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Brutus model for Trondheim

Pilot project

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Brutus model for Trondheim

Pilot project

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Approved by	**Sindre Levinsen**
Description	**A pilot project of an activity-based strategic model, developed in Finland under the name "BRUTUS". The purpose of the assignment is to uncover the advantages and disadvantages of using an activity-based transport model, compared to a 4-step methodology transport model like regional transport model RTM.**

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Contents

1. Introduction

In this project, Ramboll has developed an activity and agent-based model BRUTUS by Ramboll (further "Brutus") for Trondheim and applied the model on a set of scenarios. The project aims at showing to the Norwegian Public Roads Authority (NPRA) how a disaggregated model such as Brutus differs from aggregate four-step models in terms of accuracy, functionality, and development process. Therefore, this study allows to increase understanding of activity-based and agent-based modelling and its relevance for transportation planning. The study does not imply building a fully calibrated model but delivering of a model that illustrates the capabilities of an agent-based model. The scenarios tested with Brutus mostly relate to projects / policy measures promoting cycling and demonstrate the strength of agent-based models for appraisal of cycling projects. This technical report compliments the model. The model results are available in the Brutus UI[1].

The report aim is to facilitate a common understanding of the project, how it is executed and what the findings are. The report describes goals, scope, and process of the model building project of Brutus in Trondheim for the Norwegian Public Roads Authority (NPRA), as well as scenarios and their testing.

2. Activity and agent-based models

Activity and agent-based models are proclaimed the next generation of transport models. "Agent-based" means that the individuals' behaviour is captured and "activity-based" refers to demand derived from people's desire for activities. The concepts of such models are not new. However, these models are still less widely used than traditional four-step (trip- and tour- based) ones. Agent- and activity-based models allow modelling at higher level of details with more natural representation of reality compared with the traditional models. On the other hand, their use is hindered by the development and operational costs and by data requirements. This chapter provides a high-level explanation of what activity and agent-based models are and how these compare to traditional models based on several key concepts.

2.1 Key differences between transport model types

Four major types of models can be distinguished, by the level of aggregation:

1. Trip-based four-step-models: High level of aggregation. An individual trip is the unit of travel.
2. Tour-based four-step models: Tour (a trip chain from home to one or more destinations and then back home) is the unit of travel.
3. Activity-based models: Travel demand derives from the desire for activities. The model combines the tours into a daily schedule. The demand component of such models is usually agent-based in nature.

[1] Brutus UI can be accessed from here: https://brutus.mobilityanalytics.ramboll.com/
Note that access needs to be granted before being able to see the results. Access can be requested from the web page.

4. Agent-based models: models which have representation of each individual and/or vehicle separately, without aggregation. While agent-based models could refer just to the assignment step (where autonomous agents are routed through the network), here it refers to the entire model.

- Activity-based models are usually agent-based at the demand level as they require synthetic population generation and allow modelling individual behaviour. Before the traffic assignment step, however, in activity-based models the demand is often aggregated into O-D matrices. Integration of agent-based and activity-based models allows eliminating the need to use the O-D matrices and means that the entire model becomes fully agent-based. This implies that individuals are assigned directly to vehicles, without aggregating them into O-D matrices.
-
- A full agent-based model is not necessarily an activity-based model. In an agent-based model the demand can be modelled in a simplified way, without modelling the activities but directly generating for the synthetic population the tours with time, mode, and locations characteristics. This could be done, for example, by extrapolating the mobility patterns from household travel surveys.

Table 1 provides a summary of the explanation of the key differences between the transport model types that are explained in this paragraph.

Table 1: Key differences between transport model types

	Trip-based four-step-models	Tour-based four-step models	Activity-based models	Agent-based models
Level of aggregation	Aggregated	Aggregated	Disaggregated	Disaggregated
Spatial and temporal interaction	Ignored	Limited	Individual trip chains in tours	Dependent on implementation
Behavioural description	Homogenous	Homogenous	Heterogenous	Dependent on implementation
Interaction between decision makers	None	None	Limited	Full interaction
Data requirements	Transport networks, land-use in transport analysis zones, aggregated travel survey data.	Transport networks, land-use in transport analysis zones, dis-aggregated travel survey data.	Transport networks, land-use in transport analysis zones, dis-aggregated travel survey data.	Transport networks, land-use in transport analysis zones, dis-aggregated travel survey data.
Calculation time	Pproportional to the number of zones.	Proportional to the number of zones.	Proportional to the number of decision makers (or agents).	Proportional to the number of decision makers (or agents).

Solution properties	Unique and most likely continuous solution.	Unique and most likely continuous solution.	Non-unique, stochastic (discrete) solutions.	Non-unique, stochastic (discrete) solutions.
Applications	Modelling of policy measures/scenarios in which interactions between the agents are not essential, and no possibility to perform detailed analysis for different user strata.	Modelling of policy measures/scenarios in which interactions between the agents are not essential, and limited possibility to perform detailed analysis for different user strata.	Modelling of policy measures/scenarios, including the ones with interactions between the agents at the demand level; possibility to perform detailed analysis for different user strata.	Modelling of policy measures/scenarios, including the ones with interactions between the agents; possibility to perform detailed analysis for different user strata. Better possibility to model shorter trips, including active mode trips, due to higher spatial resolution and level of details.

2.1.1 Level of aggregation

Four step models (either trip or tour-based) simulated aggregate flows of travel between different areas. Activity-based (and sometimes agent-based models) model travel demand on the level of individual decision-makers (Figure 1).

2.1.2 Spatial and temporal interaction of trips

In trip-based models, each trip unit is modelled separately, while in tour-based models, the trip is constructed in a tour. Using trips to describe the travel demand means that any spatial or temporal interactions between trips are usually ignored. Disaggregated models can apply the tour (a sequence of two or more trips starting and ending at home) as their unit of travel, thereby enforcing temporal and spatial interactions being accounted for, improving the accuracy of these models.

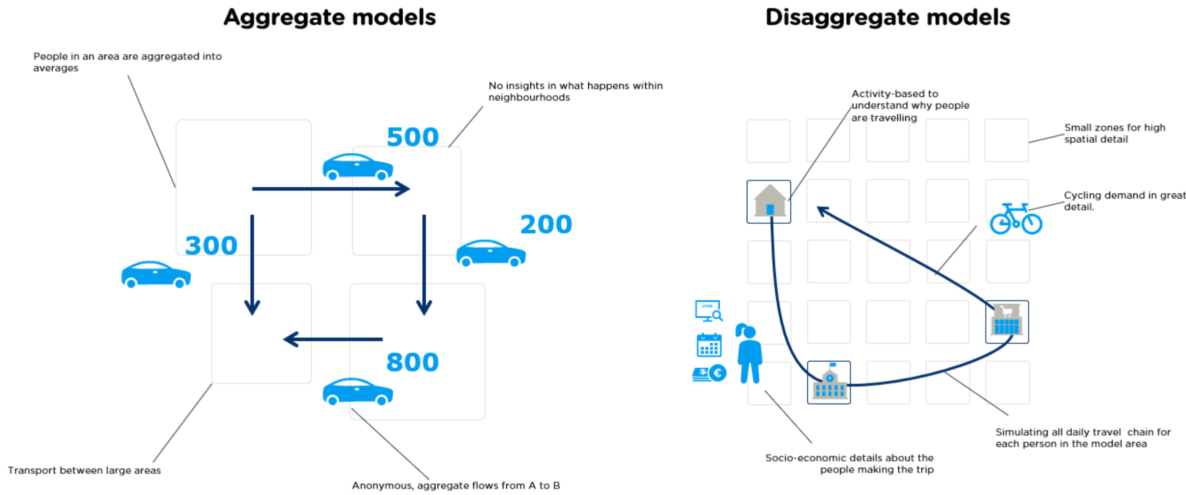

Figure 1: Difference in level of aggregation between different model types.

2.1.3 Behavioural description

In a four-step model, model behaviour of people is considered homogenous across the population. Personal preferences or constraints are not accounted for. By segmenting the population (e.g., car owners versus non-car owners) and the trip purposes into clusters and estimating models for each cluster, it is possible to add some behavioural variation to an aggregated model. Disaggregate models describe the behaviour of individual agents (persons and/or households) and can take personal characteristics into account. This is possible due to the use of a synthetic population that is a simplified microscopic representation of the actual population. Such approach can improve the accuracy of the models and allows the model user to use available person(type)-specific variables in scenario evaluation (e.g., the effects of an aging society, or the effects of different attitudes towards new transportation concepts).

2.1.4 Interaction between decision makers

Interaction on a decision maker level is typically not available in aggregate models[2]. Full agent-based models consider interaction between decision makers in the simulation space. Interaction in space and time is integral part of agent-based models. Examples of such interaction in transport modelling are:

- Interaction within a household as of who is to take the car or if rides are shared.
- Interaction between vehicles on the network.

Both activity and agent-based models do not include interaction between decision makers at the demand level by default. Normally the possibility to model such interactions depend on the availability of the household travel survey for the study area, as opposed to individual travel survey.

2.1.5 Data requirements

In terms of the input data for the demand modelling part, tour-based and agent-based models require more fine-grained data, disaggregated in space and time, with details about individuals

[2] Only type of interaction such models employ are on a system level through iterative demand modelling and assignment. Travel times are updated after an assignment, which in turn influence the choices in the demand model up to the moment an equilibrium is achieved.

trip chains in the study area. Therefore, activity and agent-based models require often more data and aggregate models, usually on two frontiers:

- Land-use data can be more disaggregated as runtime is less defined by the number of zones.
- Travel survey data requires to be more disaggregated to derive information on tour level (or even sub-tour level) and person / household background variables.

The prior point is no hard requirement as trade-offs can be made regarding spatial resolution if needed. The requirement regarding travel survey is usually stricter. The travel survey is typically used to estimate more models (in terms of segmentation) but also regarding aspects that are modelled: e.g., the population or long-term choices such as car-ownership. This is a significant cost component for disaggregate models. In part this may be overcome by geographical model transferability.

2.1.6 Calculation time

The calculation time of the aggregated model is relatively low and roughly proportional to the number of zones in the model, whereas calculation time of agent- or activity-based models is relatively high and roughly proportional to the number of agents described by the model. With increasing spatial resolution of the zones, there exists a tipping point above which it becomes computationally more attractive to describe individuals using the agent- or activity-based model rather than applying the aggregated model on the zonal level.

2.1.7 Solution properties

The favourable model properties of agent- and activity-based models are at the cost of some favourable model properties from aggregated models. With respect to solution properties, it has been proven that the aggregated gravity model yields the solution that adheres to conditions of maximum entropy treating all input and output as deterministic continuous variables. This means that these models calculate the most likely solution, which is unique but not discrete. Agent- or activity-based models employ stochastic processes on (mostly) discrete variables and generally do not adhere to a prespecified solution condition yielding non-unique stochastic and discrete solutions.

2.1.8 Applications

Possibility to model different policy measures / scenarios and perform corresponding analysis for different user groups highly depends on the model disaggregation level.

The aggregated nature of traditional transport models typically does not allow modelling of policy measures/scenarios with detailed analysis for different user groups. Splitting the demand in different user strata allows to overcome this limitation, however, the number of such strata must be limited due to the total number of possible combinations. For example, if the model distinguishes the users with an access to a car (has access or no access) and by employment status (employed, non-employed, student), such model requires 6 population strata. This imposes higher requirements on the survey sample size, so that it covers each stratum sufficiently to draw statistically significant conclusions. Activity- and agent-based models which rely on synthetic population allow to perform analysis for any combinations of individual characteristics which are available in the synthetic population. E.g., analysis can be performed for a certain age, gender, income group.

Disaggregated nature of agent-based models, including higher spatial resolution, gives wider opportunities in modelling short trips. This is especially relevant for modelling active modes (walking and cycling), which normally imply relatively short distance trips. In an aggregated model these trips often happen at the intra-zonal level and, therefore, are frequently omitted at the traffic assignment step. Having small traffic analysis zones / grid allows to model these trips as inter-zonal and to have more realistic connectors from the zones to the network, diminishing the aggregation error.

Lack of possibility to model policy measures which highly depend on the interactions between the agents is another limitation of traditional aggregated models. Such policy measures, for example, include on-demand transport modes, managing the curb, restriction zones and park & ride / bike and ride facilitation. Therefore, agent-based models allow to test the influence of the corresponding policy scenarios on traffic and emissions.

2.2 Relevance of activity and agent-based models

Activity-based models (and in some cases agent-based models) provide a more natural representation of the transport system by modelling individual people using personal preferences and the constraints from travel chains. This has in turn benefits in terms of what is possible to analyse and simulate.

The advanced features of activity and agent-based models are increasingly deployed in travel demand models. And although these methods have their strong benefits, one must be aware of the higher costs of such models due to data requirements and model development. Traditional models can still have benefits for specific use cases, especially when it concerns the traditional public and private vehicle centred transport planning questions regarding congestion. These solutions are less data intensive and offer stable solutions, which makes scenario analysis more robust for cost-benefit analyses.

Of the new demand modelling practices, activity-based models have the strongest theoretical basis. These models, on the other hand, have drawbacks of having a very large and challenging formulation and imposing higher requirements on the survey data. These higher requirements include larger survey sample, to cover various combinations of activities, socio-demographic characteristics, modes and their attributes, destinations, and time of the day, etc. Additionally, there should be a possibility to match the survey respondents to a relatively high spatial resolution zoning system / grid. This would allow to maximise the benefits of using the synthetic population and from the agent-based nature of the activity-based demand models.

2.3 Brutus model in brief

Brutus is an agent- and activity-based discrete Monte Carlo travel demand simulation model that accounts for trip chains, operates at a very detailed spatial resolution and is very flexible toward different applications. Brutus incorporates many advances in travel demand modelling and in many ways resembles activity models, without being tied to this definition. Brutus modelling includes generation of synthetic population, assignment of daily trip patters to each individual, followed by combined destination and mode choice model, to define how the activities are executed in terms of location and means of transport. Brutus also has a traffic assignment step, and graphical user interface (GUI). This report presents technical description of the Brutus model and its application for the study area of Trondheim. This includes the overall study outline, data inventory and data processing, modelling concepts, estimation and validation results.

3. Pilot study modelling framework and implementation

3.1 Project outline

This section presents the study modelling framework and provides a detailed description of the model, including the input data used, model calibration and validation. The study modelling framework consists of the four main building blocks as presented in Figure 2.

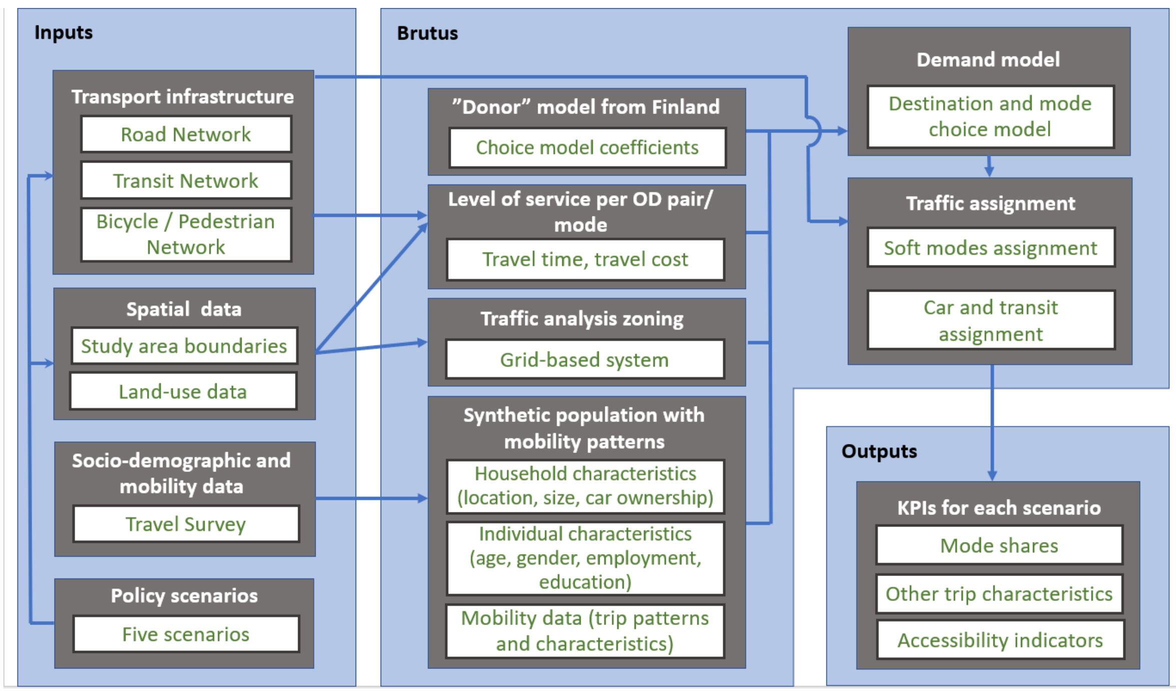

Figure 2: Study modelling framework

The first block represents all the model inputs. The data covers available transport infrastructure and services (road, transit, bicycle, and pedestrian networks), the spatial definition of the study area and land-use data, socio-demographic and mobility data, and policy scenarios. The elements of this block covering the existing transportation system are discussed in section *the Study scope and characterization of the study area*.

All the data from the first building block are used to divide the study area into grids, to generate synthetic population with attributed socio-demographic characteristics and mobility patterns and assign it to the grid system. Additionally, level of service for each transport alternative is calculated using the network characteristics. These characteristics will be used as inputs in the demand and traffic assignment models. This block also includes fetching demand model coefficients from a donor model to skip the demand model estimation step and reduce the data requirements and modelling efforts.

The third building block represents demand and traffic assignment modelling steps. The demand model is calibrated using the travel survey for the study area and the inputs from the previous two building blocks.

The synthetic population and its socio-demographic characteristics are generated based on census data (2019) and processed survey data from the donor model (HLT) (2016), expanded to the total population, by generating synthetic households' compositions with similar mobility profiles as the population of the survey sample. The trip patterns of each representative of the synthetic population and their spatial distribution are obtained based on the travel survey revealed preference. The model generates the mobility of these individuals constrained to their generated residential location, land-use distribution in the study area, and the transportation network performance for the generated transport modes. The estimated mode choice model produces the probabilities used to assign a transport mode for each trip chain. The development of this stage is described in the section "Modelling current travel demand".

After development of the model for the baseline, in discussion with the NPRA, a set of policy scenarios was developed, a total of five scenarios. These scenarios are described in detail in the section "Setting the scenarios".

The synthetic mobility dataset and the different transport policy scenarios were then tested in the Brutus simulation model. The following chapter describes how the scenarios are modelled using Brutus. The outputs for each tested scenario include modal shares, travel times, average trip distance per different demand segments, and emissions. Section "Results" present these outputs. Finally, the report contains a chapter with the results validation, summary of the study findings and proposals on future developments.

