Waterborne public transport

A feasibility study on agent-based simulation and CBA readiness

Henrik Sjöstrand
Chengxi Liu

VTI rapport 1245A
Utgivningsår 2025
vti.se/publikationer

Foto: Sten-Åke Lindbäck/Mostphotos.com

VTI rapport 1245A

Waterborne public transport

A feasibility study on agent-based simulation and CBA readiness

Henrik Sjöstrand

Chengxi Liu

Author: Henrik Sjöstrand (VTI), Chengxi Liu (VTI)
Reg. No., VTI: 2024/0261-7.4
Publication: VTI rapport 1245A
Published by VTI 2025

Publikationsuppgifter – Publication information

Titel/Title

Vattenburen kollektivtrafik. En förstudie/Waterborne Public Transport. A Feasibility Study

Författare/Author

Henrik Sjöstrand (VTI, orcid.org/0000-0003-3230-559X)

Chengxi Liu (VTI, orcid.org/0000-0001-6966-9077)

Utgivare/Publisher

VTI, Statens väg- och transportforskningsinstitut/
Swedish National Road and Transport Research Institute (VTI)
www.vti.se/

Serie och nr/Publication No.

VTI rapport 1245A

Utgivningsår/Published

2025

VTI:s diarienr/Reg. No., VTI

VTI: 2024/0261-7.4

ISSN

0347–6030

Projektnamn/Project

VATTENKOLL, Vattenburen kollektivtrafik. En förstudie/Waterborne Public Transport. A Feasibility Study

Uppdragsgivare/Commissioned by

Trafikverket/Swedish Transport Administration

Språk/Language

Engelska/English

Kort sammanfattning

Denna förstudie vidareutvecklar och tillämpar WUM (Waterborne Urban Mobility), en dynamisk trafiksimuleringsmodell i mjukvaran MATSim. Syftet är att analysera hur två nya båtsystem i Stockholmsområdet påverkar passagerarflöden och restider, samt undersöka hur WUM-modellen kan användas för att förbättra samhällsekonomiska kalkyler för kollektivtrafik på vatten. Förstudien lägger grunden för en större studie där modellen kan användas för analyser med ett komplett nätverk av linjesträckningar.

Två nya linjer simuleras i projektet: en reviderad tidtabell för linje 89 (mellan Ekerö och Klara Mälarstrand) i Stockholm med eldrivna Candela P-12-färjor, samt en helt ny linje mellan Lilla Essingen och Liljeholmen med eldrivna Cstrider-färjor. För båda fallen görs iterativa justeringar av tidtabellen baserat på det simulerade resandet per avgång. Resultaten visar att införandet av täta avgångar, och i Candelas fall snabbare färjor, leder till ett ökat nyttjande, särskilt under morgon- och eftermiddagstoppar. Samtidigt visar resultaten att eldrivna färjor med låg kapacitet kräver flera fartyg i drift för att möta efterfrågan under högtrafik. Justerade tidtabeller minskar antalet avgångar med en efterfrågan som överstiger utbudet och förbättrar utnyttjandegraden. Effekterna på totala färdmedelsandelar i regionen är dock begränsade, eftersom färjetrafiken utgör en liten andel av det totala resandet. Dessutom gör stokastisk variation i modellen det svårt att särskilja mindre effekter från slumpmässiga fluktuationer.

Som nästa steg föreslås att hela nätet simuleras med flera linjer för att fånga nätverkseffekter och generera mer robusta resultat. Att genomföra flera modellkörningar med olika startvärden skulle också minska känsligheten för stokastiska variationer. Kommande studier bör fokusera på att undersöka hur modellens nyttobedömningar (scoring) kan harmoniseras med ramverket för nyttokostnadsanalyser (CBA). En annan förbättring vore att kombinera WUM med Sampers för att dra nytta av styrkorna hos båda modellerna. Slutligen bör körningstiderna av modellen förbättras, då dessa utgjorde en begränsning i projektet.

Genom dessa steg blir det möjligt att genomföra robusta nyttokostnadsanalyser av Candelas och Cstriders båtsystem, och därmed besvara den centrala frågan om små eldrivna pendelbåtar är samhällsekonomiskt lönsamma, eller om kostnaderna överstiger nyttorna.

Nyckelord

Vattenburen kollektivtrafik, VKT, eldrivna färjor, WUM-modellen, MATSim, agentbaserad modellering, samhällsekonomisk analys, nyttokostnadsanalys, CBA

Abstract

This feasibility study further develops and runs WUM (Waterborne Urban Mobility), a dynamic agent-based traffic simulation model in the software MATSim. This is done to study the effects of two novel vessel systems in Stockholm on passenger flows and travel times. Also, it is analyzed how WUM can improve cost-benefit calculations for waterborne public transport trips. The study lays the foundation for a larger study where the WUM model will be used for scenario analysis with a complete network layout.

Two new ferry lines are simulated in the project: a revised timetable for line 89 (between Ekerö and Klara Mälarstrand) in Stockholm using electric Candela P-12 vessels, and an entirely new line between Lilla Essingen and Liljeholmen using electric Cstrider vessels. For both cases, an iterative adjustment of the timetable is carried out based on simulated demand per departure. The simulations show that the introduction of frequent (and in Candela's case, faster) vessels leads to increased usage, especially during morning and afternoon peak hours. At the same time, the results indicate that low-capacity electric vessels require multiple vessels in service to meet demand during peak periods. Adjusted timetables reduce the number of departures with excessive load, improving utilization. The effects on overall mode choice are, however, limited, as ferry traffic constitutes only a small share of total travel. Moreover, stochastic variation in the model makes it difficult to distinguish small effects from random fluctuations.

As a way forward we propose simulating full network assignments with multiple lines, in order to capture system-wide adjustments and generate more robust inputs. Running several simulations with different starting positions would also help reduce sensitivity to stochastic variation. Another improvement for future work is to consider how scoring (i.e., benefits of certain travel chains) in the simulation can align with the CBA (cost-benefit analysis) framework. Furthermore, WUM and Sampers should be used in combination in order to utilize the strengths of both models. Also, further work should focus on improving the runtime, which became a limiting factor in this project. With these steps, it will be possible to conduct robust CBAs of Candela's and Cstrider's vessel systems and thereby answer the essential question of whether small electric commuter ferries are socioeconomically viable, or if the costs outweigh the benefits.

Keywords

Waterborne public transport, electric vessels, WUM model, MATSim, agent-based modeling, economic appraisal, cost-benefit analysis, CBA

Contents

Preface

This report has been produced within the project VATTENKOLL – Waterborne public transport, funded by the Swedish Transport Administration's research and innovation portfolio for shipping. The project was carried out by the Swedish National Road and Transport Research Institute (VTI). The report was written by Henrik Sjöstrand and Chengxi Liu at VTI.

The project was conducted in collaboration with Candela Technology AB and Cstrider AB, which provided valuable input and data regarding their respective vessel systems. We are grateful to the members of the reference group, including representatives from Blidösundsbolaget, Styrsöbolaget, Region Stockholm, the City of Stockholm, Ekerö Municipality, Transdev, and Torghatten AS, for their constructive comments and insights throughout the project. We would also like to thank Ida Kristoffersson (VTI) for her review of this final report, and the Swedish Transport Administration for the financial support that made this study possible.

Stockholm, October 2025

Henrik Sjöstrand
Project Manager

Granskare/Examiner

Ida Kristoffersson, VTI.

Publikationen godkänd för publicering/Publication approved for publication

Jan-Erik Swärdh, VTI.

1. Introduction

Stockholm, like many other Swedish cities, have a long history of waterborne public transport. Despite this, waterways today remain a potentially underutilized resource in urban mobility systems. Current ferry services in the Stockholm region are characterized by high emissions per passenger kilometer compared to other modes of public transport. This can largely be explained by two factors: low average occupancy rates on many routes, and the continued reliance on fossil-based marine fuels. For example, line 89 (a commuter ferry line) between Ekerö and central Stockholm operates vessels with a capacity of nearly 200 passengers, yet average load factors are as low as 20 percent.[1] Also, fuels used in conventional vessels emit substantially higher levels of greenhouse gases and air pollutants compared to the renewable fuels and electrification already introduced in land-based public transport (Sjöstrand et al. 2020).

Candela Technology AB use hydrofoil technology that reduces energy demand by up to 80 percent (Candela n.d.), enabling the electrification of smaller, fast vessels. The Candela P-12 vessel is now being tested in Stockholm. Similarly, Cstrider AB has designed a system of small, electric vessels with flexible routing, enabling high-frequency services that can be adapted to real-time demand. Both solutions address the twin challenges of environmental performance and low occupancy rates, while also offering opportunities for shorter travel times. However, their limited passenger capacity poses a challenge for scaling up operations, especially during peak travel periods. Moreover, staffing costs per passenger are higher than for conventional vessels due to their smaller size.

To assess the potential of these new concepts, modeling tools are needed. Traditional static assignment models, such as the Swedish national passenger transport model Sampers, provide limited ability to capture the complex dynamics of multimodal journeys, congestion effects, and user heterogeneity. To overcome these limitations, the Waterborne Urban Mobility (WUM) model was developed at VTI (Flötteröd, 2020). WUM is based on the agent-based simulation framework MATSim, and allows for detailed representation of travelers' socio-demographic characteristics, preferences, and mode choices. This provides a more realistic basis for evaluating new public transport services, including waterborne solutions, and for integrating results into cost–benefit analyses.

The present feasibility study builds upon WUM. The project has three main objectives: (1) to further develop the WUM model to represent different types of vessel systems, (2) to simulate the effects of introducing Candela's and Cstrider's vessels on selected routes in Stockholm, and (3) to explore the implications of these results for economic appraisal. By doing so, the project contributes to better-informed decisions in public transport planning, while also laying the groundwork for a larger study including societal appraisals of a full network layout of electric public transport ferries in Stockholm.

The transition to fully electric vessels has gained traction worldwide, and several examples illustrate both the opportunities and the challenges of integrating such vessels into public transport systems. Market researcher Fortune Business Insights predicts that by 2027, the electric ships market will be valued at nearly 110 billion SEK – nearly double that of 2019 (Condé Nast Traveler 2023). For example, the Norwegian startup Hyke launched its first Smart City Ferry in 2024 as a public transport shuttle in Fredrikstad. The 15-meter-long vessel can carry up to 50 passengers and has a cruising speed of 15 knots (28 km/h). It is fully electric and features a catamaran hull. The ferry connects local stops across the river in a pilot test in downtown Fredrikstad, replacing diesel ferries (Baird Maritime 2024). Another example is Artemis Technologies that is developing a hydrofoil electric vessel for the Belfast‑Bangor route. The new ferry is 24 meters long and can carry 150 passengers, and is designed

---

[1] Own calculations based on data from Region Stockholm on the number of departures and passengers per month.

for speeds up to 38 knots. The pilot testing has been delayed and is now scheduled for late 2025 (McBride 2024).

There are examples of studies examining how MATSim[2], which is used in this study, can be used to provide input to a cost–benefit analysis[3] (CBA). In Grunicke (2020), the authors build a pilot simulation for Göttingen, Germany, comparing a baseline scenario with and without a demand-responsive transport (DRT) service[4]. They show that MATSim can integrate both internal and external costs, such as travel time, user costs, congestion, and emissions, into simulation scenarios and that agent-based modeling can act as a foundation for conducting realistic CBA studies of public transport systems.

