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Prototype of a fully Integrated behavioural (data-driven) simulator

D4.4

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Short Description	*The focus of this deliverable is mainly to briefly describe the prototype behavioural simulation model and the results obtained by performing those simulations with a few policy scenarios for the three iSCAPE cities. It has been found that policies in relation to restricting car traffic are more effective in terms of reducing traffic from the network and also shifting of car drivers/passenger to other modes of travel. The enhancement of bus infrastructure in relation to increasing the frequency of bus routes and also tweaking activity start time (changing open and end times) are not able to significantly reduce car traffic. Especially, improvement of bus infrastructure causing shifting of bicyclist towards public transport, which is an undesirable result of the policy. The outputs obtained are then used in*

	deliverable 4.5 in order to estimate emissions and pollutant concentrations and further it would be used for estimating exposure in task 7.3 of WP 7.		
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DOW	Description of Work
FEATHERS	Forecasting Evolutionary Activity-Travel of Housedhold and their Environmental RepurcussionS
FMI	Flemish Meteorological Institute
GTFS	General Transit Feed Specification
HSL	Helsinki Region Transport
IMOB	Instituut Voor Mobiliteit (Transportation Research Institute)
IPU	Iterative Proportional Updating
MATSIM	Multi-agent Transport Simulation
OLS	Ordinary Least Square
OSM	OpenStreetMap
OVG	Onderzoek VerplaatsingsGedrag
POI	Point of Interest
PT	Public Transport
RMSE	Root Mean Square Error
SPSA	Simultaneous Perturbation Stochastic Approximation
SRMSE	Standardized Root Mean Square Error
TDM	Travel Demand Management
TPER	Trasporto Passeggeri Emilia-Romagna SpA
WP	Work Package

1 Executive Summary

The focus of this deliverable is mainly to briefly describe the prototype behavioural simulation model and the results obtained by performing those simulations with a few policy scenarios for the three iSCAPE cities. The output obtained are then used in deliverable 4.5 in order to estimate emissions and pollutant concentrations and further it would be used for estimating exposure in task 7.3 of WP 7.

Hasselt case behavioural simulation framework is more detailed and comprehensive. It involves the use of a detailed activity-based model (FEATHERS) which is further integrated with traffic simulation model (MATSIM). The mechanism through which both models are integrated with each other is well described in deliverable 4.3. Three simulation runs are performed, the first one representing the base case, which is also calibrated with available traffic count data. The results are reasonably replicating the observed traffic counts. Other two simulations present results of the two distinctive policies: 1) Restriction of car access on the inner ring and surrounding roads and 2) Increase of bus frequency for several bus routes in Hasselt. The impact of car restriction policy are more significant compared to the 2nd policy, as not only car traffic is reduced but also changes are noticed in relation to shifting of travel mode from car to others (such as bus, bicycle etc.)

In the case of Bologna and Vantaa, a light version of the activity-based model is used. This is based on producing the required input for MATSIM, and using its full functionality to not only change in route choices but also mode, departure times and activity duration choices. Similar to Hasselt case, for both cities base case simulations are performed and calibrated with available traffic count (Bologna) and travel time (Vantaa) data. For both cities, two policies simulations are also performed as identified by the relevant stakeholders. In the case of Bologna, the first policy is related to restriction of car access in some roads surrounding the ring road (electric cars and buses are allowed). The second policy is related to delay in the opening times of big shops and malls by an hour to reduce the traffic in the morning rush hour. Again, significant impacts are noted for the first policy than the 2nd one. In the case of Vantaa, the policies examined are similar to the Hasselt case. The results are also similar; however, car restriction policy impacts are not that significant as noted in the case of Hasselt.

It has been found that policies in relation to restricting car traffic are more effective in terms of reducing traffic from the network and also shifting of car drivers/passenger to other modes of travel. This is in line with the results reported in other similar studies. The enhancement of bus infrastructure in relation to increasing the frequency of bus routes and also tweaking activity start time (changing open and end times) are not able to significantly reduce car traffic. Especially, improvement of bus infrastructure causing shifting of bicyclist towards public transport, which is an undesirable result of the policy. It is, therefore, important that these policies are to be implemented together to have more appropriate effect. Deliverable 4.5 presents the further use of the results reported in this deliverable to estimate emission and pollutant concentrations.