3.2 Study scope and characterization of the study area

The study area covers Trondheim municipality and three other adjacent municipalities: Malvik, Melhus, and Stjørdal. The study area is 2644 km2. The study area had 256 thousand inhabitants and nearly 140 thousand jobs (SSB, Statistikk Rutenett, 2019). Figure 3 shows the distribution of the population and Figure 4 shows the distribution of jobs in the study area. The figures are based on the grid system developed for the Brutus model application in the study area and described further in section *Input data and tools*. Around 12% of the study area has population and approximately 4% has jobs registered in it. Most of the population and jobs are in the Trondheim city centre, as well as along the E6 highway, connecting Trondheim with Oslo.

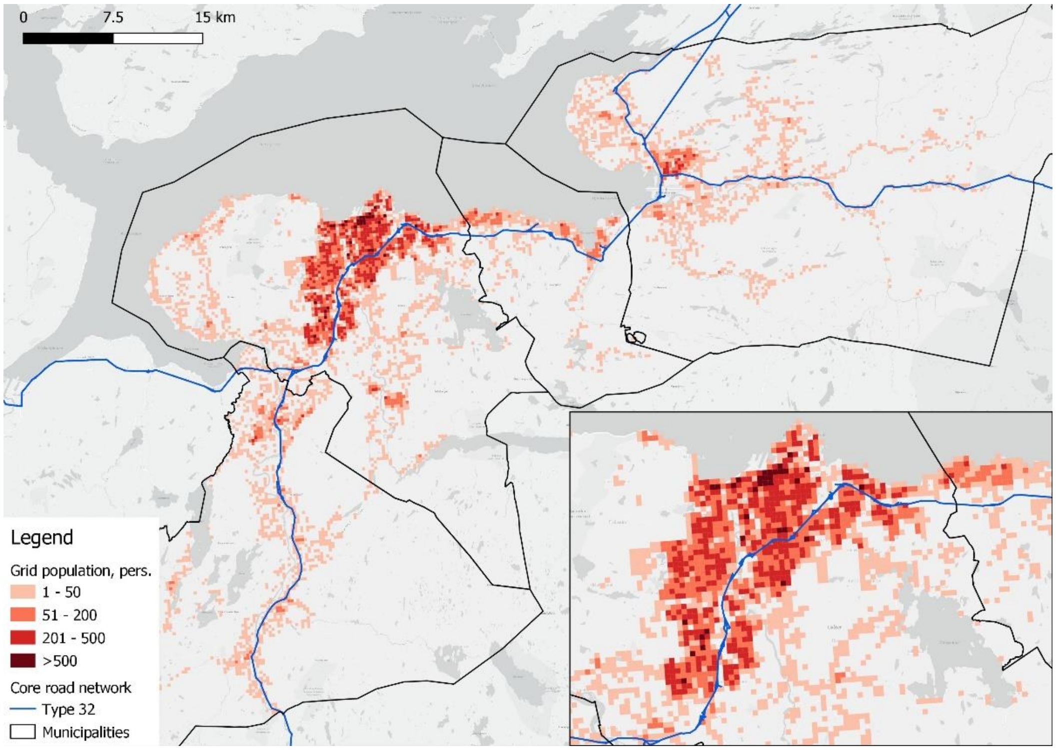

Figure 3: Population distribution in the study area

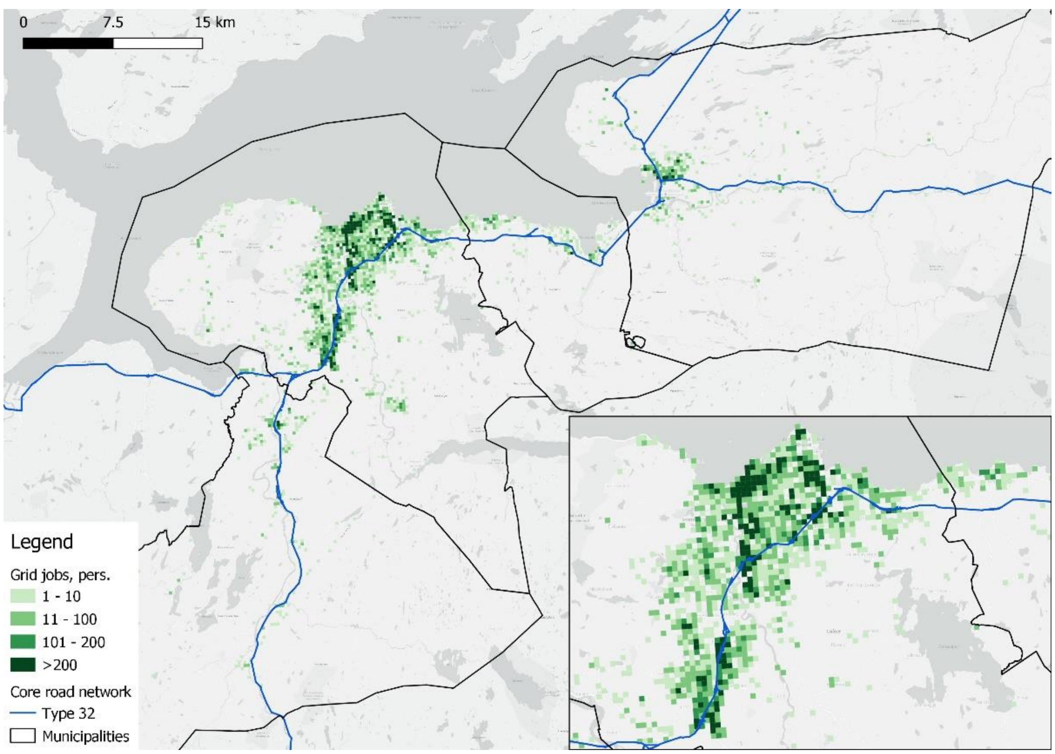

Figure 4: Jobs distribution in the study area

The trip ratio calculated from the RVU for the study area is 2.54 trips per person, meaning that over 650 thousand trips took place within the study area on an average day in 2021. 17.5% of the trips took place during the morning peak period from 7 to 9 am, and 10.5% during the afternoon peak from 4 pm to 6 pm. Most of the trips are by car, accounting for more than a half of the mode share (including driving and being a car passenger), followed by walk. Non-motorised trips account for slightly above one third of all the trips (Table 2).

Table 2: Mode shares and daily number of trips in the study area, calculated from RVU 2021

Mode	Number of trips per day, thousand	Mode share
Bicycle	42.5	7%
Car driver	283.0	43%
Car passenger	73.1	11%
Pedestrian	190.9	29%
Transit	60.4	9%

In the 60s the road network played a crucial role in the city transportation. During last couple of decades transport planning authorities have made efforts to encourage a shift from private cars to public transport (tram and bus) and active modes (walking and cycling). The city, counties and the state initiated a partner program for sustainable transport, called Miljøpakken (Greener Trondheim) in 2008. From 2010 to 2029, 25 billion NOK will be invested into the transportation system to reduce congestion, air pollution, traffic noise, and traffic accidents and to promote public transport and active modes in the city[3].

In 2016, the city developed a walking strategy. One of the main goals was to achieve 30% of daily trips to be made on foot by 2025, from 27% in 2013. To encourage the citizens to shift the travel mode, the city has been investing significantly into pedestrian shortcuts. By the beginning of 2023 over 100 shortcuts have been created / improved[4]. The main square in city has become free of cars, only available to pedestrians and cyclists.

During the last two decades, the city of Trondheim has put an effort into developing a public transport system with buses playing the main role. Greener Trondheim has made the bus system their main priority in the matter of public transport. In parallel, the city has introduced the road toll, which allowed to reduce the car share by more than 10% since 2009[5]. The city also had a metro bus system going through the centre, long-distance and of high capacity. The metro bus is connected with regular buses, which increases the average number of transfers but provides better capacity. There is also a light rail (tram) system in the city.

[3] Miljøpakken (Greener Trondheim), available at https://miljopakken.no/, accessed on the 15th of March 2023.
[4] Miljøpakken (Greener Trondheim), available at https://miljopakken.no/prosjektliste/page/2?prosjekttype=6, accessed on the 15th of March 2023.
[5] Miljøpakken (Greener Trondheim), available at https://miljopakken.no/, accessed on the 15th of March 2023.

3.2.1 Forecast year

For the future year 2030, for which this study produces transportation forecast, the total population of the study area goes up by 9% and becomes 280.5 thousand people (calculated based on the ADV land-use forecasting tool (further ADV), while the area where the population resides shrinks by 4% (Figure 5). The proportion of the aged people increase in the forecast year. These changes in demographic data reflect the trends happening and forecasted to persist in the following years: aging of population and urbanisation. The jobs and their distribution are assumed not to change in 2030.

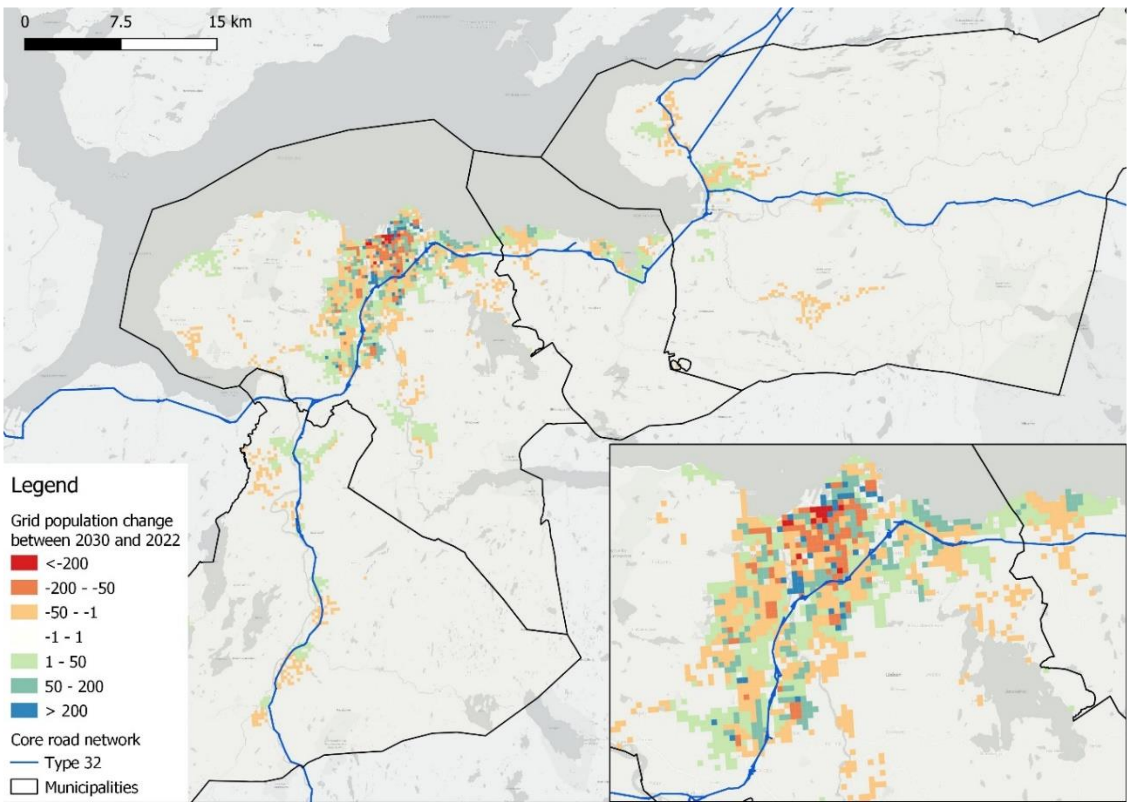

Figure 5: Grid population difference between 2030 and 2022

The forecast grid shows that population declines in the urban centre (Figure 5), contrary to what one might expect intuitively, and the contrast in change between cells seems stark. These changes in population are the result of how the population calculation for both years (2022 and 2030) is implemented. The calculation is based on the combination of different data sources on two spatial levels.

The four data sources were available for the base line and the forecast year 2030:

- ADV 2022, on grunnkrets level[6] (which is a population forecast based on 2018);
- ADV 2030, on grunnkrets level (a population forecast for 2030);
- SSB 2022, on grunnkrets level (based on the population data from Statistics of Norway, 2020);

[6] Grunnkrets correspond to areas smaller than municipality (with an average size of around thirty-three square kilometres.

- SSB 2022, on grid level (based on population on the grid level from SSB data, Statistikk Rutenett, 250m, 2019).

For 2030, the ADV 2030 was used as an absolute target, with disaggregation of the population totals to the grid level. The disaggregation process is described further in this report, in section 3.3.1. For 2022, the SSB data on grid level was used, which matches the SSB 2022 on grunnkrets level but differs from ADV 2022.

This choice to use ADV 2030 and SSB 2022 was made to match better the population totals and to be in line with the approach used in the Regional Transport Model (RTM). The results at the grid level (Figure 5) are consistent with the results using the same two data sources on grunnkrets level (Figure 7). However, when comparing ADV 2022 and ADV 2030 at the grunnkrets level, the population increases or remain the same across the model area, including the city centre (Figure 6), and there are no areas for which the population decreases. Therefore, the observed decrease of the population in certain grids is due to the mismatch between ADV 2022 and SSB 2022.

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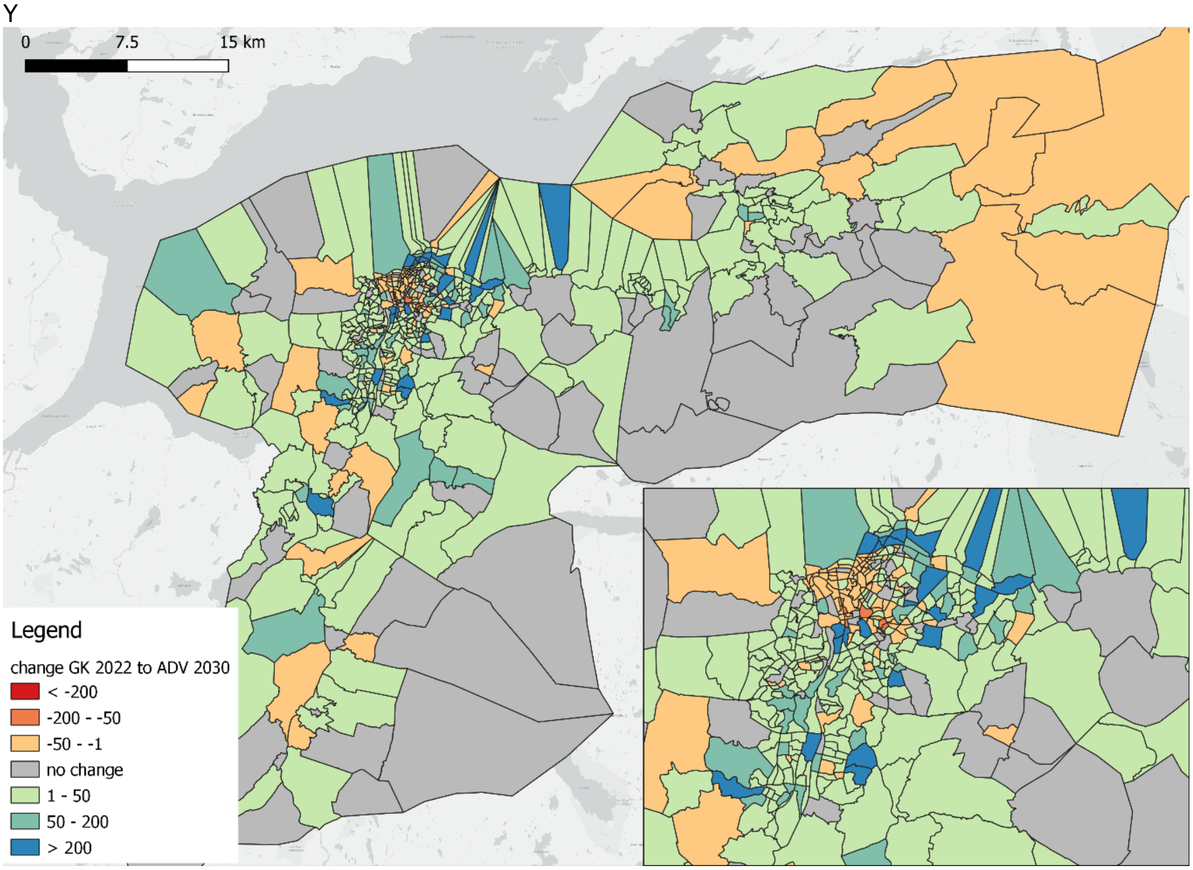


Figure 6: Change in population between actual values for 2022 on Grunnkrets level and ADV 2030.

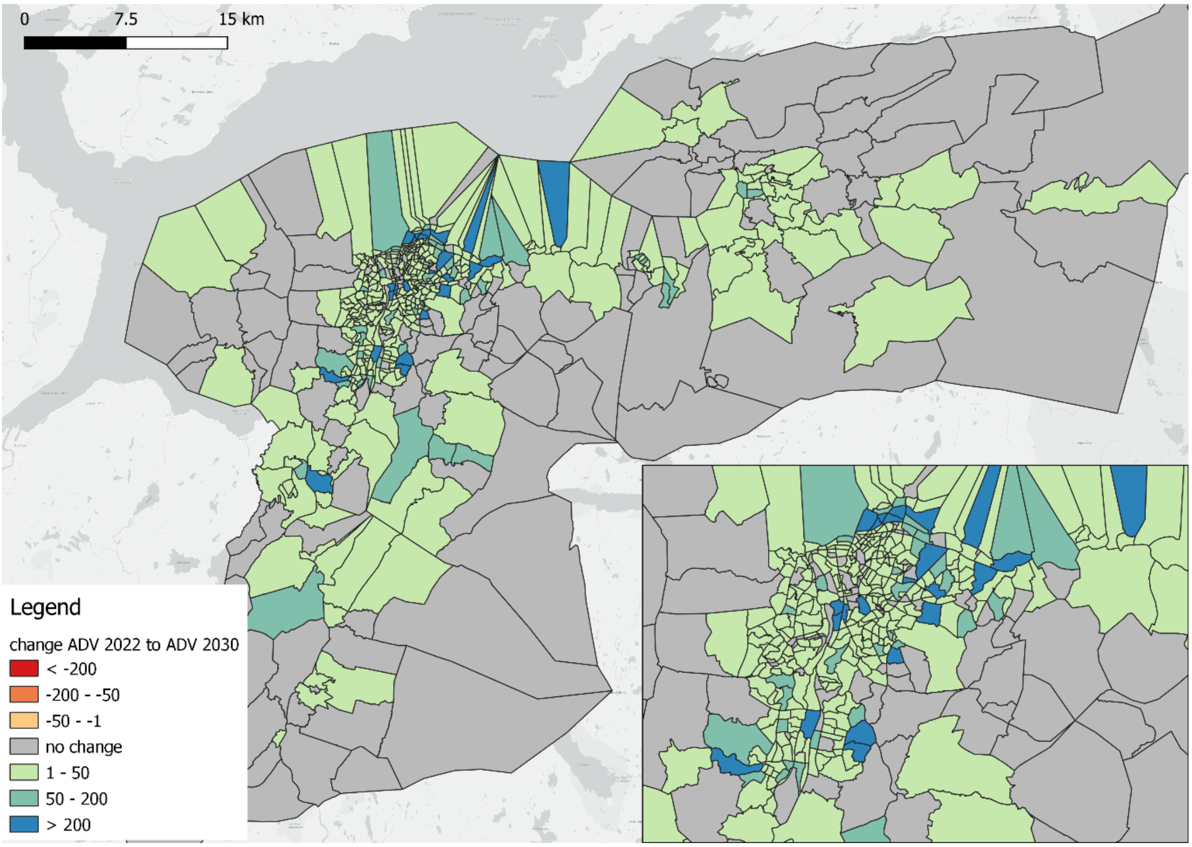


Figure 7: Change in population between prognosis in ADV 2022 and ADV 2030.