Rødseth et al. (2023) analyze the technical and economic feasibility of introducing battery-powered high-speed vessels in Oslo, using an optimization model that minimizes total system costs, including operator, passenger, and external road transport costs. Unlike the WUM model, which dynamically simulates travel behavior and system-wide effects in a multimodal network, the model by Rødseth et al. (2023) is a static optimization model designed to minimize total system costs for a single vessel route, focusing on speed, frequency, and charging decisions rather than network-level travel dynamics. They do not present a full cost–benefit analysis. Instead, the difference in total system costs between diesel and electric operation is expressed as an abatement cost of approximately 2,600 NOK (≈ 2615 SEK) per ton of CO_2, which exceeds the Norwegian government's estimated social cost of carbon of 2,000 NOK per ton (≈ 2010 SEK).

Kanchiralla et al. (2025) conduct a life-cycle assessment and cost analysis of electric vessels, focusing on energy use, emissions, and costs over the vessels' lifetime. The study does not model passenger flows, travel times, or mode shifts, but rather evaluates the environmental and economic performance of electric vessels as a technical system. They conclude that using electric vessels instead of conventional gas oil-powered vessels can lead to more than 90 % reduction in CO_2 emissions. This calculation accounts for the manufacturing of batteries and other electric powertrain components. They find that the cost of carbon reduction is around 100 euro (≈ 1100 SEK) per tonne CO_2-equivalents.

---

[2] MATSim is an open-source agent-based transport simulation framework that models the travel behavior of individual agents, to analyze the performance and dynamics of transport systems.

[3] A cost–benefit analysis (CBA) is a systematic method for comparing the total societal benefits and costs of a project or policy, to determine whether it increases overall welfare.

[4] DRT is a public transportation service that adapts its routes and schedules to passenger requests, operating on-demand rather than on a fixed timetable.

2. Simulation of waterborne traffic in Stockholm

2.1. The WUM model

The simulation model for the Stockholm region has been further developed based on a baseline version from the earlier Waterborne Urban Mobility (WUM) project (Flötteröd, 2020). The model is built on MATSim (www.matsim.org), which currently provides the most comprehensive agent-based simulation infrastructure for mobility research. As an open-source software, it is freely available online (e.g. https://github.com/matsim-org/matsim-example-project) and is highly flexible, allowing both the use of pre-built model components and the implementation of custom modules.

Figure 1 illustrates the core concept of MATSim simulations, commonly referred to as the 'MATSim loop'. In this framework, each agent repeatedly optimizes its daily activity schedule while competing with other agents for space-time slots in the transport network.

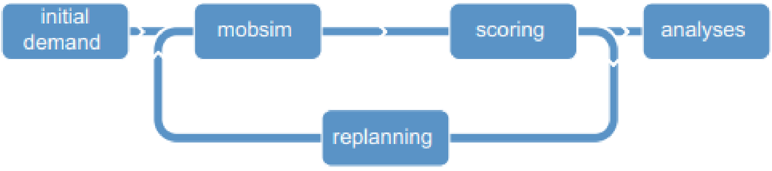


Figure 1. MATSim loop (Horni et al. 2016).

The process begins with the agent's initial travel demand, defined as a sequence of activities and trips between the activities (with an initial travel mode that may later change). A typical initial plan may look like:

Agent *X*:

- Activity: Home (coordinates, activity end time)
- Trip: Car
- Activity: Work (coordinates, activity end time)
- Trip: Car
- Activity: Home (coordinates, activity end time)

This example illustrates an agent starting the day at home, departing at a certain time by car to work, and then returning home at the end of the day. All agents' initial travel demand is then submitted to mobsim[5], the simulation engine. In mobsim, the interactions between all trips in the transport network are modeled. For example, congestion effects may arise in the road network if too many vehicles choose the same routes. Mobsim calculates travel times, travel distances, and routes for each trip. This means that trips in the initial plan also contain information about travel time, distance, and routing.

Once all trips have been simulated, each agent's travel plan must be evaluated to determine whether it meets the agent's travel needs. For instance, a car journey with a very long travel time due to congestion should receive a low score. This evaluation step is referred to as *scoring* in Figure 1. After all plans have been scored, they can be adjusted for the next iteration, at which point they are simulated again in mobsim. This is the *replanning* step shown in Figure 1. Examples of modifications include changing the travel mode, departure time, or selecting alternative routes. There are many different approaches for the selection of different possible modifications (discussed in detail below in

---

[5] Mobsim is the simulation engine within MATSim that models how all agents move and interact in the transport network, calculating travel times, routes, and congestion effects for each trip.

the subsection *Replanning*). The convergence is not assured, rather it checks whether each iteration actually improves the scoring and if the scoring has not been improved after many iterations, it is believed that the convergence is reached.

The simulation model used in this project has the following specifications regarding the components of the MATSim loop.

2.1.1. Initial demand

The study area covers the entire Stockholm County. We simulate 5 % of the population in this area, corresponding to 68,905 agents randomly sampled from the whole population. Each agent is assigned attributes such as gender, age, employment status, car availability (determines if car is a viable mode option for that agent), and income. These attributes influence the *scoring* stage (see below). Each agent has an initial travel plan generated from the results of the Sampers regional model. This means that activities and activity sequences are predefined in the simulation.

All agents follow a tour-based travel plan, where a tour is defined as starting from home, performing one activity, and then returning home. An agent may undertake multiple tours, for example: home–work–home–shopping–home. In the first iteration, we assume that all trips between activities are made by car, which is later adjusted during the simulation process.

The WUM model does not capture induced demand, since the total number of agents in the simulation is fixed and cannot increase when transport conditions improve

2.1.2. Mobsim

Mobsim simulates vehicle movements for cars and public transport, while walking and cycling trips are represented through teleportation — that is, physical movements are not simulated, and instead the traveler “flies” in a straight line from the origin to the destination. This simplification was introduced because simulating walking and cycling would require importing a highly detailed pedestrian and cycling network consisting of millions of links, which would increase computation time significantly – in the order of a week. Since the project involves multiple scenario runs, the project group decided not to simulate walking and cycling explicitly in the network. For cars, Mobsim captures congestion effects in the road network according to traffic flow theory, producing a realistic representation of how congestion arises and spreads. For public transport, a concrete multimodal travel chain must be constructed, beginning and ending with walking to and from stops (access and egress), and consisting of a sequence of public transport modes: bus, ferry, train, metro, and/or tram. An agent may therefore combine several modes in one trip — for example, first taking a bus and then a ferry. Transit walking is included in the sequence whenever the boarding and alighting stops are not located at the same place. This means that walking appears in the model in two forms: either as an independent trip, or as walking within a public transport chain.

2.1.3. Scoring

Scoring of simulated travel plans is carried out using so-called utility functions. In the WUM model, the same type of utility function is applied as in Sampers, where costs are multiplied by the corresponding utility parameters.

For walking, cycling, and car trips, the utility function includes only travel time and distance. For public transport trips, the utility function also accounts for waiting time, transfer time, and both access and in-vehicle time. In-vehicle time is valued equally across modes — such as bus, ferry, train, metro, or tram — but a specific *boat factor* is introduced to distinguish ferries from other public transport modes. This has been tested in WUM and found to have a large impact on passenger volumes. A boat factor of 1 implies that ferry travel time is valued the same as other modes, while a value below 1 indicates that ferry trips are perceived as less burdensome per minute compared with other modes. In the analysis conducted in this study, the boat factor is set to 1, given that there is currently no empirical studies examining how perception of ferry in-vehicle time should differ from that of other public transport modes.

2.1.4. Replanning

In each iteration, the WUM model allows the following elements of the travel plan to be modified: departure time, route, and travel mode. MATSim provides several strategies for replanning, ranging from random mutations to best-response strategies, where the optimal solution is sought in each iteration. For example, route choice is often adjusted using a best-response strategy (shortest route), while replanning of departure time and mode is typically performed through random mutations. In the current version of the WUM model, a customized replanning algorithm is applied, which evaluates and optimizes new travel plans in order to determine which proposed plans should be adopted in the next iteration (Flötteröd, 2024). This accelerates the convergence of the model.

According to the project plan, the WUM model was to be further developed by adding new functionality for simulating demand-responsive transport and flexible boarding points. However, during the reference group meeting, public transport operators pointed out that fixed timetables are preferred over demand-responsive services, due to the way public transport procurement and contracts are structured. The project group therefore decided instead to carry out several scenario analyses with fixed timetables.

An iterative process was conducted as follows:

1. Run the baseline scenario.
2. Run a scenario for a proposed line with an initial timetable (high service frequency).
3. Analyze boardings and alightings for each departure and propose a revised timetable, i.e. reduce the number of departures at times with no or very few boardings.
4. Run a scenario for the proposed line with the adjusted timetable.
5. Return to step 3, or the simulation is ended by user.

Through iterative runs, this process produces a timetable adapted to the number of passengers at the level of individual departures.

2.2. Simulation results

The project includes two scenario analyses:

- Line 89 using Candela vessels.
- A new line between Lilla Essingen and Liljeholmen using Cstrider vessels.

In both scenarios, Candela and Cstrider first propose a desired timetable based on planned number of vessels for operation. In constructing the timetable, both the vessels' range and charging times are considered (as both Candela and Cstrider vessels are electric). The completed timetable is then used as the initial timetable in the simulation — corresponding to step 2: *"Run a scenario for the proposed line with the initial timetable (high frequency)."* As we will see, changes of the initial timetable are needed to better match simulated passenger volumes. The adjusted timetable will be evaluated in the simulation which then indicates changes in number of vessels needed.

In addition to these two scenarios, there is also a comparison scenario representing today's ferry traffic. We therefore use the current timetables, including Line 89. At present, there is no ferry traffic between Lilla Essingen and Liljeholmen.

Compared with today's fossil-fueled ferries, the simulation must account for several aspects specific to electric ferries. The most important difference is that electric vessels are often faster, meaning that the constructed timetable must reflect shorter travel times. The timetable also incorporates charging times and range limitations.

Electric vessels typically have lower passenger capacity. For example, Cstrider vessels carry a maximum of 12 passengers. This creates challenges for the simulation, since only 5 % of the population is represented, meaning that each agent corresponds to 20 real-world passengers. Test runs with 10 % of the population showed that simulation times become very long — up to a week before convergence is reached. Even with 5 %, each run takes about two and a half days. For this reason, we simplify the simulation by not introducing capacity constraints[6]. Instead, we assume that the number of vessels per departure is scaled to match the number of passengers wishing to travel. If the simulation result suggests that each departure may require more vessels, it is an indication that the maximum number of vessels required for such a timetable will increase for Candela and Cstrider, and so do the operational costs.

2.2.1. Base scenario

Simulation configuration

The simulation model includes the following modes of transport: walking, cycling, private car, and public transport. Public transport is further divided into bus, metro, light rail, railway, and ferry. Vehicle movements for both private cars and public transport are simulated through networks in the model, where the networks for each mode are imported into the simulation. Walking and cycling trips are simulated as being teleported by beeline distance, i.e. not via the physical network. The simulation covers the entire Stockholm County. The road network for car traffic is imported from Sampers (Figure 2 blue), while the public transport network is imported from GTFS Sweden 2[7] via Trafiklab: https://www.trafiklab.se/api/gtfs-datasets/gtfs-sverige-2/ (Figure 2, red). We use a timetable for a normal working day in January in 2024. Note that GTFS Sweden 2 covers the whole of Sweden. Therefore, public transport lines are filtered out if all their stops lie outside the study area.

---

[6] Capacity constraints refer to limitations on how many passengers a transport service can accommodate.

[7] GTFS (General Transit Feed Specification) is a standardized data format used worldwide to share public transport information such as routes, stops, and timetables in a machine-readable way.

