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Mobility simulation in Hamburg considering various capacities for the Elbe Tunnel

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Abstract

This paper presents the results of a mobility simulation study conducted for the city of Hamburg, Germany, using the MATSim software. The study aims to evaluate the impact of various capacities for the Elbe Tunnel on the total travel time and waiting time of people using different modes of transportation, including private and shared cars, buses, regional trains, underground, and ferries. The study also assesses the total amount of CO_2 emissions released by these modes of transportation. To conduct the simulation, we investigate a scenario-based model that considers different capacities for the Elbe Tunnel, i.e., the most significant chokepoint of the city's road system, changing the current capacity by considerably different percentages.
The model includes data on the demand for transportation, road and traffic networks, and emission factors for different types of vehicles. The simulation is run for a 24-hour period, and the results are analysed using different performance indicators.

Keywords: Mobility simulation; MATSim; Scenario-based; Hamburg; Elbe Tunnel

1. Introduction

Mobility simulation is an essential tool for transportation planning and decision-making. One widely used open-source software for mobility simulation is MATSim (Multi-Agent Transport Simulation), which simulates the travel behavior of individual travelers and their interactions with the transportation network (Horni et al., 2016). It is widely used in research and practice to evaluate the impacts of transportation policies and infrastructure changes on mobility, emissions, and other relevant indicators.

MATSim begins by defining the network and generating a synthetic population of agents. Each agent is assigned a daily plan that outlines their activities and corresponding travel. The simulation then iterates over time steps, where agents execute activities, make travel decisions, move through the network, and respond to events through replanning. This iterative process captures the dynamics of transportation behavior, allowing for the evaluation of system performance and analysis of different scenarios. MATSim provides a flexible framework for comprehensive simulations of transportation systems, facilitating insights and policy assessments.

In recent years, MATSim has been used to study various transportation problems, such as congestion, environmental impacts, and equity issues. Ziemke et al. (2019) describe the development of the *MATSim Open Berlin scenario*, a multimodal agent-based transport simulation scenario that is based on synthetic demand modeling and open data. Viergutz and Schmidt (2019) compare the performance of demand-responsive transport (DRT) and conventional public transportation (CPT) systems in the rural town of Colditz, Germany, using a simulation model in MATSim. The comparison is made from the perspectives of operators, customers, society and ecology. The operators' perspective includes the required number of vehicles running the offer of a town bus line, the capacity, the vehicle kilometers, the number of paying passengers, and the ratio of empty runs. The customers' perspective includes the waiting time and the in-vehicle travel time.

Zwick and Axhausen (2020) apply MATSim to simulate ridepooling trips of one day in Hamburg, Germany and to analyse the effect of two ridepooling strategies, including DRT and the autonomous mobility on-demand on efficiency, mileage, mean travel and waiting time. The results show that the two strategies have similar results in terms of travel and waiting time, but service efficiency varies depending on demand and supply.

Ewert et al. (2021) consider the limitations of battery capacity and energy consumption of battery-driven electric vehicles (EVs) and apply the microscopic agent-based simulation in MATSim to address the vehicle routing problem for the EVs. Based on a case study focusing on food retail distribution in Berlin, the impacts of the limitations of the EVs on freight transport demand, road mileage performed and the resulting transport costs, and greenhouse gas (GHG) emissions are analysed. The major results show that introducing taxes on GHG-emissions will motivate more usages of the EVs, and due to the limited range of the EVs, a slight increase of the total number of vehicles used and kilometers driven can be determined in comparison to the baseline scenario with only internal combustion engine vehicles.

Rojano-Padrón et al. (2023) apply MATSim to design the network of charging points for EVs on Tenerife, Spain. First, they use a multiple regression model to estimate the number of EVs per year from 2018 to 2040 using a range of socioeconomic variables, such as the historical evolution of population and gross domestic product (GDP). Second, they calculate the number of charging points based on the number of EVs and the number of parking spaces of different types of buildings. Next, they collect the data from the geolocation records of mobile terminals, travel data from the public transport card, capacity data, and surveys of both residents and non-residents to obtain the mobility data used for the simulation. Running the simulation model in MATSim, the results not only show the total number of charging points, but also the number of slow charging points and semi-fast charging points in each municipality given an allocated budget.

Klüpfel and Lämmel (2016) estimate the influence of relocating a highway, B75, on the evacuation traffic in Wilhelmsburg, Hamburg by implementing simulations in MATSim. The influence is measured by three metrics, i.e., the overall evacuation time, clearing time of different cells and the number of cars using the road network. The results are used to demonstrate the evacuation contribution of MATSim.

Bassolas et al. (2019) use MATSim to simulate the impact of a cordon toll policy in Barcelona, Spain. The cordon toll policy is a type of congestion pricing scheme that charges drivers of private cars a fee for entering a designated area (or cordon) during peak hours. The simulation is based on the data of call-detail records that can provide information about people's locations and travel patterns. Four scenarios for implementing the cordon toll policy are simulated, in which the charging standard and charging time are changed. A total of 22 metrics are used to analyse the impact of the cordon charging policy, e.g., the total number of trips and cars. The results demonstrate the potential of using the data of call-detail records for traffic planning and modeling, and can inform policy decisions aimed at reducing traffic congestion and improving urban mobility.