3.2.2 The current Regional Transport Model (RTM) and the traffic analysis zoning system

In Norway, transportation policy makers use the regional and national passenger transport models for strategic analyses. The models can be categorized as a strategic tour-based four-stage transport model with a static demand model with deterministic route selection. The model must be seen as an advanced and detailed four-stage model with many time periods, multiple travel agents and capacity-dependent demand calculation and route selection.

The demand model in RTM (tramodby) calculates trip demand producing trips for each population segment of the population considering generalized travel cost. The destinations are selected depending on the zone attraction via gravity models. There is little correspondence between different parts of the travel chains although tour chains are calculated in tramodby. In the latest version of tramodby, some increased functionality has been added around limiting the number of municipalities for the possible destinations, but there is no connection between trip legs beyond this.

In terms of traffic assignment, RTM is a deterministic model based on incremental loading. RTM calculates the route selection based on generalized cost for various travel purposes but recalculates the best route choice over multiple iterations. Delay is calculated via using volume-delay functions specific to different road types, at link level.

Today, RTM is used as a tool for strategic analysis in urban areas in Norway. The model reflects different time periods, is multimodal and has capacity-dependent calculation of both demand and route selection for car traffic. Despite these capabilities, due to its structure and low spatial resolution of the zoning system. The model is not able to capture the effect of certain policy interventions, which are of interest for the transportation authorities. In a demand context, this may particularly apply to factors related to departure time, household internal dynamics and means of travel made on short journeys where the basic circuit trip in RTM becomes too rough. Furthermore, the calculation of public transport in some areas has been simplified. This may be especially true in relation to the calculation of congestion and correspondence between public transport.

RTM is tailored for regional modelling and lack of capacity to reflect certain transport policy interventions. The relatively coarse zoning system does not allow to model shorter trips, such as most of pedestrian and cycling trips. In case of public transport, transfer cost is not reflected in RTM), while RTM has penalties for the boarding and considers the headway. No activities / trip chains can be modelled in RTM. The aggregated zonal population (as opposed to synthetic population) also does not allow analysis at the individual level, which can be especially relevant for accessibility and equity studies.

For the study area, the RTM model consists of 594 zones called grunnkrets. The grunnkret's area varies from 0.1 sq. Km to 162 km, with smaller zones corresponding to the more densely populated areas, such as the Trondheim city centre. The public transport network includes nearly 64.000 stops (Figure 8). The road transport network consists of nearly 40.000 links of 15 types, with average length of 330 meters (Figure 9).

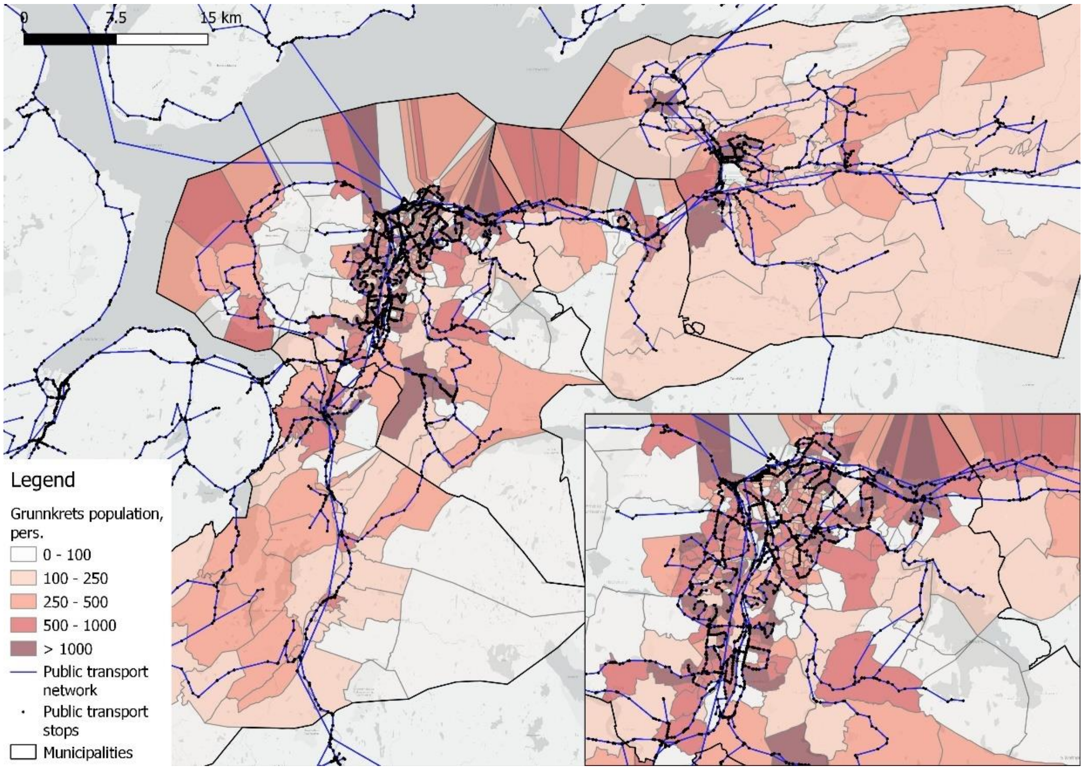


Figure 8 Grunnkrets zoning system and public transport network

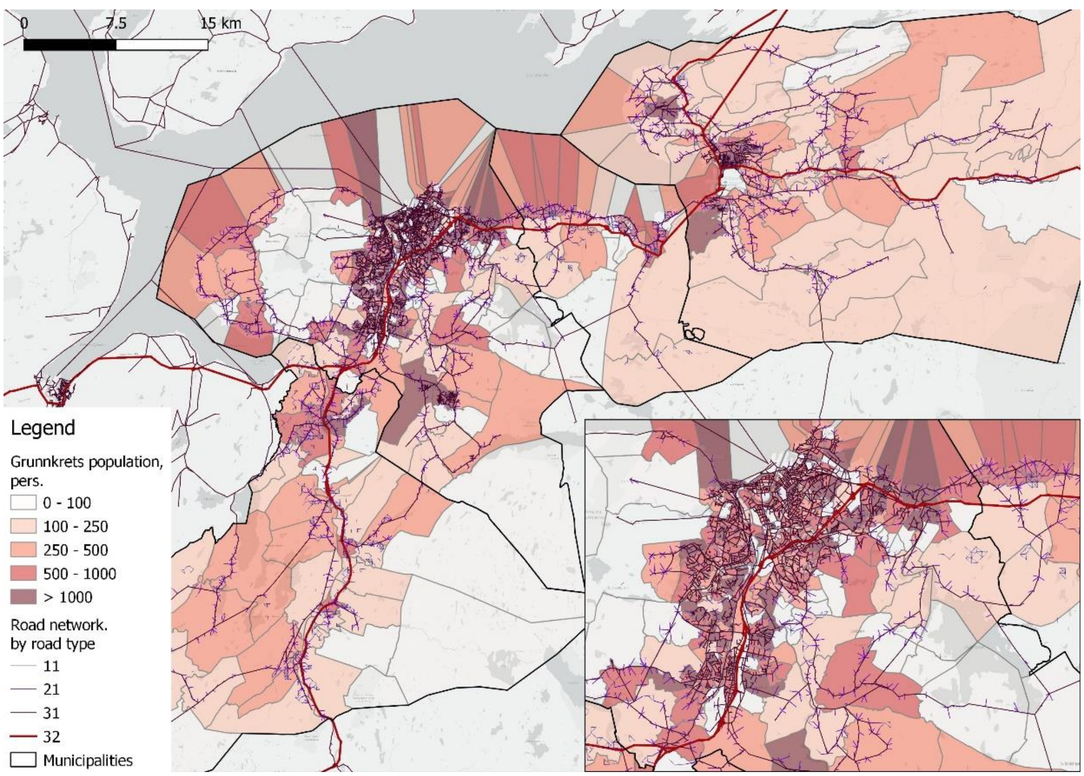


Figure 9 Grunnkrets zoning system and road transport network

3.3 Methodology application to the study area

3.3.1 Input data and tools

Data required to estimate and use the Brutus model is very similar to that of traditional models. The tree data categories required by Brutus include socio-economic and land-use data to model trip attraction, network data to represent the supply, and travel survey data to derive behavioural parameters of the decision-makers in the model. As distinct to the traditional models, the required data are generally of much higher resolution, meaning a more detailed description of land use and transport networks.

<u>The zoning system and land use for the baseline scenario</u>
As a zoning system, the Brutus model uses a 250 x 250-meter regular grid. This provides a good balance between accuracy of representation of the study area and computational complexity. The relatively high spatial resolution allows to model shorter trips, many of which are by bicycle and walking. This is distinct from traditional zoning systems where the zones tend to be bigger and short trips happen often entirely within one zone. The use of the grid gives a possibility to connect each zone to the network in a more realistic way and represent spatial variation of the land-use and population characteristics at a more detailed level, given the data availability. The grid-based zoning system allows calculation of more detailed results providing transport indicators disaggregated to the level of the grid cells.

For the study area, the grid system consisting of 42 307 cells, out of which 4 949 grid cells have population and 1709 have registered jobs for the baseline scenario. In 2030 these numbers become 4730 and 1709 cells accordingly. The land use data was available at three spatial resolution levels and as location points:

1. 250x250 grid, SSB data, Statistikk Rutenett 250m:
   - Population, 2019
   - Buildings, 2022 (Bygningsmasse) - number of buildings per type (museums and libraries, colleges and universities, and buildings related to sports, culture, religion)
   - Businesses, 2022 (Virksomheter) - number of employees

2. Grunnkrets - areas smaller than municipalities, total 592 grunnkrets are in the study area with the following data (from SSB) used in this study:
   - Age groups
   - Parking costs, 2020
   - Job categories, 2020
   - University/college places, 2020
   - Population, 2030

3. Districts – 42 larger areas, each consisting of around 10 grunnkrets, with data on:
   - Household groups, 2020

4. Point data for schools (provided by the Ministry of Education):
   - Daycare places (<u>downloaded from GeoNorge web portal.</u>)
   - Comprehensive school ("grunnskoler") (<u>downloaded from GeoNorge web portal.</u>)

- Secondary school (high school and vocational school) (downloaded from GeoNorge web portal.)

Grid cells were connected to the grunnkrets. For that first, each grid cell was connected to the grunnkrets, to which its centroid belongs. For the grunnkrets which did not have any grid cell centroid within it, the grid cell was assigned so that the grunnkret's centroid belongs to this cell. Grid cells were also connected to districts based on their grunnkrets connections, as one grunnkrets is always part of one district.

Further, the land-use data was distributed from the grunnkrets and district levels to the grid level proportionally and using some interpolation in case of missing data. Using the data which came at the grid level directly and which was distributed from the grunnkrets and district levels, resulted in each grid cell having the following attributes:

- Population
- Age groups (0-4, 5-9, …, 90-94, over 95 – 19 groups in total)
- Number of jobs in 21 categories
- Parking cost
- Number of buildings by one of four categories (music, sport, entertainment, religion)
- Number of day-care, university, and college places
- Shares of households of different size (1 person, 2 persons, 3 persons, 4 and more persons)[7].

Land use data in the Brutus model is used mainly for two things: to construct a synthetic population by generating individuals, whose total distributions match the data available for each grid cell, and to act as destinations that attract trips (e.g., school student places or number of buildings of certain type).

Forecast data

Input data that was used in building the 2030 grid was forecast population from the Area Data Tool (ADV)[8]. For other attributes, the same input data as in grid 2022 was used. The following data for 2030 was available at the grunnkrets level and used to model 2030: number of people per age-gender-group in grunnkrets, sums to total population. The data on job categories was available but not used due to assumed lack of its reliability. The data showed that the number of total jobs significantly decreased in 2030 compared with 2022, whereas population increased, including working age population.

The model grid cells were matched to grunnkrets with minor simplifications. More specifically, the Grid cells that were originally connected to multiple grunnkrets were assigned to the only one with most population in forecast data; and grid cells that had no population in the baseline data were not connected to any grunnkrets to ensure that the increasing population would not be assigned to completely undeveloped areas but rather to already attractive neighbourhoods.

[7] The calculation of the household shares assumes that households have only one child below the age of 18, so larger households are likely to be less prevalent in the grid than in reality.

[8] ADV is a land use model that interacts with the regional transport model RTM. The actual growth forecasts at the aggregate level are produced by models outside ADV and come from Statistics Norway's forecast models. The ADV distributes the population growth across the zones considering accessibility measures (logsums) calculated from the RTM and the zone capacity. The latter influences the distribution significantly, while accessibility effect is relatively marginal.

For each grunnkrets, the difference in total population was calculated with total population of the cells in that grunnkrets and the forecast population in that grunnkrets. This difference in population in the grunnkrets was distributed evenly between the grid cells of that grunnkrets. The 2022 grid population variable was used as the starting value to which the calculated differences would be added. For example, if the population in a grunnkrets was forecasted to increase (decrease) by 100 in 2030, and the grunnkrets was connected to 20 grid cells with population, each of those cells would be assigned an increase (decrease) of 5 in population. In case this step resulted in a negative population in a cell, the population of this cell was set to zero.

The interpolation of forecast age groups to the grid level was performed similarly to the baseline scenario but using the new interpolated total population for weighing and distribution. The 2030 age group shares reflect the aging of population trend (Table 3). Other variables were interpolated from same data and with same method as in the baseline scenario.

Table 3: Synthetic population by age group in base and forecast year.

Ages	Synthetic population in 2022	Synthetic population in 2030
7-17	32 540	32 168
18-29	48 348	49 686
30-44	54 261	62 360
45-64	62 279	65 766
65 +	39 968	50 002

Validation of the land-use distribution was performed both at the grid level and comparing the synthetic population characteristics with the available statistical data for the study area. At the grid level the population statistics were compared with the aggregated values at the grunnkrets and district level, including population totals in the reference and the interpolated data, and relative difference between the reference and the interpolated data. The comparison between the produced interpolated data and the statistical data, after aggregation at the district level, has showed that per each district an average relative difference is below 3% (if considering absolute values). The total difference in population for the entire study area is about 2%.

Transport Networks

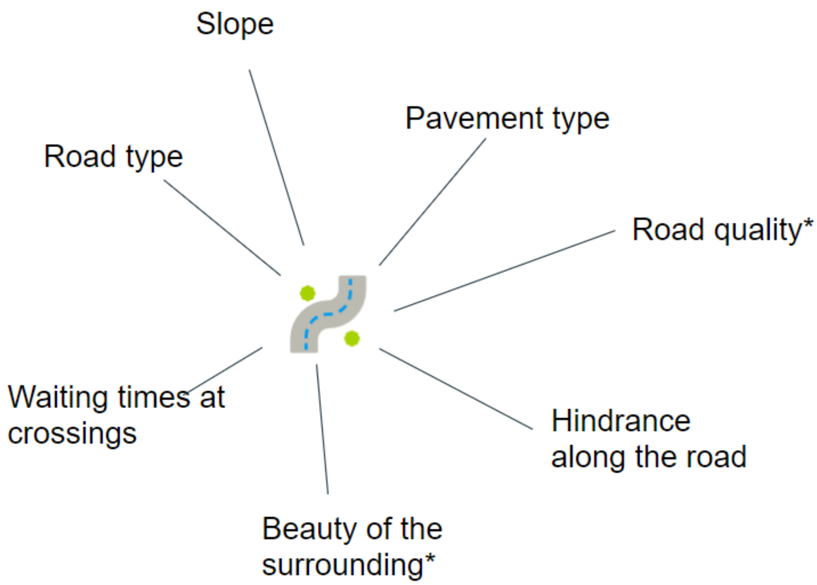


Figure 10: Network details considered in Brutus, *not available from the Open Street Map, and, therefore, for the current case study

The Brutus model for Trondheim uses the road and public transport networks from the RTM model (described in section 3.2.2). The walking and cycling network are built based on OpenStreetMap.

The road network for the auto network is taken as is. However, longer links are shortened to connect all grid cell centroids to the network. The turn restrictions from the RTM network are not included as Brutus currently does not support this feature. Consequence is that car traffic may take turns it is not supposed to. The speeds on link level from RTM are used to calculate impedances. Public transport travel times are also taken from the RTM network. The pedestrian network (described below) is connected to the public transport network as auxiliary network.

For the cycling network, the OpenStreetMap (OSM) was used, and the network was updated and validated to reflect the current state of the actual network. The same network is used for pedestrians. The network for the entire study area consists of nearly 380 thousand links.

Link attributes are derived from OpenStreetMap's tags. In addition, Brutus does a simple preliminary car traffic assignment to derive intersection delays and on-road car hindrance calculations. Also, parallel roads are identified to see if certain roads have a bicycle or sidewalk adjacent. Slopes are derived from a digital elevation model.

Travel times on the link is build up based on the following factors:

- Link type determines the default speed. Link type indicates the facilities and attractiveness for cyclists. There is distinction between designated bicycle infrastructure, roads with cycling friendly features such as suggestion lanes, roads shared with cars (but still suitable), footways and unattractive ways. A special type is reserved for high quality cycling highways. Each get their own default speed (ranging from 6.3 km/h for sidewalks shared with pedestrians to 20 km/hr for cycle highways).