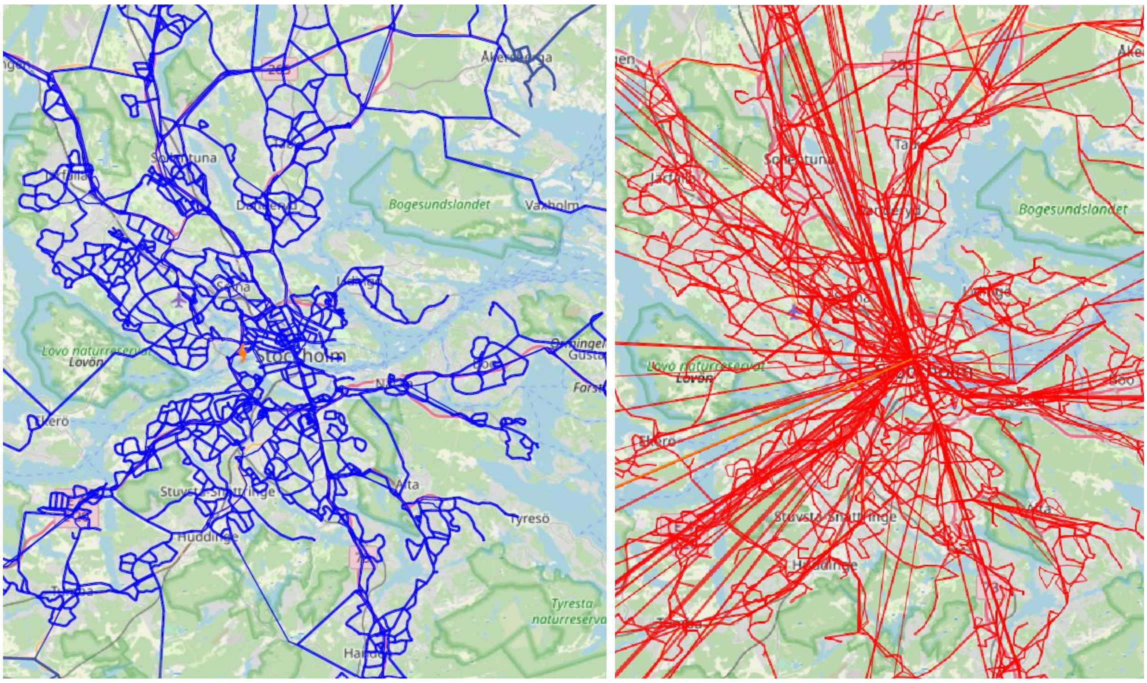


Figure 2. Private car network (blue) and public transport network (red), zoomed in on Central Stockholm. Source: Sampers and GTFS Sweden 2.

It is important to note that the simulation of vehicle movements is carried out separately for private cars and public transport. This means that congestion in the road network does not affect buses. Public transport vehicles follow the timetable strictly, and any delays are not captured in the model. This configuration is a deliberate choice, as previous simulation experiments within the WUM project (Flötteröd, 2020) showed that a joint simulation of private cars and buses on the same road network has a major impact on individuals' mode choice, which could not correctly capture impacts of delays in public transport on individual mode choice. This leads to unexpected simulated behaviors in the model and makes the interpretation of the results more difficult.

The initial travel plans were created in the earlier WUM project, based on the results from an older version of Sampers (Canella et al. 2016). We simulate 5 % of the population in the study area.

The model is calibrated so that the mode shares calculated by the model match the Stockholm regional travel survey, RVU (Trafikförvaltningen 2020). This is done by adding mode-specific constants (walking, cycling, private car, and public transport) to the "scoring" function and running the simulation iteratively until convergence:

- Run one simulation with the initial mode-specific constants C_m and obtain the mode shares P_m for walking, cycling, private car, and public transport.
- Calculate the logarithmic difference between the model-estimated mode shares P_m and the RVU mode shares R_m: $Ln(\frac{R_m}{P_m})$
- Update the mode-specific constants as follows: $C_m^{nextIter} = C_m + Ln(\frac{R_m}{P_m})$ then return to step 1.

This process is based on the assumption that the simulation can be interpreted as a Logit model[8], where the "scoring" function corresponds to a utility function. It is worth noting that it takes many

---

[8] A logit model is a statistical choice model used to estimate the probability that an individual selects a particular alternative based on the relative utility (or attractiveness) of all available options.

iterations (more than 20 iterations) until the mode-specific constants are calibrated following the process above.

Simulation results

We present here the results from the calibrated simulation for the base scenario. A total of 125 iterations were run. Figure 3 shows the development of the average executed "score" over the iterations. The executed scores reflect the average of scores of the simulated travel plans in each iteration. Note that the iteration starts from 100, which is simply a manual setting where we label the 1st iteration as "iteration 100". It is clear that once the iteration number passes 200 (i.e. running 100 iterations), the score stabilizes at around -47. It is possible that the score could still be marginally improved with additional iterations. However, given the long runtimes (around 2.5 days), we chose to end the simulation after 125 iterations.

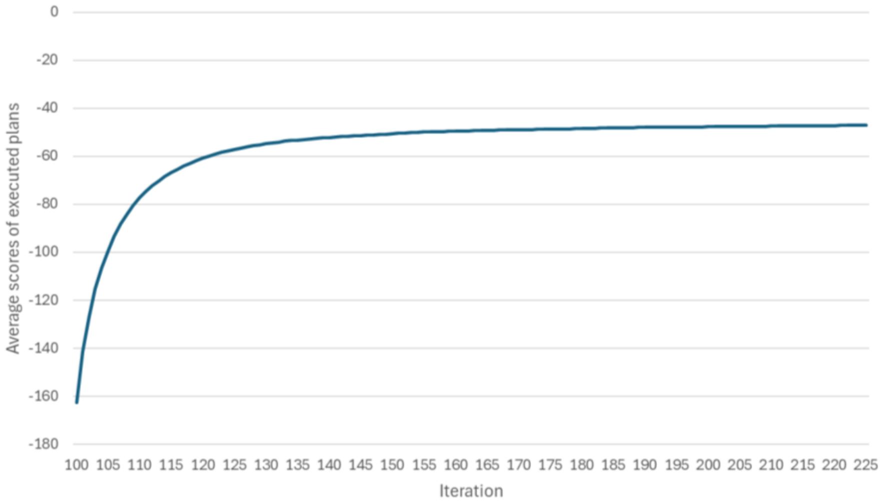


Figure 3. Evolution of scoring over iterations.

Figure 4 shows the development of mode shares over the iterations. Initially, all travel plans start with only private cars, which we set as the starting point. Thereafter, the mode shares gradually change and stabilize after about 200 iterations. The final shares are presented in Table 1.

It is important to note that ferry traffic – which is the focus of this study – represents only a small share of the total public transport travel in the Stockholm region. At a meeting with the reference group, Region Stockholm pointed out that public transport lines with low passenger flows are difficult to capture with VISUM, the model currently used by Region Stockholm.

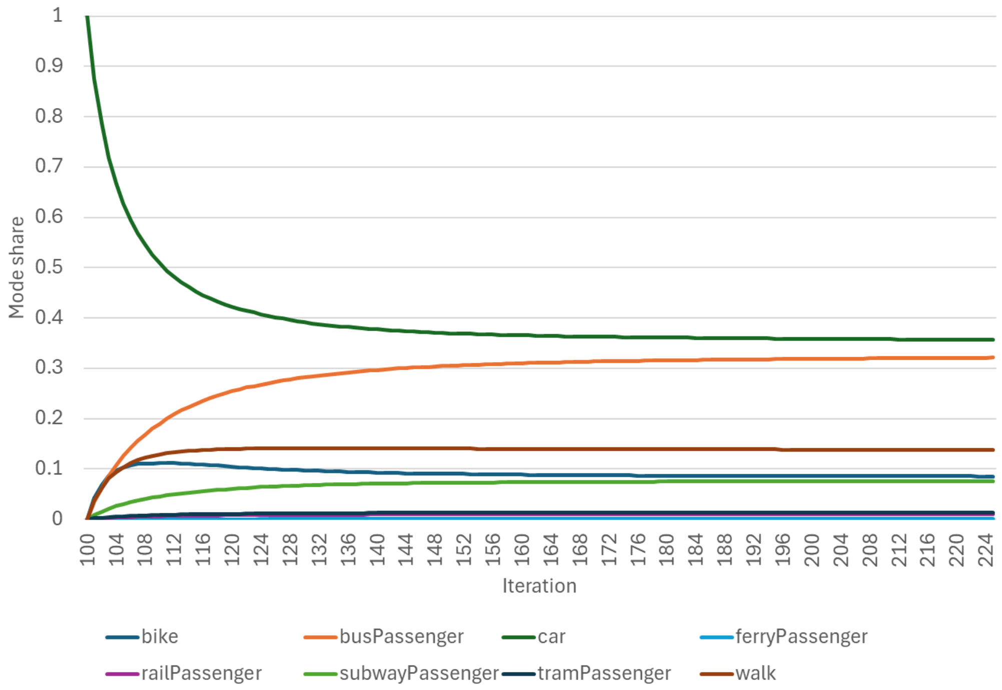


Figure 4. Evolution of modal share over iterations.

Table 1. Modal share in the calibrated simulation for the baseline scenario.

Mode	**Percentages**
Walking	13.8
Cycling	8.5
Private car	35.7
Bus	32.1
Rail	1.0
Subway	7.6
Light rail	1.3
Ferry	0.014

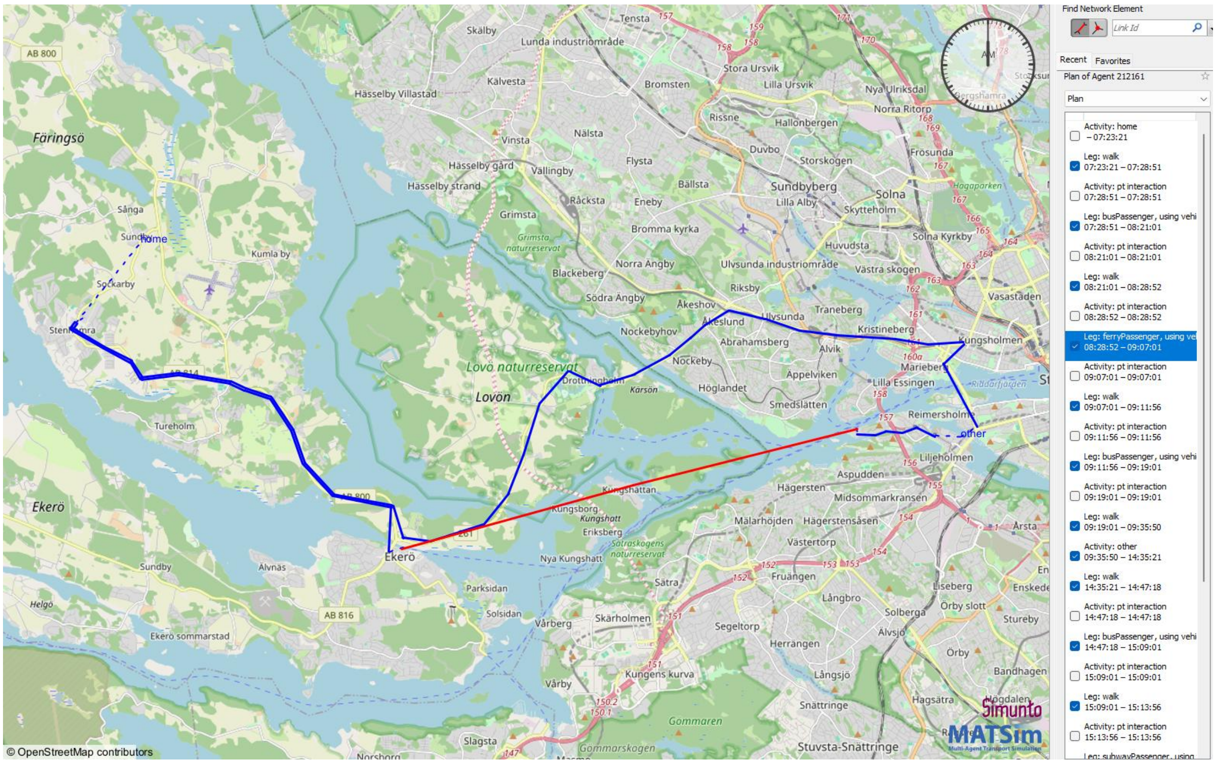
We then compare the simulated passenger flow with passenger flow data from Region Stockholm. Since there is no ferry traffic between Lilla Essingen and Liljeholmen (the Cstrider route), we can only compare the simulated flow with real passenger flow for line 89 between Ekerö and Klara Mälarstrand (Table 2). It is clear that the passenger flow varies greatly between months, with summer passenger flows being 4–5 times higher than winter passenger flows. The travel plans generated from the Sampers demand model – that is, the localization of activities – are based on an average working day and therefore do not include summer holiday trips. In addition, in the simulation we used the timetable for a weekday in January. We have therefore chosen to use the average number of passengers during the period November to February, which yields about 193 passengers per day.