2 Introduction

This section describes the background and contextual details on which this deliverable for task 4.2.3 of work package (WP) 4 of the project is based. Furthermore, it describes the scope under which this deliverable is prepared keeping in view the description of work (DOW) for task 4.2.3. and other earlier deliverables (such as deliverable 4.2 and 4.3) coming out from the same major task of WP 4. The DOW defines the task 4.2.3 as follows:

> *4.2.3 Behavioural Simulation Execution:*
>
> Once this model has been designed, we are ready to conduct simulations and personal exposure measurements. As mentioned above, the advantage of the approach proposed is that conclusions can be extrapolated and are not limited to the city which is used for deployment, but also the model can be used to conduct different simulations (scenario's). In this task we will include the development, assessment and deployment of more conventional transportation (behavioural) interventions such as actions to promote changes in transport mode choice for EU Cities inhabitants (e.g. like traffic restrictions, pricing mechanisms, etc.). Next to transportation measures, we will calculate the effects of certain scenarios with no obvious direct relation to transport or air quality. Although, we believe there is also an indirect behavioural effect for these measures. To this end; institutional (e.g., changing working hours, changing shop opening hours) and demographical changes (e.g., aging of the population, changing percentage of part-time workers, more one-adult households) will therefore also be assessed.

The text for task 4.2.3 primarily mentions the execution of behavioural simulation for selected iSCAPE cities and assessment of different policy scenarios in relation to mobility aspects. The policies/interventions that can be examined via the developed behavioural simulation framework is described in great detail in deliverable 4.2. Furthermore, deliverable 4.2 also demonstrates some examples of the impact of such policies. The interested readers are directed towards that deliverable. In addition to this, the text also gives the impression to estimate personal exposure. However, it can be noted that in this deliverable results of the behavioural simulation platform are discussed. Based on these results, deliverable 4.5 (also due in month 30) will present emission estimation and run dispersion model to estimate pollutant concentrations for the base and policy scenarios. Furthermore, the outputs presented in this deliverable and deliverable 4.5 are combined together to estimate personal exposure as part of the task 7.3 (WP 7) for which deliverable 7.3 and 7.4 will be prepared by month 36. This is important to avoid duplication of work and also in alignment with the project flow and other tasks.

Based on the above discussion and further considering the overall objectives of WP 4, within this deliverable, two major aspects are required to be focused. These are as follows:

1) A brief discussion on the tools used to develop behavioural simulation framework – (can also be considered as a prototype) to provide a context to this deliverable. A more comprehensive discussion can be find in deliverables 4.2 and 4.3, where the design of this framework is presented.
2) TDMs (travel demand management measures) or mobility based behavioural interventions/policies for selected iSCAPE cities are required to be implemented and simulated. The obtained results in relation to their impact on mobility aspects are required to be presented and commented with justifications.

2.1 Scope of the Deliverable

This deliverable is prepared to accomplish the requirement of the two major aspects discussed above. Below we list the main scopes of this deliverable.

1) Illustration of the simulator, its various components and its comprehensive design are already discussed in deliverable 4.2 and 4.3, however, here only brief summary of the simulator is provided to give the context to the deliverable.
2) The focus of this deliverable is more towards mobility simulations, and explaining the obtained results in light of the assumptions and local context for three selected cities within iSCAPE consortium. Furthermore, it is not included in the scope of this deliverable to present results of personal exposure estimation however, it is explained here that how the obtained results from the simulation (this deliverable) and also from deliverable 4.5 can be further integrated to give this personal exposure, which is mainly the task 7.3 of WP 7.
3) Three behavioural simulations are implemented/executed for the city of Hasselt, Bologna and Vantaa. The first simulation is to run a base case based on the availability of the data and then run two distinct policy scenarios whose recommendations are received from the stakeholder and respective partners.
4) The base case calibration results are also presented for three cities to highlight the fact that the model is behaving well in current conditions and to an extent the policy scenario results can be believable.
5) Brief details are also discussed about how the policy scenarios are implemented in the simulator e.g. what parameters or inputs are changed in the simulator to execute the desired policies/intervention.
6) An account of sensitivity of results are also presented based on the previous work of an author with a similar simulation model. This is provided to emphasize the fact that how much results are sensitive to any change in the model inputs and parameters. We have not performed any sensitivity analysis for the three cities, however, we discussed about how much it can impact the outputs. So that decisions at policy level should be taken carefully.
7) This deliverable should be considered as a building block for the subsequent work to be conducted within WP 4, not only for task 4.3 but also for task 4.4, where the final outputs from these simulations may also be presented to the stakeholders. In addition, the output mentioned in this deliverable will be further linked with outputs of task 4.3 to make the basis for task 7.3 of WP 7.

2.2 Layout of the Report

The report is structured along six key sections. Section 3 presents the bigger picture and some brief discussion to provide the context to this deliverable. In section 4, we provide the detailed account of three city cases where base situation is simulated and calibrated. In addition, 2 policy scenarios for each city are simulated and presented along with some justifications of the obtained results. Section 5 presents some discussion on uncertainty of obtained results and then also discuss the integration framework to use the obtained results for personal exposure assessment. Section 6 concludes the deliverable and puts forward some recommendations for the next deliverables of the WP 4 and WP 7 of the iSCAPE project.