- Pavement type: In this implementation, cobblestone roads get a 20% speed reduction.
- Has parallel bicycle path or sidewalk: A speed penalty of 50% is given to roads which have a parallel road more attractive for cyclists. This is to prevent that cyclists use the main road if better alternatives are available. Taking out these roads would compromise the routebility of the network.
- Estimated preliminary car volume: A simple car traffic assignment is done, generating trips from jobs and population data on the land-use grid. Cycling speed on a link goes down proportional to the volume of cars on the link to account for unattractiveness to cycle on roads shared with many cars.
- Slope: Digital elevation data is used to derive slopes of the links. Slope influences speed based on constant power.
- Delay: Delay represents intersection delays. Each passing vehicle on incoming links adds 0.0015 seconds of delay up to a maximum of 25 seconds.

The OSM network and the Brutus bicycle network (created based on the OSM) used in the study were validated versus the ATP network provided by the client (Figure 11).

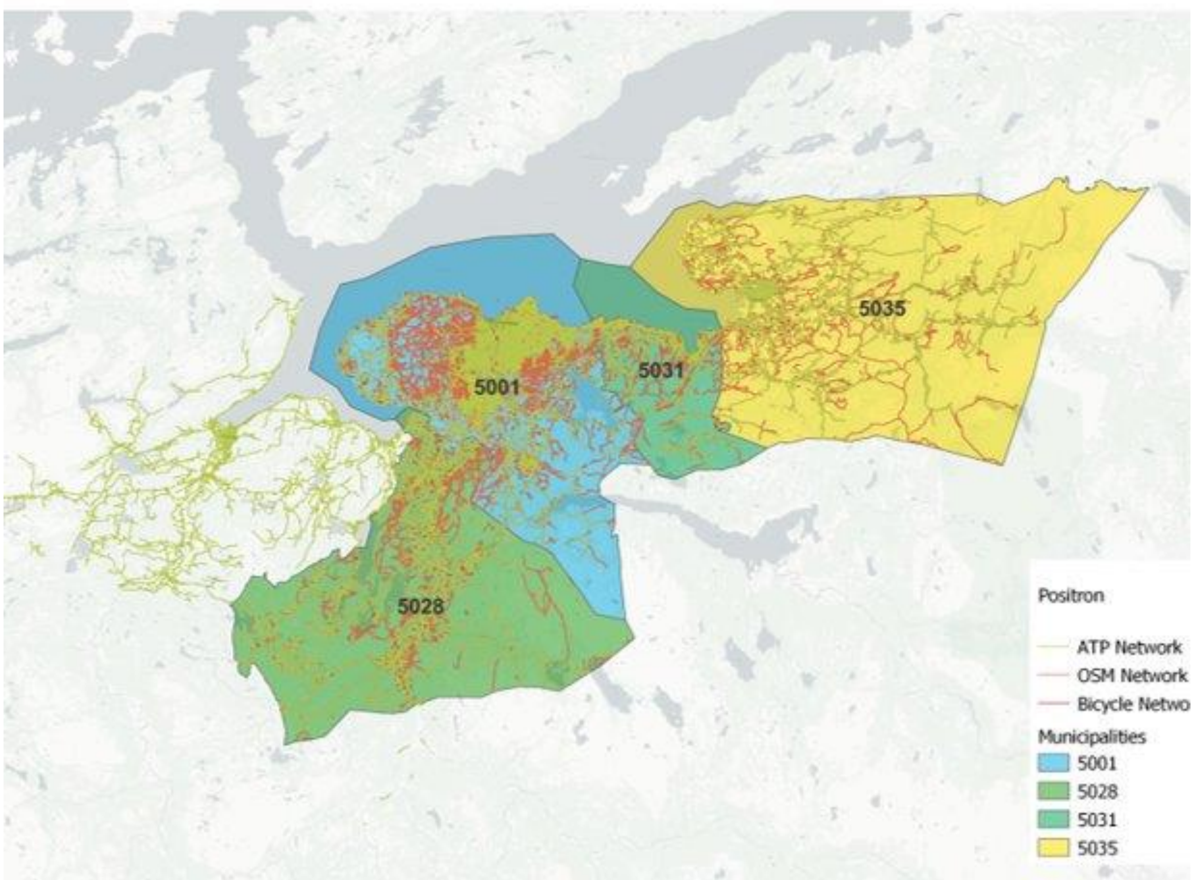


Figure 11: Networks considered for the study

Both OSM and ATP networks have relevant columns (Road category, speed and slope on both directions, one-way information) needed for Brutus network building. Additionally, both OSM and ATP networks have all the information of both the direction's information available in one link. However, as the comparison showed, the length of the OSM and Brutus bicycle networks is almost two times bigger than the length of ATP, which means that the number of network segments included is much larger (Table 4). ATP network provides a simplified representation of road network. There is always one line-segment representing a road in ATP, but whereas in OSM network, the road segments are very detailed. Every different road type (sidewalk, motorway) in the OSM road segment is represented with a separate link. The OSM network also represent even the smallest pedestrian access routes but whereas the ATP network only shows the main routes (Figure 12).

Table 4: Network distance comparison

Municipalities	ATP Network, km	OSM Network, km	Bicycle Network*, km
5001	2188.15	4199.28	4012.25 *
5028	1037.71	531.78	1441.48 *
5031	379.19	673.58	604.3 *
5035	1126.32	572.49	1475.56 *
All	4731.37	7977.13	7533.64 *

* For bicycle network built using Brutus, the connector links (Link 21) and one of the opposite links for all the bidirectional segment are removed and only then the network length is calculated

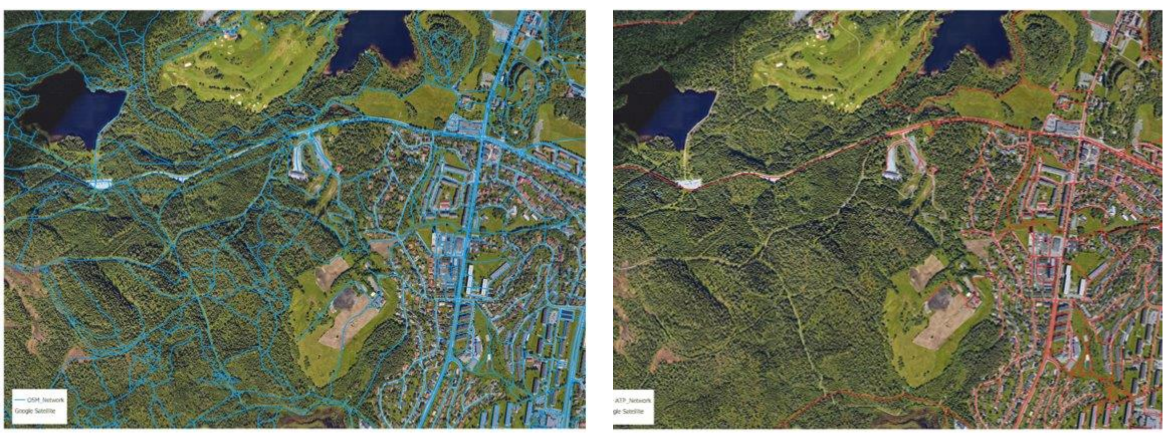


Figure 12 Example of visual comparison of the outskirts representation by ATP and OSM networks

As the ATP network does not include lower-level road hierarchies, it implies that footpath and sidewalk related information/network would be missed out in the model and it will be insufficient input in bicycle and pedestrian modelling. In Brutus (OSM-based) network the links are first broken into smaller segments, and then the slopes are identified, which leads to possibility to obtain more accurate slope values in Brutus bicycle network.

Travel Survey

For information about people's travel behaviour, Brutus requires data from a travel diary study, in which a random representative sample of the population is asked about their trips of one day and their background information. While the RVU survey data was available for this project, to reduce the time spent on modelling, a donor model from another similar city in Finland, Turku, was used for the mode and destination choice model, as well as for generating daily trip patterns for the synthetic population. The alternative-specific constants in the mode choice utility functions were further adjusted to reflect the mode shares observed in the study area. The available survey data for the study area (RVU, 2021) was used for the model validation and calibration.

3.3.2 Concepts and Estimation

Brutus includes several modelling advances typical to activity models and other modern models: handling of individuals, handling of trip chains and a continuous time dimension. Like traditional models, Brutus has destination and mode choice models, but they are connected and interdependent rather than separate sequential steps.

<u>Model Structure</u>

Given land use data, transport networks for different travel modes and destinations, we simulate all trips of all people of a synthetic population sample and validate it using the travel survey (RVU, 2021). Steps are outlined below with details in following subsections. The steps are

5. Synthetic population generation, representing all individuals residing in the study area, similar to census data. From this entire population, we further select either on over- or an under-sample for simulation.
6. For each member of the population, we select demographically, socioeconomically and by residential area type a similar survey person and we select that survey person's trip endpoint types, departure times, etc. As the trip yield for the population member. The survey underlying the donor model is used in this case study for this step.
7. For each trip of each population member, we choose trip endpoint locations with each travel mode separately using a destination choice model, considering the context of each trip in its trip chain.
8. For each chain, we compare the properties of realizations of the same chain in different travel modes and using a mode choice model, we choose one of these modes also considering the context of the household's car ownership and choices of other household members.

<u>Individuals</u>

Handling of individuals (or "disaggregate" modelling as opposed to aggregate models) primarily means that modelling is closer to the actual level of decision making and can include factors that affect behaviour on an individual or household level, both demographic and socioeconomic factors as well factors resulting from chaining of trips at times. Traditional models that deal with mean values of explanatory variables within enumeration areas and operate on OD-matrices cannot be expected to have realistic dynamics. They can be estimated to replicate current mobility distributions and traffic counts but cannot reliably model changes that operate at a different level. E.g., an increase in car ownership might be modelled as a 0.1 increase in the mean car ownership over an area, while households consider increases of zero or one car and make decisions based solely on their own change. Traditional models have tried to mitigate aggregation problems by using matrix segmentation, i.e. Having separate OD-matrices for different types of people, but the matrix space quickly blows up and makes any useful or especially new analyses difficult – e.g., Adding one more person type classification when already having three with five values each means an increase of 500 matrices. As the needed level of detail of analyses increases, the simplifications of traditional models no longer offer efficiency benefits of computation and data storage, but rather simulation becomes the more efficient alternative.

The socio-economic data at the grid level and the social characteristics from the trip survey are the input data for the generation of the synthetic population in Brutus. The synthetic population generation process in Brutus for this study first includes generation of people in each grid cell with certain age assigned to each person, using the age distribution available for this cell. Then we assign to each person employment status based on conditional probabilities for a person of certain age of that area having a particular employment status. Then these people are grouped into households. Finally, characteristics which are modelled on the household level are added, such as car ownership (Figure 13).

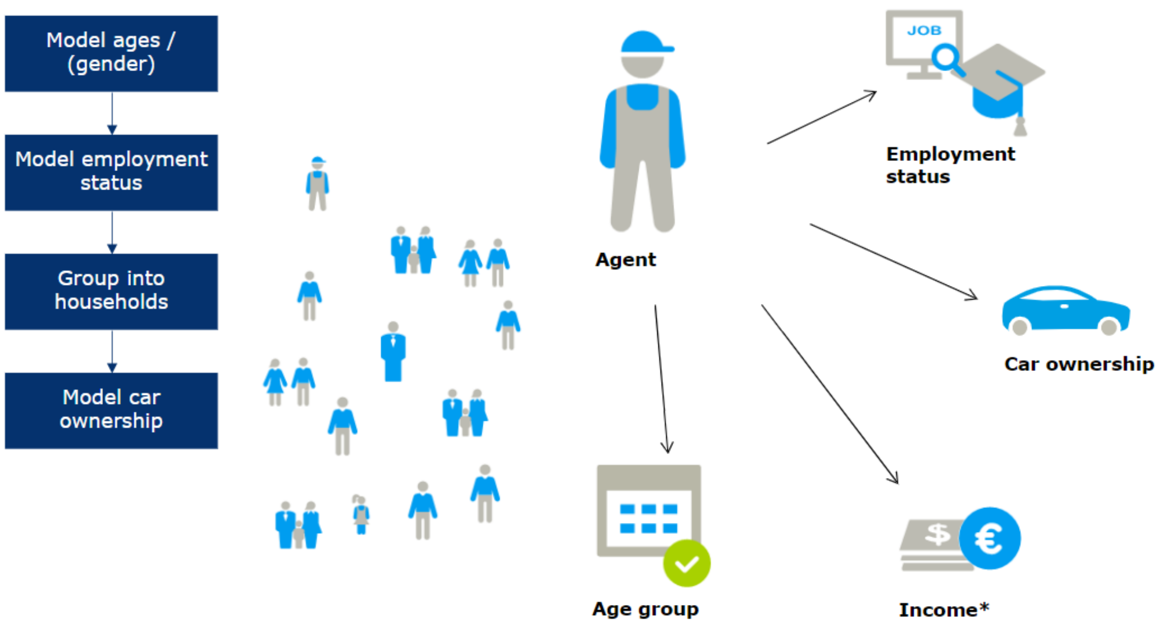


Figure 13: Synthetic population generation in Brutus

The synthetic population obtained for the baseline scenario and for the forecast year (2030) has been validated against the survey data (RVU, 2021). The obtained results show that the age distribution in the synthetic population follows well the one observed in the survey, with some under-representation of the people between 20 and 29 years old (Figure 14). The survey does not include any responses from the children under 10 years old, while the synthetic population does contain children, being a representation of the reality. For the 2030 forecast year the synthetic population reflects the population aging trend, showing higher share of aged people than in the survey data and in the synthetic population of the baseline scenario.

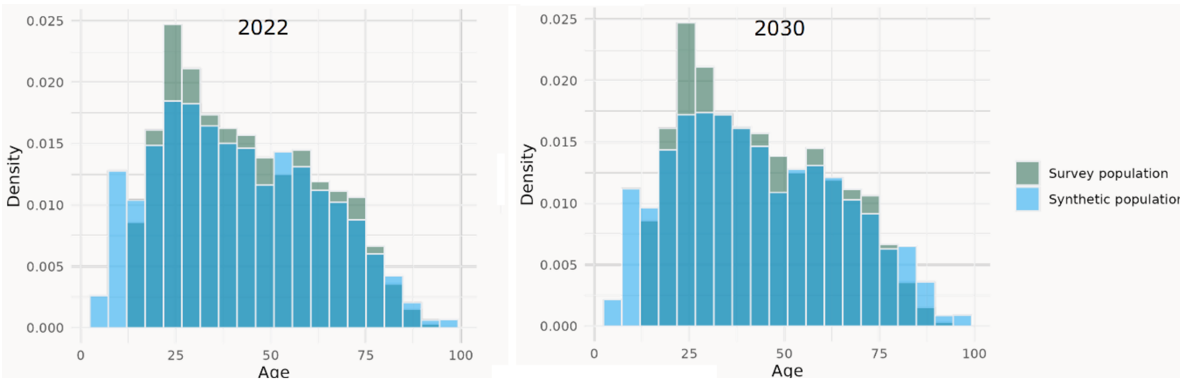


Figure 14: Validation of the density of the synthetic population vs. The survey population (RVU, 2021), for each age group

Trip Chains

Simulating trips of individuals makes it possible to take trip chains into account. A trip chain means a sequence of two or more trips, each to its own destination, in which the traveller returns to the original place of departure, usually home (Figure 1). Accounting for trip chains is especially relevant for non-home-based trips and mode choice involving personal vehicles. Non-home-based trips account for a large share of shopping and other service trips and their sensible modelling requires knowledge of the preceding and following parts of the chain – e.g. After-work grocery shopping can be expected to take place somewhere between work and home. The more common it is to have more than two trips per chain, the more severe the error in trip-based models becomes. Traditional models also have the problem that they cannot associate any demographic or socioeconomic variables (e.g., car ownership) with non-home-based trips as those variables are tied to home areas and those models, due to their structure, can only use data from trip endpoint areas. For mode choice, accounting for trip chains means that mode choice can be done for the whole chain instead of individual trips, which again means that modes that involve a personal vehicle (car, bicycle, etc.) Can be enforced to be used for the whole chain to avoid the inconsistency of leaving one's vehicle behind or reusing it from a location where it was not left. This problem comes up e.g. With varying public transport frequency, where a person working early morning shift might not have public transport available for the morning commute and therefore will have to use a car and cannot use public transport for the afternoon commute either, even if a trip-based model would suggest it.

Brutus handles trip chains as static and decision making as sequential. The big difference to activity models is that Brutus does not model the activities themselves, i.e. Does not have any underlaying choice or rule-based model determining which kinds of trips are made or which trips are chained together. Instead, Brutus uses survey data directly, if people make and chain trips with the exact amount and combinations as found in survey data. For this study the survey from the donor model was used for that purpose.

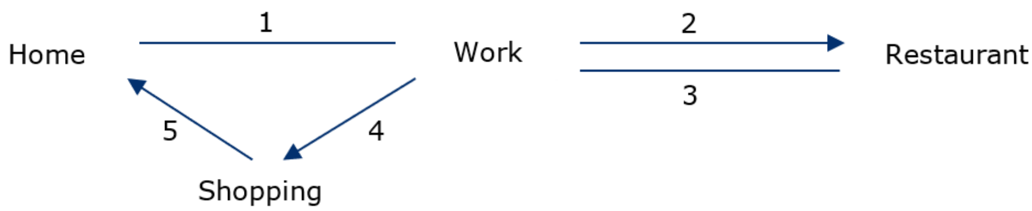


Figure 15: An example of trip chains: home → work → restaurant → work → shopping → home form two separate chains, in both of which one returns to the original point of departure

The relative importance of the trip endpoints on a chain is determined by time spent at the endpoint. Thus, trip endpoint locations are chosen in decreasing order of time spent, with trips considered from the previous fixed location and to the next fixed location, regardless of whether those trips would be made. For example, on a home → work → shopping → home chain the decision making would consider first trips home → work → home to choose a work location relative to home and then trips work → shopping → home to choose a shopping location relative to work and home.

For this case study we consider fourteen activity types. The land-use data is used for the attraction variables to model the destination choices (Table 1). The following section presents how the destination choice is modelled.

Table 5: Activity types used in the Brutus model for Trondheim

Activity type code	Activity type name	The attraction variables / amount of land-use variable used for Trondheim
1	Home	NA
2	Work	Total jobs
3	Business	Total jobs
4	School	School places
5	Study	University / college places
6	Visiting	Total residents
7	Pick-up	Total jobs
8	Daycare	Daycare places
9	Groceries	Jobs in groceries
10	Shopping	Jobs in specialty stores
11	Errands	Jobs supporting errands

12	Restaurant	Jobs in accommodation and catering
13	Free time	Building with a recreational or leisure purpose
14	Recreation/nature	Building with a recreational or leisure purpose

Destination Choice

The Brutus destination choice model is a multinomial logit model applied sequentially to parts of chains consisting of two trips and three endpoints (Figure 16).