In the simulation, we obtained 7 agents traveling on line 89 from Stadshuset to Ekerö. Since we simulate 5 % of the population, this corresponds to 140 passengers in reality. The results show that the simulation appear to underestimate the number of passengers on line 89 in the direction Stadshuset → Ekerö. The main reason for this is most likely the large seasonal variation, which the current transport model cannot capture. For example, if we exclude November and calculate an average only for the period December to February, we obtain 140 passengers per day – which aligns well with the simulation results.

Table 2. Passenger flows for line 89 Stadshuset → Ekerö.

Linje 89, number of passengers, Stadshuset --> Ekerö												
Year	Jan	Feb	Mar	April	May	June	July	Aug	Sep	Oct	Nov	Dec
2023	4139	4254	4525	10403	17679	21550	19081	20462	18724	13364	10602	4175

To illustrate the simulation results, we show below a simulated travel plan for an agent (ID 212161) who used line 89 (Figure 5). The agent lives in the southern part of Sånga-Sundby and begins the day by walking to a bus stop in Stenhamra, where he/she takes a bus to Ekerö Centrum. From there, the agent takes line 89 and boards the ferry at 08:30 from Ekerö to Ekensberg (marked with a red line in Figure 5). Afterwards, he/she transfers to a bus to continue to the destination at Liljeholmsstranden. On the way home, the agent chooses an alternative route: first a bus to Fridhemsplan, then the metro to Brommaplan, and finally a bus home again.



Plan of Agent 212161

☐ Activity: home
– 07:23:21
☑ Leg: walk
07:23:21 – 07:28:51
☐ Activity: pt interaction
07:28:51 – 07:28:51
☑ Leg: busPassenger, using vehi
07:28:51 – 08:21:01
☐ Activity: pt interaction
08:21:01 – 08:21:01
☑ Leg: walk
08:21:01 – 08:28:52
☐ Activity: pt interaction
08:28:52 – 08:28:52
☑ Leg: ferryPassenger, using ve
08:28:52 – 09:07:01
☐ Activity: pt interaction
09:07:01 – 09:07:01
☑ Leg: walk
09:07:01 – 09:11:56
☐ Activity: pt interaction
09:11:56 – 09:11:56
☑ Leg: busPassenger, using vehi
09:11:56 – 09:19:01
☐ Activity: pt interaction
09:19:01 – 09:19:01
☑ Leg: walk
09:19:01 – 09:35:50
☑ Activity: other
09:35:50 – 14:35:21
☑ Leg: walk
14:35:21 – 14:47:18
☐ Activity: pt interaction
14:47:18 – 14:47:18
☑ Leg: busPassenger, using vehi
14:47:18 – 15:09:01
☐ Activity: pt interaction
15:09:01 – 15:09:01
☑ Leg: walk
15:09:01 – 15:13:56
☐ Activity: pt interaction
15:13:56 – 15:13:56
Leg: subwayPassenger, using

Figure 5. A simulated agent's travel plan with line 89. Source: MATSim.

The simulation model is intended to be used for evaluating different timetable configurations. It is therefore important to demonstrate how the model can contribute in this respect. For each ferry departure, we calculate both the number of agents transported and the maximum number of agents on board (i.e., since the number of passengers onboard varies during the ferry journey, the maximum reflects to what extent the number of passengers onboard exceeds the vessel capacity for that departure). As shown in Table 3, no agents traveled on line 89 from Stadshuset to Ekerö during the morning, while all 7 agents departed after 15:30. In the opposite direction – from Ekerö to Stadshuset – more agents traveled in the morning and fewer in the afternoon. This reflects the typical peak-hour commuting pattern, where residents of Ekerö work in the city and therefore travel from Ekerö to Stadshuset in the morning and return in the afternoon. The maximum number of agents on board is 2 in the Stadshuset → Ekerö direction (corresponding to approximately 40 passengers), and 3 in the opposite direction (approximately 60 passengers), given that the simulation represents 5 % of the population. The conventional ferry serving line 89 has a capacity of 190 passengers (140 under winter conditions), which indicates that capacity constraints do not pose a problem according to the simulated results.

Table 3. Number of agents onboard and transported for each departure. Note that 1 agent corresponds to approximately 20 passengers.

Direction: Stadshuset → Ekerö		
Departure time	**Max No. agents onboard**	**No. agents being transported**
07:40	0	0
08:20	0	0
09:30	0	0
10:20	0	0
14:30	0	0
15:30	1	1
16:30	2	2
17:30	1	1
18:20	2	3

Direction: Ekerö → Stadshuset		
Departure time	**Max No. agents onboard**	**No. agents being transported**
06:40	3	3
07:20	0	0
08:30	2	2
09:20	2	2
10:30	3	3
11:20	1	1
15:30	1	1
16:30	1	1
17:30	0	0

We also calculate vehicle-kilometers with empty running, which is a key metric from the operator's perspective. Vehicle-kilometers with empty running are calculated the same way as by tracking the number of agents on board in the simulation. For example, for a departure running from stop A to stop C via stop B, the simulation records the number of agents on board for the segments A → B and B → C. If no agents are on board during a particular segment (e.g., B → C), this segment is classified as empty running, and the distance is counted as vehicle-kilometers without passengers. The results show that the total number of vehicle-kilometers reaches 333.04 km, of which 209.80 km consists of empty running. This means that vehicle-kilometers with passengers on board is 123.24 km, corresponding to 37 %. We also calculate travel times and distances broken down by mode, which are important metrics for cost-benefit analysis.

2.2.2. Cstrider

Figure 6. Cstrider passenger vessel (www.cstrider.com)

In this scenario, we test the use of the Cstrider vessel on a new line between Lilla Essingen and Liljeholmen (Figure 7). Here, Cstrider aims to maintain a certain level of service frequency, and then with the help of the simulation results determine the number of vessels needed (for CBA analysis). The Cstrider vessel has a capacity of 12 passengers. In the first iteration, we test a service frequency of 5 minutes in both directions, with departures between 06:00 and 19:00. This results in a total of 157 departures per direction. Travel time between stops is calculated based on the vessel's speed and the straight-line distance between the stops. The total travel time between Lilla Essingen and Liljeholmen is estimated to be 16 minutes, meaning that a round trip takes 32 minutes.

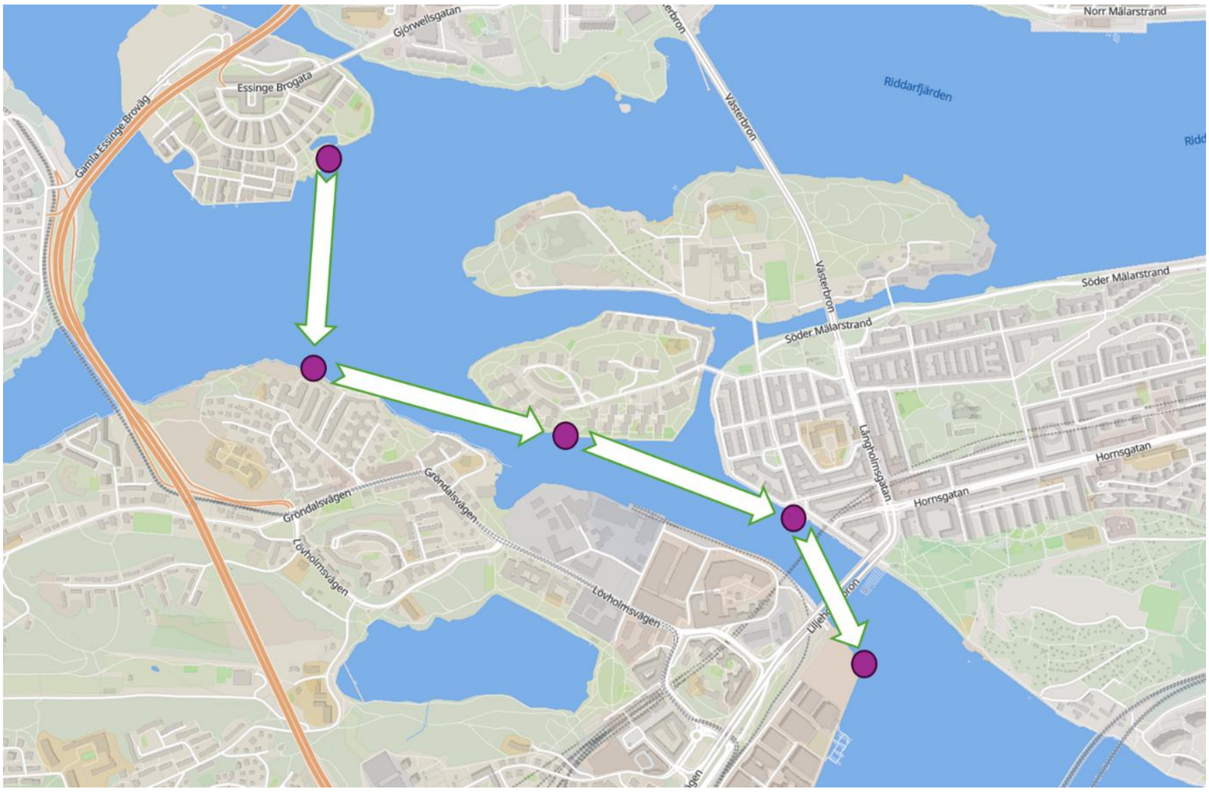
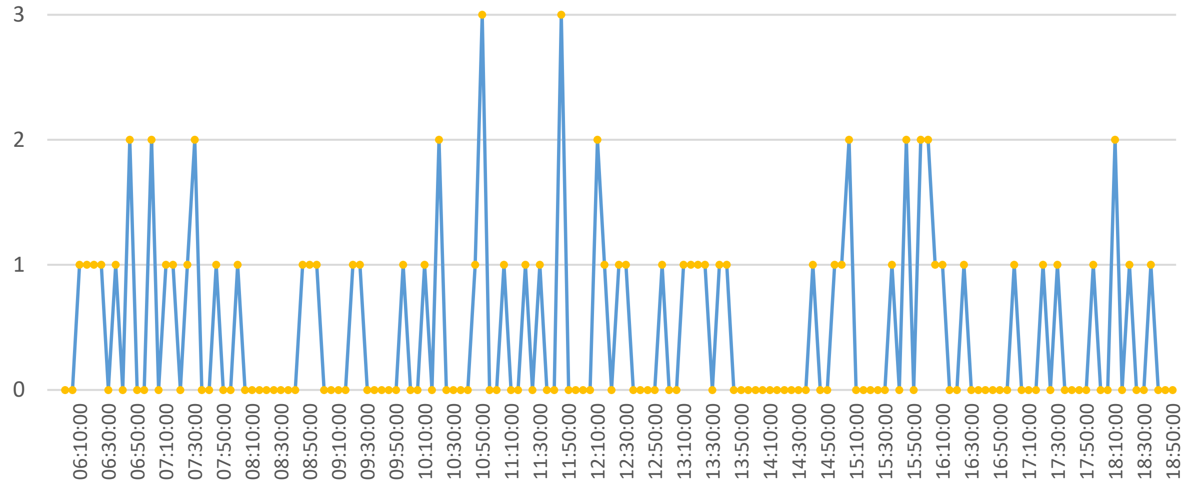


