacity-Increased-allDay	9.46	0	0.02	5	14.47	28.38	59.48	1324	61385	-16.1%
Medium-Capacity-Increased-PostDisr	9.5	0	0.02	4.61	14.47	28.7	59.48	1330	61645	-15.7%
Equilibrium+Medium-Increase-Capacity	4.49	-47.44	-0.02	0.45	7.43	15.06	300	628	29135	-60.2%
Large-Capacity-Increased-allDay	9.07	0	0.02	4.51	14.05	28.35	59.48	1269	58855	-19.5%
Large-Capacity-Increased-PostDisr	9.12	0	0.02	4.14	14.05	28.38	59.48	1276	59179	-19.1%
Equilibrium+Large-Capacity-Increase	3.01	-50.83	-0.72	0	5.5	15.06	300	421	19531	-73.3%

We also analyzed to figure out the most used vehicle/line by the directly affected agents. Line11 was the most non-disrupted line used by the directly affected agents. As it can be observed in Table 34 that adding to the vehicle capacity of line11 ("Line11-Large-Capacity-Increased") results in less delay for directly affected gents comparing to increasing the capacity of the line10 ("Line10-Large-Capacity-Increased"). Therefore, by considering the travel behavior of affected agents, authorities can make a more efficient decision and offer a better option for the management of the disruption.

Besides, from Table 34, the following points can be concluded:

- By implementing the information strategy as a management action of disruption to mitigate the downside of the disruption, if agents become aware of the disruption at the Start of disruption, instead of when they want to start their trip, their delay decreased by 23.48%, and the result in saving 22451.94 CHF (30.7%) monetary value time of agents.

- Information strategy plays a significant role in disruption management as a disruption management action for reducing the delay that agents experience. In Table 34, it can be seen that informing agents about the disruption, at the start time of the disruption, can reduce the delay the same as scenarios in which increasing the capacity/frequency of lines used as a disruption management action. In Scenario “Start of disruption,” agents experience an average of 11 minutes delay while agents in scenarios “Line10-Large-Capacity-Increased”, “Line10-Frequency-Increased”, “Line72-Large-Capacity-Increased” and “Line33-Large-Capacity-Increased” also experience an average delay of 11 minutes.

- However, if an analysis has been done to figure out the most used pt line by the directly affected agents, and then increase the capacity of that particular pt line, then it results in significantly less delay for directly affected agents. Therefore, by considering the travel behavior of affected agents, authorities can make a more efficient decision and offer a better option for the management of the disruption. Agents in scenarios “Line11-Large-Capacity-Increased” experience on average 9 minutes delay, which is around 18% less than scenarios “Start of disruption”, “Line10-Large-Capacity-Increased”, “Line10-Frequency-Increased”, “Line72-Large-Capacity-Increased”, and “Line33-Large-Capacity-Increased”.

- By increasing the capacity of vehicles in the public transport network as a management action of disruption, the scenario “Large-Capacity-Increased-PostDisr” yields to 19.1% reduction in the delay that agents experience, compared with the scenario “Start of disruption”. Whereas by a medium increase, scenario “Medium-Capacity-Increased-PostDisr”, we can have quite the same result with a reduction of 15.7%. The same comparison can be extended to the monetary value of time illustrated in a separate column in Table 34.

- By comparing "Line10-Large-Capacity-Increased" and "Line10-Frequency-Increased" scenarios, we can see that our simulation produces results according to our statement that adding to the frequency yields to less delay that agents experience compared with adding to the capacity of vehicles. Although increasing the settings of service frequencies and vehicle capacities have significant consequences for operational costs.

- Increasing the vehicle capacity of pt vehicles to a medium level can have quite the same effect on agents (causes a reduction of 19.1% in the delay) compared with increasing the capacity of pt vehicles by a large level (causes a reduction of 15.7% in the delay).

- Adding to the frequency of a line with fixed departure time yields to 0.4% less delay that agents experience compared to adding to the capacity of vehicles.

8.3.2.3.2. Mode choice analysis for PT disruption

The mode choice analysis in this research is based on each stage that agents traveled and for the whole day (before and after disruption time). The stage is continuous movements with one mode of transport. Each trip can include one or more stages. For example, an agent may go from work to home (one trip) with walking to the nearest bus station (stage1), then traveling with bus80 (stage2), then train S5 (stage3) and then bus215 (stage4). Therefore, in the mentioned example, the mode choices of the agent consist of 25% walk-mode (he passed one stage by walking), 50% Bus-mode (he passed two stages by buses), and 25% train-mode (he passes one stage by train).

We have the four modes of traveling, public transportation (pt), car, walk, and bike. In order to have a more precise investigation, pt- mode is also divided into the bus, tram, train, and other modes.

The percentage of statistics of the mode choice under different scenarios are shown in Figure 12. The X-Axis shows the scenarios, Y-axis, the percentage, varying from 0 to 1; the mode choices are represented in the legend with specific colors. The number on the right side of each column in the Figure stands for the sum of all pt vehicles' types, illustrated in the legend with red color.

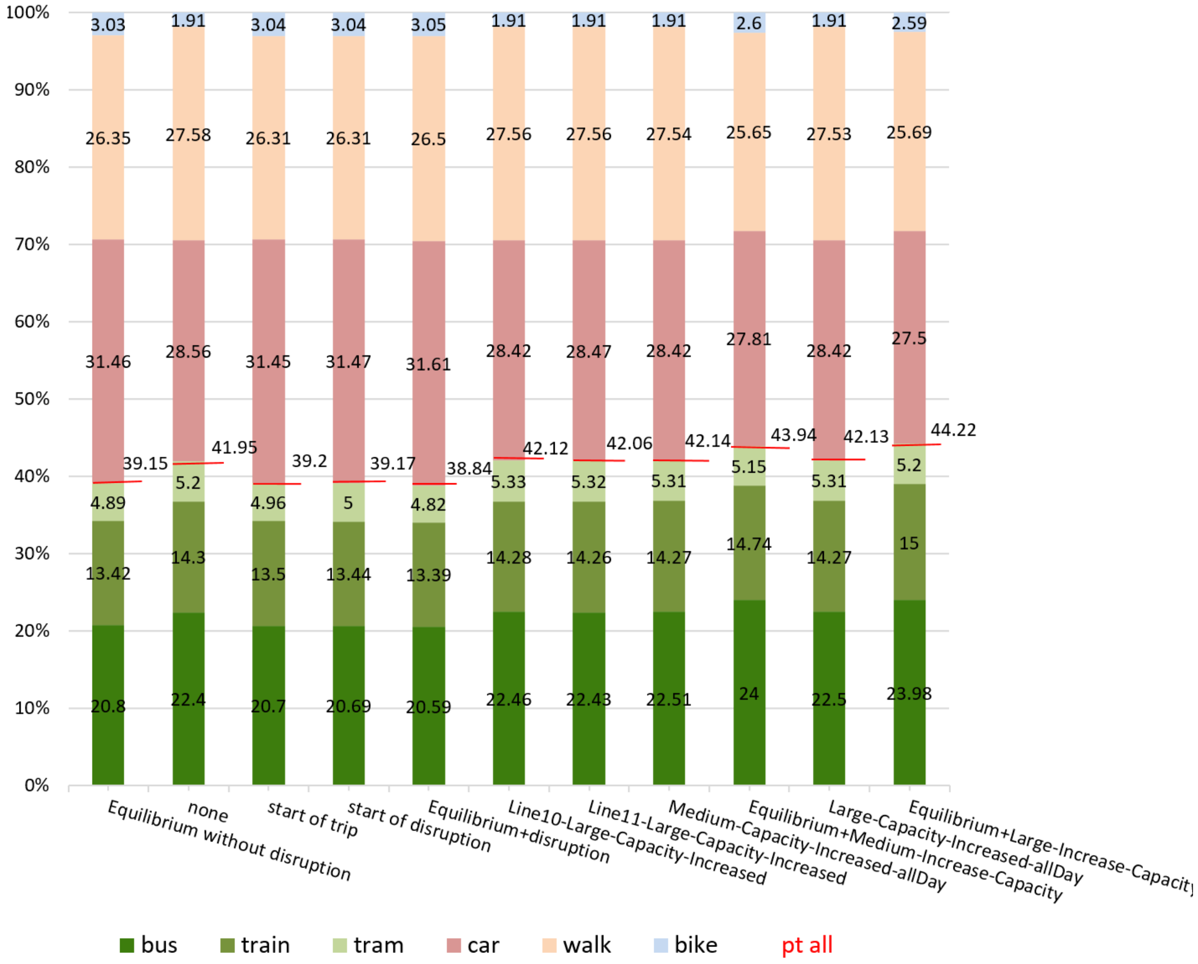


Figure 12: mode choice analysis in scenarios for all agents (based on each stage that agents traveled)

Figure 12 shows the following points:

- Among the mode choices of traveling, pt-mode is the most used means of transport by the agents in the scenarios. In more detail, the bus-mode among four categories of pt-mode is the most used pt-mode by the agents. After pt mode, the rank of the most used mode of traveling is the car, then walk, and finally bike, with the lowest usage.
- Among the different vehicle types of pt mode, the bus has the highest number of usages by the agents.
- By comparing "Equilibrium without the disruption" and “Equilibrium+ disruption” scenarios, it can be seen that in equilibrium solution in the case of disruption, overall usage of pt (sum of all sort of vehicles' types in pt) experiences a decrease of 0.51%, while increases of 0.15% in using car-mode, 0.15% in walk-mode, and 0.02% in using a bike-mode. It means that disruption in the pt yields a decrease in using pt-mode while a slight increase in other modes of travel.
- Comparing "Equilibrium without the disruption" and “Equilibrium+Medium-Increase-Capacity”, we can see that a medium increase in the pt capacity, even in disruption situation, yields to an

increase of 4.79% in choosing pt-mode (sum of all sorts of vehicles' types in pt) by the agents, whereas a decrease of 3.65% in choosing car-mode by the agents.

- In general, by increasing the vehicle capacity (scenarios “Equilibrium+Medium-Increase-Capacity” and “Equilibrium+Large-Increase-Capacity”), more agents are willing to use the pt mode, while fewer agents willing to use car-mode.
- Besides, by comparing the results in “Equilibrium+Medium-Increase-Capacity” and “Equilibrium+Large-Increase-Capacity” scenarios, it can be observed that a large increase in the vehicle capacity of trains results in an increase of 0.28% in usage of train-mode and an increase of 0.05% in usage of tram-mode by the agents. Nevertheless, as the capacity of buses in the scenario, “Equilibrium+Medium-Increase-Capacity” is increased by large-range, while other sorts of pt vehicles experience an increase in vehicle capacity by medium-range, it can be observed that bus-mode attracts more attention by the agents in “Equilibrium+Medium-Increase-Capacity,” comparing to “Equilibrium+Large-Increase-Capacity.”

Therefore, we can conclude that a medium increase in the pt vehicle capacity results in quite the same effect on the mode choice of agents in the network compared to a large increase in the capacity (by 100%) that indeed requires a huge amount of investment.

8.3.2.3.3. Mode choice analysis for directly affected agents

So far, we have investigated the mode choice for all agents. However, in the disruption's situation, not all the agents are affected by the disruption. Therefore, in order to investigate more precisely the effects of the disruption on the affected agents and the impact of vehicle capacity management of those affected agents, it is necessary to do extra mode choice analysis for 140 affected agents by the disruption. In this section, we quantify the mode choice in scenarios for directly affected agents by the disruption.

The statistics of the mode choice percentage under different scenarios are shown in Figure 13. Similar to Figure 12, The X-Axis shows the scenarios, Y-axis, the percentage, varying from 0 to 1; the mode choices are represented in the legend with specific colors.