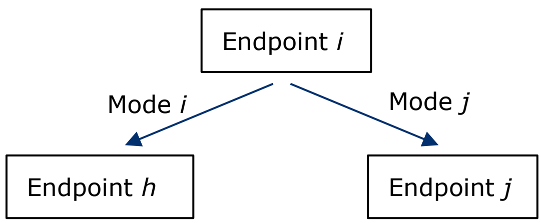


Figure 16: Part of a trip chain examined when applying a destination choice model to endpoint *i*. The full chain can include more endpoints, including ones between *h* and *i*, and *i* and *j*

The destination choice model chooses an endpoint based on travel weights from the previous fixed endpoint and to the next fixed endpoint and the attraction of land use in candidate grid cells. Endpoint at location i is being determined, whereas endpoint h and endpoint j are known (fixed) locations. Therefore, the destination choice utility function for grid cell i is:

$$V_i = \beta\left(t_{hi,mode} + t_{ij,mode}\right) + \mathrm{Log}\, m_i$$

Where β is the negative coefficient for travel time, $t_{hi,mode}$ Is the travel weight from the previous fixed endpoint to point i with the considered mode, $t_{ij,mode}$ Is the travel weight from point i to the next fixed endpoint with the considered mode and m_i Is the amount of attraction at cell i. So, an endpoint (activity) is evaluated in relation to the previous and next endpoints (activities). The selection probability of cell i from among n total cells is then defined via the above utilities as:

$$P_i = \frac{e^{V_i}}{\sum_{j=1}^{n} e^{V_j}}$$

The β coefficient of destination choice models are estimated by interpreting trip chains from survey data, sampling alternatives that the survey person could have chosen instead and then applying usual multinomial logit model estimation procedures. With a dense land use grid, all cells that contain land use of a particular type cannot be used for estimation as that would make the optimization process of the estimation too computationally complex. A random sample of alternatives for each trip can be expected to produce unbiased estimates and after estimation can be used as is for simulation with a full set of alternatives[9]. Sample sizes around 100 have been used in Brutus and additionally the set of alternatives has been limited in both model estimation and use by travel times around 180 or 360 minutes for two trips total, mainly to avoid unrealistic alternatives for walking and bicycle trips in regional models.

Destination choice models are estimated for all combinations of three endpoint types and two modes. For this case study it resulted in 555 models, total. The rarest of these combinations do not have enough observations and are supplemented by somewhat similar trips to reach at least 10 or 20 trips for estimation. Considering that the sampling of alternatives and supplementing of trips are both done stochastically, the estimation results are also stochastic. To avoid that being an issue, models are estimated around 10 or 20 times and the final β coefficients used are medians of those estimation rounds.

Mode Choice

Unlike in trip-based models, when doing mode choice for an entire chain, we are not necessarily choosing just one mode, but possibly several that can be combined in a single chain. Usually, this combination refers to combining walking and public transport, i.e., choosing public transport for the long trips and walking for the short ones. Theoretically, also being a passenger in someone else's car should be freely combinable, but in practice has been limited to the whole chain to avoid unrealistic mode choice shifts due to not having a helper model for the availability of a ride in someone else's car.

Brutus accounts for constraints caused by mode choices made for previous trips in the tour (e.g., If public transport was used for the first trip in the tour, mode car will not be available for subsequent trips in the tour, as it would still be at home). Mode and destination choice are done sequentially for each member of the household to take car ownership and availability into consideration. This means that the same chain can in different modes result in entirely different locations. For example, a shopping chain could by foot be directed to a small local store, by public transport with good radial connections to the city centre, and by car to a mall across town.

To choose one of the alternative realizations and thus a mode, the mode choice model considers attributes of the trips and endpoints in the chain as well as the person's demographic and socio-economic characteristics as explanatory variables. For each of these explanatory variables a parameter is estimated. Similarly, as in the destination choice model the estimation of these parameters is done using log-likelihood minimization on survey data. The mode choice utility V for mode i is of the form:

$$V_i = \beta_{i_0} + \beta_{i_1} x_{i_1} + \beta_{i_2} x_{i_2} + \cdots$$

Where β_{i_0} Is the mode specific constant and β_{i_k} Is the sensitivity for attributes comprising the destination choice. Common attributes in the mode choice model are amongst others the total travel time weight for a chain, car ownership, amount of socio-economic activity at the endpoint. Furthermore, the model includes the destination choice logsum for the chain.

[9] For a detailed analysis of sampling of alternatives and its implications, see Moshe Ben-Akiva and Steven R. Lerman. Discrete Choice Analysis. Theory and Application to Travel Demand. The MIT Press, 1985

For this study, the alternative-specific constants of each travel mode of the donor model were adjusted so that the modelled mode shares match the ones observed in the RVU 2021.

3.3.3 Tour simulations

During simulation, one household, one person, one trip chain and one mode are iterated at a time. The destination choice model is used sequentially according to the trip chain handling logic, producing trip endpoint locations and trip travel weights for each mode. When those locations are known, the simulation proceeds to calculate summaries required by the mode choice model for each chain and each mode.

Mode choice is done for one household at a time to be able to account for the households' car ownership. Car ownership is only assumed to affect "main chains", which are work or school chains that have a duration of over five hours. This means an assumption that for evening leisure activities people would adjust their departure times so that a car is available for whoever needs it. As the current version of Brutus model does not adjust departure times, the same car can be used by multiple household members on non-main chains at the same time. Mode choice begins from the main chain of the person with the highest selection probability to use a car, i.e., the person who needs a car the most, gets to choose first. If a car is chosen, then one car is marked as reserved and if no cars are left free, cars are removed from the alternatives of remaining unresolved main chains. After car use has been controlled for main chains, all other chains can be resolved independent of each other. Repeating these steps for all trip chains, all people and all households, the model produces a result trip table with each trip of every one of the sampled populations in a table very similar to travel survey data, but with a desired sample size. Usually after estimating a model, looking at validation results and making corrections to it, some significant deviations from reality will remain. Commonly, the urban vs. Rural balance in mode choice and trip lengths can be off due to various factors that the model does not and maybe even cannot account for. As a final step, correction factors are calculated based on comparing simulation results with the travel survey. Commonly these correction factors are calculated by fixing the total amount of trips by mode and endpoint municipalities. Those same correction factors are then applied the same way in all scenarios by adjusting expansion factors of individual trips.

3.3.4 Supply modelling

Brutus' assignment is relatively simple for most modes compared to assignment algorithms available in certain aggregate modelling solutions. Except for cycling, all traffic chooses the route with the lowest impedance. Impedance is calculated based on generalised cost of the route, expressed in time units. To convert cost units to time units and adapt the impedances to the Norwegian prices, the value of time (VOT) was calculated using the purchasing power parities (PPP)[10] between Finland (the country of the donor model) and Norway. For public transport the generalised cost includes weights reflecting perception of transfer and access / egress time compared with in-vehicle time.

During the assignment step, there is no interaction on the network between decision makers.

[10] OECD 2023, accessed at: https://data.oecd.org/conversion/purchasing-power-parities-ppp.htm

Pedestrian
The pedestrian network shares the same geometry as the bicycle network. Demand is assigned by routing each trip based on the lowest impedance route following Dijkstra's shortest path algorithm. All speeds are assumed to be 4.4 km/hr at roads that have some sort of facilities for cyclists. Other roads such as roads for cars, or roads which have a walkway in parallel get assigned a lower speed (2.2 km/hr).

Bicycle
The bicycle network is based on OpenStreetMap. Various quality aspects are considered to determine the link impedance, such as slope, pavement, and facilities for cyclists. Nuisance for cyclists is also incorporated through intersection delays) and hindrance of cars on the roads based on traffic volumes on links (which are both determined based on a simple a-priori car traffic assignment. The bicycle network has been validated based on the ATP network, provided by the client, as presented in chapter *3.3.1 Input data and tools*.

Each cycling trip is assigned on one of three best routes using a path-sized logit model, to consider the preferences of different cyclists. However, no person characteristics are considered in choosing the route.

Public transport
The public transport network consists of transport lines and the earlier conducted pedestrian network. Walking is in all cases assumed to be the auxiliary mode and is a direct copy of the earlier described pedestrian network. Headways and in-vehicle times are extracted from the RTM network.

Trips are assigned to the lowest impedance route. Costs are not considered when choosing the route (only the destination). Travel impedance is based on travel time, plus various waiting, boarding and in-vehicle penalties and travel time weights.

Car
All trips by cars are assigned to the destination with lowest impedance. Impedance is built up based on travel time. For this Brutus implementation, cost is not affecting route choice due to absence of a feature in Brutus to restrict certain turns. Travel times on link level are transferred from RTM to account for congestion. Currently, no different time-of-day travel times are considered. However, it is possible to use different travel times on link level for different day times.

Technical Implementation
The Brutus model is implemented as interdependent packages for the R programming language and statistical environment. R is used for data preparation, model estimation, model runs and analysis of results. The workflow is orchestrated with a tool called Snakemake. The model runs on a Linux Virtual Machine in the cloud. Brutus has no graphical interface for model estimation or for running it is seen as an in-house tool to be used by modelling experts. Input and output, however, are very open and flexible. Network and land use editing can be easily done with usual GIS tools (e.g., Arcgis, mapinfo or QGIS) and imported into Brutus. Likewise, network results (traffic volumes etc.) Can be easily exported into any usual GIS format or interactive zoomable web maps, which are viewable without any special software required. A web application has been

developed to allow browsing and analysing modelling results interactively. It is based on individual-level results residing on the server, which are aggregated based on input from the user – e.g. A select link analysis that aggregates volumes of individual trips that pass through a chosen link. See figures 2–4 for examples of input and output interfaces.

3.4 Base line results and validation

The base line results are compared and validated against the RVU travel survey and traffic counts.

3.4.1 Comparison with survey

Mode share and number of trips

The baseline scenario (2022) results produced by the Brutus simulation model are close to the ones calculated from the RVU (2021). The total number of trips differ by around 1%. The number of pedestrian trips is overestimated by the model by around 5%, while the number of car trips is underestimated by 5% for drivers and 3% for passengers, compared with the RVU values (Table 6: Number of trips per mode and mode share validation).

Table 6: Number of trips per mode and mode share validation

Transport mode	Number of trips		Shares	
	Survey	**Baseline simulation (2022)**	**Survey**	**Baseline simulation (2022)**
Pedestrian	190 944	201 527	29.33 %	31.33 %
Bicycle	42 501	40 832	6.53 %	6.35 %
Public Transport	60 395	60 219	9.28 %	9.36 %
Car driver	283 011	269 693	43.48 %	41.92 %
Car passenger	73 082	71 054	11.23 %	11.04 %
Total	*650 956*	*643 326*		

Trips lengths

Comparison between the length distributions of the trips simulated by the model and calculated from the survey show relatively good fit as well, with some exceptions for shorter trips for most modes and underestimation of trip length for public transport (Figure 17). For shorter trips (with the crow-fly distance between the trip endpoints being below 250 meters), Brutus substantially underestimates walking, and overestimates car trips. For the public transport trips, Brutus overestimates them for the distance below 2 km. For shorter trips by bicycle and walking the discrepancies can be, at least partially, explained by the difficulties of measuring the true distance. For the public transport further investigation is needed. Estimation of the choice models based on the local survey data potentially can help to reduce such discrepancies in future. Some correction factors can be also potentially calculated and applied in all scenarios by adjusting expansion factors of individual trips. This is however not done in this application currently.

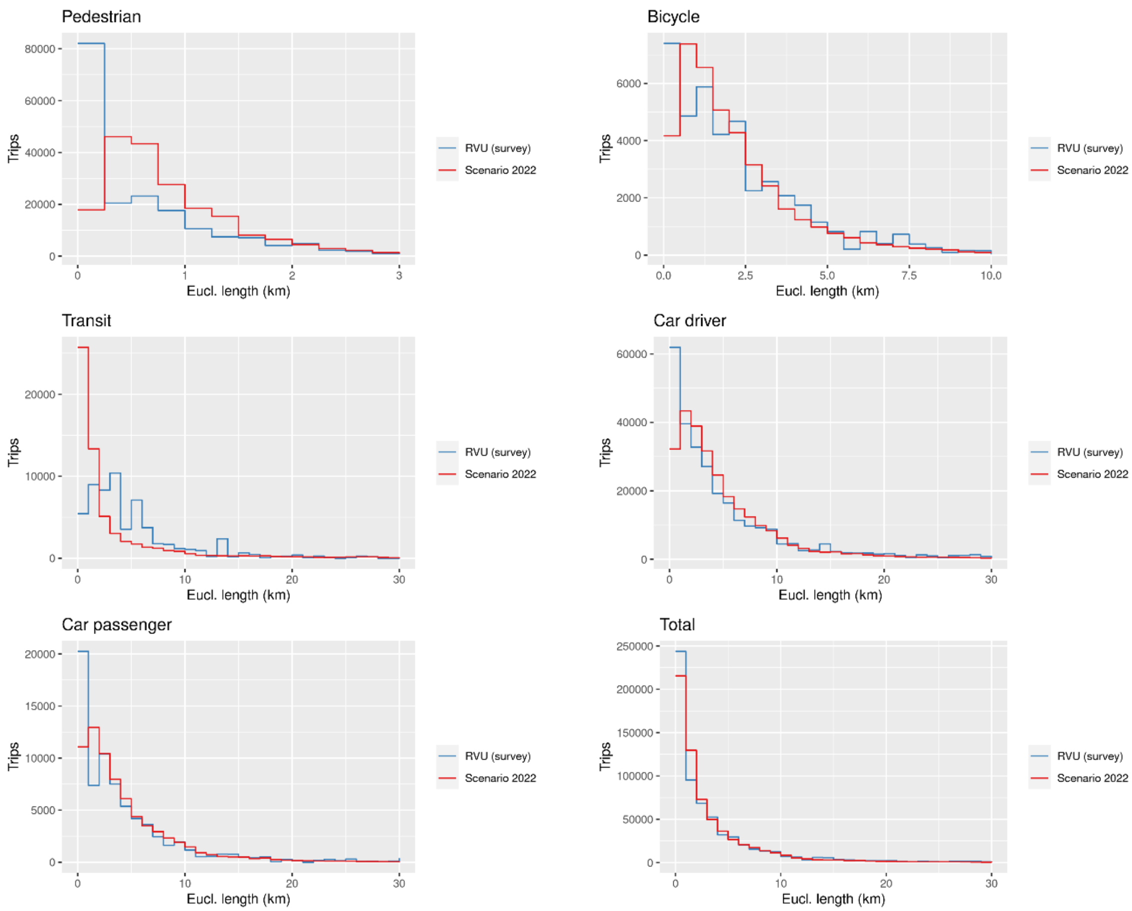
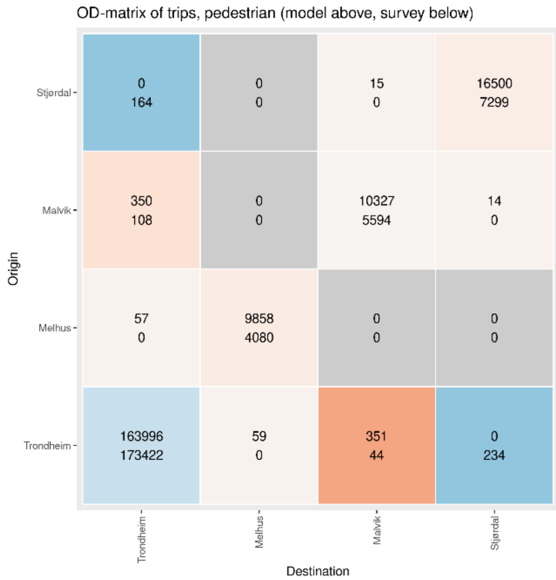
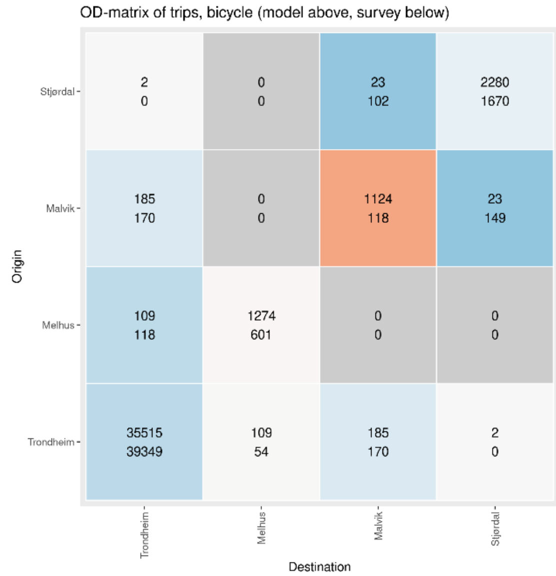


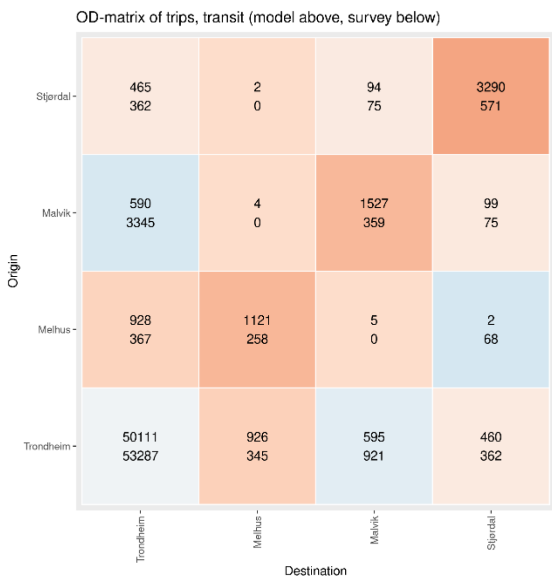
Figure 17: Trip length distributions in the model compared to the survey. NB., x-axis is scaled differently according for each mode.