Schlenther et al. (2022) apply MATSim to investigate the impact of a large roll-out of future mobility systems of Hamburg such as Mobility-On-Demand shuttles, sharing fleets and city-wide major improvements of the bicycle infrastructure, on the modal split of the motorised transport, emissions and accident costs. The results show that it is difficult to decrease the modal split of the motorised transport by implementing these future mobility systems alone. Moreover, the emissions of CO2 and NOx are highly related to the share of the private cars, but the additional miles traveled by electric shuttles increases emissions of PM and increases accident costs if driven by a human driver, but not the emissions of CO2.

Furthermore, some research aims to develop module functions to extend the application of MATSim. Charlton and Laudan (2020) describe the development of a web-based data visualisation platform for MATSim. The developed platform allows users to visualise and explore simulation results in real time, providing a more accessible and interactive way to analyse the complex transportation data. The authors introduce the design and implementation of the platform, as well as its potential application, such as showing the origin-destination flows, transit routes with specific stops and links, and emissions levels. The benefits of using a web-based platform for data visualisation can include increased accessibility, ease of use, and collaboration among stakeholders. Additionally, the platform can be customised to meet the specific needs of different user groups, and its development is seen as a step towards more effective and efficient transportation planning and policy-making.

Balac and Hörl (2021) extend MATSim by creating a genetic shared mobility module. This extended module is designed to have the features, such as simulating both human and engine-powered vehicles, station services, and multiple operating systems. The module is then implemented in an intermodal shared mobility system in the San Francisco Bay Area, USA. Four scenarios regarding the adoption rate, the number and the service mile of sharing bikes are investigated. Several metrics, such as the average access time and the average egress time are used to compare and assess the performance of the four sharing modes on the transportation system.

Müller et al. (2022) develop a new module for MATSim to simulate the intermodal routing that consists of multiple modes of transportation, such as bicycle, car, and DRT (e.g., cab, car sharing) trips in combination with public transportation. Based on the mobility diaries from the national transportation survey and the geospatial information, a case study for the city of Vienna, Austria, is conducted. The simulation results demonstrate the potential of the new module to improve the realism and accuracy of travel demand modeling, e.g., by providing information on travel distance, duration and purpose for different modes of transport. The study concludes by highlighting the importance of such tools for supporting sustainable and efficient transportation systems, particularly in urban areas with a high degree of intermodal connectivity.

The use of MATSim within a simulation-based optimization framework can be found in Nnene et al. (2023). A non-dominated sorting genetic algorithm is integrated with MATSim and applied to a case study of the bus rapid transit system in Cape Town, South Africa.

Table 1 summarises the surveyed related literature based on the application scenario, region, and model development of the works.

In this paper, we use MATSim to simulate the mobility in Hamburg and evaluate the impacts of different capacities of the Elbe Tunnel on travel time and emissions. We consider various modes of transportation, including private and shared cars, buses, trams, underground, and ferries. We use different scenarios of changing the capacity of the tunnel, ranging from -100% to +200% of the current capacity. Our main indicators are the total travel time, waiting time, and total CO_2 emissions.

The research proposal is highly relevant to the transportation planning and decision making in Hamburg, which is a major transportation hub in Germany and Europe. The Elbe Tunnel is a critical infrastructure element for the city, and its capacity has a significant impact on the mobility of people and goods. By evaluating the impacts of different scenarios of the tunnel capacity, we can provide insights into the potential trade-offs between travel time, emissions, and other relevant factors, and support evidence-based transportation planning and decision making.

The significance of this analysis lies in evaluating the potential benefits of constructing additional tunnels with capacities exceeding that of the Elbe Tunnel. It aims to assess whether such endeavors are worthwhile and can significantly contribute to improving traffic flow and mobility. Moreover, it is imperative to investigate the potential consequences if the tunnel experiences blockages or a reduction in capacity due to maintenance, repairs, or security reasons. Understanding the influence such events may have on overall traffic and city mobility is critical. This analysis also raises the question of whether alternative tunnels or alternative modes of transportation, such as specialised ships for carrying the vehicles to the other side of the river, should be considered in such scenarios.

The findings and insights derived from this study provide valuable guidance to investors and government entities regarding future projects and the allocation of resources. It helps inform decisions on whether it is advisable to invest in infrastructure projects of this nature, taking into account their potential impact on traffic management, mobility, and overall urban development. By considering these factors, stakeholders can make informed choices regarding the utilisation of public budgets and prioritise investments that align with long-term goals and aspirations.

The rest of this paper is structured as follows. Section 2 describes the methodology, then the simulation results are presented in Section 3. Finally, the conclusions are drawn in Section 4.

2. Methodology

The MATSim model of Hamburg encompasses various aspects of the city's transportation system and aims to simulate the behavior of its residents in terms of travel choices, such as mode selection, route choice, and departure time. In the following, we describe some key details about the MATSim model of Hamburg.

Network Representation: The model incorporates a detailed representation of Hamburg's transportation network, including roads, public transit lines, and other relevant infrastructure. The road network is typically derived from OpenStreetMap data and consists of nodes (intersections) and links (road segments) with associated attributes such as length, capacity, and travel time.

Agent Population: The model represents the population of Hamburg as a collection of synthetic individuals, each acting as an agent within the simulation. These agents are assigned various characteristics, such as home location, workplace location, activity patterns, and mobility preferences, based on statistical data and surveys.

Travel Behavior: The MATSim model captures the decision-making process of agents when it comes to travel behavior. All agents plan their daily activities and select modes of transportation based on their individual preferences, travel time, cost, and other factors. They can choose between different modes like car, bike, walking, or public transit, and also decide on departure times and routes.