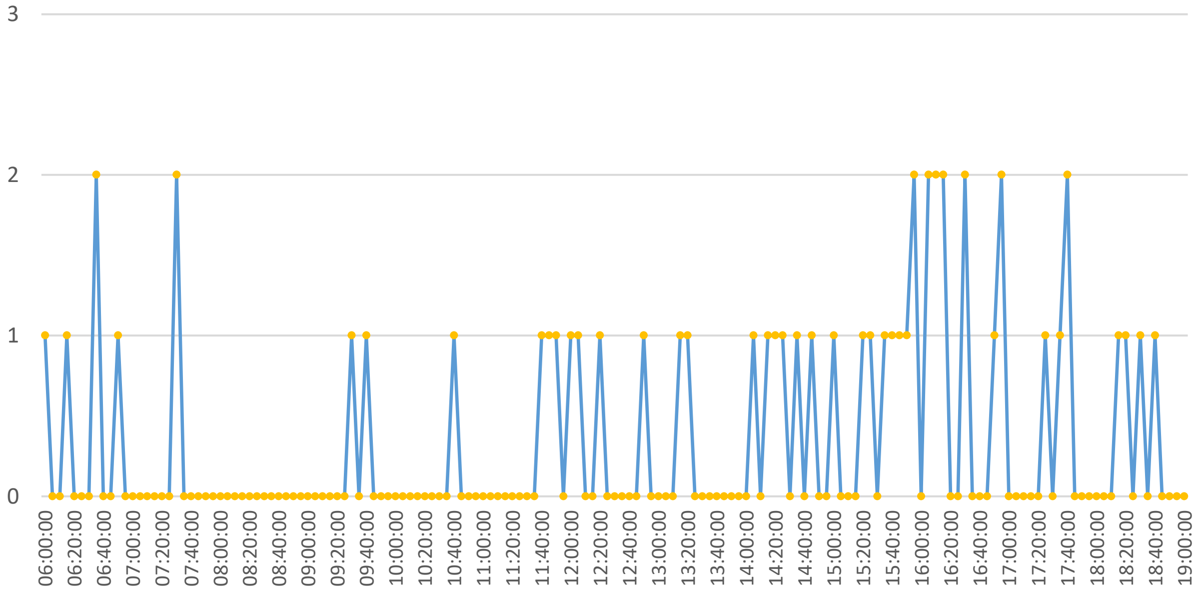
Figure 7. Tested Cstrider line, direction Lilla Essingen to Liljeholmen.

The new ferry line is then added to the public transport network, and the simulation is run again. Since the Cstrider vessel has a capacity of 12 passengers, and in the simulation one agent corresponds to 20 people, the results are interpreted such that a single simulated departure of Cstrider may require more than one vessel depending on the number of agents on board. This, in turn, affects the number of vessels needed, operating costs and the CBA.

Figure 8 shows the number of agents transported per departure on the new line. A general trend of peak-hour traffic is observed in the morning and afternoon. For the direction Lilla Essingen → Liljeholmen, an additional increase in demand is observed between 10:00 and 12:00. The results indicate that up to five vessels may be needed in service per departure during this period in order to transport all passengers (3 agents correspond to 60 passengers). At the same time, there is potential to reduce service frequency during periods of low demand.



(a) Number of agents transported per departure from Lilla Essingen to Liljeholmen.



(b) Number of agents transported per departure from Liljeholmen to Lilla Essingen.

Figure 8. Number of agents transported per departure.

We therefore adjust the timetable to match demand. The timetable was adjusted in consultation with Cstrider. The new timetable is shown in Table 4.

Table 4. Adjusted timetable.

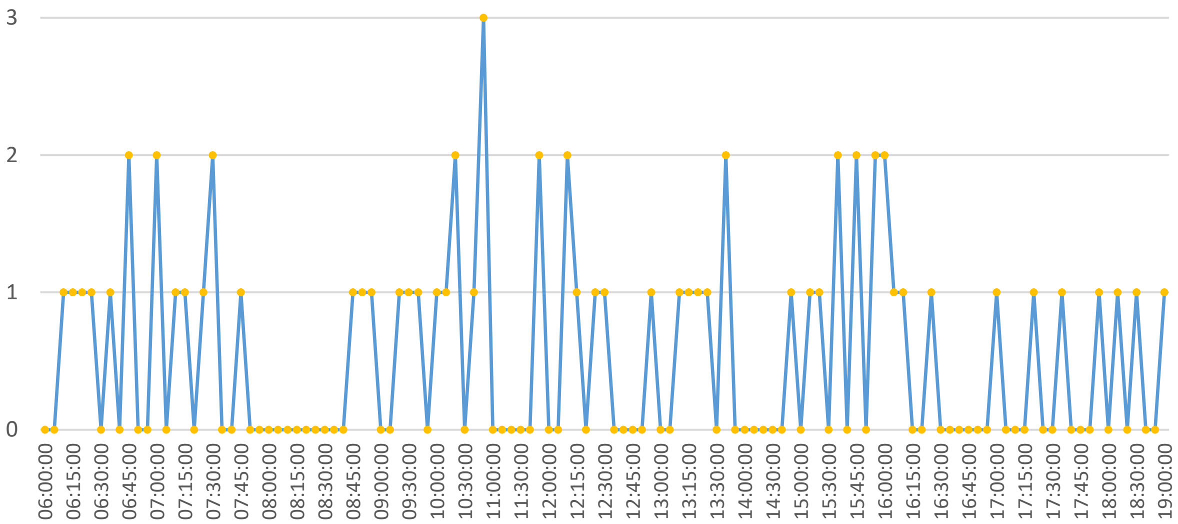
Time period	Headway[9]
6:00 – 9:00	5 min
9:00 – 12:00	10 min
12:00 – 13:30	5 min
13:30 – 15:30	10 min
15:30 – 18:00	5 min
18:00 – 19:00	10 min

Figure 9 presents the number of agents transported per departure with the adjusted timetable. The number of transported agents decreases from 71 to 64 in the Lilla Essingen → Liljeholmen direction, and from 53 to 43 in the Liljeholmen → Lilla Essingen direction. The number of departures without any passengers decreases from 213 out of 314 departures (67.8 %) to 154 out of 239 departures (64.4 %). It is, however, important to note that we only simulate 5 % of the population, and thus if 100 % were simulated, the share of departures without any passengers would decrease since more passengers will arrive at the stop but more spread over time.

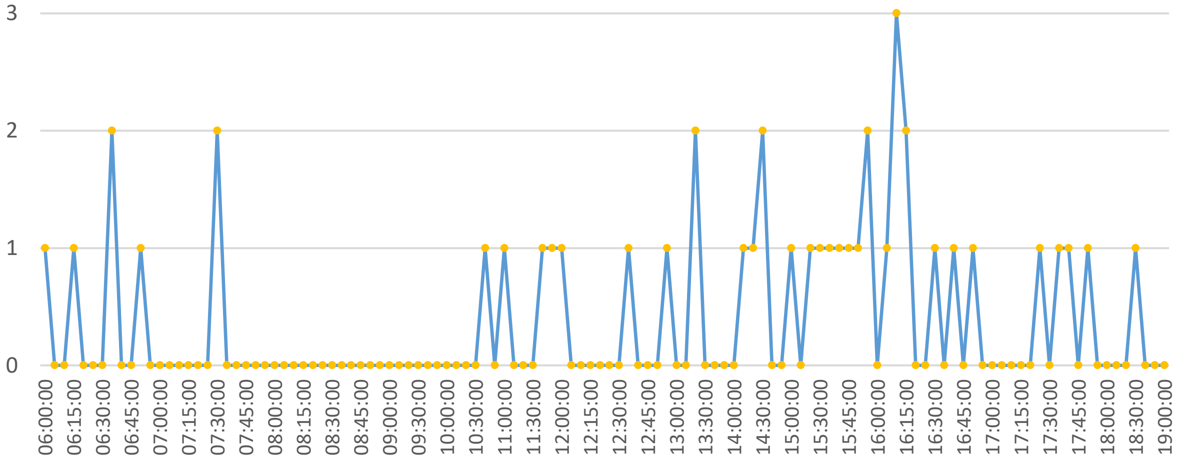
The results show that a reduction in service frequency from 314 to 239 departures per day (approximately 23 % reduction) leads to a decrease in demand, corresponding to 14 % fewer agents being transported. The observed elasticity (23 % reduction in supply → 14 % reduction in demand) is considered reasonable.

---

[9] Headway refers to the time interval between two consecutive departures of vehicles operating on the same route.



(a) Number of agents transported per departure from Lilla Essingen to Liljeholmen with the adjusted timetable.



(a) Number of agents transported per departure from Liljeholmen to Lilla Essingen with the adjusted timetable

Figure 9. Number of agents transported per departure with adjusted timetable.

Table 5 shows vehicle-kilometers with passengers on board and with empty running under the original and adjusted timetables. The share of vehicle-kilometers with passengers on board has increased from 14.2 % to 16.8 %.

Table 5. Vehicle-kilometer statistics for Cstrider's original and adjusted timetables.

Scenario	Total vehicle-kilometer	Empty run vehicle-kilometer	Vehicle-kilometer with passengers onboard
Original timetable	707.2	606.8	100.4 (14.2 %)
Adjusted timetable	538.3	447.9	90.4 (16.8 %)

In Table 6 we present the total travel time (person-hours in travel) and the total distance (person-kilometers in travel) for all agents, broken down by mode as well as by in-vehicle time and waiting time. It is clear that both travel time and distance by ferry increase significantly in the scenario with the new ferry line due to increased number of passengers onboard. However, ferry trips still represent only a small share of total travel, and the effect on overall mode choice is therefore marginal. The surprising result here is that travel time and distance by car have also increased slightly (and modal share by car increases slightly). Moreover, total travel time, i.e. sum of all travel times in the Cstrider scenario is higher than that of baseline (+5.8 hours, which corresponds to 116 hours when considering we are only simulating 5 % population). This indicates that travel time saving is negative. The sum of all waiting times is shorter in the Cstrider scenario compared to baseline (-4.8 hours) which indicates a gain in waiting time savings. Thus, the overall travel time saving can still be positive given that waiting time is weighted higher than in-vehicle time. The final scoring in the Cstrider scenario is slightly better than the baseline scenario, average score per agent is -47.14 in Cstrider scenario vs -47.16 in the baseline. This indicates that the overall travel situation is improved as agents have a better scoring but it does not necessarily indicate a shorter travel time.