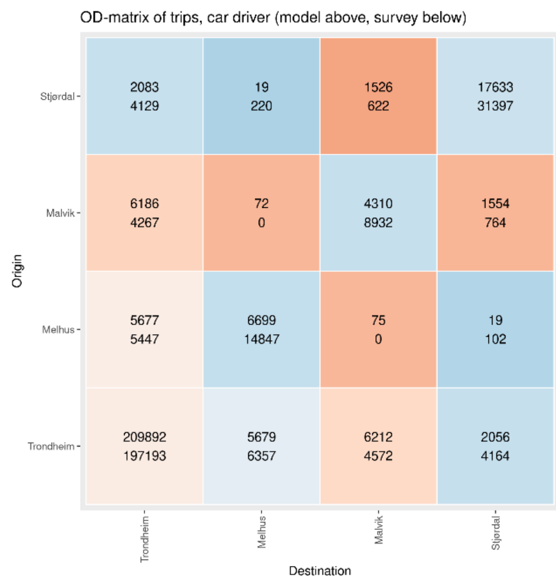
Traffic flows between origins and destinations

Comparison of the traffic flows between the four municipalities comprising the study area generated by Brutus and the ones computed from the RVU (2021) show substantial discrepancies for the intra-municipality flows, if analysed be different modes. For example, Brutus overestimates significantly (approximately twice) pedestrian intra-municipality trips in Malvik, Melhus, and Stjørdal, and underestimates the ones within Trondheim, while for driving a car it is the opposite. This pattern can be perhaps explained by the fact that short trips could be underreported in smaller municipalities. Additionally, in Trondheim Brutus does not distinguish students, which could result in underestimating pedestrian trips. Comparison of the flows for all modes do not show such pattern, and the totals seem to balance more across the modes and OD pairs. If calculating the percentage of deviations compared with the survey data, the largest deviations can be observed for the smaller zones and modes with smaller modal shares. For such cases the survey might not be necessarily a very good representation of the reality due to relatively small number of observations or even no observations. Such combinations can also be less important from policy scenario testing perspective at the level of the entire study area.


OD-matrix of trips, pedestrian (model above, survey below)
Origin
Stjørdal
Malvik
Melhus
Trondheim
Destination
Trondheim
Melhus
Malvik
Stjørdal
0 164
0 0
15 0
16500 7299
350 108
0 0
10327 5594
14 0
57 0
9858 4080
0 0
0 0
163996 173422
59 0
351 44
0 234


OD-matrix of trips, bicycle (model above, survey below)
Origin
Stjørdal
Malvik
Melhus
Trondheim
Destination
Trondheim
Melhus
Malvik
Stjørdal
2 0
0 0
23 102
2280 1670
185 170
0 0
1124 118
23 149
109 118
1274 601
0 0
0 0
35515 39349
109 54
185 170
2 0


OD-matrix of trips, transit (model above, survey below)
Origin
Stjørdal
Malvik
Melhus
Trondheim
Destination
Trondheim
Melhus
Malvik
Stjørdal
465 362
2 0
94 75
3290 571
590 3345
4 0
1527 359
99 75
928 367
1121 258
5 0
2 68
50111 53287
926 345
595 921
460 362


OD-matrix of trips, car driver (model above, survey below)
Origin
Stjørdal
Malvik
Melhus
Trondheim
Destination
Trondheim
Melhus
Malvik
Stjørdal
2083 4129
19 220
1526 622
17633 31397
6186 4267
72 0
4310 8932
1554 764
5677 5447
6699 14847
75 0
19 102
209892 197193
5679 6357
6212 4572
2056 4164

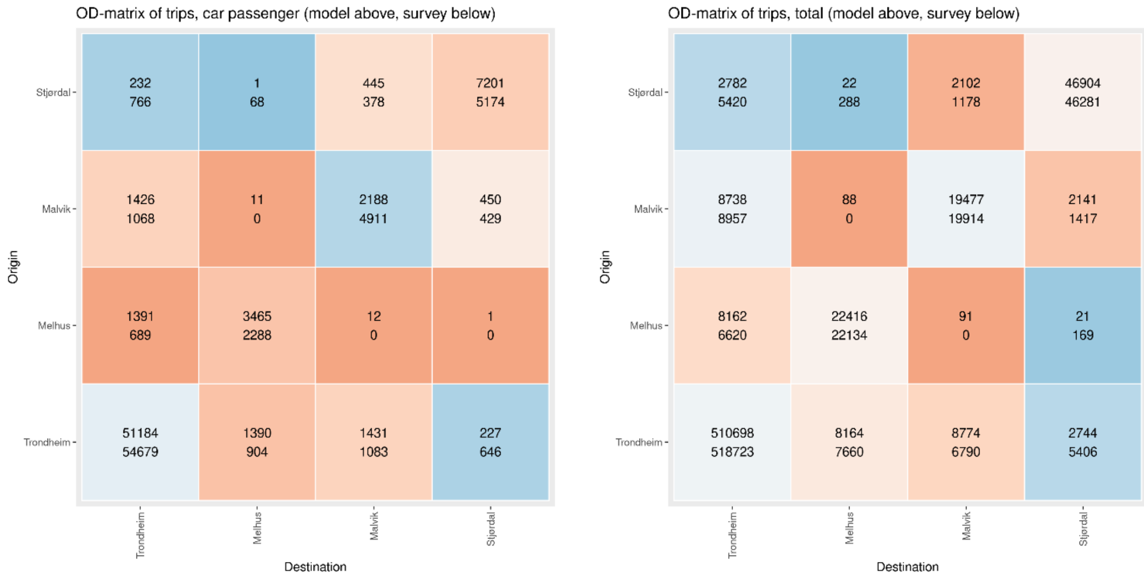


Figure 18: OD-matrices for different modes and mode totals (mode above, survey below)

3.4.2 Comparison with counts

Counts for motorized and bicycle traffic are derived from Statens Vegvesen's Trafik Data API[11]. Daily volumes for 22nd of May 2022 are used to compare against the scenario results.

<u>Bicycle counts</u>

Six count locations were available in the model region (Table 7). For some count locations, the values counted seem to deviate from the simulated values:

- Svingbrua (simulated 175 vs. 681 counted): This route is expected to be popular for environmental features. This is not addressed in the route choice. In addition, Brutus models functional traffic only (i.e., traffic to a destination to undertake an activity) and recreational trips are not considered. Such traffic can be significant on scenic routes. The network should be adjusted to account for such trips, as well as the final flows can be adjusted to match the counts.
- Rotvollekra (simulated 826 vs. 248 counted): The model simulates too high volumes there. A possible explanation is that the model simulates too few cyclists on the Ranheimsvegen (~ 270 daily cyclists). This route might be more attractive than the model considers. Despite lack of cycling facilities this route can be still attractive because of scenario and low car volumes.

All other counts are conducted at areas with a low number of values. These volumes are considered too small to drive any conclusions on deviation with the simulated results.

Table 7: Comparison of simulated volumes against count values for cycling traffic.

Count location	Simulated volume	Counted volume
Svingbrua - sykkel	175	681
Pirbrua sykkel - sørsiden	69	92

[11] https://www.vegvesen.no/trafikkdata/start/om-api

Moholt ved skiundergangen	661	589
Sandskogan fortau	53	36
Værnestunnelen - sykkeltavle	112	174
Rotvollekra - sykkel	826	248

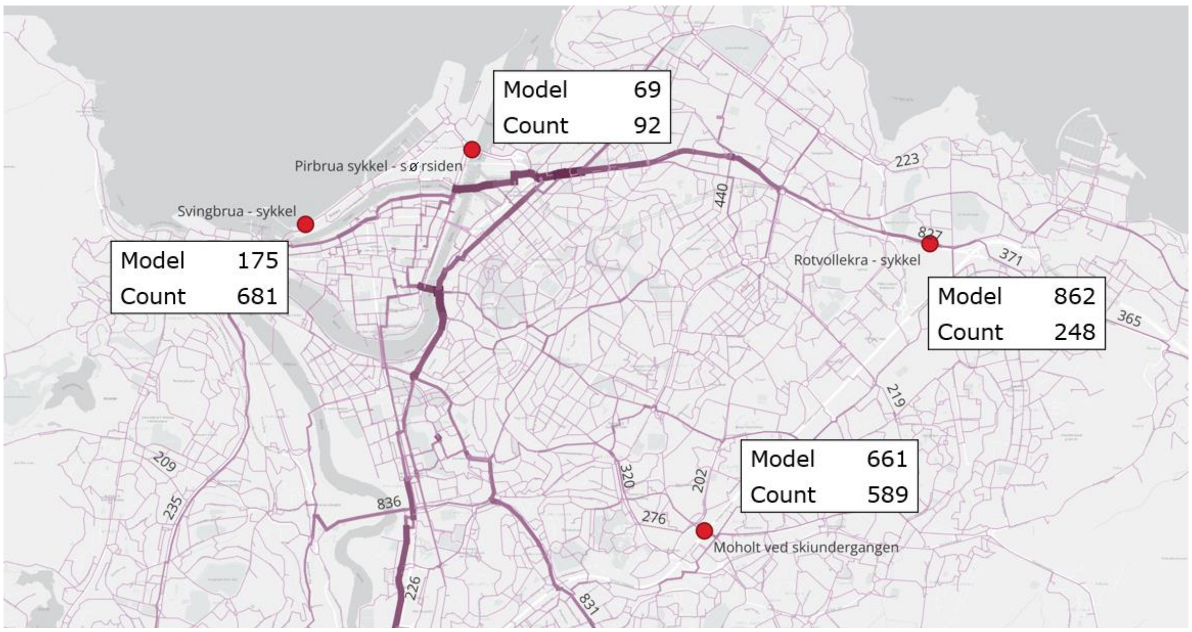


Figure 19: Bicycle flows for the base line scenario

<u>Motorised traffic counts</u>

Many counts are available for motorised traffic. The model results have been compared to a selection of counts (Figure 20) to give a representative overview of the accuracy around Trondheim. Count locations close to the edge of the study area are not considered (except for the Storlersbakken, see below). In those locations the counts deviate strongly from the simulated flows as car traffic with one or two endpoints outside the study are not included.

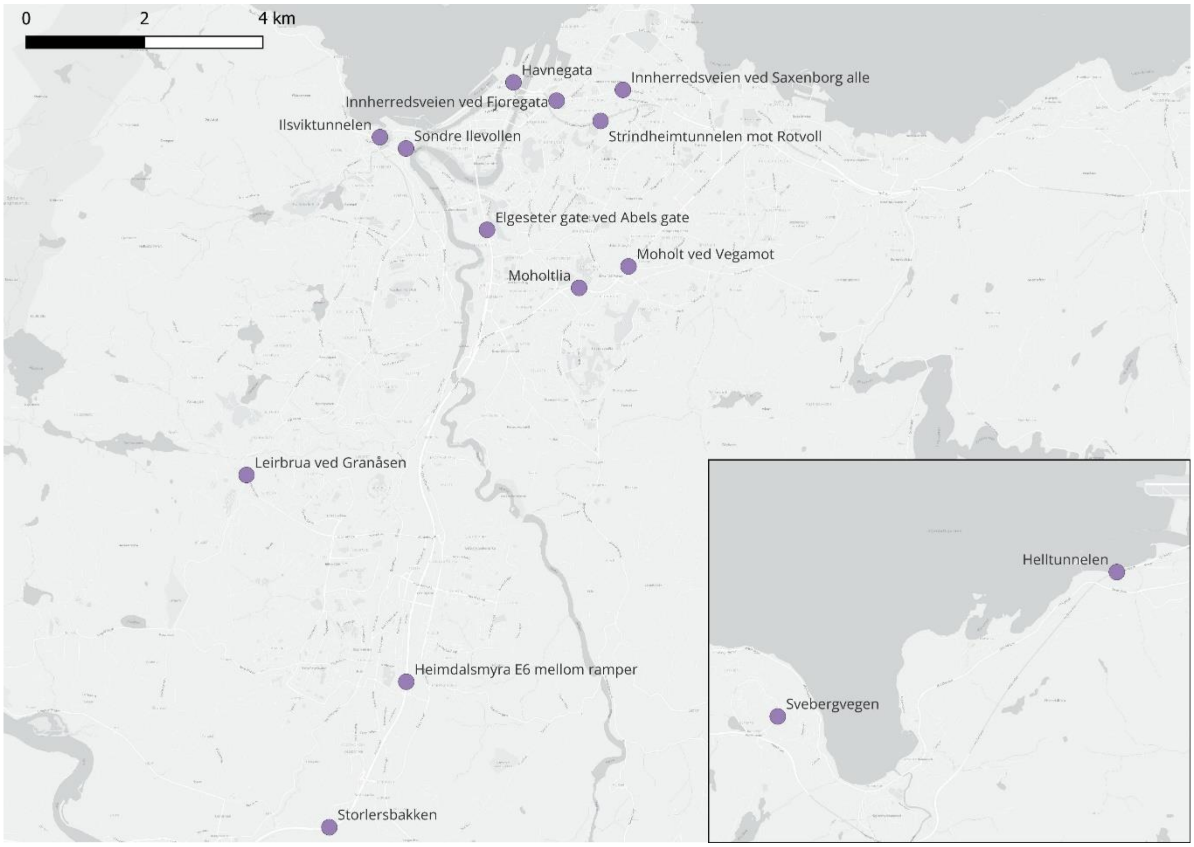


Figure 20: Locations of the selected car counters.

When analysing the counts, one can see that the order of magnitude of simulated traffic is in line with most the count values (Figure 21). Yet, for a few locations the deviation can be considered significant:

- Søndre Ilevollen – Ilsviktunnelen - Havnegata: We observe that car traffic in the model prefers crossing the Trondheim centre east west through the city centre (past Søndre Ilevollen) while in observed traffic may prefer the Ilsviktunnelen – Havengata.
- Strorlersbakken - Heimdalsmyra E6 mellom ramper: Both count locations are closer towards the model edge. One can see here the effect of only modelling traffic in the study area and not consider external traffic.
- Elgeseter gate ved Abels gate: Simulated traffic flows on this road section are higher than the counts show. An explanation may be in the overall nature of the routing methodology: Assigning all car traffic to the shortest path may lead to more concentrated flows on certain arterial roads.

The mismatch can be reduced if more time is invested on detailing the network and junctions. These improvements were beyond the scope of this pilot project and can be potentially implemented in future.

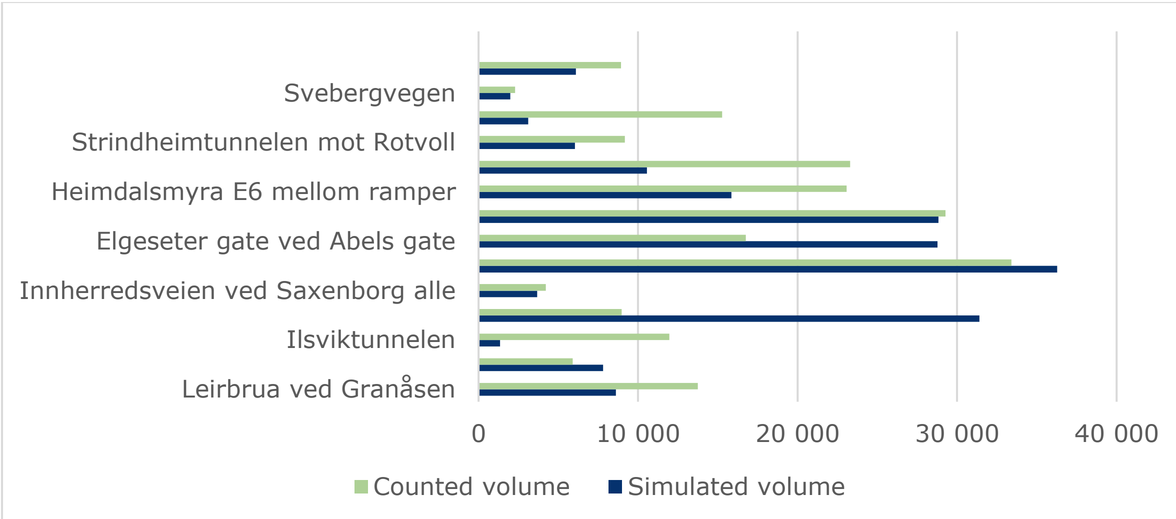


Figure 21: Comparison of simulated volumes against count values for car traffic

4. Modelling policy scenarios

Transport authorities globally are seeking to increase participation in cycling. Increased mode share of cycling leads to substantial gains for society, especially in the field in public health. Shift from motorised modes to cycling leads to reduced road congestion and pollution and help to achieve decarbonisation goals. Therefore, knowing the cycling mode share under various transport system configurations and policy scenarios is important for the authorities, the investors, and the users. The policy scenarios may include measures to promote cycling and to restrict car use. More specifically, the measures can include improvement of cycling infrastructure, intramodality facilitation, regulatory measures, and economic incentives to promote cycling and restrict car use in space and time, direct travel demand management.

As Chapter 2 describes, aggregated four-step models have limited power to reflect shorter trips such as the ones by cycle. Besides the low spatial resolution resulting in many cycling trips being intra-zonal, the RTM model captures the modal shift only if that is due to the distance reduction. Infrastructure and safety improvements or changes in costs of different modes are not reflected.

This chapter presents scenarios with different transport policy measures related to cycling promotion and car restrictions, considering forecast for 2030 (Figure 22). The scenarios are designed to test the performance of the Brutus model in terms of its ability to capture the effect of such policy measures, and, therefore, serving as a modelling tool for the related cost-benefit analysis.

2030 forecast year

New housing development in Nyhavn.

Implementation of population forecast with new synthetic population.

Cycle highway

Connecting east of city with city centre.

Bicycle highway implementation into the base bicycle network.

Bicycle bridge

New connection between Hoem and Tempe.

New connection, intended to save travel times between two neighbourhoods.

Higher driving costs

Increase of kilometre price by 50%.

Scenario to study the sensitivity of the model to reduce car usage in favour of cycling.

Figure 22: variations in the scenarios

The chapter covers both the scenario design and how it is reflected in Brutus.

4.1 Scenario 1: Cycling highway

This scenario implies implementation of major cycling infrastructure improvement: a cycling highway, which is an expressway connecting the city centre and the east part of the city (Figure 23). The alignment is implemented as described on the miljøpakken web page[12].

[12] https://miljopakken.no/prosjekter/sykkelforbindelse-pirbrua-ranheim (accessed 24.03.2023)

Figure 23: Implemented alignment for the cycling highway

Cyclists will have no level crossings or intersections with users of other transport modes. The connection starts in the east at the roundabout of the Falkenborgvegen/Gildensbrua and extends to the Skippergata along the rail tracks. Cyclists can also access the cycle highway from the Strandveien, Gregus gate, Biskop Darresgate, Anders Buens gate, Nidarholms gate, Ladeveien, Thoning Owessons gate and Bromstadvegen.

The physical design of the cycleway is limited to a maximum inclination of 5% and is designed for high speeds.

In the model, the bridge is implemented as a cycle highway into the baseline bicycle network. Cycle highways are characterised by high quality and get assigned a higher speed than other bicycle infrastructure (20 km/hr plus speed adjustments because of slopes, versus 18 km/hr for normal designated bicycle infrastructure). Slopes are also limited. Rather than the 5 % as described in the design, we follow a maximum slope of 2 %. We do this to account for possible irregularities in the elevation data.

The implemented link leads to (perceived) travel time savings, leading potentially to higher cycling shares between certain areas and to different route choices.

These characteristics mean that the users of the cycling highway will benefit from increased speed, travel time savings and improved safety. The safety level improvements cannot be reflected in the current version of Brutus, mainly due to the lack of data. A stated preference survey with choice situations reflecting safety improvements and other perception variables could help to model that in future.