Iterative Simulation: The MATSim simulation operates in an iterative manner, progressing through a series of simulation steps called iterations. In each iteration, agents execute their plans and move through the transportation network, generating traffic and interaction effects. The simulation accounts for congestion, travel times, and other factors affecting travel choices.

Feedback Loop and Learning: The MATSim model incorporates a feedback loop, allowing agents to learn from their previous experiences and adapt their decision-making strategies. This feedback mechanism enables the simulation to converge towards realistic travel patterns as agents adjust their plans based on observed outcomes and perceived utility.

Performance Evaluation: The MATSim model of Hamburg includes mechanisms for evaluating the performance of the transportation system. Metrics such as travel times, congestion levels, mode shares, and environmental im-

Reference	Application scenario	Region	Model development
Ziemke et al. (2019)	Transportation planning and policy evaluation	Berlin, Germany	New transport infrastructure, ride-sharing, and other transport policies
Viergutz and Schmidt (2019)	Public transportation in rural areas	Colditz, Germany	A stop-based and a door-to-door demand responsive transportation service is analysed along with a conventional public transportation bus line
Zwick and Axhausen (2020)	Optimisation of ridepooling services	Hamburg, Germany	Two state-of-the-art pooling strategies, demand data of the ridepooling company MOIA in Hamburg
Ewert et al. (2021)	Fleet management and logistics for delivery services of electric vehicles (EVs)	Berlin, Germany	Real-world data from an EV fleet
Rojano-Padrón et al. (2023)	Determine the number of charging points and places to install them	Tenerife, Spain	Strategies by the Government of the Canary Islands to achieve the goal of a complete electrification, mobility data (number of journeys made between the different transport zones)
Klüpfel and Lämmel (2016)	Consequences of relocating a road on the evacuation of a district	Hamburg- Wilhelmsburg, Germany	Current and new locations, citizen population size
Bassolas et al. (2019)	Evaluation of traffic demand management policies (cordon toll policy)	Barcelona, Spain	Mobile phone records to feed activity-based travel demand models
Schlenther et al. (2022)	Evaluation of future scenarios of transport systems on modal split, emissions, and accident costs	Hamburg, Germany	Multiple data sources including mobile phone trajectories and a representation of the private transport demand on a typical working day for the city of Hamburg and a larger surrounding area, commercial traffic that is generated from data provided by Hamburg's Authority for Transport and Mobility Change
Charlton and Laudan (2020)	Visualises MATSim outputs	Berlin, Germany	Build a new web-based open-source visualisation platform for MATSim outputs
Balac and Hörl (2021)	Generic shared mobility MATSim extension	San Francisco Bay Area, USA	Simulate both human and engine powered vehicles, docked/station and dockless/free-floating services, and multiple operators. Simulate and forecast the impacts of emerging shared modes on transportation systems.
Nnene et al. (2023)	Designing public transport networks to account for the stochastic behavior of commuters	Cape Town, South Africa	Simulation-based optimization
Müller et al. (2022)	Intermodal route planning considering different preferences of people	Vienna, Austria	Develop a new module that simulates the intermodal trips and the integration of different mobility behaviors based on mobility diaries from the national transportation survey and the available geospatial information

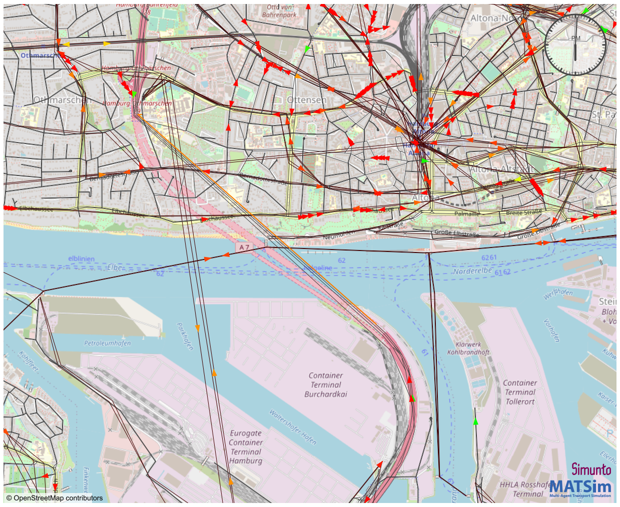
Table 1. Summary of related literature

pacts can be analyzed to assess the effectiveness of different policies or infrastructure changes.

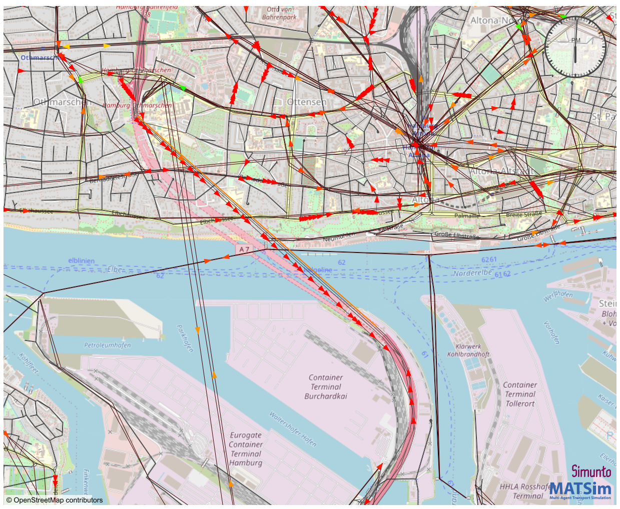
Scenario Testing: The MATSim framework allows for the creation and testing of various scenarios to explore different policy interventions and their potential impacts on the transportation system. For example, it can be used to simulate the effects of introducing new public transit lines, implementing congestion pricing, or evaluating the impact of changes in land-use patterns.