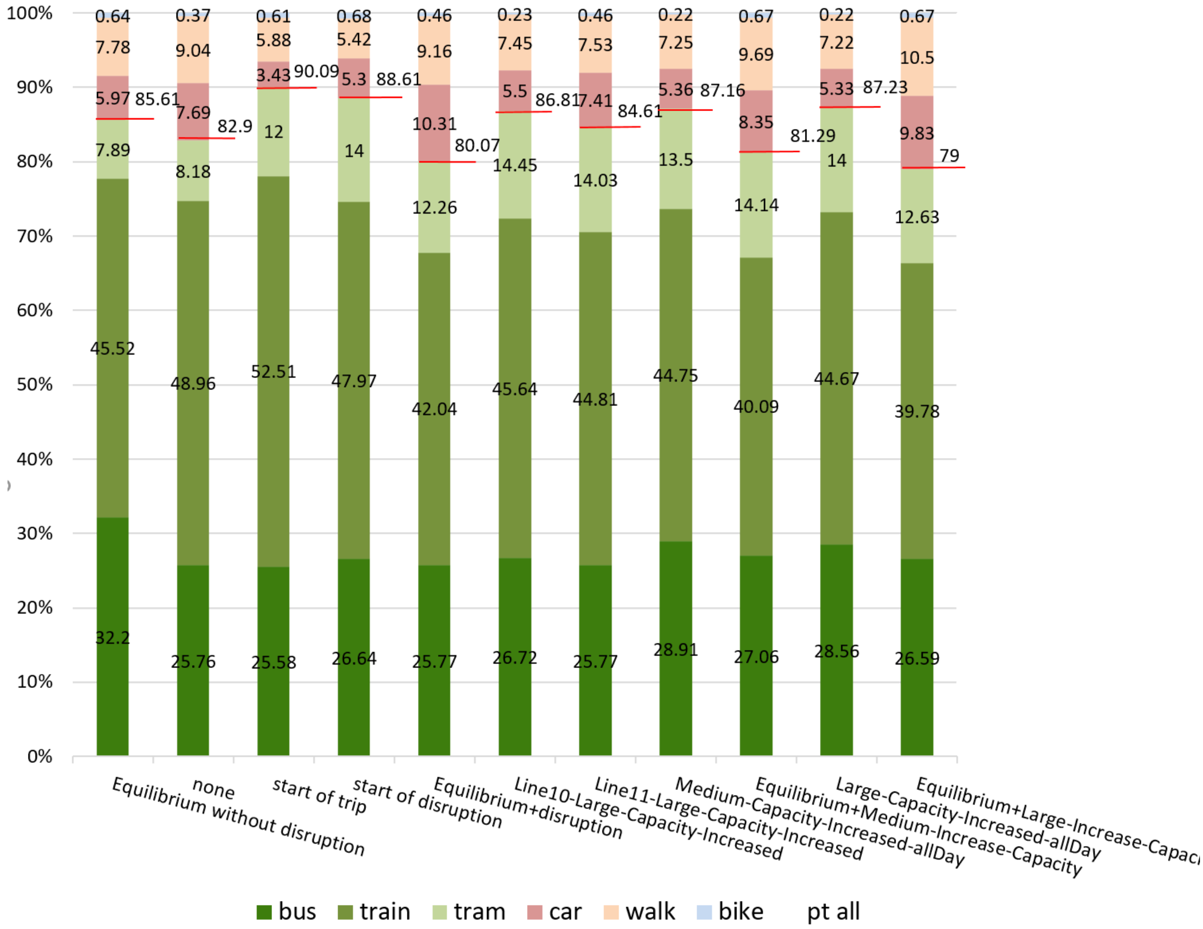


Figure 13: mode choice analysis in scenarios for affected agents (based on each stage that agents traveled)

The main points in Figure 13 are:

- Disruption yields to less usage for almost all sort of pt by directly affected agents, and yield to an increase in using car-mode, comparing the “Equilibrium+ disruption” with "Equilibrium without the disruption" scenarios. This outcome is similar to that of the previous section for all agents.

However, a few points are showing that disruption causes special effects on the directly affected agents, which comes as following compare with all agents.

- The second highest chosen mode is "bus", and "car" mode stands as the third priority for the affected agents.

- By comparing "Equilibrium without the disruption" and “Equilibrium+ disruption”, we can see that disruption in the train-mode shifts directly affected agents to use tram-mode as a substitution.

- By comparing "Equilibrium without the disruption" with other disrupted scenarios, it can be seen that disruption leads to a decrease of using train-mode by 1.43% in “Equilibrium+ disruption” and 2.86% in both “Equilibrium+Medium-Increase-Capacity” and “Equilibrium+Large-Increase-Capacity” scenarios. Therefore, we can conclude that disruption in train make train-mode less attractive for directly affected agents even if the capacity of non-disputed trains increased.

- The disruption caused a reduction in using the "bus" mode by the affected agents (comparing “Equilibrium+ disruption” with "Equilibrium without the disruption"). However, increasing the capacity of buses encourage agents to use more "bus" mode (comparing “Equilibrium+ disruption” with the “Equilibrium+Large-Increase-Capacity” and “Equilibrium+Medium-Increase-Capacity”).

8.3.2.4. Conclusion for PT

After analyzing the delay and mode share in our simulated scenarios for the pt disruption, we can conclude the following outcomes:

- By implementing the information strategy as a management action of disruption to mitigate the downside of the disruption, if agents become aware of the disruption at the Start of disruption, instead of when they want to start their trip, the delay that agents experience decreases by 23.48%, and as a result, saving 22451.94 CHF (30.7%) monetary value time of agents.

- Information strategy plays a significant role as a disruption management action for reducing the delay that agents experience. Informing agents about the disruption, at the start time of the disruption, can reduce the delay as the same as scenarios in which increasing the capacity/frequency of lines used as a disruption management action, which indeed requires enormous investment. In Scenario “Start of disruption”, agents experience an averagely 11 minutes delay while agents in scenarios “Line10-Large-Capacity-Increased”, “Line10-Frequency-Increased”, “Line72-Large-Capacity-Increased” and “Line33-Large-Capacity-Increased” also experience an average delay of 11 minutes.

- However, if an analysis has been done to figure out which pt line is the most used by the directly affected agents, and then increase the capacity of that particular pt line, then it results in significantly less delay for directly affected agents. Therefore, by considering the travel behavior of affected agents, authorities can make a more efficient decision and offer a better option for the management of the disruption. In other words, with passenger-oriented capacity management, agent experience less delay, compared to capacity management from the operator-oriented view. Agents in scenarios “Line11-Large-Capacity-Increased” experience averagely 9 minutes delay, which is around 18% less than scenarios “Start of disruption” (an information management actions), and other capacity management action scenarios such as: “Line10-Large-Capacity-Increased”, “Line10-Frequency-Increased”, “Line72-Large-Capacity-Increased”, and “Line33-Large-Capacity-Increased”.

- Increasing the vehicle capacity of pt vehicles to a medium level can have quite the same effect on agents (causes a reduction of 19.1% in the delay) compared with increasing the vehicle capacity of pt vehicles by a large level (causes a reduction of 15.7% in the delay). Indeed, increasing the vehicle capacity to the medium level requires much fewer infrastructure facilities compare with the largely increased capacity scenario.

- Adding to the frequency of a line with fixed departure time yields to 0.4% less delay that agents experience compared to adding to the capacity of vehicles.

From the mode choice point of view for pt, we can conclude that:

- Pt-mode is the most used mode of transport by the agents in the scenarios. In more detail, the bus-mode among four categories of pt-mode is mostly chosen by the agents.

- Increasing the vehicle capacity of buses results in less delay for agents compare to increasing the vehicle capacity of other sorts of vehicles in pt-mode
- By comparing "Equilibrium without the disruption" and “Equilibrium+ disruption” scenarios, it can be seen that in equilibrium solution in the case of disruption, overall usage of pt experiences a decrease of 0.51%, while increases of 0.15% in using car-mode, 0.15% in walk-mode, and 0.02% in using a bike-mode. It means that disruption in the pt yields a decrease in using pt-mode while a slight increase in other modes of travel (Figure 12).
- A medium increase in the pt vehicle capacity, even in disruption situation, yields to an increase of 4.79% in choosing pt-mode (sum of all sorts of vehicles' types in pt) by the agents, whereas a decrease of 3.65% in choosing car-mode by the agents (Figure 12).
- In general, by increasing the vehicle capacity (scenarios “Equilibrium+Medium-Increase-Capacity” and “Equilibrium+Large-Increase-Capacity”), more agents are willing to use the pt mode, while fewer agents willing to use car-mode (Figure 12).
- By the large increase in pt vehicle capacity (“Equilibrium+Medium-Increase-Capacity”), agents use train-mode 0.26% more than the scenario in which the vehicle capacity increased by medium level (“Equilibrium+Large-Increase-Capacity”). Nevertheless, as the vehicle capacity of buses in the scenario, “Equilibrium+Medium-Increase-Capacity” is increased by large-range, while other sorts of pt vehicles experience an increase in vehicle capacity by medium-range. Therefore, it can be observed that bus-mode attracts 0.02% more attention by the agents in “Equilibrium+Medium-Increase-Capacity”, comparing to “Equilibrium+Large-Increase-Capacity” (Figure 12).
- By comparing mode choice of directly affected agents in the normal day without the disruption ("Equilibrium without the disruption") with the scenario in which they become aware of the disruption at the start time of occurrence (“start of disruption”), we can see that disruption shifts directly affected agents to use tram-mode as a substitution, by an increase of 6.11% in using tram-mode in “start of disruption”. Besides, 4.37% more agents use tram-mode in “Equilibrium+ disruption” compared with the normal day scenario (Figure 13).
- Disruption leads to a decrease of using train-mode by 1.43% in “Equilibrium+ disruption” compare with the normal day and a decrease of 2.86% in both “Equilibrium+Medium-Increase-Capacity” and “Equilibrium+Large-Increase-Capacity” scenarios. Therefore we can conclude that disruption in train make train-mode less attractive for directly affected agents even if the capacity of non-disputed trains increased. In other words, although increasing the capacity of tram-mode vehicles increases the usage of tram-mode by all agents, it has different effects on directly affected agents. Disruption in train-mode makes directly affected agents so annoyed that they shift to other modes of pt, even though the vehicle capacity of non-train-mode is increased (Figure 13).
- The disruption caused a reduction of 8.43% in using the "bus" mode by the directly affected agents (comparing “Equilibrium+ disruption” with "Equilibrium without the disruption"). However, increasing the capacity of buses encourages directly affected agents to use 1.29% more "bus" mode, comparing “Equilibrium+ disruption” with the “Equilibrium+Medium-Increase-Capacity” (Figure 13).

8.3.3. Road disruption: a case study of Quaibrücke

8.3.3.1. Case study for road disruption

In this section, we simulate a road disruption scenario on Quaibrücke. Quaibrücke is the bridge that connects Bellevue Platz to Bürkliplatz in Zürich.

Our simulated road disruption has the following criteria; the disruption is for the agents who aim to pass the bridge by car, whereas pt vehicles can still pass the bridge because we aim to simulate a road disruption and evaluated the multi-modal analysis over it. The time dimension of the disruption is similar to the pt disruption, between 16:00 and 19:00. The disrupted area on the map is distinguished with red color in Figure 14. Besides, in our multi-modal disruption management actions, we add to the vehicle capacity of line10, line11, line33, and line72. Such mentioned lines, with or without a transfer, allow for a connection between those major stations. Tram10 connects the Zürich HB to Zürich Oerlikon and then Zürich Flughafen, for instance. Tram11 also server agents by providing a connection between Zürich HB to Zürich Oerlikon. Bus72 and bus33 also connect Zürich Hardbrücke to Zürich Wipkingen, which can be as a substitution of disrupted liens between these two stations.