It is also important to note that MATSim simulations are inherently stochastic, since several steps in the model – for example, replanning (see Section 2.1) – are based on random choices between alternative travel plans. Ideally, several simulations with different random seeds should be run to capture result variation. Due to the long runtimes, however, this has not been possible in the present work.

The increase in car travel time suggests that the effect of mode shift from car is very small, and the observed change is generally within the same magnitude as stochastic variation. We mainly observe a reduction in total bus travel time (in person-hours), as well as bus modal share, which indicates that the increased travel on the new ferry line primarily comes from former bus passengers in the base scenario.

Table 6. Comparison of person-hours in travel and person-kilometers in travel across different scenarios with the Cstrider vessel.

Mode	**Person-hours**			**Person-kilometers**		
	Baseline	**Original timetable**	**Adjusted timetable**	**Baseline**	**Original timetable**	**Adjusted timetable**
Bike	17 231	17 218	17 230	258 496	258 301	258 483
Bus	13 635	13 625	13 627	324 175	324 015	324 035
Bus waiting	8574	8566	8565	/	/	/
Car	13 138	13 143	13 139	940 092	940 251	940 104
Ferry	**57**	**77**	**75**	**869**	**1050**	**1032**
Ferry waiting	**33**	**38**	**39**	/	/	/
Train	4070	4068	4069	208 945	208 858	208 903
Train waiting	2051	2048	2049	/	/	/
Subway	5840	5840	5840	180 728	180 743	180 753
Subway waiting	1878	1877	1876	/	/	/
Light rail	690	687	687	14 607	14 551	14 550
Light rail waiting	249	248	248	/	/	/
Walking	67 061	67 063	67 059	256 577	256 597	256 575

2.2.3. Candela

Figure 10. Candela hydrofoiling passenger vessel (www.candela.com)

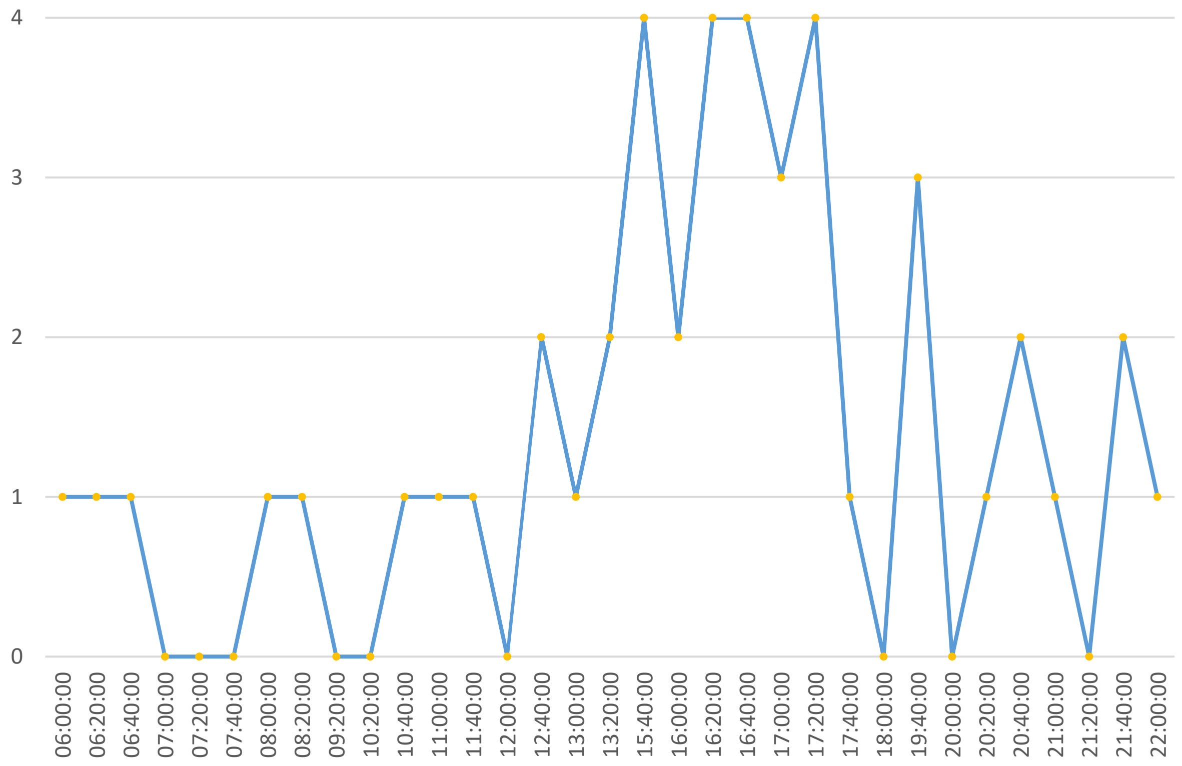
In this scenario, we test replacing the conventional vessels on line 89 with the Candela P-12 vessel. The Candela P-12 vessel has a capacity of 25 passengers plus crew. The average cruising speed is 25 knots, i.e., 46.3 km/h. Together with Candela, an initial timetable was designed, shown in Table 7, assuming four vessels in service. Compared to today's timetable (Table 3), Candela's proposed timetable features significantly more departures. Travel time also decreases from 55 to 40 minutes per single trip thanks to the higher cruising speed. Both the travel time savings and the increased service frequency are expected to have a significant effect on demand.

Table 7. Departure times for line 89 with the Candela P-12 vessel, both directions.

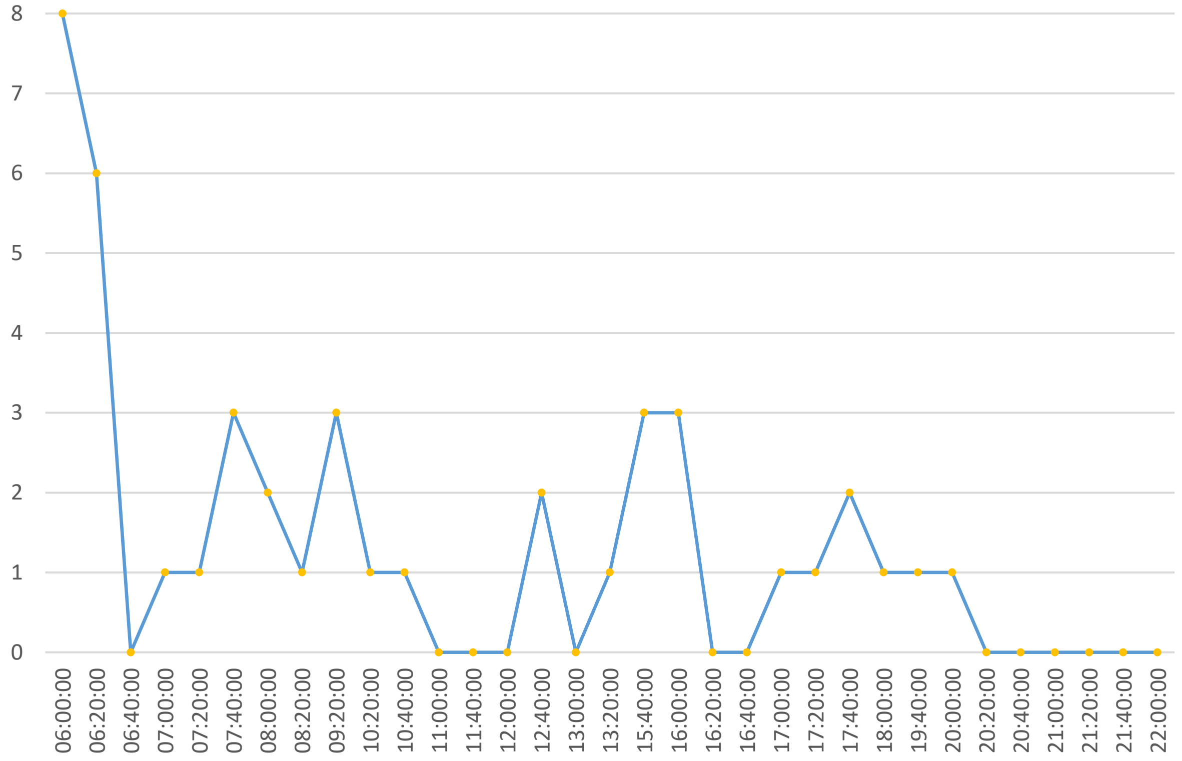
Before 12:00	After 12:00
06:00:00	12:40:00
06:20:00	13:00:00
06:40:00	13:20:00
07:00:00	15:40:00
07:20:00	16:00:00
07:40:00	16:20:00
08:00:00	16:40:00
08:20:00	17:00:00
09:20:00	17:20:00
10:20:00	17:40:00
10:40:00	18:00:00
11:00:00	19:40:00
11:40:00	20:00:00
12:00:00	20:20:00
	20:40:00
	21:00:00
	21:20:00
	21:40:00
	22:00:00

Figure 11 shows the number of agents transported per departure. A clear trend of morning commuting from Ekerö to Klara Mälarstrand is observed, with return trips in the afternoon in the opposite direction. The departures between 06:00 and 06:40 are overloaded in the Ekerö → Klara Mälarstrand direction, indicating a need to deploy additional vessels to meet demand.

The number of transported agents turns out to be 43 (corresponding to 860 people) in the Ekerö → Klara Mälarstrand direction and 45 (900 people) in the Klara Mälarstrand → Ekerö direction. In the base scenario, only 7 agents (140 people) and 13 agents (260 people) are transported in these directions, respectively. This demonstrates a substantial increase in demand as a result of the significant reduction in travel time from 55 to 40 minutes, as well as the increased service frequency from 18 departures per day to 66 departures per day in both directions.



(a) Number of agents transported per departure from Klara Mälarstrand to Ekerö



(b) Number of agents transported per departure from Ekerö to Klara Mälarstrand.

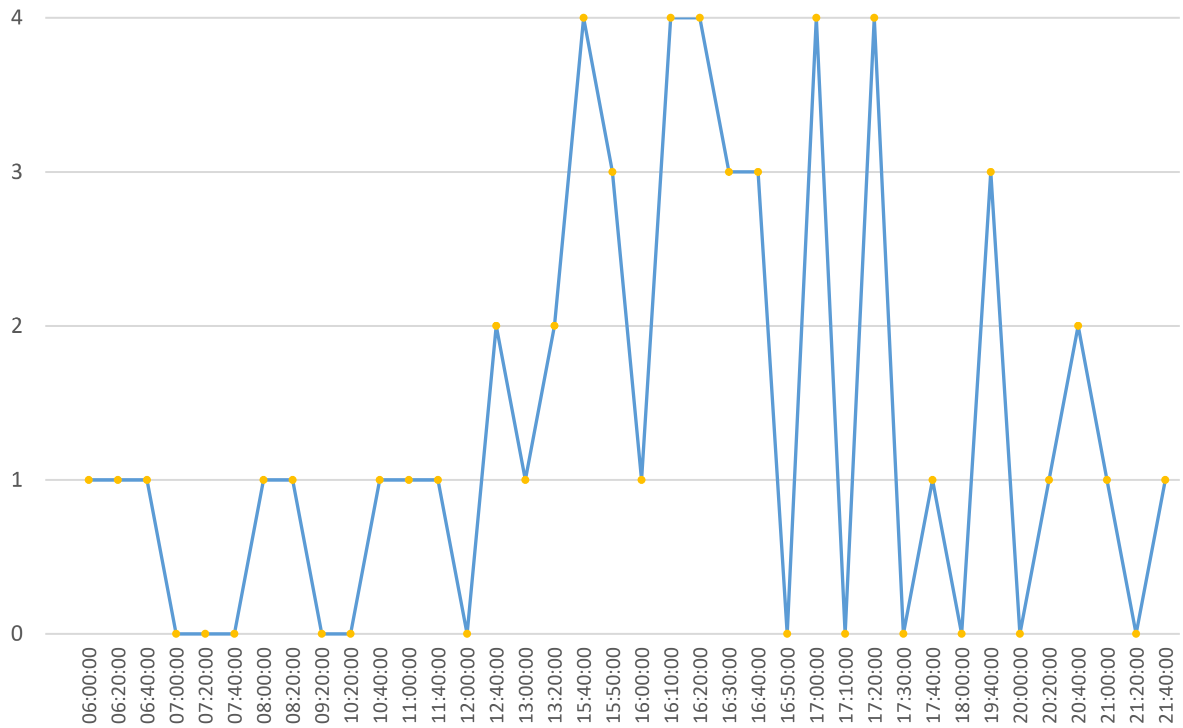
Figure 11. Number of agents transported per departure with Candela P-12.