By employing the MATSim model, the transportation planners and policymakers in Hamburg can gain valuable insights into the dynamics of their city's transportation system. It enables them to assess the potential impacts of different strategies, make informed decisions, and work towards improving the efficiency, sustainability, and overall performance of the urban mobility in Hamburg.

The MATSim simulation model of Hamburg is used from https://github.com/matsim-scenarios/matsim-hamburg and modified based on our scenarios. The three links passing through the Elbe Tunnel, which have the IDs "2193342530014f", "338176470014f" and "31271330017f", are considered. They have the original capacities of 6000, 4000 and 4000 vehicles per hour, respectively. These capacities are changed by the percentages: -100, -50, -10, 0, 10, 50, 100, 200. For each scenario, we run the simulation five times based on 25% of the Hamburg



(a) Scenario -100%



(b) Scenario +200%

Figure 1. Illustration of the mobility simulation around the Elbe Tunnel at time 18:00:00

population and execute 200 iterations. We address the average values of the metrics for each scenario regarding the five completed runs. The used computers have the following characteristics: Core(TM) i7 processor, 3.10GHz CPU and 16GB of RAM.

3. Results

Fig. 1 shows the position of the vehicles in the scenarios -100% (capacity 0 for all the links) and +200% around the Elbe Tunnel at 18:00:00 as an example time point within the rush hour. The vehicles are shown with triangles. As it is evident in Sub-fig. (b), the links through the Elbe Tunnel are considerably used by the vehicles in the scenario with the biggest capacity. Therefore, blocking the links can disrupt the mobility flow as it is observed in Sub-fig. (a).

Fig. 2 presents a comparison of the total travel and waiting times for the Elbe Tunnel scenarios. The x-axis represents the scenarios, which are expressed as percentage changes in capacity compared to a baseline scenario. The values on the x-axis range from -100% to +200%, indicating different levels of capacity changes. The y-axis represents the time in hours, specifically the total travel and waiting times. The blue line with circular markers represents the total travel time for each scenario. The red line with square markers represents the waiting time for each scenario.

From Fig. 2, we can observe the following: As the tunnel capacity decreases (negative scenarios), both the total travel time and the waiting time increase. This is evident from the upward trend of the blue and red lines for scenarios -100%, -50%, and -10%. At 0% capacity change (the baseline scenario), the total travel time is around 2,159,017 hours, while the waiting time is approximately 391,781 hours. As the tunnel capacity increases (positive scenarios), the total travel time decreases. This is indicated by the decreasing trend of the blue line for scenarios 10%, 50%, 100%, and 200%. The waiting time also decreases as the tunnel capacity increases. This is evident from the decreasing trend of the red line for scenarios 10%, 50%, 100%, and 200%. Overall, the figure provides a visual representation of how changes in tunnel capacity impact the total travel and waiting times for different scenarios. It highlights the relationship between capacity and the efficiency of travel in terms of reduced travel and waiting times.

Fig. 3 represents the total CO_2 emissions for different scenarios in tons. The line plot in the figure shows a decreasing trend in emissions as the capacities increase. Starting from the left side of the graph, as the capacity decreases by 100% (Scenario -100%), the total emissions are approximately 230,000 tons. Moving towards the right, with a 50% decrease in capacity (Scenario -50%), the emissions decrease to approximately 180,000 tons. Continuing along the x-axis, as the capacity decreases by 10% (Scenario -10%), the emissions further decrease to approximately 150,000 tons. Coming to the baseline scenario (0% change in capacity), the emissions become approximately 120,000 tons.

At the 10% increase in capacity (Scenario 10%), the emissions decrease even further to approximately 110,000 tons. As we continue to increase the capacity, reaching Scenario 50% (50% increase in capacity), the emissions decrease to approximately 100,000 tons. Moving towards the right, Scenario 100% (100% increase in capacity) shows a reduction in emissions to approximately 90,000 tons. Finally, at Scenario 200% (200% increase in capacity), the emissions decrease even more, reaching approximately 80,000 tons.

In summary, the figure demonstrates a clear inverse relationship between increasing capacities and decreasing emissions. Higher capacities result in lower emissions, emphasising the importance of capacity improvements in reducing the overall environmental impact.