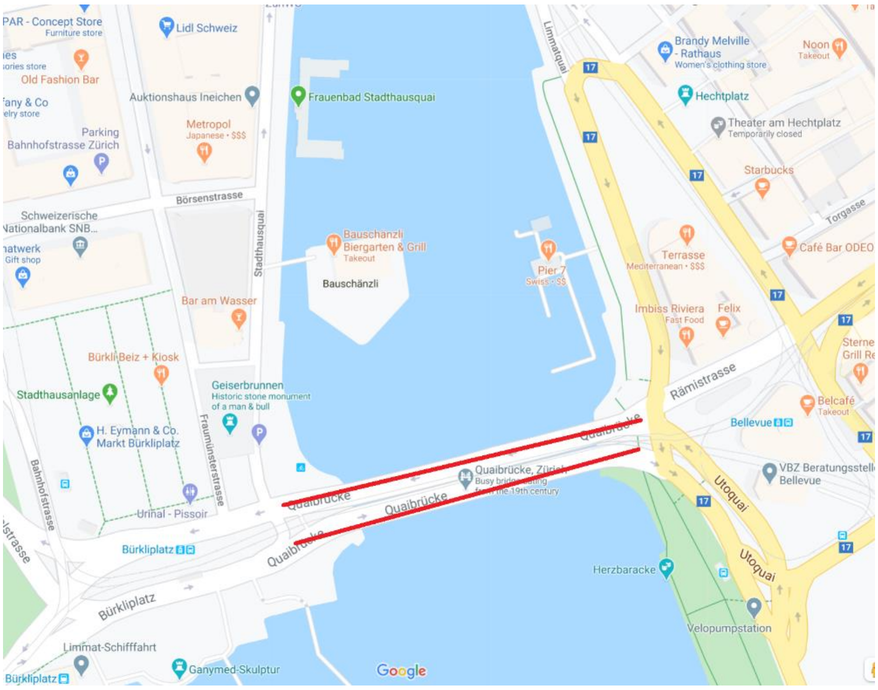


Figure 14: Disruption in Quaibrücke-Image:google maps

For simulating a road disruption, our approach was to reduce the speed of the link (a connection between two nodes in the map) to a minimal value. Initially, the link will still be used, but very slowly, it causes the delay for agents who pass the links, and eventually (in day-to-day iterations), all agents prefer a different route.

In the simulated test case, 65 agents (therefore corresponding to 6'500 people in real life) cannot perform their usual trip. These agents are called "directly affected agents", and we analyze their delay and mode choice in detail.

Understanding the number of directly affected agents is important because if we consider 65 agents with all the rest of 12’007 agents (all together 12'072), then the total delay will fade among the whole population of Zürich population. Therefore, we present mode choice analysis for both categories of whole agents and directly affected agents and then compare the results.

8.3.3.2. Disruption management actions for road disruption

8.3.3.2.1. Information management actions

We consider two information scenarios for none information and full information. Therefore, we present the following scenarios:

For evaluating the effects of the disruption in Quaibrücke, we consider the following scenarios:

- "Quaibrücke-none”. In this scenario, agents have no information about the disruption. We are reducing the speed of the link to a minimal value. Initially, agents pass the link but with a very low speed that yields to experience delay for them.
- “Equilibrium-Quaibrücke”. In this scenario, agents have full information about the disruption, considering the location and time dimensions. From the simulation point of view, this scenario is equivalent to Quaibrücke-none plus running it through the iterative process of day-to-day replanning in the agent-based simulation for several iterations in order to reach the equilibrium state. In this scenario, we also reduce the speed of the link to a minimal value, and eventually (in equilibrium solution), all agents prefer a different route.

8.3.3.2.2. Adding new Lanes as management actions

As a disruption management action, we aim to mitigate the downside of the disruption by increasing lane on routes. For such an aim, we remove side parking places and change the functionally of the parking places to the extra lane of the road that agents with cars can pass. In other words, we add a new lane on each road. We aim to add new lanes to all the routes between Bürkliplatz and Bellevue when Quaibrücke is disrupted. There are three bridges for cars. We have shown on google maps the routes by putting Bürkliplatz as origin and Bellevue as destination and vice versa. Figure 15 shows all the possible routes for which we have increased the lane on the routes.

Therefore, we have the scenario for increasing the lane on routes:

- “Equilibrium-Quaibrücke-increased-lane”. It is equivalent to "Quaibrücke-none" plus that we remove side parking places and change the functionally of the parking places to the extra lanes of the road, plus that we run it through the day-to-day iterations.

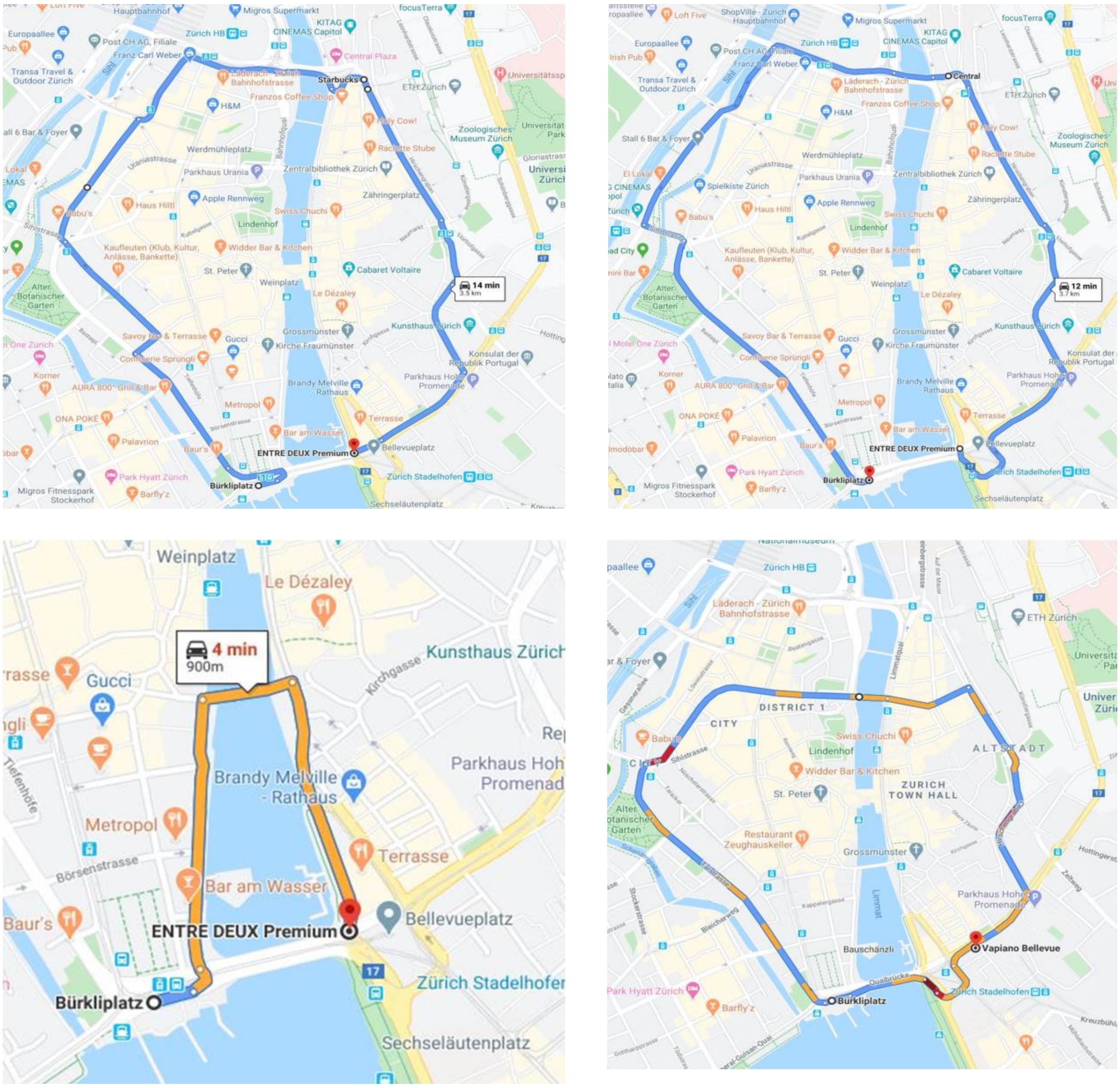


Figure 15: visualization of routes for which the lane has been increased, in other words, removing side-parking places-Image:google maps

8.3.3.2.3. Capacity management action

As one of the aims of this study is to have a multi-modal analysis of the traffic control, we simulate two scenarios in which the pt system helps in mitigating the downside of the disruption on the road in the Zurich network.

- “Equilibrium-Quaibrücke-Medium-increase”. It is equivalent to "Quaibrücke-none" plus increasing the capacity of the whole network by medium (39.67%) during the whole day, plus running through the day-to-day iterations.
- “Equilibrium-Quaibrücke-Large-increase”. It is equivalent to "Quaibrücke-none" plus a large increase in the capacity of the whole network during the whole day, plus running through the day-to-day iterations.

8.3.3.3. Results for road disruption

8.3.3.3.1. Delay Analysis for Quaibrücke Scenario

The amount of the delay that all the agents have experienced in the scenarios with the disruption in Quaibrücke is presented in Table 35. As the "Equilibrium without the disruption" is the reference for the activity delay; therefore, the amount of activity-delay is zero for this scenario.

The number of total agents is 12'072 agents; each agent represents 1% of the Zürich population.

Table 35: Statistics of delay that situation in Quaibrücke for all 12'072 agents

Scenarios	Activity-delay (minutes)						Monetary value of time (CHF)	%Monetary value of time Compared with Equilibrium-Quaibrücke
	average	min	50 %	90%	max	Total delay		
Quaibrücke-none	0.452	-7.67	0	0	180	5453.574	30514777	1.829
Equilibrium-Quaibrücke	0.160	-126.0	0	1.09	180	1927.749	10786473	0.000
Equilibrium-Quaibrücke-increased-lane	0.151	-126.0	0	1.1	180	1828.243	10229697	-0.052
Equilibrium-Quaibrücke-Medium-increase	-0.696	-110.2	0	0.69	146	-8397.996	-46989913	-5.356
Equilibrium-Quaibrücke-Large-increase	-0.698	-110.2	0	0.69	146	-8422.305	-47125931	-5.369

Table 35 illustrates that the scenario "Quaibrücke-none" causes an averagely 0.45-minute delay for the whole agents in the Zürich. In the equilibrium situation, when agents adapt their travel plan based on the new disruption situation and through the iteration, the amount of the delay that agents experienced reduced by 64.4% (compare with the "Equilibrium-Quaibrücke" scenario).

Table 35 also shows that by multi-modal management and dedicating the parking spaces in particular routes to the driving space, then the amount of the delay that agents experienced can be reduced by 66.6%, compared with "Quaibrücke-none".

In Table 35, the minus value for averages shows that agents have arrived earlier in such scenarios compared to the normal day ("Equilibrium without the disruption"). Earlier arrival in the scenarios in which the capacity is increased is caused because pt vehicles can serve more agents, and therefore, agents experience less denied on-board due to the full capacity.

In order to have a more precise investigation, we identify the directly affected agents who, on a normal day without the disruption, pass the Quaibrücke as their daily activity between 16 and 19 o'clock in their car. The number of 65 agents (each agent represents 1% of the Zürich population) has been identified. Therefore, in the disruption situation, these 65 agents cannot follow their travel plans. Directly affected agents will find another route for their travel plan through the iteration as they learn that the Quaibrücke is not available anymore. The delay that directly affected agents experienced in the equilibrium situation with the disruption condition is shown in Table 36.

Table 36: Statistics of delay that 65 directly affected agents experience in the disruption situation in Quaibrücke

Scenarios	**Activity-delay (minutes)**						**Monetary value of time (CHF)**	**%Monetary value of time Compared with Equilibrium-Quaibrücke**
	average	**min**	**50%**	**90%**	**max**	**Total delay**		
Quaibrücke-none	71.37	0.13	67.3	109.5	148	4639.479	139776	0.907
Equilibrium-Quaibrücke	37.42	-10.28	34.4	96.3	146	2432.769	73293	0.000
Equilibrium-Quaibrücke-increased-lane	37.39	-10.03	34.4	96.2	146	2430.412	73222	-0.001
Equilibrium-Quaibrücke-Medium-increase	35.58	-5.39	26.2	96.2	146	2312.728	69677	-0.049
Equilibrium-Quaibrücke-Large-increase	35.56	-5.39	26.2	96.2	146	2311.864	69651	-0.050

By comparing the average value in Table 35 and Table 36, we can see a substantial difference in the delay time that whole agent's experience compared with the delay that directly affected agents experienced. It means that disruption in the Quaibrücke affects the agents in all public transport of Zürich partially, while it causes an averagely more than half-hour delay for directly affected agents.