However, the Candela P-12 has a maximum capacity of only 25 passengers, corresponding to about 1.2 agents. This means that several vessels are required to meet demand (up to 4 vessels for certain departures). We therefore propose increasing the service frequency during periods of high boarding demand. More specifically, we propose:

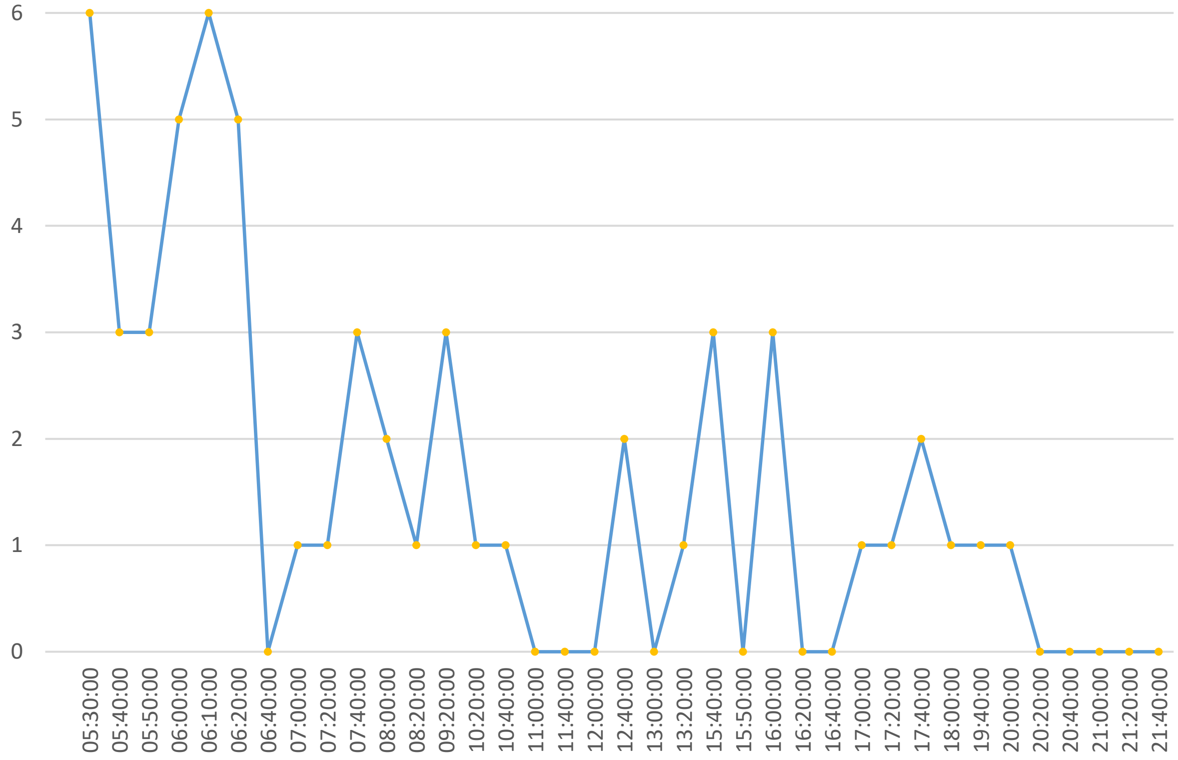
- departures every 10 minutes between 05:30 and 06:20 and between 15:40 and 16:00 in the direction from Ekerö to Klara Mälarstrand and
- departures every 10 minutes between 15:40 and 17:20 in the direction from Klara Mälarstrand to Ekerö.

Figure 12 shows the number of agents transported per departure with the adjusted timetable. A total of 57 agents (corresponding to 1,140 people) are transported in the Ekerö → Klara Mälarstrand direction, and 53 agents (1,060 people) in the Klara Mälarstrand → Ekerö direction. Compared to the timetable before the adjustment, this represents an increase of 14 agents in the Ekerö → Klara Mälarstrand direction and 8 agents in the opposite direction.

This indicates a substantial demand for travel along line 89 when service frequency is increased and travel times are reduced. In the Ekerö → Klara Mälarstrand direction, the peak load also decreases from 8 to 6 agents between 05:30 and 06:20, while the effect of the additional departures on the afternoon peak (15:40–17:20) in the opposite direction (Klara Mälarstrand → Ekerö) is less pronounced. These results suggest a need for significantly more vessels in service to meet the high travel demand.



(a) Number of agents transported per departure from Klara Mälarstrand to Ekerö



(b) Number of agents transported per departure from Ekerö to Klara Mälarstrand

Figure 12. Number of agents transported per departure in adjusted timetable for Candela P-12.

Table 8 presents vehicle-kilometers with passengers on board and with empty run for line 89. The results show that the current winter timetable has a low utilization rate, with only 37 % of the total vehicle-kilometers operated with passengers on board. With the new Candela P-12 vessels, which reduce travel time from 55 to 40 minutes and provide a substantially increased number of departures, the share of vehicle-kilometers with passengers on board increases to 42 %. This indicates a significant potential for the Candela P-12 to improve accessibility in waterborne public transport. However, the adjusted timetable has little effect on the share of vehicle-kilometers with passengers on board, which is expected since it primarily aims to reduce peak load.

Table 8. Vehicle-kilometer statistics for today's timetable, and for Candela's original and adjusted timetables.

Scenario	**Total Vehicle-kilometer**	**Empty run Vehicle-kilometer**	**Vehicle-kilometer with passengers onboard**
Today's timetable	330.0	209.8	123.2 (37.0 %)
Original timetable	1187.8	695.1	492.7 (41.5 %)
Adjusted timetable	1385.7	778.5	607.3 (43.8 %)

Table 9 presents person-hours and person-kilometers in travel for different scenarios. We primarily observe a reduction in total bus travel time, while total travel time by car again increases slightly, which, as interpreted by the authors, has the same cause as in the Cstrider case, i.e. the impact is of the same magnitude as variation caused by randomness. Person-hours and person-kilometers for ferry travel do increase significantly, but since the absolute levels remain low, the effect on other modes is limited. When it comes to the differences in total travel time by all modes, the total travel time for all modes is higher in the Candela scenario compared to baseline (+1.3 hours), which again indicates that the travel time saving is negative. Waiting time by all modes, however, turn out to be higher in the Candela scenario as well (+7.1 hours), indicating a negative travel time saving in total. The final scoring in the Candela scenario is again slightly better than the baseline scenario, average score per agent is -47.15 in the Candela scenario vs -47.16 in the baseline, but the difference is very small.

Results from both the Cstrider and Candela scenarios on line 89 highlight a general challenge in using a stochastic simulation to evaluate system investments with small effects, where the impact can be difficult to distinguish from random variation.

Table 9. Comparison of person-hours in travel and person-kilometers in travel across different scenarios with the Candela vessel.

Mode	**Person-hours**			**Person-kilometers**		
	Baseline	**Original timetable**	**Adjusted timetable**	**Baseline**	**Original timetable**	**Adjusted timetable**
Bike	17 231	17 226	17 226	258 496	258 432	258 425
Bus	13 635	13 613	13 608	324 175	323 496	323 334
Bus waiting	8574	8566	8563	/	/	/
Car	13 138	13 146	13 145	940 092	940 095	940 092
Ferry	**57**	**83**	**93**	**869**	**1478**	**1694**
Ferry waiting	**33**	**45**	**48**	/	/	/
Train	4070	4072	4073	208 945	209 140	209 173
Train waiting	2051	2053	2054	/		
Subway	5840	5831	5827	180 728	180 425	180 343
Subway waiting	1878	1877	1876	/	/	/
Light rail	690	689	687	14 607	14 569	14 534
Light rail waiting	249	249	249	/	/	/
Walk (incl. access/egress)	67 061	67 059	67 063	256 577	256 601	256 623

3. WUM and economic appraisal

This section provides a brief description of how costs and benefits are defined in an economic appraisal. It then presents an account of how the WUM model contributes to analyses of costs and benefits related to changes in public transport supply. The section concludes with a discussion on how assumptions in the WUM simulation model may affect the outcomes of such analyses. One aim that emerged during the study was to calculate the societal costs and benefits of the simulated ferry services and to compare them with existing services. However, this was not possible to achieve in practice, as explained below.

3.1. Conceptual basis

A fundamental principle in economics is that resources are always limited. From a societal perspective, this means that shared resources should be allocated in ways that maximize overall welfare. A key distinction is between societal costs and business (or private) costs. Societal costs capture the total costs to society as a whole, including so-called external costs that affect third parties, such as environmental damage or traffic accidents. Business costs, by contrast, are those considered by firms when making economic decisions, such as production costs, wages, and raw material prices. These are often referred to as internal or private costs, reflecting only the company's direct expenditures. Societal benefits and costs represent the sum of business (internal) and external benefits and costs. It is important to note that some external costs are indirectly included in operators' calculations through internalizing taxes and charges[10].

In a cost–benefit analysis, the project alternative (PA) is compared with the baseline alternative (BA). The PA consists of the measures under consideration, while the BA describes how the situation would develop in the absence of such measures. The BA represents the point of departure in the analysis and serves as the reference for assessing the effects of the PA. The BA should include existing infrastructure, already decided measures, and expected developments in traffic, population, and related factors.

3.2. WUM and CBA

Compared with existing static traffic simulation models, the WUM model can provide more realistic and detailed input to cost–benefit analyses of waterborne public transport. One of WUM's strengths is its ability to analyze distributional effects across different groups of travelers. Since each agent in the model is assigned individual attributes such as age, gender, income, and employment status, the model can show how a given measure affects different segments of society. For example, it is possible to examine whether a new line improves access to the labor market for low-income groups in peripheral parts of the city, or how travel time savings are distributed between women and men. This enables a more accurate and transparent distributional analysis within the framework of the Swedish Transport Administration's Samlade effektbedömning (SEB, "Comprehensive Impact Assessment"), where equity aspects and equal access to transport opportunities are important evaluation criteria.

In addition to direct effects on travel behavior, WUM also makes it possible to analyze secondary effects in the broader transport system, such as how traffic volumes on road and rail networks change when some trips are shifted to waterways. By quantifying these effects, external costs (such as congestion, emissions, and accident risks) can be incorporated into the analysis with greater accuracy. WUM's data compatibility with Sampers and Dynameq also makes it possible to compare and

---

[10] When external costs are fully internalized, for example through taxation or regulation, firms include these costs in their own calculations. In that case, private costs and societal costs become identical, meaning that decisions made at the firm level optimize not only company profits but also overall social welfare.

integrate the results with established travel demand models, including the valuations specified in the Swedish guidelines for cost–benefit analysis (ASEK) for the transport sector.