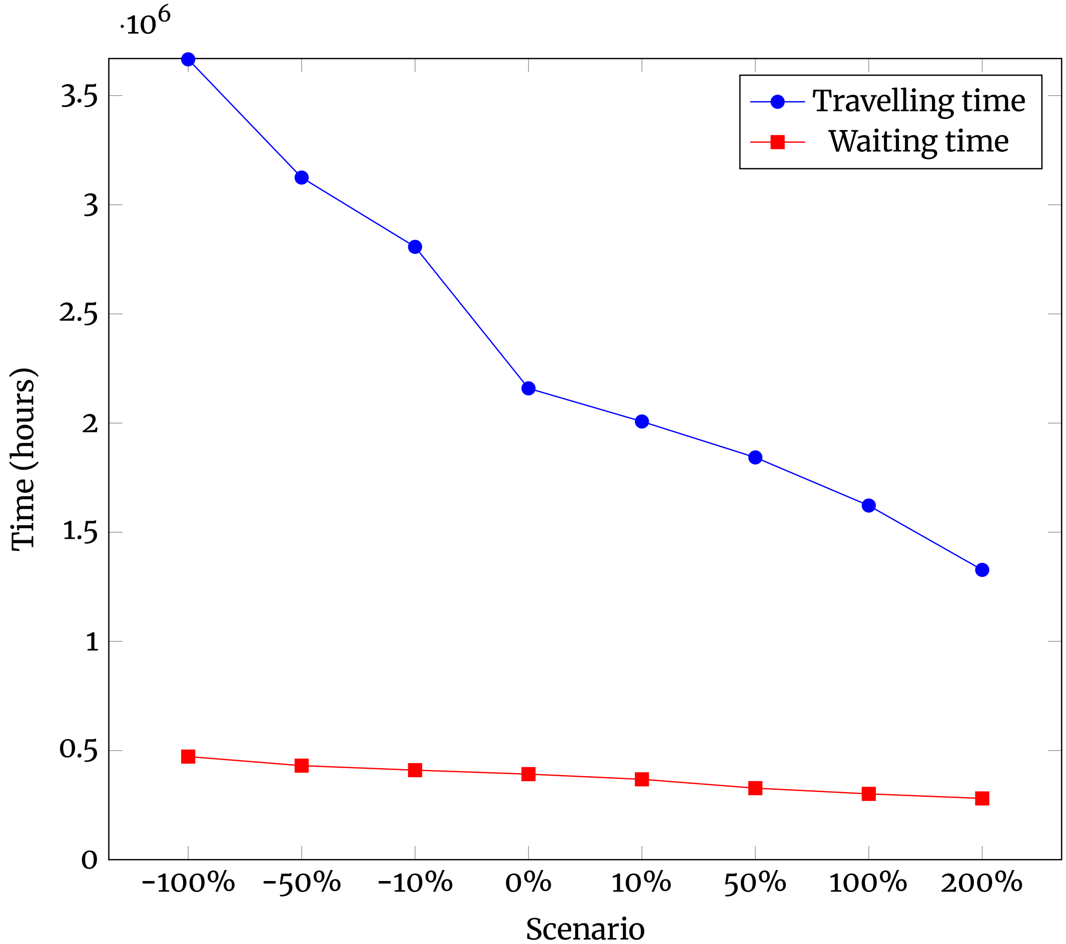


Figure 2. Comparison of travelling and waiting times for different scenarios

Our next analysis is about the optimisation mechanism embedded in MATSim, which works based on scoring and evaluation of the chosen plans of all agents after each iteration. We aim to show how the values of the addressed metrics are improved while MATSim proceeds iteratively further.

Figures 4-6 illustrate the evolution of MATSim results in terms of total travel time, total waiting time, and total CO2 emissions over iterations 1, 50, 100, and 150 in a single run of the simulation model. These results demonstrate the progressive improvement achieved through the evolutionary optimisation scheme employed in MATSim.

Figure 4 showcases the total travel time obtained in each iteration, there is a notable decrease in total travel time. In the initial iteration, the total travel time is approximately 8,470,375.39, 7,533,914.95, 6,582,803.03, 4,813,928.96, 4,273,846.55, 3,857,940.04, 3,610,048.43, and 2967613.96 hours for the scenario -100% to 200% , respectively. However, in iteration 150, they reduce to 4,039,950.48, 3,480,966.58, 3,049,586.32, 2,341,651.01, 2,240,126.32, 1,947,036.56, 1,720,582.01, and 1,412,228.03 hours. This significant reduction indicates that MATSim successfully refines the travel time estimation, leading to more efficient transportation solutions.

Figure 5 focuses on the waiting time experienced during the iterations. Similar to the total travel time, the waiting time decreases with each iteration. Starting from 1,122,624.57, 1,005,502.26, 965,694.30, 934,848.87, 871,896.94, 762,773.48, 712,576.57, and 661,728.95 hours for the first to the last scenario in iteration 1, the values decrease to 498,341.21, 452,493.04, 431,323.08, 417,821.95, 391,541.30, 346,049.87, 322,157.45, and 294,740.62 hours in iteration 150. The diminishing waiting time signifies that MATSim optimises the scheduling and coordination of transportation options, resulting in reduced waiting periods for commuters.

Lastly, Figure 6 depicts the total CO2 emissions across the iterations. As expected, there is a decline in CO2 emissions throughout the simulation process. The initial iteration indicates emission of 569,837.61, 435,746.94, 358,838.58, 284,703.08, 262,126.61, 241,993.82, 218,094.42, and 190,603.04 tons of CO2 for the scenarios -100% to 200%, while the emissions decrease to 245,498.74, 191,086.93, 159,149.58, 126,347.89, 117,376.66, 106,244.11, 95,131.71, and 84821.19 tons in iteration 150. This reduction reflects the effectiveness of MATSim in