Table 36 shows that Disruption in Quaibrücke yields an averagely 71.37 minutes delay for directly affected agents, scenario Quaibrücke-none, when agents do not have any information about the disruption and without any disruption management actions. Through the equilibrium solution, the delay that directly affected agents experience reduce by 47%, comparing “Quaibrücke-none” and “Equilibrium-Quaibrücke”.

8.3.3.3.2. Mode Share Analysis for the Quaibrücke Scenario

The statistics of the mode choice percentage under different scenarios are shown in Figure 16. The X-Axis shows the scenarios, Y-axis, the percentage, varying from 0 to 1; the mode choices are represented in the legend with specific colors.

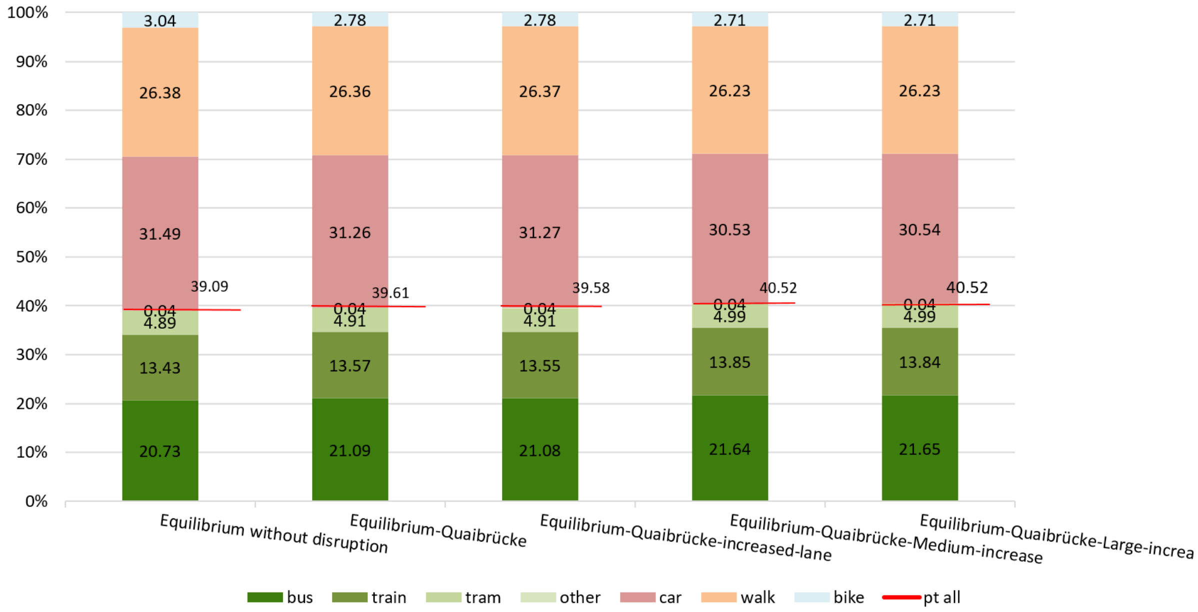


Figure 16: mode choice analysis for Quaibrücke in scenarios for all 12'072 agents (based on each stage that agents traveled)

From Figure 16, it is visible that in all scenarios, public transport mode (pt) is the most used means of transport in one day. In more detail, the bus from the pt is the most used mode among the agents. After pt mode, the rank of the most used mode of traveling is the car, then walk, and bike, with the lowest usage.

Figure 16 shows that by increasing the capacity (“Equilibrium-Quaibrücke-Medium-increase” and “Equilibrium-Quaibrücke-Large-increase” scenarios), 0.91% more agents are willing to use the pt mode, while 0.28% fewer agents willing to use car-mode, compare with "Equilibrium-disruption".

By comparing "Equilibrium without the disruption" and “Equilibrium-Quaibrücke” scenarios, it can be seen that in equilibrium solution in the case of disruption without any disruption management, usage of car as a mode of traveling experiences a decrease of 0.23%. Besides, the road disruption on Quaibrücke results in an increase of 0.52% in using pt (sum of all sorts of changes in pt).

From Figure 16, it can be seen that increasing the capacity of transit vehicles by medium results in an increase of 1.43% of using pt-mode (sum of all sorts of changes in pt) comparing with “Equilibrium without the disruption”.

8.3.3.3.3. Mode choice analysis for directly affected agents for Quaibrücke Scenario

So far, we investigated the mode choice for all agents under four equilibrium scenarios. However, in the disruption's situation, not all the agents are affected by the disruption. Therefore, in order to investigate more precisely the effects of the disruption on the affected agents and the impact of vehicle capacity management of those affected agents, it is necessary to do extra mode choice analysis for 65 (each agent represents 1% of the population) affected agents by the disruption. In this section, we quantify the mode choice in scenarios for directly affected agents by the disruption.

The statistics of the mode choice percentage under different scenarios are shown in Figure 17. Similar to Figure 16, The X-Axis shows the scenarios, Y-axis, the percentage, varying from 0 to 1; the mode choices are represented in the legend with specific colors.

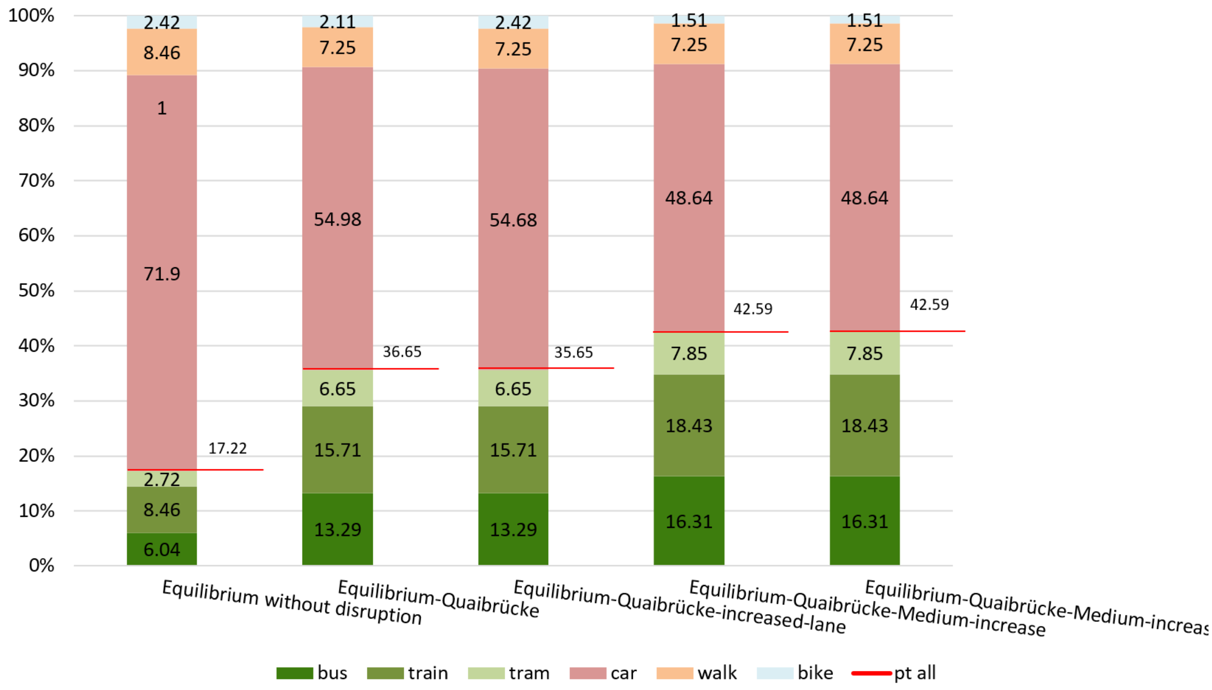


Figure 17: mode choice analysis in Quaibrücke scenarios for 65 directly affected agents (based on each stage that agents traveled)

It can be seen in Figure 17 that road disruption causes less usage car-mode by directly affected agents in all five equilibrium scenarios to compare to "Equilibrium without the disruption". Figure 17 also shows that implementing disruption management actions and increasing the capacity increase the usage of all pt modes.

From Figure 17, it visible that increasing the vehicle capacity of transit lines lead to more usage of all sort of pt by the directly affected agents. More precisely, in the scenario “Equilibrium-Quaibrücke-Large-increase,” directly affected agents by the road disruption use bus-mode more than three times compared to "Equilibrium without the disruption" and more than two times compared with “Equilibrium-Quaibrücke” and 18.04% more compared with “Equilibrium-Quaibrücke”.

The main points in Figure 17 are:

- Road disruption in Quaibrücke yields to an increase in the usage of pt-mode by the directly affected agents by 18.43%, comparing “Equilibrium-Quaibrücke” and "Equilibrium without the disruption".
- Road disruption results in a decrease in using car-mode by the directly affected agents. Directly affected agents in the scenario "Equilibrium without the disruption" use car-mode 16.92% less than in the scenario “Equilibrium-Quaibrücke”.
- Although increasing the vehicle capacity of the transit lines causes to increase of 0.01% in using car-mode by all the agents, it does not encourage the directly affected agents to use more car-mode. More precisely, adding to the apace of driving in not-disputed roads, cause a reduction of 0.30% in using car-mode by the directly affected agents, comparing “Equilibrium-Quaibrücke-Large-increase” with " “Equilibrium-Quaibrücke” " scenario.

8.3.3.4. Conclusion for road disruption

After analyzing the delay and mode share in our simulated scenarios for the road disruption, we can conclude the following outcomes:

- Adding lanes to the roads as a disruption management action reduces slightly amount of the delay that agents experienced.
- By implementing multi-modal management and increasing the vehicle capacity of pt vehicles in a road disruption, 19% agents experience earlier arrival. Because of two factors: pt vehicles can serve more agents, and therefore, agents experience less denied on-board due to the full vehicle capacity, as mentioned by increasing the capacity of vehicles 1.43% more agents using pt-mode and consequently, the traffic load on the road are fewer and agents on the road also experience earlier arrival.
- Disruption in the Quaibrücke affects the agents in all public transport of Zürich partially (an average delay of 0.45minutes), whereas it causes an averagely more than half-hour delay for directly affected agents.
- Disruption in Quaibrücke yields an averagely 71.37 minutes delay for directly affected agents, scenario Quaibrücke-none, when agents do not have any information about the disruption and without any disruption management actions. Through the equilibrium solution, the delay that directly affected agents experience reduce by 47%, comparing “Quaibrücke-none” and “Equilibrium-Quaibrücke” (Table 36).

From the mode choice point of view for pt, we can conclude that:

- Road disruption on Quaibrücke reduces the usage of cars as a mode of traveling slightly. Besides, the road disruption on Quaibrücke increases the usage of pt-mode (sum of all sorts of changes in pt).
- Adding lanes as a disruption management action increases the usage of car-mode by all agents, whereas reducing the usage of car-mode by the directly affected agents
- Increasing the capacity of pt as a multi-modal action for disruption management causes more agents to use the pt mode, while fewer agents willing to use car-mode.
- Public transport mode (pt) is the most used means of transport by all the agents. In more detail, the bus from the pt is the most used mode among the agents. After pt mode, the rank of the most used mode of traveling is the car, then walk, and bike, with the lowest usage (Figure 16)
- By increasing the capacity (“Equilibrium-Quaibrücke-Medium-increase” and “Equilibrium-Quaibrücke-Large-increase” scenarios), 0.91% more agents use the pt mode, while 0.28% fewer agents use car-mode, compare with "Equilibrium-disruption" (Figure 16).
- By comparing "Equilibrium without the disruption" and “Equilibrium-Quaibrücke” scenarios, it can be seen that in equilibrium solution in the case of disruption without any disruption management, usage of car as a mode of traveling experiences a decrease of 0.23%. Besides, the road disruption on Quaibrücke results in an increase of 0.52% in using pt (sum of all sorts of changes in pt) (Figure 16).

- Increasing the capacity of transit vehicles by medium results in an increase of 1.43% of using pt-mode (sum of all sorts of changes in pt) comparing with “Equilibrium without the disruption”. (Figure 16).

- Although increasing the capacity of the transit lines causes to grow by 0.01% in using car-mode by all the agents, it does not encourage the directly affected agents to use more car-mode. More precisely, adding lanes to the road for having more apace to drive in not-disputed roads cause a reduction of 0.30% in using car-mode by the directly affected agents, comparing “Equilibrium-Quaibrücke-Large-increase” with “Equilibrium-Quaibrücke” scenario.