While WUM provides important advantages compared with traditional static models, it also has limitations from a cost–benefit analysis perspective. The model does not generate long-term forecasts of travel demand based on macroeconomic variables such as GDP growth, fuel prices, or demographic change. This restricts its use as a tool for projecting future scenarios, which are often central to CBAs of major infrastructure investments. However, this is not an issue when it comes to assessing the effects of introducing, changing or adding a public transport line, since such an assessment is not necessarily dependent on long-term forecasts.

The model does not capture induced demand, meaning that potential new travelers attracted by improved services are not represented. This may lead to an underestimation of benefits when evaluating new or expanded services. Also, some travel modes are simplified in WUM. For example, walking and cycling are modeled through teleportation (linear movements) rather than physical network representation, which can reduce accuracy for multimodal trips where these components are significant. Furthermore, capacity constraints are difficult to represent, meaning that congestion on individual ferries or buses is not captured. In the current version of WUM, ferries (and other public transport modes) are assumed to have unlimited capacity. This means that the need for additional vessels when passenger numbers increase is not accounted for. It is therefore important to adjust for this assumption when carrying out cost–benefit analyses, by explicitly adding more vessels in cases where demand exceeds the capacity of a single vessel.

Finally, the stochastic nature of agent-based simulations introduces variability between runs, which makes it harder to isolate small effects from random fluctuations. Taken together, these factors imply that while WUM can provide valuable insights into system interactions and distributional effects, its results (as results from other models such as Sampers) must be interpreted with caution when used as input to CBAs.

3.3. Limitations preventing CBAs and ways forward

One aim that emerged during the course of the study was to calculate societal costs and benefits of introducing Candela’s and Cstrider’s vessels, and to compare these with existing services. However, despite considerable efforts it turned out not to be possible to carry out such analyses. In the Candela case, the model reported increases in both total waiting time and total travel time over all modes, despite the fact that Candela’s vessels are faster than the conventional vessels they replace. We interpret this as being related to three factors: (i) the stochastic variation inherent in agent-based simulation, which can produce random fluctuations between iterations, (ii) the relatively small magnitude of the changes tested, which makes it difficult for the model to generate stable effects at the system level[11], and (iii) the scoring function that is optimized in the simulation takes into account more factors (e.g. congestion costs and number of transfers by public transport). This means that an improvement in the scoring function does not necessarily mean a decrease in travel time since other factors may be improved at the sacrifice of travel time gain, e.g. in-vehicle time by public transport increases while number of transfers decreases when a new public transport line is introduced.

To address these limitations, and to reduce the sensitivity to stochastic variation, more substantial changes at the network level are required. In particular, a full network assignment including several lines and ferry systems, rather than changes in isolated services, would allow the model to capture system-wide adjustments and generate more plausible and robust results. Ideally, several simulations

---

[11] This challenge is not unique to WUM but also applies to Sampers, where, according to Isak Jarlebring Rubensson at Region Stockholm who was part of the project reference group, small-scale changes in supply are often difficult to capture reliably at the system level.

with different starting positions should be run to capture result variation. However, due to the long runtimes this has not been possible in the present work. Results from both the Cstrider and Candela scenarios highlight a general challenge in using a stochastic simulation to evaluate interventions with small effects, where the impact can be difficult to distinguish from random variation.

Another improvement for future work is to consider how scoring in the simulation can align with the CBA framework. Currently, the scoring parameters are taken from Sampers, but they differ from the ASEK values used in CBA. Sampers parameters are calibrated for behavioral modeling and thus are not numerically identical to ASEK's monetary valuations; a mapping or re-parameterization is needed to align scoring with ASEK. One possible solution is to use ASEK weighting parameters in the scoring function in the simulation. Furthermore, using a combination of WUM and Sampers should be explored in order to utilize the strengths of both models. One idea is to investigate to what extent the analysis at the departure level (i.e. in MATSim) can be utilized in Sampers. A straightforward and easy implementation, for instance, would be to calculate average waiting time at each stop from MATSim instead of half-headway as used in Sampers.

4. Discussion and conclusion

This report describes the use of MATSim as a simulation tool for evaluating effects of new vessel lines on passenger transport systems. The study had three main objectives: (1) to further develop the WUM model to represent different types of vessel systems, (2) to simulate the effects of introducing Candela's and Cstrider's vessels on selected routes in Stockholm, and (3) to explore the implications of these results for economic appraisal.

The WUM model is developed by allowing individual vessel lines to have different vehicle types (i.e. electric) with specific attributes, i.e. different speeds. The results show that MATSim is a useful tool for evaluating and optimizing waterborne public transport. Fast and frequent electric vessels can attract new passengers, primarily from bus travel in the tested scenarios, and the simulations can be used to support timetable planning and capacity dimensioning. With that said, operational constraints such as capacity and charging need to be considered.

Furthermore, this study set out to explore the potential of agent-based modeling for assessing societal impacts of waterborne public transport in Stockholm. The WUM model demonstrates important strengths compared with traditional static approaches, due to its ability to evaluate individual departures which a static approach cannot evaluate, as well as to capture distributional effects, multimodality, and secondary impacts across the transport system. These features make it a valuable complement to established models such as Sampers, and highlights its potential contribution to more comprehensive cost–benefit analyses.

At the same time, the model in the Candela case reported increases in both total waiting time and total travel time over all modes, despite the fact that Candela's vessels are faster than the conventional vessels they replace. This outcome reflects stochastic variation inherent in agent-based simulation, the relatively small scope of the tested interventions, and the fact that the scoring function accounts for additional factors beyond travel time, such as car congestion costs and number of public transport transfers. Additional challenges include the absence of induced demand in the model.

Looking ahead, we propose ways forward. First, more substantial interventions should be simulated, including full network assignments with multiple lines, in order to capture system-wide effects and generate more robust outputs. Running several simulations with different starting positions would also help reduce sensitivity to stochastic variation.

Another improvement for future work is to consider how scoring in the simulation can align with the CBA framework. Currently the scoring parameters are taken from Sampers, but they differ from the ASEK values used in CBA. This introduces mismatch between CBA and the simulation, since they are measured by scoring in the simulation, where different weighting parameters are used. One solution is to use ASEK weighting parameters in the scoring function in the simulation.

Furthermore, WUM and Sampers should be used in combination in order to utilize the strengths of both models. Also, further work should focus on improving the simulation runtime, which became a limiting factor in this project.

With the above-mentioned steps, it will be possible to conduct robust CBAs of Candela's and Cstrider's vessel systems, thereby answering the essential question of whether small electric commuter vessels are socioeconomically viable, or if the costs outweigh the benefits.

References

Baird Maritime. 2024. VESSEL REVIEW | Shuttle 0001 – Norwegian startup places new electric commuter vessel into service. https://www.bairdmaritime.com/passenger/ferry/vessel-review-shuttle-0001-norwegian-startup-places-new-electric-commuter-ferry-into-service [2025.10.11].

Candela n.d. Frequently asked questions. https://candela.com/faq/ [2025.10.12]

Canella, O., Flötteröd, G., Johnsson, D., Kristoffersson, I., Larek, P. and Thelin, J. 2016. Flexible coupling of disaggregate travel demand models and network simulation packages (IHOP2), CTS Working Paper 2016:3 https://www.diva-portal.org/smash/get/diva2:1835183/FULLTEXT01.pdf

Condé Nast Traveler. 2023. You're About to See Electric Vessels Everywhere—Here's What to Know https://www.cntraveler.com/story/electric-ferries [2025.10.11].

Flötteröd G. 2020. Waterborne Urban Mobility, VTI PM D.nr.: 2018/0356-7.1, https://www.diva-portal.org/smash/get/diva2:1430091/FULLTEXT01.pdf

Grunicke, C., Schlüter, J. C. & Jokinen, J.-P. 2020. Implementation of a cost-benefit analysis of Demand-Responsive Transport with a Multi-Agent Transport Simulation. arXiv preprint arXiv:2011.12869. https://www.researchgate.net/publication/346373557_Implementation_of_a_cost-benefit_analysis_of_Demand-Responsive_Transport_with_a_Multi-Agent_Transport_Simulation

Horni, A., Nagel, K. & Axhausen, K. 2016. The Multi-Agent Transport Simulation MATSim. London: Ubiquity Press. https://doi.org/10.5334/baw

Flötteröd G. 2024. A simulation heuristic for atomic dynamic traffic assignment with a possibly stochastic dynamic network loading.

Kanchiralla, F. M., Grunditz, E., Nordelöf, A., Brynolf, S. & Wikner, E. 2025. Environmental and economic assessment of electric vessels with different lithium-ion battery technologies. Applied Energy, 396. https://www.sciencedirect.com/science/article/pii/S0306261925010049

Mcbride, M. 2024. Bangor-Belfast commuter pilot vessel launch delayed. BBC. https://www.bbc.com/news/articles/c5y9y79vvdpo [2025.10.12].

Rødseth, K. L., Fagerholt, K. & Proost, S. 2023. Optimal planning of an urban vessel service operated with zero emission technology. Maritime Transport Research, 5, 100100. https://www.sciencedirect.com/science/article/pii/S2666822X23000199

Trafikförvaltningen (2020). Resvanor i Stockholms län 2019. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjin8va256QAxXTKxAIHRM0FVEQFnoECBcQAQ&url=https%3A%2F%2Fwww.regionstockholm.se%2F4a272f%2Fcontentassets%2Fd6c4da12e11843c0ab8249c297dfd8fe%2Fresvaneundersokning-2019.pdf&usg=AOvVaw2ztdsmLIH0qs5VEW_C_HEJ&opi=89978449

Sjöstrand, H., Merkel, A. & Vierth, I. 2020. Inlandssjöfart–offentlig upphandling och regelverk i Sverige och Europa: delrapport i projektet Hållbar inlandssjöfart–offentlig upphandling som katalysator. Statens väg-och transportforskningsinstitut. https://urn.kb.se/resolve?urn=urn:nbn:se:vti:diva-15696

Mikael Damkier/Mostphotos.com

The Swedish National Road and Transport Research Institute (VTI) is an independent and internationally prominent research institute in the transport sector. We conduct research and development to advance the state of knowledge within infrastructure, traffic, and transport. Through our work we contribute to the attainment of Sweden's transport policy goals related to accessibility, safety, environment, and health.

We conduct commissioned research within all modes of transport and work in an interdisciplinary organisation. Knowledge that we develop provides important information for stakeholders in the transport sector and in many cases leads to direct applications within both national and international transport policies.

As well as research we also undertake investigations, provide counselling, and perform various services related to measurement and testing. At VTI we have a wide range of advanced research equipment along with world-class driving simulators. We also have accredited laboratories for road material testing and crash safety testing.

The National Transport Library at VTI is a national resource that collects and disseminates information about Swedish transport research. The library provides support and guidance to anyone looking for information in the field, which includes loan and copy services. Examples of assignments are information searches, guidance in reference management and bespoke services for authorities and organisations.

In Sweden, VTI collaborates with universities that conduct related research and education. We participate regularly in international research projects, primarily in Europe, and are active within international networks and alliances. We have about 240 employees and are located in Linköping, Stockholm, Gothenburg and Lund.

Swedish National Road and Transport Research institute • www.vti.se • vti@vti.se • +46 (0)13–20 40 00