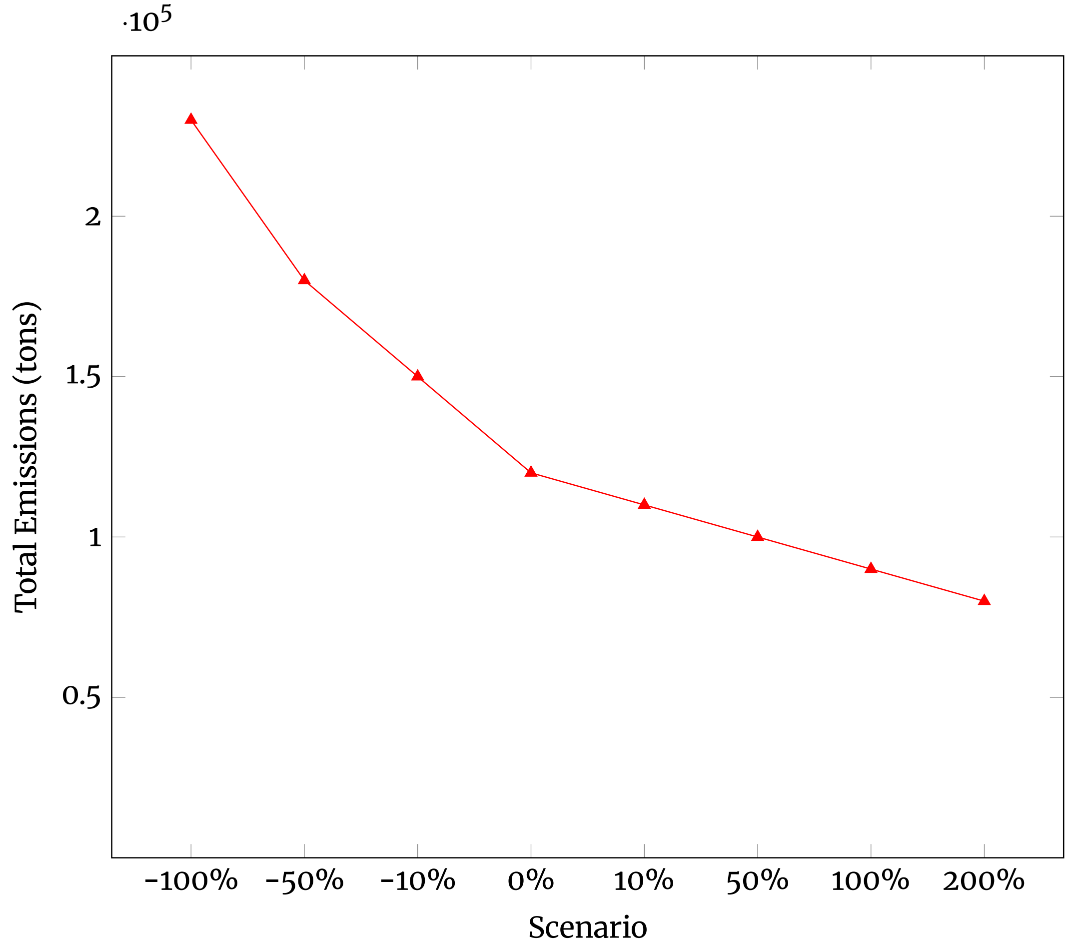


Figure 3. Total CO_2 emissions for different scenarios

promoting more sustainable transportation patterns and minimising environmental impacts.

In summary, the results obtained from MATSim demonstrate the successful convergence towards improved transportation outcomes. The iterative optimisation approach employed in MATSim contributes to the reduction of the analysed metrics. The rate of reduction is the highest from iteration 1 to iteration 50, and it decreases as we progress further. Consequently, the smallest reduction occurs between iteration 100 and 150. It is worth noting that there is still potential for further enhancement. Future efforts could focus on accelerating the convergence towards optimal results, aiming to achieve even faster and more efficient transportation systems.

4. Conclusions

In this work, we addressed the effects of the Elbe Tunnel capacity on the mobility in Hamburg. Our approach was simulation using MATSim and referring to some metrics such as the total travelling and waiting time as well as total CO_2 emission. It is observed that this tunnel plays an important role in the mobility in the city, so that reducing its capacity or excluding it from the transportation network will result in considerable raises in the metrics. This also leads to non-trivial environmental effects.

This study highlighted the need for a comprehensive presentation and thorough examination of the problem in the case study. It underscores the importance of addressing this analysis and understanding its implications for urban planning and traffic management. We realised the potential benefits of constructing additional tunnels with higher capacities than the Elbe Tunnel and their potential impact on traffic flow and mobility. Furthermore, the study emphasises the significance of considering possible scenarios such as tunnel blockages or capacity reductions and their effects on overall traffic and transportation options.

The findings from this study affirm the effectiveness of MATSim in achieving enhanced transportation outcomes through successful convergence. The iterative optimisation approach employed within MATSim significantly contributes to the reduction of total travel time, waiting time, and CO2 emissions. These positive results highlight the potential for continued advancements in transportation optimisation. Future research and development should