The simulation shows that the bicycle highway attracts around 1 000 cyclists (Figure 24). Traffic flows on the Innherredsveien decreases from 1 500 daily cyclists to around 1 000 too. Which suggests that the cycling highway provides a viable alternative for several cyclists.

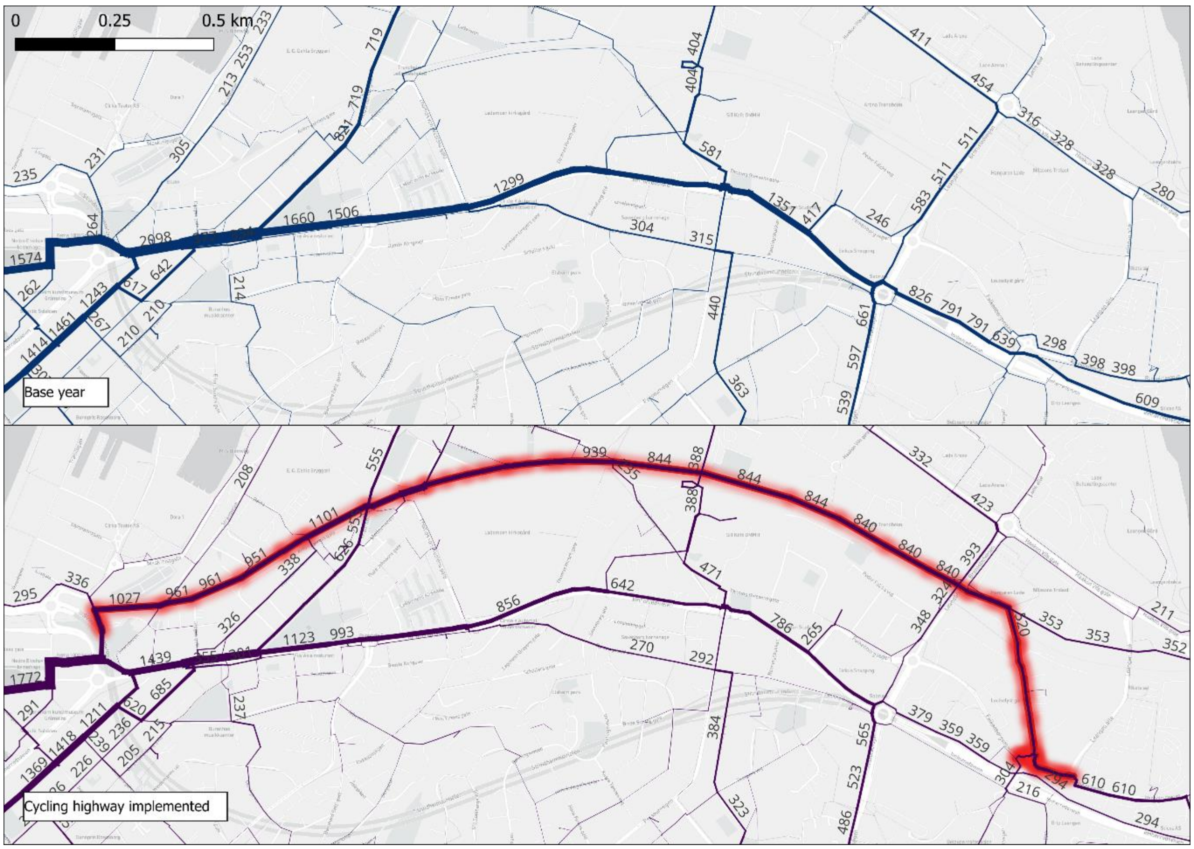


Figure 24: Bicycle volumes on the new cycling highway and surrounding (below) compared to the baseline scenario (above). New cycling highway highlighted in red.

When considering mode shift towards cycling, a small effect can be observed (Table 8). It relates to an increase 500 daily cyclists. The result seems to be reasonable as one bike-link cannot change the mode share substantially for the entire city, rather it changes the shares in the part of the city where it is added. This is also conditioned by relatively short distances of bike trips. At the same time, if a new network in the entire city was modelled, it would be possible to see more significant effect on the mode share. Increased price for car use, which would affect the entire city, therefore, would maybe have more effects.

Table 8: Mode share comparison between the baseline and scenario 1

Mode share	Baseline simulation (2022)	Cycling highway simulation (2022)
Pedestrian	31.33 %	31.24%
Bicycle	6.35 %	6.43%
Public Transport	9.36 %	9.36%
Car driver	41.92 %	41.94%
Car passenger	11.04 %	11.03%

In terms of travel-time savings the cycling highway has little effect, leading mostly to a maximum weighted travel time saving of 1 minute (Figure 25).

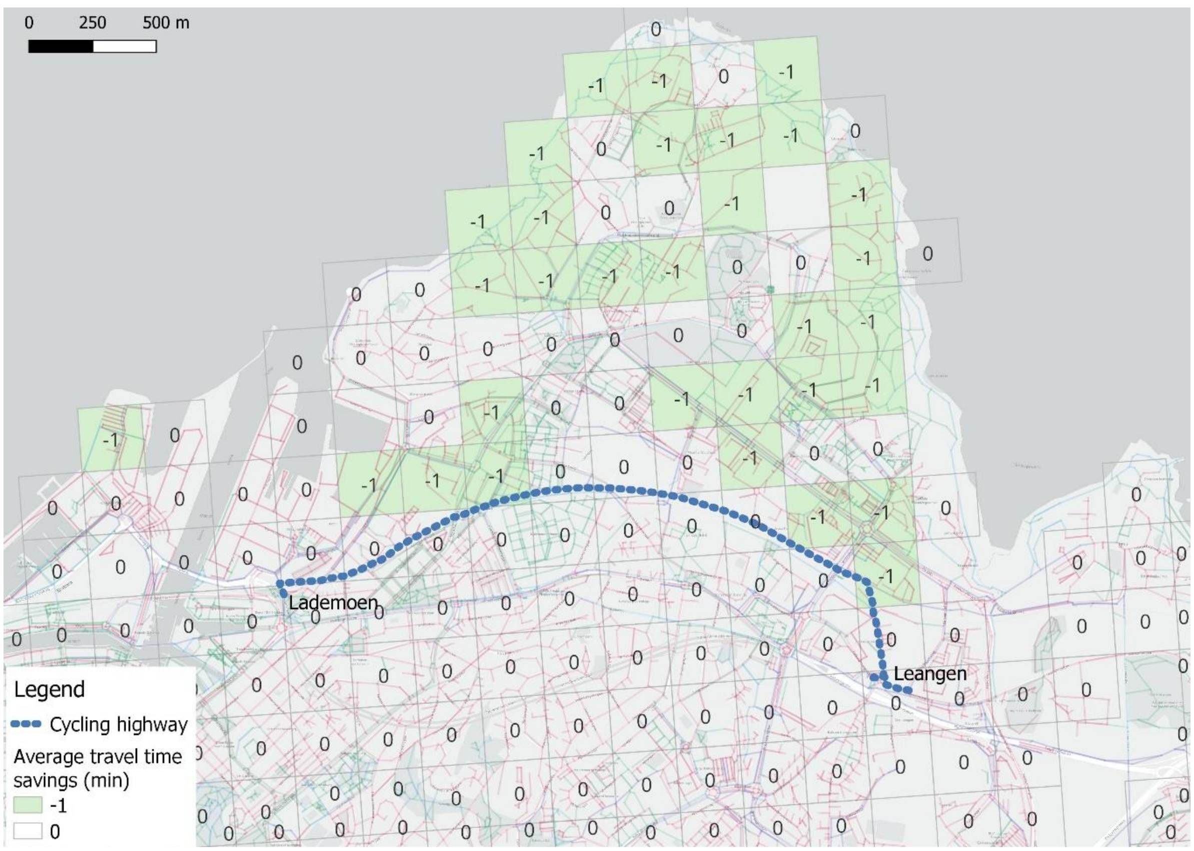


Figure 25: Average travel time savings for travellers from grid cells, scenario 1

4.2 Scenario 2: Change of strategic land-use planning (2030 population forecast)

This scenario assumes change in the population of the model area between the baseline and 2030. Input for the changes are the prognoses in ADV. A significant change is the new housing development in the former industrial area northeast of the city centre of Trondheim.
These population changes are also visualised in Figure 5. In this simulation demand is simulated with the 2030 population. No changes in employment, services or economy are assumed.

Table 9: Number of trips per day, baseline, and scenario 2

Number of trips	Baseline simulation (2022)	Forecast year simulation (2030)
Pedestrian	201 527	228 901
Bicycle	40 832	46 838
Public Transport	60 219	66 953
Car driver	269 693	291 410
Car passenger	71 054	75 076
Total	*643 326*	*709 177*

Table 10: Mode share comparison between the baseline and scenario 2

Mode share	Baseline simulation (2022)	Forecast year simulation (2030)
Pedestrian	31.33 %	32.28%
Bicycle	6.35 %	6.60%
Public Transport	9.36 %	9.44%
Car driver	41.92 %	41.09%
Car passenger	11.04 %	10.59%

Results show that there is an increase in the total number of trips (Table 9). Mode share changes slightly (Table 10). This can all be explained by the change in population. The population in 2030 has a higher share of people in the older age groups (see also Table 3).

Carbon emissions are also calculated for each scenario. It is calculated that the emissions go down from 198 465 to 178 605 tons[13], that is, by around 10%.

[13] Figure includes transformation of the vehicle fleet to cleaner vehicles. Figures based on LIPASTO database by VTT (http://lipasto.vtt.fi/en/).

4.3 Scenario 3: Cycling highway in 2030

This scenario is a combination of scenario 1 and scenario 2. Significant land-use development occurs in proximity of the cycling highway. The effect of the population changes is therefore of interest for future usage of the cycling highway of scenario 1.

Figure 26: Cycling flows at the cycling highway in 2022 and 2030.

The result shows that cycling flows increase somewhat, especially on the west stretch of the cycling highway.

4.4 Scenario 4: Cycling and pedestrian bridge

In this scenario, a cycling bridge and connecting infrastructure is implemented to connect the Hoem and Tempe / Sluppen area (Figure 26).

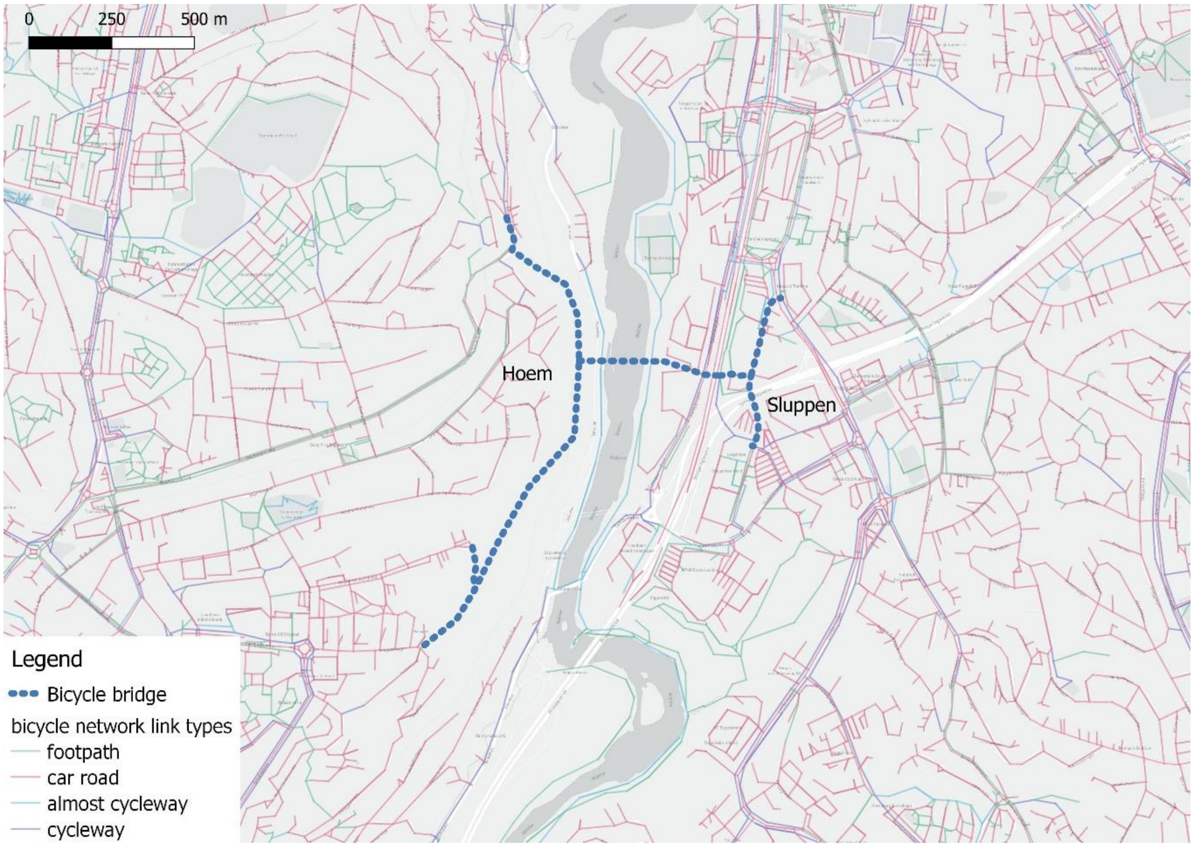


Figure 27: Implemented alignment of the cycling bridge and surrounding connecting infrastructure

The bridge and connecting infrastructure are implemented as high quality cycling infrastructure but not as cycling highway. Speeds are (excluding speed modifiers through slopes) set to 18 km/hr. In the west, a new cycling path branches out from the Bøckmans veg to the new bridge. In the east, the bridge extends into high quality cycling infrastructure across the Tempevegen. The bridge is assumed to be accessible for pedestrians too.

Figure 28 shows a side-by-side comparison of the simulated bicycle flows in the base scenario with the bridge and in the scenario with the bridge. The map shows that the bridge attracts almost 1 000 daily cyclists. The average travel time savings are more substantial than in case of scenario 1 (cycling highway), being up to 8 minutes for travellers departing from the grids located to the West from the bridge (Figure 29).

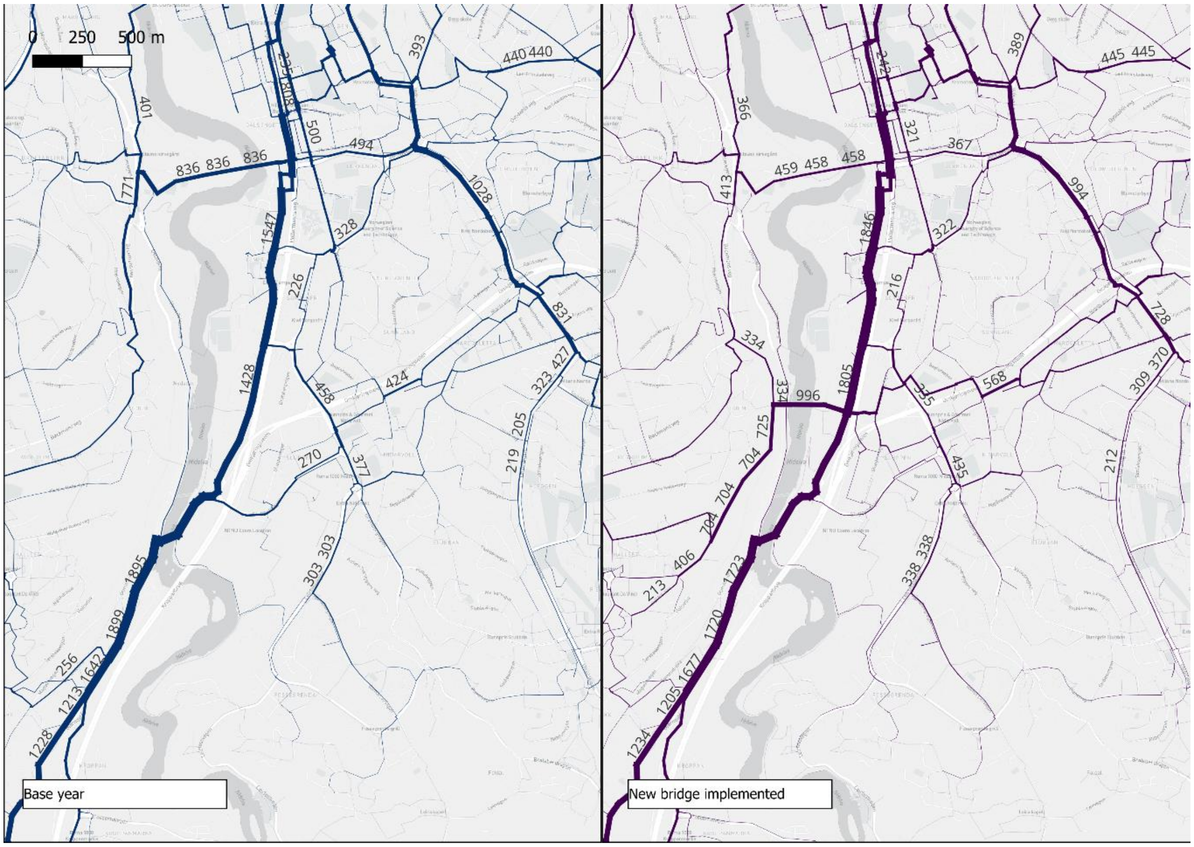


Figure 28: Simulated bicycle flows in the baseline and the scenario with the new bridge implemented.

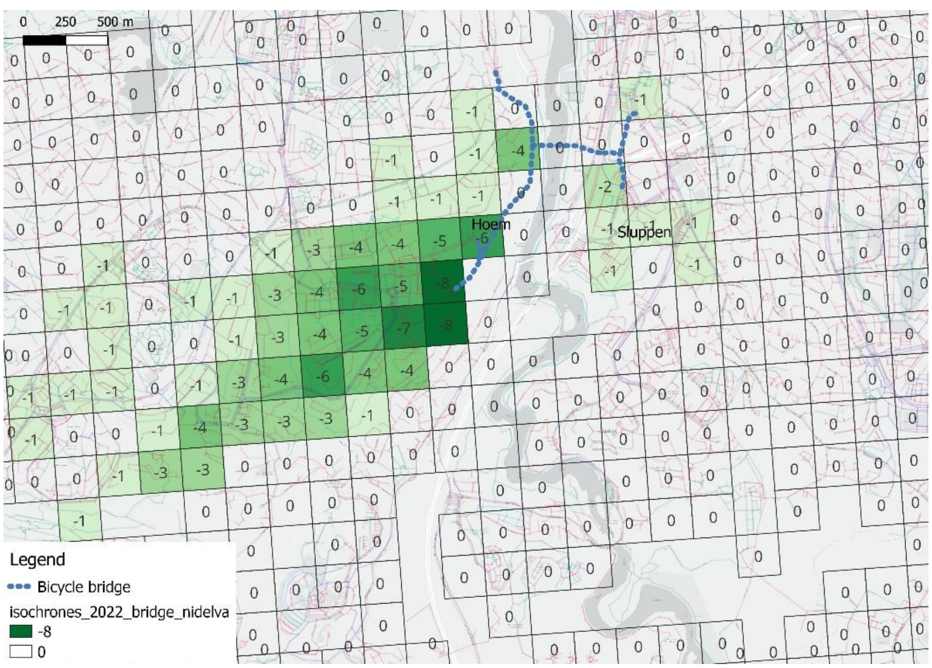


Figure 29: Average travel time savings for travellers from grid cells, scenario 4

4.5 Scenario 5: High costs of driving a car

This scenario is implemented to understand how discouraging car usage would lead to more sustainable travel behaviour. Therefore, we increased the kilometre cost of driving a car by 50 percent.