- Road disruption in Quaibrücke yields to an increase in the usage of pt-mode by the directly affected agents by 18.43%, comparing “Equilibrium-Quaibrücke” and "Equilibrium without the disruption". Besides, disruption in Quaibrücke caused a reduction of 16.92% in using car-mode by directly affected agents, comparing “Equilibrium-Quaibrücke" with “Equilibrium without the disruption” (Figure 17).

- Increasing the capacity of transit lines lead to more usage of all sort of pt by the directly affected agents. More precisely, in the scenario “Equilibrium-Quaibrücke-Large-increase,” directly affected agents use bus-mode more than three times compared to "Equilibrium without the disruption" and more than two times compared with “Equilibrium-Quaibrücke” and 18.04% more compared with “Equilibrium-Quaibrücke” (Figure 17).

8.4. *Microscopic simulation approach*

8.4.1. Introduction

Zurich urban network and its neighborhood, illustrated in Figure 18, is used as the studied area. It covers an area of about four km^2, including four different traffic modes: individual vehicle, bus, tram, and bike. There are 24 public transport lines in the network, consisting of 14 tram lines and 10 bus lines. The free flow speed is set to 45 km/h in all links. Traffic lights at signalized intersections operate on a two-layers of perimeter control scheme (Menendez *et al.*, 2018).

Figure 18 Zurich city network

Based on the demand data of a week in October 2015, for the evening peak hours from 17:00 to 18:00, a Vissim simulation Scenario has been constructed by city authorities. The Scenario consists of about 250 pairs of origin and destination centroids with static traffic assignments. The network faces serious congestion problems during the peak hour, with extended queues that spill back and block upstream intersections. Data collection and network performance indicators are obtained every 2 minutes to evaluate network performance in different simulated scenarios.

In the current work, the disruption takes place on Quaibrücke (see Figure 18), and this specific road is inaccessible for all the vehicles, including buses. Trams are allowed to travel in both directions as they use separated infrastructure, i.e., dedicated lanes. Three disruption Scenarios on Quaibrücke are taken into consideration.

In the first Scenario (unmanaged -- no bypass), the car lanes of Quaibrücke were inaccessible for all vehicles; therefore, they needed to wait for passing through the bridge. Only trams were allowed to pass the bridge through the separate infrastructure. There was no traffic management policy dealing with the disruption, and demand for vehicles and trams was assumed to remain the same. Vehicles did not change their static routes, with the queue lengths increasing over time; this case was used as a benchmark Scenario. In the second Scenario (bypass without demand change), the car lanes at

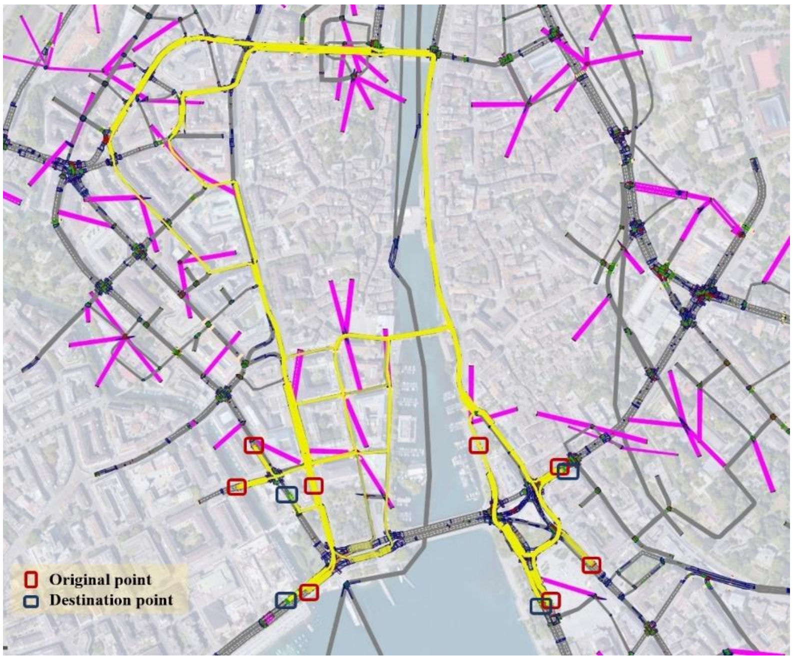


Figure 19 Alternative routes bypassing Quaibrücke

Quaibrücke was again inaccessible for vehicles; all the vehicles had to bypass the closed road through alternative routes, whereas trams could again pass through directly. This Scenario represents the situation where there exists some rerouting guidance (such as variable message signs) set up upstream of the disrupted road. The (static) routes of vehicles that want to pass through the closed road are changed, while the demand for vehicles and trams is assumed to remain constant. For different origins and destinations, the new alternative routes were classified into four origins and two destinations west and four origins and two destinations east of the bridge, respectively, based on traffic volumes (Figure 19). Traffic assignment among different alternative routes was pre-computed accordingly. Moreover, due to the new set of alternative routes, the signal timing of some intersections should be adjusted, and this was performed by utilizing internal Vissim routines; Figure 20 illustrates the 6 modified signalized intersections.

In the third Scenario (bypass with a change in demands), based on the former Scenario, the demand changes of vehicles and trams were taken into consideration. It represents the situation that not only the rerouting guidance is available on the road, but also real-time traffic information has been broadcasted to the users before their departures. In this scenario, the vehicle volume passing through the closed road was reduced by 50% (see Figure 21); the corresponding demand has been shifted to the 5 tram lines that pass through Quaibrücke (Figure 22 illustrates the starting and ending tram

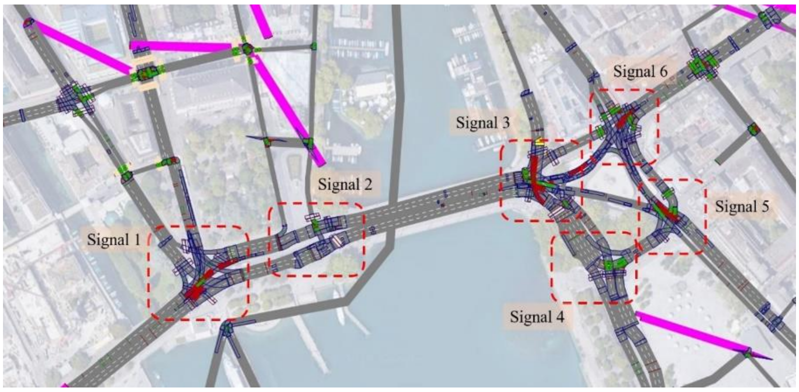


Figure 20 Modified signal plans due to disruption

stations, respectively). The added tram volume was calculated by the total demand balance. Table 37 summarizes the general configuration of the 3 studied Scenarios.

Table 37 Summary of Scenarios and implemented measures

	Scenario 1	Scenario 2	Scenario 3
Rerouting	No	Yes	Yes
Demand Change	No	No	Yes

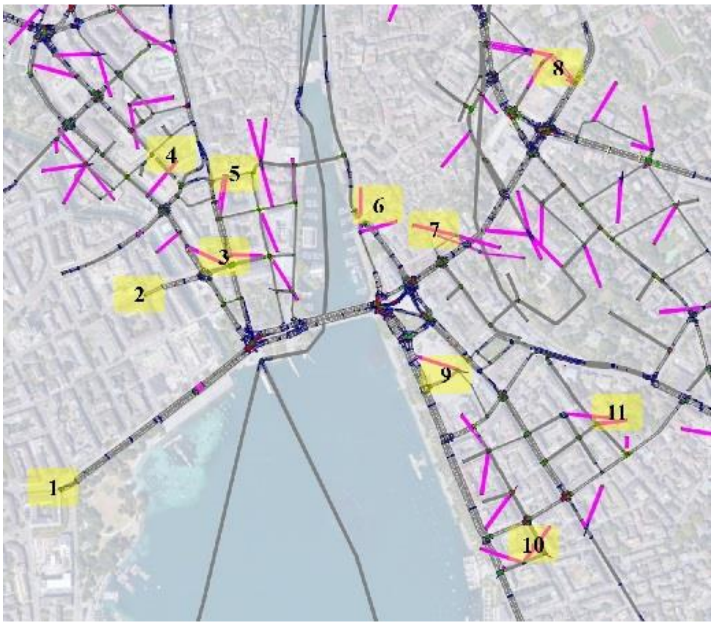


Figure 21 Vehicle input points used for re-balancing the traffic demand by modes (Scenario3)

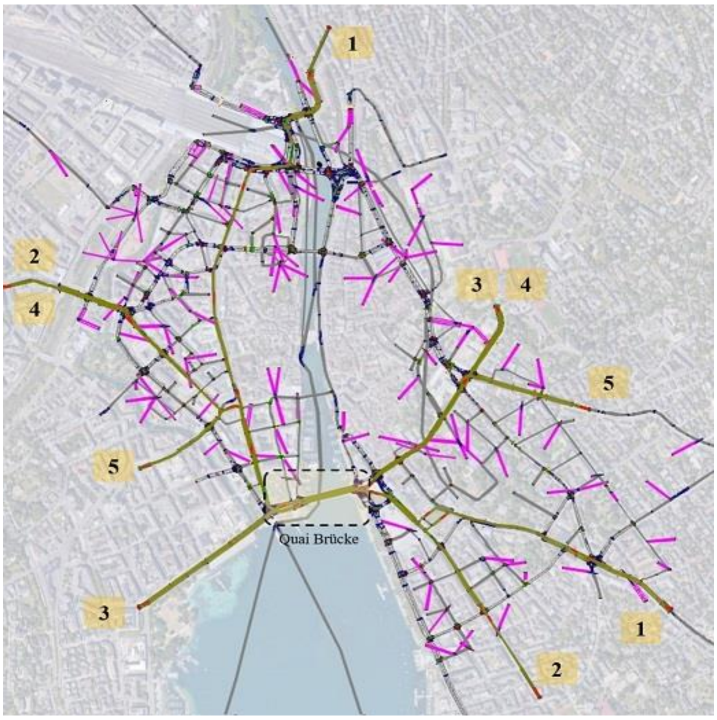


Figure 22 Tram lines passing through Quaibrücke

8.4.2. Methodology

For the demand modification and re-balancing after the disruption occurrence, a simple Logit model was utilized to calculate the traffic assignment ratios for different alternative routes. Since the route costs order of magnitude is too high, the final assignment ratios were computed after a trial-and-error process for the Logit model parameters. More specifically, the equation reads

$$P(k) = \frac{exp\,[-\theta t_k \,/\, \bar{t}]}{\sum_{i=1}^{m} exp[-\theta t_k \,/\, \bar{t}]}$$

Equation 22

where *P(k)* denotes the assignment ratio for the k-th route; θ = 3.00 ~ 3.50 is a tuning parameter; *m* is the number of alternative routes; t_k and $\bar{t}$ are the k^{th} and average route time costs, respectively.

Note that in all the simulation experiments, the actual control logic implemented in the city of Zurich is applied. This happens through an external virtual machine build by PTV that changes the signals dynamically based on the prevailing traffic conditions, in the same way, that is implemented in real life at the traffic operations center of the city. Moreover, in our disruptive Scenarios, some intersections signal plans are modified to accommodate the excessive demand caused by rerouting (Figure 20 Modified signal plans due to disruption presents these intersections). For this purpose, we utilize the Vehicle Actuated Programming (VAP) method in Vissim as the new signal timing scheme. This method contains a minimum and a maximum green time; the final green is calculated in real-time based on traffic flow measurements.