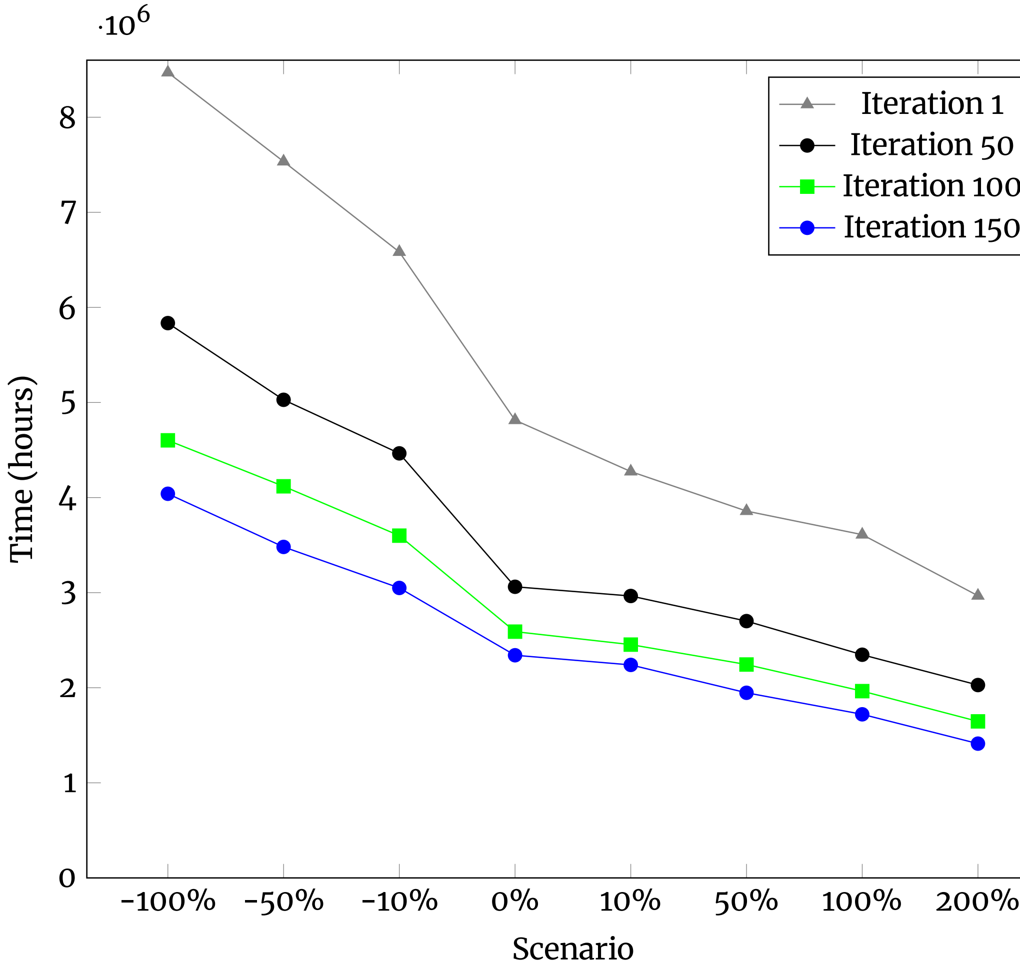


Figure 4. Total travel time obtained over iterations 1, 50, 100, 150 of MATSim

prioritise strategies aimed at accelerating the convergence process, leading to even faster and more efficient transportation systems. By continually pushing the boundaries of optimisation techniques, we can pave the way for sustainable and streamlined urban mobility in the years to come.

The findings of this research provide valuable insights for investors and government authorities involved in infrastructure planning. They offer guidance for future projects and resource allocation, aiding in informed decision making regarding the feasibility and benefits of investing in such infrastructure developments. It is recommended that further research be conducted to delve deeper into the economic and social implications of constructing an additional tunnel, considering factors such as environmental impact, cost-effectiveness, and long-term sustainability. Moreover, exploring alternative transportation modes and their integration into urban planning strategies could contribute to a more comprehensive and efficient mobility system. By addressing these aspects, future research can contribute to the advancement of urban transportation planning and enhance the overall quality of life for residents.

In addition, implementing the same simulations based on larger proportion of the city population can be followed. Obviously, it needs an enhancement in the computation power. The effects of adding some new roads to the network is a practical future work, too (e.g., simulating the impact of an Eastern ring highway from the Northwest to the Southeast of the city). From an academic standpoint, one may focus on mathematical modeling approaches with right-hand-side uncertainty, where such an uncertainty could be motivated from the availability of infrastructure or infrastructure components, as e.g. envisaged in Ge et al. (2022) for the case of integrated vehicle and crew scheduling.