The model shows almost no decrease in car usage for the total number of trips and in mode share (Table 11). This could be because the car users' demand is quite inelastic. However, the average length of a ride by car goes down (Table 12Table 12) and so do emissions from car traffic (from 191 270 to 175 185 tons, that is by 9.5%).

Table 11: Number of trips per day, baseline, and scenario 5

Mode share	Baseline simulation (2022)	Simulation with 50 percent driving costs increase (2022)
Pedestrian	31.33 %	31.59%
Bicycle	6.35 %	6.41%
Public Transport	9.36 %	9.33%
Car driver	41.92 %	41.42%
Car passenger	11.04 %	11.24%

Table 12 Average trip length for baseline scenario and Scenario 5

Trip length	Baseline simulation (2022)	Simulation with 50 percent driving costs increase (2022)
Pedestrian	1.23 km	1.23 km
Bicycle	3.03 km	3.03 km
Public Transport	4.68 km	4.61 km
Car driver	7.65 km	7.06 km
Car passenger	6.71 km	5.96 km
Total	4.96 km	4.61 km

5. Discussion, next steps

The model developed is a pilot model, aiming to show the capabilities of activity-based models on an urban scale, focused on cycling. The model is built using the highest spatial resolution. The model has been calibrated for mode share. No tailored choice models have been estimated. Rather, choice models are transferred from a donor model (Turku, Finland). No time is spent on calibrating results on link level.

The model performs reasonably well. Mode share in the model is in line with survey results. Trip length distribution of bicycle trips and car traffic is also in line with the survey. Walking trips are longer than in the survey. Trip length distributions of public transport has room for improvement too.

The model is a full activity-based model, using discrete choice models and Monte Carlo sampling to generate results. The model could be further developed on the following topics:

5.1 Improvements of the data

5.1.1 Land-use

Spatial resolution
Various data processing steps have been done to increase the spatial resolution of various sources, mostly on grunnkrets level to the spatial grid. Assumptions were needed for example to distribute job types or age distributions from larger zonal areas to the grid. This approach proves feasible but may lack accuracy compared to the actual situation in the model area. Providing all model land-use input data on statistical grid level would improve the accuracy of spatial representation and the synthetic population too. The model building process would also become simpler. Naturally, higher spatial resolution data may come with privacy considerations, which should be covered in a data processing agreement.

Household composition data
An important step in the synthetic population generation is the grouping of decision makers into households. Information on household level sizes is important. For this pilot project, only household size information was available on person level rather than households. The number of children was not specified either, leading probably to an underestimation of household size.

Land-use forecast data
The ADV 2030 prognosis was used for the future population. This proved to be inconsistent with the status in 2022 (SSB data). An updated ADV prognosis would make the 2030 scenario in Brutus more useful for deriving conclusions in comparison with the baseline scenario. Having the prognosis data on the SSB grid level, which matches the Brutus model grid, would also help to improve the forecast.

5.1.2 Survey

Endpoint accuracy
The survey provides grunnkrets-level endpoint accuracy. For the pilot with the donor model this was no significant problem. The only drawback is in the validation of trip lengths. The trip lengths derived from the survey may not be as accurate as the trip lengths the model produced from gird cell to grid cell. Having a more detailed endpoint accuracy would enable better validation.

For the case of model estimation, higher endpoint accuracy would be of value as trip lengths are more accurate and attraction variables can be better matched to the destination choice.

Time resolution
The current version of the travel survey has all trip timestamps registered on an hourly basis. This does not allow to model very realistically the demand distribution during the day, and, consequently, the traffic flows.

Surveying entire households
Performing household travel survey rather than an individual one would allow to account for household interactions and model better, for example, car passenger trips, "kiss and ride" options, etc.

Increase of the sample size
Activity- and agent-based models account for various combinations of activities, destinations, modes, time of the day, socio-demographic variables. Large number of variables used lead to large number of their combinations and, therefore, to be able to model such trips, larger survey sample is needed. On the other hand, "rare" combinations usually do not significantly affect the results of the transport policy appraisal. Therefore, a balance between the desired model precision, statistical confidence and cost of data collection should be found. The required sample size can be mathematically calculated based on the given the margin of error to be attained and confidence level, number of model variables and their order of magnitude, anticipated non-response rate, etc.

Stated preference regarding attitudes to changing modes and additional mode attributes
The scenario simulations show that people do not easily shift between modes. This is in part in line with the expectations. Travel time improvements of several minutes do not lead to large changes in mode preferences and usage. However, cycling interventions may in the future improve also cycling culture. Cycling culture can entice people to use the bike for other reasons than captured currently in the travel impedance and mode choice models. Having stated preference survey data on attitudes towards cycling may in that case increase the predictive value of the model. Collecting stated preference data can be especially beneficial if any new travel modes are considered in the city (e.g., shared modes) and / or significant changes of the existing modes are planned (e.g., increased safety of cycling routes).

5.1.3 Network
The RTM network was very suitable in this pilot, with the only drawback that the existing road toll for cars could not be successfully modelled. In part this is due to Brutus' inability to restrict certain turns on the network. However, if network geometry would be more accurate this may not have been such a problem: if the highway roads in opposite directions would not be drawn on top of each other but as separate drive lanes (as they are in reality). That is, the turn penalties should be "decoded" as one-directional links in the network.

5.2 Improvements to Brutus

5.2.1 More policy measures

The methodology can be further developed to enhance predictive value. Below are some relevant developments which increase the number of different policy measures that can be evaluated with the model.

1. Incorporate scenic factors in travel impedance and route choice models for walking and cycling.
2. Model mode choice to and from public transport stations. Currently, all access and egress modes in the model are walking. Implementing a feature to model the access and egress mode enhances predictive value, for example on the topic of bicycle parking at hubs.
3. Adapt the model for on-demand and shared mobility modelling. This would require expanding the model with an on-demand module or feed the results into an external tool such as the VISUM on-demand modeller.
4. Modelling of Park-and-ride: Currently, intermodal trips are not supported (except walking plus public transport). Park-and-ride and nowadays mobility hubs are popular concepts to make transport more sustainable.
5. Modelling of vehicle type would allow for considering for example electric vehicles. Emission classes could be considered too. This would be helpful for more accurately modelling emissions for example or for planning of EV charging infrastructure. Also, connecting a synthetic population with a car ownership model can enable modelling the transformation of the vehicle fleet in the model area over time.
6. Environmental zones can be considered in the model. However, in the current setup, no distinction between vehicles is made. Modelling vehicle types as explained in point above would better enabling modelling environmental zones. Connecting it to modelling park-and-ride would also open the opportunity to model mode transfer during a trip for people who drive with a banned vehicle to the edge of the environmental zone to continue their journey.

5.2.2 Opportunities for technical enhancements

The base line model can be improved in various ways to improve the accuracy of the model results. The room for the improvement is partially conditioned by the pilot nature of this study, whereby the model was built in a very short time to demonstrate the benefits of agent- and activity-based models. Additionally, some technical enhancements can be suggested for Brutus in future.

1. First improvement would be to estimate the choice models based on Norwegian RVU travel survey rather than using the choice models from the donor model. The survey characteristics for synthetic population and activity modelling could be extracted from the RVU survey:
   - The local context would be reflected in the model parameters with fewer calibration. The models based on local survey data are expected to have higher sensitivity for mode changes and better reflect the local value of time.
   - More explanatory variables relevant for the model scope could be added to the models. Examples are better separation of cost and time component, but also availability of parking.
2. The model results could be calibrated to mobile phone network data to better reflect the actual travel flows between origin and destinations.
3. As described in the report, Brutus derives a lot of different destination choice models for different mode and trip purpose combinations. Not all these models have significant

parameters. The largest share of trips is served with a significant model. However, there is room for improvement to consider the segmentation to serve more trips with significant model.

4. Separately modelling long-term decisions, specifically work or school location would be of value to better study the effect of certain interventions on mode choice. In current setup, decision makers can simply change work or school locations. Decision makers might be more constrained. Modelling these long-term choices first enables setting these as constraint in mode and destination choice. The model would then better represent substitution of mode.
5. Current model implementation considers the same travel times (skim matrices) for the whole model period, while there are no obstacles to use different travel times in different times of day. Reason for current setup is that the donor model follows the same approach.
6. Departure time modelling would increase predictive value of the model. Currently, departure times are sampled from survey records when modelling the activities. That means that the model is not able to simulate changes in departure time, for example triggered by changes in timetables or flexible timing.
7. Brutus' implementation of public transport is relatively simple. Different modes are distinguished but decision makers do not consider these explicitly. Public transport is considered on mode in the model and impedance of the shortest path is considered in mode, destination, and route choice. Separately distinguishing separate public transport modes (e.g., train and bus-tram-metro) as choice options would enable the model to consider different offerings in public transport better.
8. Brutus' assignment is relatively simple. Most trips are routed using the shortest path. No queueing is considered. Cycling traffic is routed somewhat differently as individual decision makers choose between three best routes. A benefit of this simple approach is that individual routes are easily traced back in the simulation. However, congestion cannot be modelled. Also route choice may not always be as realistic as possible. There are various options to improve the assignment:
    - Iterative aggregated assignment could be employed to update travel times. This would mean that the network for motorised traffic would not need pre-simulated travel times from aggregated assignment. This would enable the methodology to model travel times without needing to model demand in an aggregate model. The final simulation could still be done in Brutus as individual trips.
    - Similar as with cycling in Brutus, motorised traffic could consider different route options, using a path-sized logit model.
    - Public transport assignment could improve by grouping people into separate vehicles so that concepts such as capacity and crowding can be better considered.
9. Brutus is a stochastic model. Many processes rely on Monte Carlo simulations to pick discrete outcomes. Result is that there is significant noise in the model results. This makes it sometimes difficult to compare two scenarios with each other. Being able to do this is important for cost-benefit analyses. There are various options to grapple stochasticity or reduce random noise in the results:
    - Multiple runs: One option to deal with stochasticity is to execute multiple runs of a scenario. This is not considered in this pilot case, but this is possible. The simulation run time for Brutus Trondheim is well under half an hour on a 32 cores compute setup.
    - Oversampling of decision makers: In current implementation, only the population in smaller municipalities is oversampled. This is done to get more stable results when validating the model on flows between municipalities. However, oversampling the

complete population is possible too. This would increase runtime but also reduce stochasticity. This is easier to set up multiple runs. Yet, one cannot derive confidence intervals on the simulation results.

- Variance reduction techniques: Methods to reduce random noise in activity-based models are not that established. Various developments are however happening in this field. Established methods to lower variance relate to importance sampling or using Halton draws. Other solutions are also under development or implemented but not described in detail, most often because these are proprietary methods. Monte Carlo sampling can also be replaced in certain steps of the model. For example, the population synthesiser could employ iterative proportional fitting methods to eliminate noise in a particular step of the model.

5.3 Alignment with RTM

Activity-based models have unique features which aggregate models do not have. However, aggregated models such as RTM also have their strengths, such as stable solution properties, advanced aggregated assignment methods and inclusion of freight (or at least heavy goods vehicles). These are topics in which activity- and agent-based models excel less.
Stable solutions are crucial in cost benefit analyses (CBA) when various options are to be compared. We therefore see a place for an aggregate model with deterministic properties for assessment of large projects. Brutus can still provide valuable input and be used in CBAs, especially if multiple runs are performed.
In addition, we see a place for Brutus in smaller projects around tactical interventions to improve infrastructure within urban areas or for active modes. The disaggregate travel demand is a helpful platform for travel demand analysis because of the high level of detail of individual trips and tours with socio-economic background variables.
The demand of Brutus can be aggregated in OD-matrices (losing the individual observations) and assigned using the tools available within RTM. Brutus' demand can be combined with matrices from RTM for freight distances and long-distance travel to generate an accurate picture of the network conditions, including queuing and modelled travel times.

6. Conclusion

This report describes the pilot development and application of an activity and agent-based model Brutus for a city of Trondheim. The project aims at showing to the NPRA how a disaggregated model such as Brutus differs from aggregate four-step models in terms of accuracy, functionality, and development process, that is, to illustrate the capabilities of an agent-based model.

The current RTM model used as a tool for strategic analysis in urban areas in Norway is tailored for regional modelling and has lack of capacity to reflect certain transport policy interventions. The model accounts for different time periods, is multimodal and has capacity-dependent calculation of demand. The model has an equilibrium-based traffic assignment part allowing to account for congestion and to model related policy interventions such as toll roads. Despite these capabilities, due to its structure and relatively low spatial resolution of the zoning system, the RTM is not able to provide some of the outcomes of interest for the baseline scenarios and for the scenarios implying changes in the transportation system. In a demand context, this may particularly apply to factors related to departure time, household internal dynamics, activities / trip chains, means of travel made on short trips, analysis of the effects of transport policies on individual level.

Agent- and activity-based models such as Brutus allow to overcome the listed above RTM shortcomings in demand modelling. To demonstrate that and to achieve the project aims in a short time, in a “pilot” format, Brutus model was developed with a shortcut of using a donor model from Turku, a city of a comparable size in Finland. The scenarios tested with Brutus mostly relate to projects / policy measures promoting cycling and aim at demonstration of the strength of agent-based models for appraisal of cycling projects. The latter is especially important for expensive bicycle investments and efficient project prioritization and public spending, aimed at reaching strategic goals of cities.

Based on the results presented in this report, two main conclusions can be highlighted. First, Brutus (or an activity- / agent-based model in general) can be used for urban transportation planning as a stand-alone model in Norway. Second, the use of agent-based model can successfully compliment the regional transport model (RTM) in modelling certain policy measures, for which RTM is less suitable / sensitive.

These two conclusions are supported by the demonstrated ability of Brutus model to adequately represent the baseline scenario, and to be sensitive in capturing traffic changes due to local interventions into the cycling network. Overall, the report shows that Brutus can produce reasonable results, which were validated using the available statistical data and expert judgement. The success of Brutus is especially remarkable, given the short time nature of the project and consequent simplifications and assumptions applied to make it possible to complete the project within the short period.

Further enhancements of Brutus and tailoring it more to the study area will likely maximise the benefits of the model application for transport policy appraisal. These improvements can follow several directions, such as input data improvement, enhancement of the BTURUS’ capabilities to model the baseline and various policy scenarios of interest for the authorities, and some technical enhancements aimed at making the model more efficient and user-friendly. Calibrating the model using the local survey would be the first natural step in this direction.

More detailed data to support Brutus or activity- / agent-based models in general can be collected in future. More specifically, this would include higher endpoint accuracy of the survey, larger sample size to account for various combinations of activities / destinations / modes / socio-demographic characteristics of travellers, etc.; surveying households rather than individuals to account for the household interactions in the model; higher time resolution for the answers. More detailed examination of the survey can be proposed as a step towards successful use of agent- and activity-based models in Norway.

Appendix 1
All scenario KPI results

Scenario	RVU	2022	2022_bridge_nidelva	2022_hovedsykkelv
Res_total	256282	256282	256282	2562
Jobs_total	139515	139515	139515	1395
Ntrips_pd	190944	201527	202655	2010
Ntrips_bc	42501	40832	41078	413
Ntrips_tr	60395	60219	59593	602
Ntrips_cd	283011	269693	268573	2698
Ntrips_cp	73082	71054	70839	709
Ntrips_tot	650956	643326	642737	6434
Mode_pd	29.33%	31.33%	31.53%	31.24
Mode_bc	6.53%	6.35%	6.39%	6.43
Mode_tr	9.28%	9.36%	9.27%	9.36
Mode_cd	43.48%	41.92%	41.79%	41.94
Mode_cp	11.23%	11.04%	11.02%	11.03
Length_pd	0.592966	1.230461	1.2304	1.2344
Length_bc	2.252932	3.02768	3.033119	3.0144
Length_tr	1.33496	4.679837	4.59767	4.6877
Length_cd	8.814769	7.647905	7.68575	7.6848
Length_cp	7.522276	6.708276	6.762684	6.7201
Length_tot	4.897583	4.962731	4.964973	4.9824
Traveltime_pd	8.137738	17.54022	17.54101	17.599
Traveltime_bc	8.066597	10.75022	10.77077	10.70
Traveltime_tr	16.98266	24.34501	24.1392	24.316
Traveltime_cd	10.84995	8.912016	8.939236	8.9344
Traveltime_cp	9.418126	8.020446	8.07277	8.0293
Traveltime_tot	10.27017	13.0777	13.08223	13.095
Trplength_per_inhabitant_pd	0.42577	0.967571	0.972939	0.9684
Trplength_per_inhabitant_bc	0.361093	0.482387	0.486157	0.4865
Trplength_per_inhabitant_tr	0.305249	1.099637	1.069088	1.1015
Trplength_per_inhabitant_cd	8.355378	8.048124	8.054347	8.0922
Trplength_per_inhabitant_cp	1.766353	1.859857	1.86927	1.8613

Trplength_per_inhabitant_tot	11.21384	12.45757	12.4518	12.510
Ttime_per_inhabitant_pd	5.843174	13.79272	13.87056	13.806
Ttime_per_inhabitant_bc	1.292888	1.712785	1.726369	1.7282
Ttime_per_inhabitant_tr	3.883215	5.720428	5.613045	5.7140
Ttime_per_inhabitant_cd	10.28449	9.378386	9.367949	9.4080
Ttime_per_inhabitant_cp	2.21153	2.223653	2.23139	2.2239
Ttime_per_inhabitant_tot	23.5153	32.82797	32.80931	32.880
Co2_tr	2054861	7195636	6995735	72080
Co2_cd	2.03E+08	1.91E+08	1.91E+08	1.92E+
Co2_tot	2.05E+08	1.98E+08	1.98E+08	2E+