Finally, in the current study, a 3D-MFD model is introduced to evaluate network performance. Given both the accumulations of private and public transport vehicles, 3D-MFD reflects the relationship between the accumulation of vehicles, public trams and buses, and network total exit volume(Geroliminis, Zheng and Ampountolas, 2014) .This way, our Scenario evaluation analysis takes into consideration the different transport modes. Regarding the total network flow, we have

$$Q = Q_m\,(n_v, n_p) = Q_v\,(n_v, n_p) + Q_p\,(n_v, n_p)$$

Equation 23

where n_v denotes the accumulation of private vehicles, n_p the accumulation of public transport vehicles, Q_m is the total network flow for each mode $m \in \{v, p\}$, i.e. private and public vehicles, respectively, and Q the total network flow, which is the summation of vehicle flows for all modes. As Q_m is linear to the exit flow A_m, as defined in (Daganzo and Geroliminis, 2008) , the equation can be readily modified to

$$A = A_m\,(n_v, n_p) = A_v\,(n_v, n_p) + A_p\,(n_v, n_p)$$

Equation 24

8.4.3. Results

8.4.3.1. Aggregated results for all modes

Figure 24 and Figure 25, some fundamental network performance indicators are presented for all Scenarios. These statistics are obtained by Vissim at the end of the simulation runs. The three Scenarios presented above, together with the baseline, non-disrupted Scenario (called here original), are illustrated. We can observe that the original Scenario has the best performance, as the occurrence of disruption inevitably leads to worse network performance.

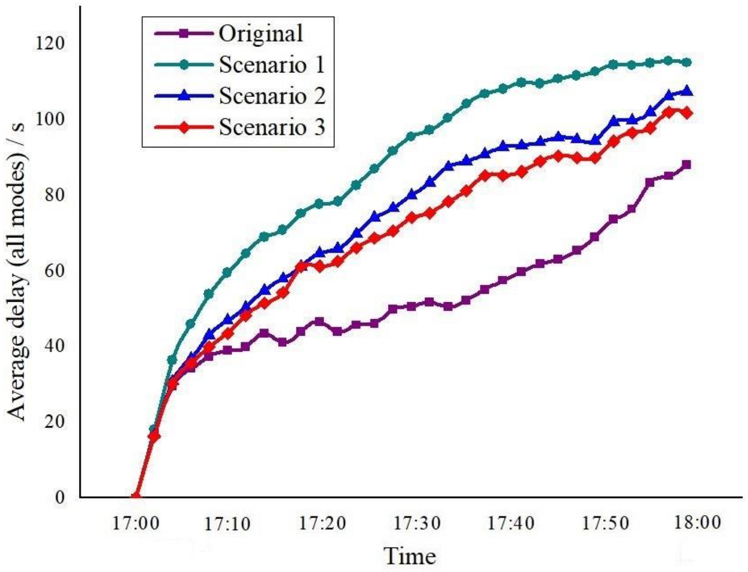


Figure 23 Average delays for all traffic modes

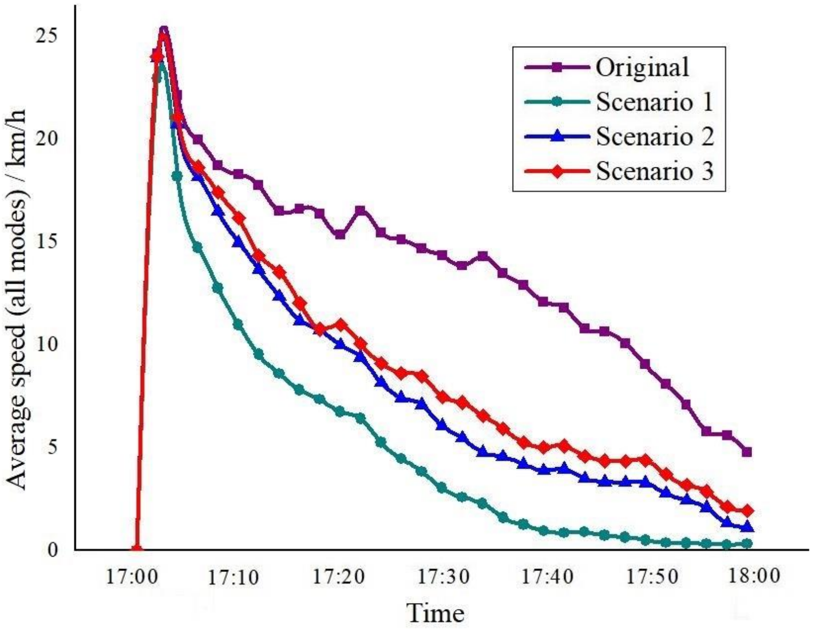


Figure 24 Average speed for all traffic modes

More specifically, after around time 17:35 in the original Scenario, the average speed and total exit flow (vehicle arrival amount) drop sharply. The reason is that the traffic in Loewen street spills back to the upstream intersection at that time, and this creates a problem in the network that cannot be dissolved until the end of the simulation. The other Scenarios present the same trend; while in Scenario 1 this occurs at 17:22, in Scenarios 2 and 3 it occurs at 17:28. Scenario 1 has the worst performance but this is reasonable as no rerouting is applied; vehicles have to wait behind the closed road, and queues grow longer over time.

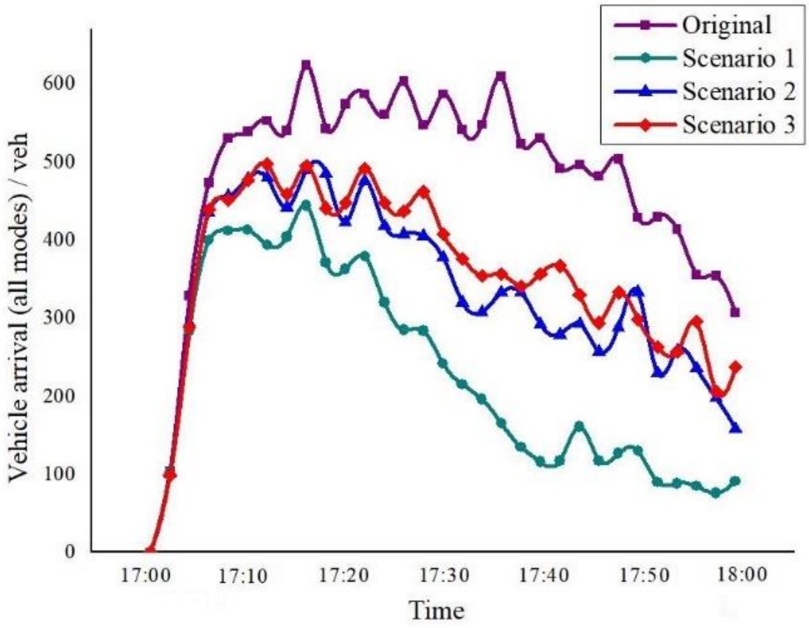


Figure 25 Network total exit flow

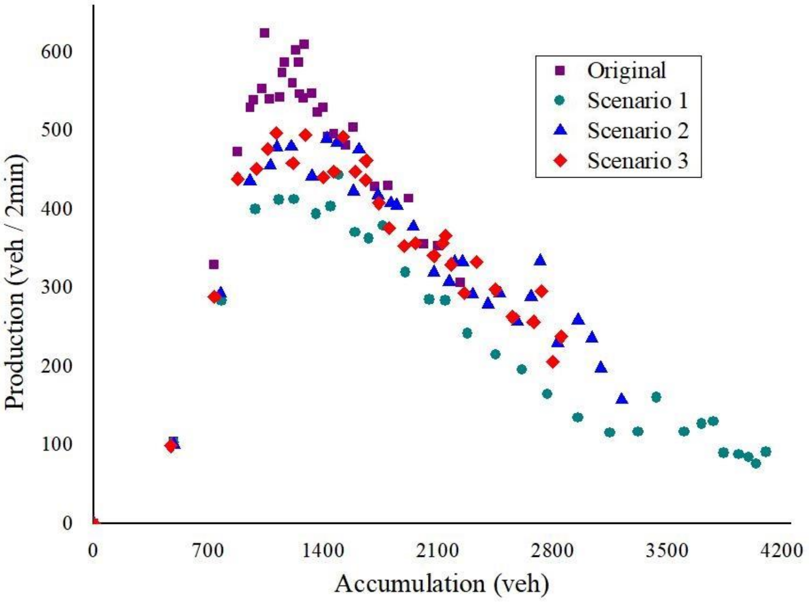


Figure 26 Network performance of all traffic modes evaluated by MFD

The performance of Scenario 3 is slightly better than Scenario 2, especially after that congestion starts to propagate in the entire network. In Scenario 3, contrary to scenario 2, there are fewer vehicles with routes passing through the disrupted link due to the shifting of demand to public transport, which means that alternative bypassing routes experience lower flows. In other words, the amount of bypassing vehicles in Scenario 2 is large, and the two alternative routes have a lower capacity, and, at the same time, higher cost compared to the disrupted route.

As can be seen in the Macroscopic Fundamental Diagrams of Figure 26, the different scenarios' performance difference is very clear. The original Scenario has the highest MFD curve, Scenario 1 has the lowest one, and Scenario 3 achieves slightly better performance compared to Scenario 2. Moreover, our findings confirm that the change of density distribution in the network leads to MFD shape change (Knoop and Hoogendoorn, 2013). In the different Scenarios, the maximum network outflow (vehicle arrival flow) is 624 veh/2min for the original Scenario, and 413 veh/2min, 495 veh/2min, and 497 veh/2min for Scenarios 1, 2, and 3, respectively. The arrival rate of Scenario 3 is the same as that of Scenario 2 before the critical density point, and the former is slightly better than that of the later after that point. In other words, the MFD evaluation results confirm the conclusions derived by the performance indicators obtained by Vissim.

8.4.3.2. Results for each transport mode

Considering the demand shift in scenario 3, it is worth evaluating the network performance for each mode separately; the results are presented in Figure 27, Figure 28, and Figure 29. In both private and public transport modes, the performance of the original Scenario is obviously the best, and Scenario 1 is the worse. In the case of private vehicles, the performance of Scenarios 2 and 3 are almost the same because the individual vehicle model accounts for the majority of motorized trips. In public transport, the arrival rate of Scenario 2 is similar to that of Scenario 3; the average delay of Scenario 3 is smaller than Scenario 2 from 17:30 to 17:45 and larger than Scenario 2 from 17:45 to 18:00. An explanation for this could be that because of congestion spilling back to upstream intersections, and due to Scenario 3 having more trams, they take much more road space, and this worsens the propagation effect, causing more delays in this Scenario.