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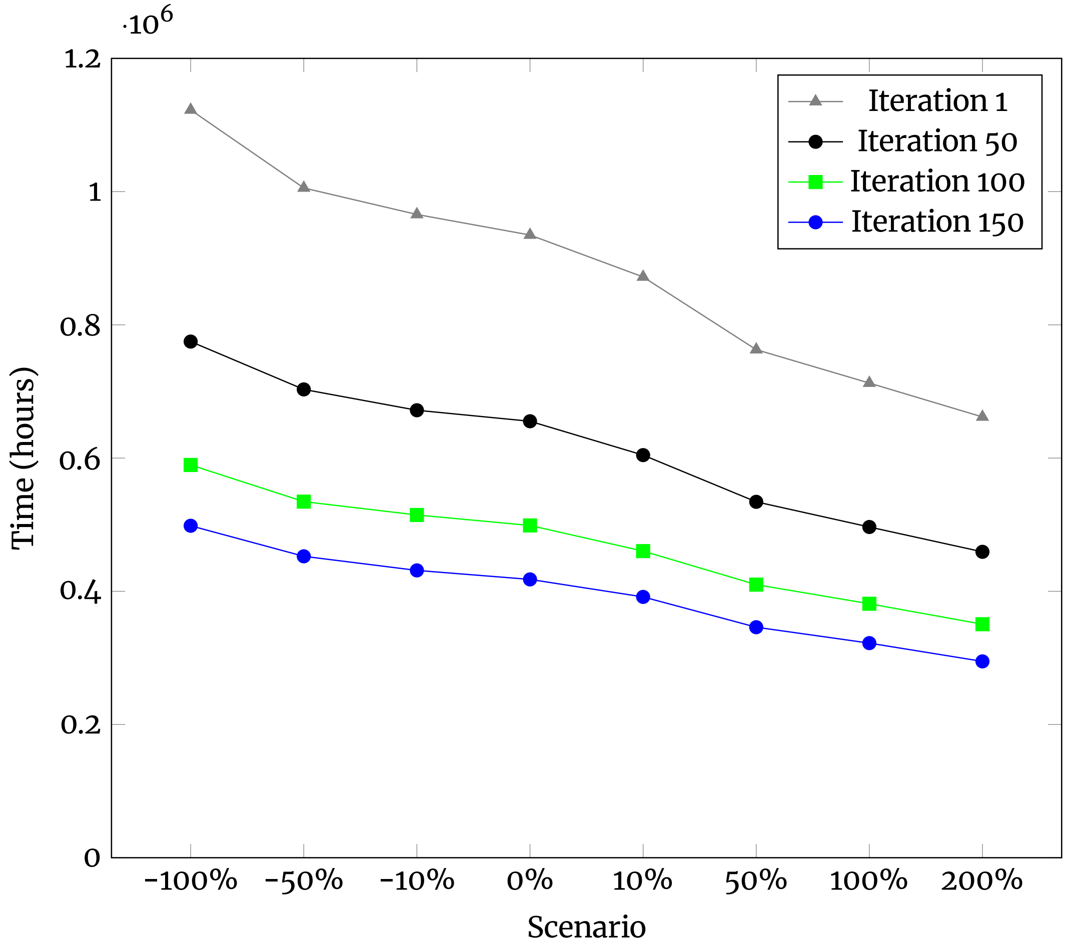

Figure 5. Waiting time obtained over iterations 1, 50, 100, 150 of MATSim

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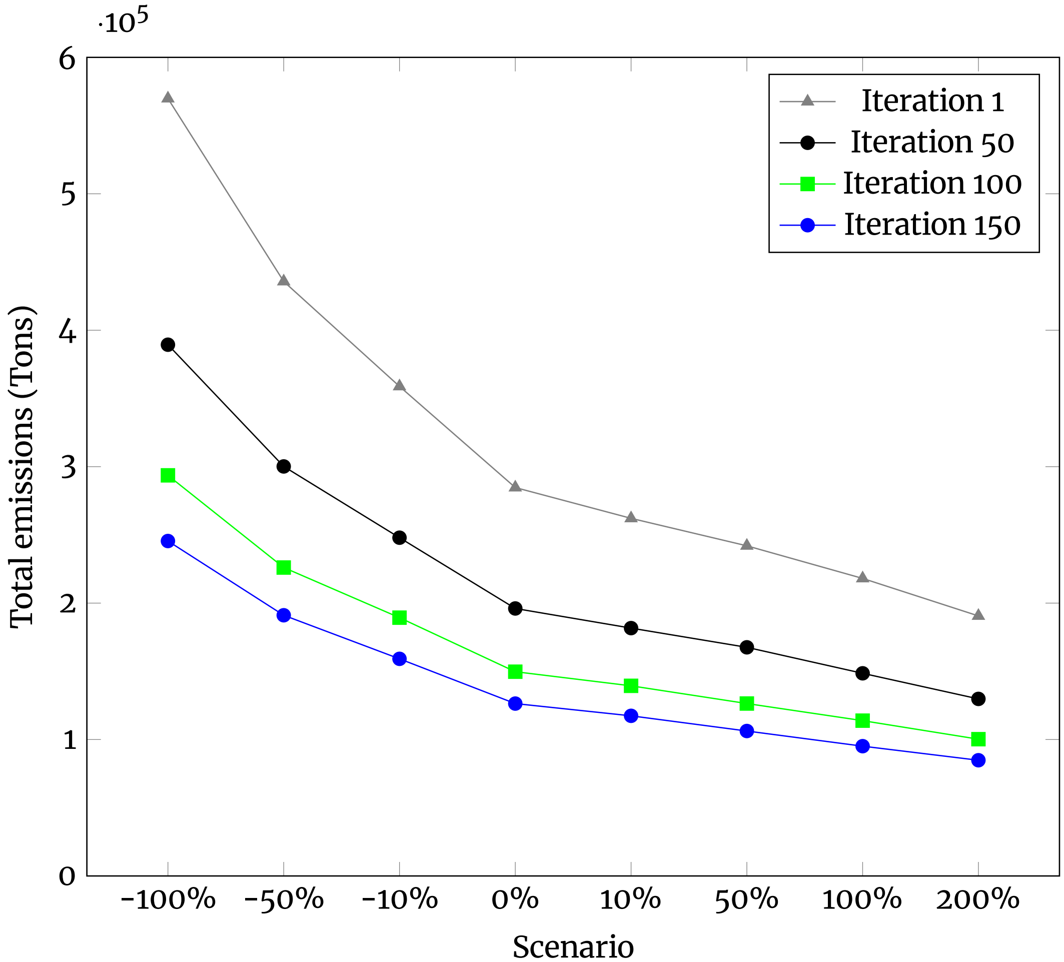

Figure 6. Total CO_2 emissions obtained over iterations 1, 50, 100, 150 of MATSim

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