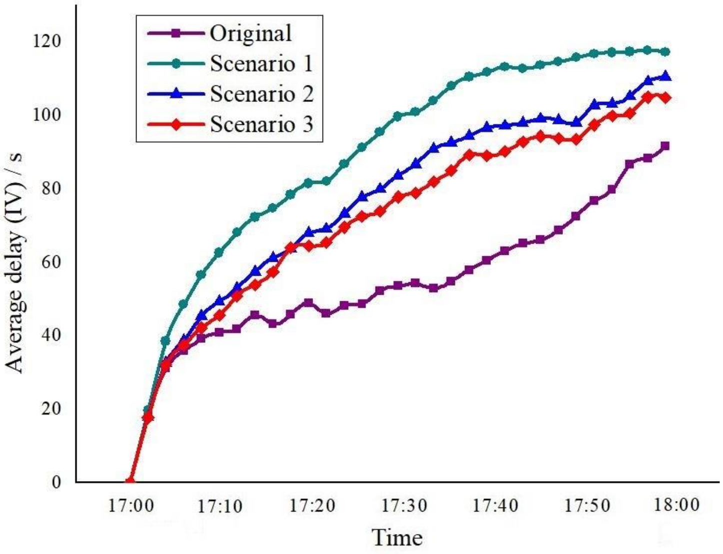


Figure 27 Average delay for private vehicles

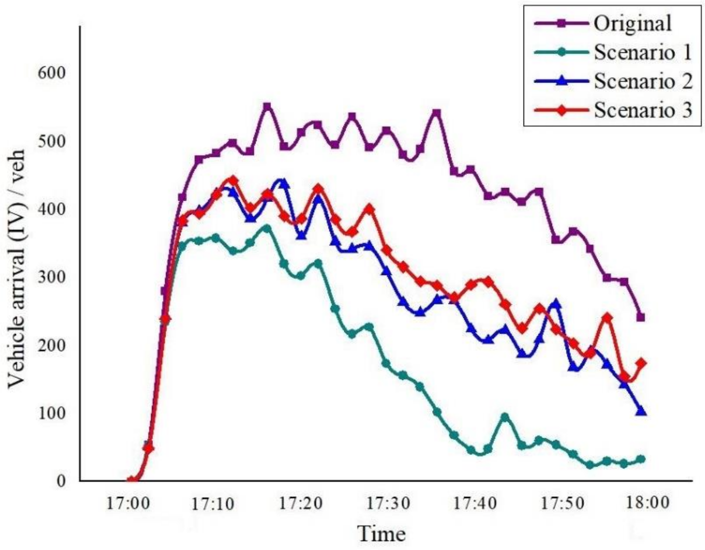


Figure 28 Arrival flows for private vehicles

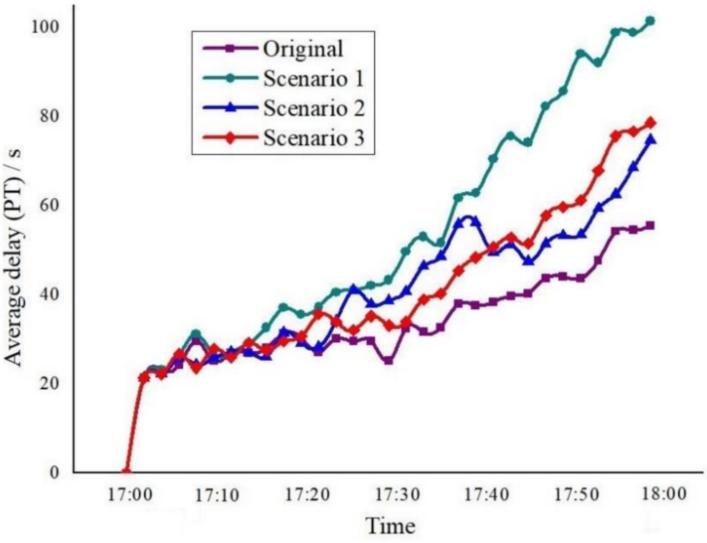


Figure 29 Average delay for public transport

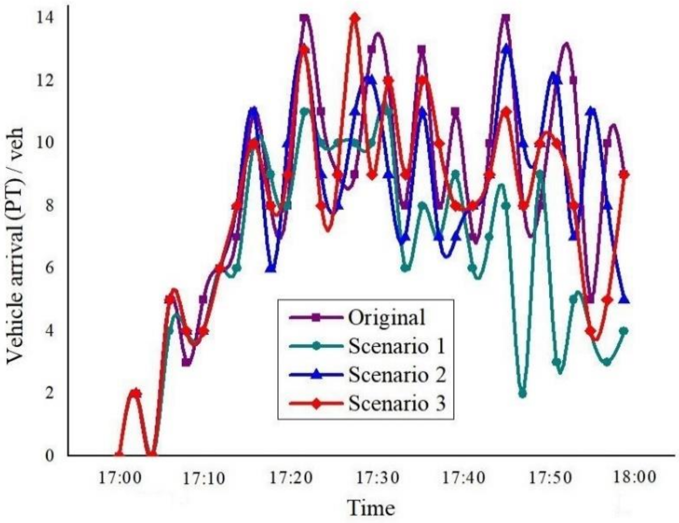


Figure 30 Arrival flow for public transport

Finally, as depicted in Figure 32 of 3D-MFD and Figure 33 of MFDs for each mode, we obtain a similar result as before; the performance of the original Scenario is the best, Scenario 1 is the worse, and Scenario 3 is better than Scenario 2. Interestingly, both the MFD for private vehicles and public transport are similar to the aggregated MFD for all modes. This result could be used to design a perimeter control strategy.

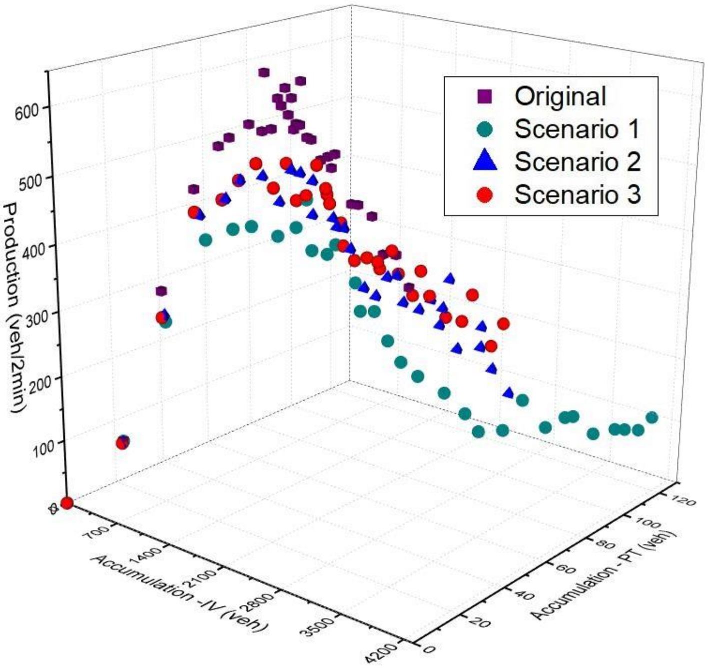


Figure 31 Network performance evaluated by 3D MFD

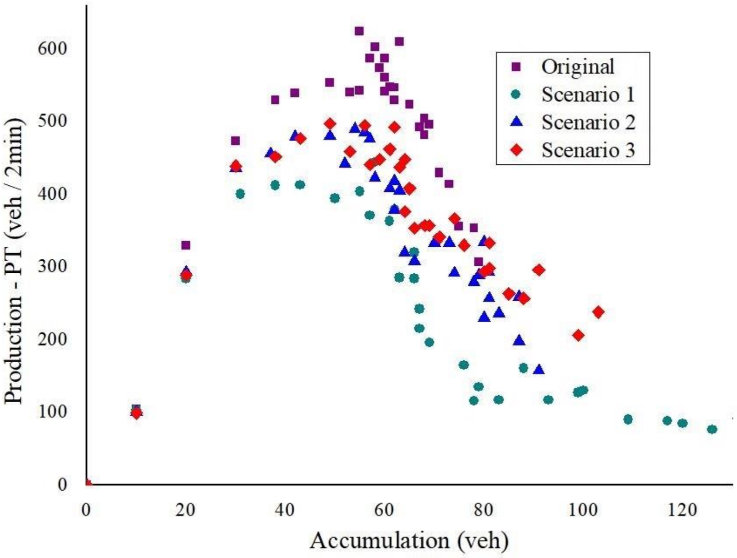


Figure 32 MFD based on private vehicle accumulation

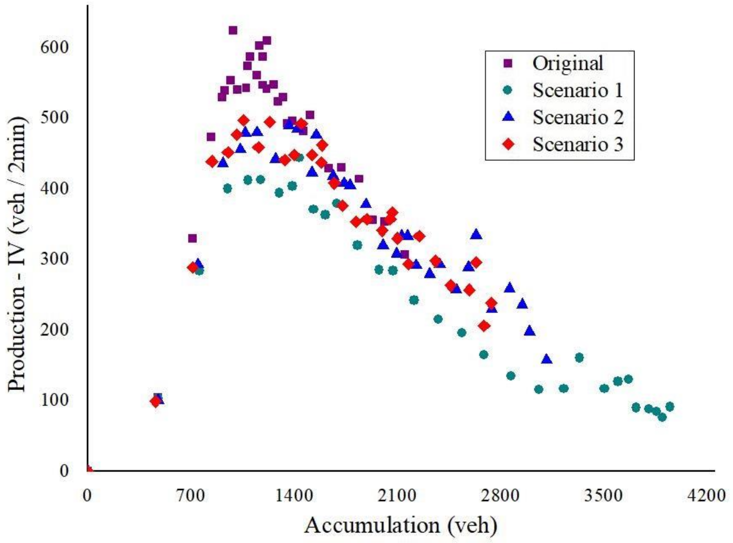


Figure 33 MFD based on public transport accumulation

8.4.3.1. Results in monetary terms

Similar to other case studies we have translated the results in to monetary values. Based on the value of time provided in appendix 11.3, and the occupancy rate of 1.09 provided in appendix 11.4

Table 38 Results in monetary terms

	Delay total all users (h)	Difference to Original	Monetary Value CHF
Original	965.6	0	0
Scenario1- Without any measures	2248.4	1282.7	42,839
Scenario2: Route Guidance	2089.7	1124.0	37,540
Scenario3: Route Guidance and 50% Demand shift to PT	1602.6	636.9	21,272

8.4.4. Conclusions

In the case study presented in this chapter, we evaluated traffic management measures and network performance in a disrupted scenario for the city of Zurich. Based on the analysis of the results, the following conclusions can be made:

After the occurrence of disruption on Quaibrücke, the network performance inevitably deteriorates. Especially without any management policies implemented, the network faces a sharp decrease in all performance indicators. If traffic guidance measures are deployed utilizing VMS around the disrupted road to reroute the users, the network performance is better than without any measures. If both traffic guidance utilizing VMS and traffic information broadcast measures are applied, the network performance improves even more. The same result can also be obtained for each mode separately, as described in the previous section.

The influence of traffic management measures is limited by network topology and the location of the disrupted link. In this study, we deliberately decided to disrupt Quaibrücke, due to its criticality for the Zurich network, and tried to experiment with simulation and assess the impact of measures that are applicable for such cases. Other traffic management measures depending on the specific road network and traffic conditions are also possible. In general, it is important to avoid oversaturated traffic states, as even effective measures can become invalid, or even harmful, to the overall performance due to the oversaturated conditions.

These conclusions can be used to guide traffic management practice during a disruption in the Zurich network due to e.g., road construction or traffic accidents. It should be noted that some parts of this study could be further improved. For instance, the optimal vehicle reduction rate passing through the disrupted link could be calculated, and the mechanism for demand shift measures and demand reduction should be further investigated. Moreover, the demand balance between individual vehicles and public transport should be more accurately estimated. Future studies will focus on the balance beyond modes and dynamic perimeter control.

9. Conclusions

This report investigated the potential for multimodal traffic control, which is expanding the choice for moving goods and people to multiple modes, to exploit at best their complementarity. A multimodal traffic management system is a system which, by a coordinated action of available infrastructure resources (lanes, railways, stations, vehicles, etc.), software process (decision support systems, data collection, and sharing), and organizational aspects (well-defined responsibilities, redistribution of benefits across modes and authorities, political and societal support) allows a user with mobility desire to freely choose from a set of alternatives based on different modes (i.e. train or car), or even combining multiple modes in the same alternative (i.e., park & ride).

The underlying assumption is that having multiple available modes provide additional capacity to allow movements of larger flows; variety, to cater to different tastes of the users; redundancy and resilience, against regular or irregular non-performance. A well-functioning multimodal management requires actions at strategic, tactical, and operation scale. The actions encompass infrastructure and hardware, software and decision support systems, and political and organizational aspects.

Considering the state of the art, most of the recent academic studies focus on determining the optimal solution to balance the strengths of different modes in their reaction to variable demand. The goal is to compute a system optimum, which minimizes externalities, or travel times, assuming specific controllability of the different modes. The focus of the academic approaches is on relatively small problems, for instance, in terms of links, alternative routes, amount of passengers or vehicles, and they do no study large-scale (national) systems. Moreover, some practical aspects of organizational or infrastructure requirements are based on assumptions, and rarely discuss all the required steps for implementation, including cost-benefit analysis. The behavioral response of travelers is often based on assumptions that might have a limited realism. Approaches that consider a multi-layer, nationwide multimodal management schemes still result in too large complexity to be in the focus of theoretical researchers.

From a practical point of view, multiple projects, pilots, and implementations aim to address some aspects of multimodal traffic management. Most of those approaches identify data collection and integration; and definition of standards and exchange format, as prerequisites for any further decision support. From the viewpoint of the users of the infrastructure, it is straightforward to create a unified platform (e.g., mobile app) that can integrate all data and information needed to plan a trip. Such applications exist in different concepts and scales. However, from the operator viewpoint, designing a system that could integrate all operations of different transport modes and make cross-modal real-time decisions about traffic management would not be a trivial task and require considerable investment and manpower. To begin with, advanced hardware installations would be needed (ITS equipment, communications, actuators) to deal with such a decision support development. Secondly, appropriate algorithmic development (software) would be needed to support smart multimodal traffic management operations. Nevertheless, some systems have been implemented in multiple cases, though no test case reaching the size of a country like Switzerland, explicitly including long-distance train, is known.

Actions improving the possibility of multimodal traffic management can be classified according to the time required to be implemented. For many systems (e.g., pricing), their operational usage is in any case based on infrastructure available, requiring a long time to be designed and implemented (e.g., sensors and state estimation, determination of optimal pricing, political acceptance, and organizational support; implementation of a system to collect the requested price).

In the current study, to determine the potential and barriers for the implementation of such a system, a set of scenarios have been considered as extreme, exemplary cases. Those scenarios assume perfect controllability of networks; or perfect dissemination of information. The test cases investigated represent a meaningful set of possible cases: freight trasport; passenger traffic in interurban links, or corridors; passenger transport in a densely served urban area. We focus on disruptions, which have a stronger impact, and assumingly the potential of multimodal traffic management is the highest. In disruptions, the impact on a restricted set of traveler/commodities is very high, while the general impact on the overall flow might still be limited. There is thus an unavoidable tradeoff to improve traffic performance for few travelers/commodities facing serious non-performance, against a very limited change (positive or negative) for everybody else. A drawback of disruptions is that it is less easy to make statistics out of exceptional events.

The benefits of multimodal management for passenger traffic and freight can be quantified, depending on the number of people/commodities involved and their travel time or delay reduction, which can be further translated to a cost. Mode shift is mostly a question of having a cost for mode shift (psychologic resistance, unavailability of vehicles, requirements for infrastructure and equipment) smaller than the cost for the delay incurred when remaining in the original mode.

For freight, those two costs are very variable for organizations, goods exchanged, availability of equipment, size of the shipment, the main mode used, availability of alternative modes, and moreover, dependent from a large set of technical and organizational constraints. A mode shift per se is only interesting in case of large delays, which are related only to large disruptions, or goods with extremely rapid delivery times. Apart from the purely economic aspect, a large burden comes from legal and organizational constraints.

For passengers, we considered cases of perfect controllability, full information available at some moment about the networks and the behavior of the users, and limited handling of capacity constraints, for demand peaks in railway systems. We base our analysis on the average demand assumed in national transport models. We assume user equilibrium solutions describe the baseline conditions, which can be improved by system optimal control, within one mode, or within multiple modes. We also include the activity pattern of users, and rerouting choices in complex multimodal networks. The principal benefits are related to what follows.

Information and guidance can effectively replace infrastructure if they are used to steer travelers to the available potential of the same mode, or of another mode. If the information and guidance are the only tools used to steer passengers, the effect is to be limited by the compliance rate of the users. Even within the same mode, the potential of routing advice is large. The information, though, assumes existing technical capabilities to sense an incumbent disruption, and disseminate this to travelers in real-time, and provide them with an optimal route. In numerical values, effective information might have comparable effects than cost-intensive adjustment of infrastructure and vehicles.

When taking management measures going beyond information and involving infrastructure change (extra lanes), or usage of further resources (larger vehicles, or increased frequency), the determination of the precise management action requires an effective understanding of the disruption and its effect, and size. While many management measures improve situations, their effectiveness is highly variable, and the costs for such actions are difficult to be evaluated, and in general, high. Moreover, any measure needs to be communicated to the travelers. Simply improving the supply of a single-mode without complementing information and guidance attracts people to a limited amount against large resource requirements.

Traffic operators can try to “push” the system from user equilibrium (UE) within one mode, to system optimum (SO) across all modes. Assuming that a system operates under UE, this is a simple and effective way to approach multimodal management and provides an upper bound for the room for improvement. There is strong evidence in the literature that cooperative strategies across transport modes can increase efficiency and social welfare when compared to competitive strategies. Nevertheless, there is a necessity for investment in ITS infrastructure for building and operating such a system. Providing incentives to the users (e.g., monetary, environmental) is another way to influence the state of the system and move towards SO.

The benefits of multimodal traffic management are limited by the type of disruption, the available services and resources, the demand available for change, whether the disruption is planned or unplanned, and the topology of the network. Planned disruption allows for a larger solution space from the travelers and an overall higher chance of reduced negative effects. This is especially important for public transport, where it is hard to imagine a generalized mode shift to private cars, in case of an unplanned disruption.

Current demand models are unable to estimate the effect of increased flows towards travel time in operations of public transport networks, thus making it difficult to compute a theoretical optimal route choice. They are moreover limited in propagating the consequences of multimodal management towards larger networks. The academic world lacks integrated models that could simulate cross-modal interactions and their effects on daily commuting and congestion patterns. Current analytical models focus specifically on one mode and can perform detailed analyses and provide metrics and statistics. Even research groups are structured in such orientation (i.e., focusing on separate specific transport modes), which makes multimodal integration even more difficult. Both theoretical and technical integration is required in order to move effectively towards multimodal management.

In the first case study, regarding the multimodality in freight transport, we can conclude the following: Mode shift as a multimodal management measure is not inherently desirable. Customers and transport operators design/choose the most efficient transport chain for their specific goal; a mode shift always increases costs and complexity from this original optimum. Mode shift alone requires equipment and time, thus reducing efficiency. The government's support on combined transport and synchromodal freight transport concepts could include flexibility at a planning stage and counterbalance those efficiency losses.

The general conclusion from the interurban case studies is that there are limited tools to consider all aspects of multimodal management strategies in case of a disruption in a national network level. For instance, as mentioned in conclusions in Section 7.7, it is noted that only the local effects of a disruption in an interurban bottleneck are studied, and propagated effects in the whole network are neglected. Therefore, developing a tool that combines different modes in a nationwide network level can be beneficial for further analysis of a multimodal management system. Moreover, the tool should also consider different aspects of multimodal management policies, e.g., environmental and user satisfaction aspects.

In the urban case study the benefits of multimodal management strategies are estimated by two simulation tools with different detail. A dense public transport network, and avilability of alternatives in city allows more measures to be implemented, and evaluated with greater detail. However, there are further improvements possible by, for instance, including futuristic transport technologies and more coordinated control policies. Moreover, the implementation of a urban traffic control room would require harmonizing requirements from many stakeholders, and the availability of technology for sensing, control, and implementation of actions, that could serve the transport of people and goods more efficiently.

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11. Appendices

11.1. *Details about interviews on freight disruptions*

Table 39 Interview summary

Group	Number contacted	Number conducted	Rate of participation
General Expert	20	11	0.55
Transport Operator	11	4	0.36
Industry	7	2	0.29
Government	3	2	0.66
Total	41	18	0.44

The potential general experts are identified during the literature review or are known by personal contacts. The other potential interview partners are contacted because of common knowledge and are mostly from Switzerland. All interview partners from industry or transport operators work or have worked in the logistics or freight transportation department of their respective organizations. Furthermore, a snowballing method is run asking interview partners for further recommendations and contacts. Table 39 shows a summary of the conducted interviews and Table 40, an overview of interview partners who agreed to be mentioned by name.

Table 40 Interview partners

Group	Name	Affiliation or Company
General Expert	Prof. Dr. Tomas Ambra	Vrije Univeristeit Brussel
	Philipp Buhl	SBB Infrastruktur
	Prof. Dr. Elise Miller-Hooks	George Mason University
	Prof. Dr. Erik Jenelius	KTH Stockholm
	Prof. Dr. Rico Maggi	USI Lugano
	Dr. Milan Janić	TU Delft
	Prof. Dr. Rudy Negenborn	TU Delft
	Prof. Dr. Rob Zuidwijk	Erasmus University Rotterdam
	Prof. Dr. Dirk Bruckmann	Hochschule Rhein-Waal
	Peter Somaglia*	Former Positions in Swiss Air and Cargologic
	Thomas Schmid	Rapp Trans
Transport Operator	Joel Baeriswyl	SBB Cargo
	Thomas Ernst	Swiss Post
	Dr. Dirk Pfister	BLS Cargo

	**	Pflanzer
Industry	Peter Geiger	Migros Cooperative Group
	Cornelia Peter	MAN Zurich
Government	Andreas Jeppesen	Swiss Federal Office for National Economic Supply
	René Sigrist	Swiss Federal Office for Transport

* Only specific questions, no complete interview

** Questions were answered via email by different persons

11.2. *BPR calibration and statistic tests*

Once the model is calibrated, it shall be appropriately validated.

The validation tests that are carried out are the one mentioned in section 7.3

Student's t-test; F-test or Fisher test , R^2 statistic, and $R^2, corr$ statistic.

Starting from the *t-Student test*, the results obtained are reported in the following table. The number of parameters for the BPR functions is two, and the result shows when using a BPR, the parameters are always statistically significant.

Table 41 t_student test of BPR function

Alternative: Main Road				
Origin: Geneva Destination: Lausanne				
Parameters	t-Statistic	Probability	Threshold	Condition
tα	25.281	99.00%	5.597	Verified
tβ	16.549	99.00%	5.597	Verified
Origin: Lausanne Destination: Geneva				
Parameter	t-Statistic	Probability	Threshold	Condition
tα	13.340	99.00%	5.597	Verified
tβ	18.778	99.00%	5.597	Verified
Alternative: Highway				
Origin: Geneva Destination: Lausanne				
Parameters	t-Statistic	Probability	Threshold	Condition
tα	64.778	99.00%	5.597	Verified
tβ	25.140	99.00%	5.597	Verified
Origin: Geneva Destination: Lausanne				
Parameters	t-Statistic	Probability	Threshold	Condition
tα	114.788	99.00%	5.597	Verified
tβ	33.310	99.00%	5.597	Verified

The results obtained for the *F-Test* are provided in the following table for the BPR function. the F-test is verified.

Table 42 F-Test results of BPR function

Origin: Geneva Destination: Lausanne				
Alternative	F-Statistic	Probability	Threshold	Condition
Main Road	273.9	99.00%	31.33	Verified
Highway	632.0	99.00%	31.33	Verified
Origin: Lausanne Destination: Geneva				
Alternative	F-Statistic	Probability	Threshold	Condition
Main Road	352.6	99.00%	31.332	Verified
Highway	1109.5	99.00%	31.332	Verified

Finally, the results for the *R^2* and *R^2,corr* for the BPR are provided:

Table 43 R^2 and R^2,corr results of BPR function

Origin: Geneva Destination: Lausanne		
Alternative	R^2	R^2,corr
Main Road	0.9856	0.9760
Highway	0.9937	0.9895
Origin: Geneva Destination: Lausanne		
Alternative	R^2	R^2,corr
Main Road	0.9888	0.9813
Highway	0.9964	0.9940

The R^2 value for the BPR function is not equal to 1, although Visum implements a BPR to calculate travel times. This is because Visum simulates the entire Swiss network and not just the network made up of the 3 alternatives we consider. Consequently, if in Visum we have had a model consisting only of the three alternatives, we would have obtained the cost function of the arcs, since we have the entire network, this does not happen, and therefore the coefficient does not assume a maximum value.

11.3. *Value of Time*

In order to transform the results in monetary values following table is used as a reference for the value of time according to (Axhausen *et al.*, 2008)

Table 44 Value of Time according to (Axhausen et al.*, 2008)*

	Trip Purpose			
	Business	Commuting	Leisure	Shopping
PT travel time (CHF/h)	49.57	27.81	21.84	17.73
Car travel time (CHF/h)	50.23	30.64	29.2	24.32

11.4. *Occupancy rates*

The occupancy rated base on the Cost-Benefit Analyzes for Road Traffic by the Swiss Association of the Road and traffic experts VSS in 2007.

Table 45 Occupancy rate values

Occupation rate values for different travel purposes					
Year	Travel purpose				
	All purposes	Commuting trip	Commercial trip	Shopping Trip	Leisure Trip
2000	1.59	1.15	1.27	1.61	1.92
2005	1.55	1.12	1.26	1.58	1.85
2010	1.52	1.09	1.24	1.56	1.80
2020	1.46	1.05	1.22	1.52	1.71
=>2030	1.43	1.03	1.20	1.50	1.67