3 Behavioural Simulation Framework - Prototype

This section provides the context to this deliverable by providing some discussion on the prototype developed to perform behavioural simulation for three selected iSCAPE cities. The behavioural simulation framework we are using is based on an Activity-based approach and the operational tool used for the Hasselt case is a combination of FEATHERS (an operation Activity-based Model) [*Baqueri et al., 2019, Bellemans et al., 2010, Kochan et al., 2013*] and MATSIM simulation platform [*Horni et al., 2016a, Ziemke et al., 2015*]. The model cyclic chain starts from the synthetic population (containing socio-economic properties of person and household) of the city, predicting their travel routine (in the form of activity-travel diary) and then executing it on the transportation supply network to obtain traffic volume on the links for an entire day. This is done in a way that individual properties are kept intact at the supply side. In the case of the other two cities, Bologna and Vantaa, the framework integrates a light version of activity-based model to integrate it with MATSIM due to the unavailability of required data and other resource constraints. In this connection, first a bigger picture is described and then behavioural simulator is discussed at length.

3.1 A Bigger Picture

This section highlights the bigger picture where most of the work package 4 tasks are briefly explained to illustrate the flow of work and models used to provide different outputs based on the given inputs.

In task 4.1, from which deliverable 4.1 is produced, a soft behavioural intervention is designed for which activity-travel diary data of sampled individuals in Hasselt, Bologna, Guildford and Dublin are collected and exploited from the developed smart phone application. This activity-diary data of each individual was collected for at least two weeks; however, the sample is quite low compared to the overall population of the city. This data is exploited to study the effectiveness of an informational intervention study. More details can be seen from the deliverable 4.1 and also in [*Ahmed et al., 2018*]. Another major use of such detailed activity-diary data is to use it in the activity-based model for calibration of a variety of sub-models within this framework. However, in the case of Hasselt, with the availability of OVG data (Personal activity-travel survey for entire Flanders region) [*DMPW, 2019*], FEATHERS model is calibrated and with the Hasselt city (Hasselt is part of the Flanders region in Belgium) recorded data for around 33 individuals, the calibrated FEATHERS is further adjusted to model Hasselt citizen in more appropriate manner. For other iSCAPE cities, due to the limited availability of detailed activity-travel diary data, a light version of activity-based model is developed and the recorded small datasets from these cities are then further used to adjust the model.

In task 4.2.1, (from which deliverable 4.2 is produced) FEATHERS and MATSIM are proposed to be used as a behavioural simulation in an integrated framework. The justification of using MATSIM is because of its open access availability and also traffic assignment procedures are performed in a manner that individual's identity is kept intact, which is more appropriate for personal exposure assessment. Within this task detailed description of the two operational tools are discussed along with their cost/utility functions to illustrate the type of policy scenarios can be examined via these tools. A detailed account of policy scenarios is presented within this deliverable and also some of them are examined to showcase the capability of the simulator for the Hasselt case. As part of task 4.2.2, (from which deliverable 4.3 is produced), detailed design of the behavioural simulator is described. Deliverable 4.3 explains the simulator design on various aspects such as generation of synthetic population using an Iterative proportional updating algorithm (IPU) [*Ye et al., 2009, Cho et al., 2014a*] from census data and total marginal data of socio-economic properties based on some spatial units of a particular city. Furthermore, it also discuss about the development process of input data (road and bus network data) for MATSIM for each selected city from OpenStreetMaps (OSM) and general transit feed specification (GTFS) [*Cich et al., 2016, Vuurstaek et al., 2018*]. The deliverable also explains the FEATHERS calibration (Hasselt case) and also development of a light activity-based model (Bologna and Vantaa cases) to generate another important input for MATSIM in terms of individual plans. Furthermore, execution of MATSIM and the calibration of final outputs are also described in an integrated framework. The task 4.2.3, is about using the simulation platform to execute those mobility-based simulations and run few policy scenarios and describe the results.

In task 4.3, (from which deliverable 4.5 is produced) the outputs from behavioural simulations are then further used to estimate emissions along with other emission inventory data. This emission results are then fed into the dispersion model where, with other meteorological data pollutant concentration maps are produced for base case and also for policy scenarios for the three cities. In addition to these certain other climate projection scenarios are also tested by using the dispersion model. The outputs from 4.5 are then further integrated with output of this deliverable to allow for appropriate estimation of personal exposure, this is task 7.3 of WP 7.

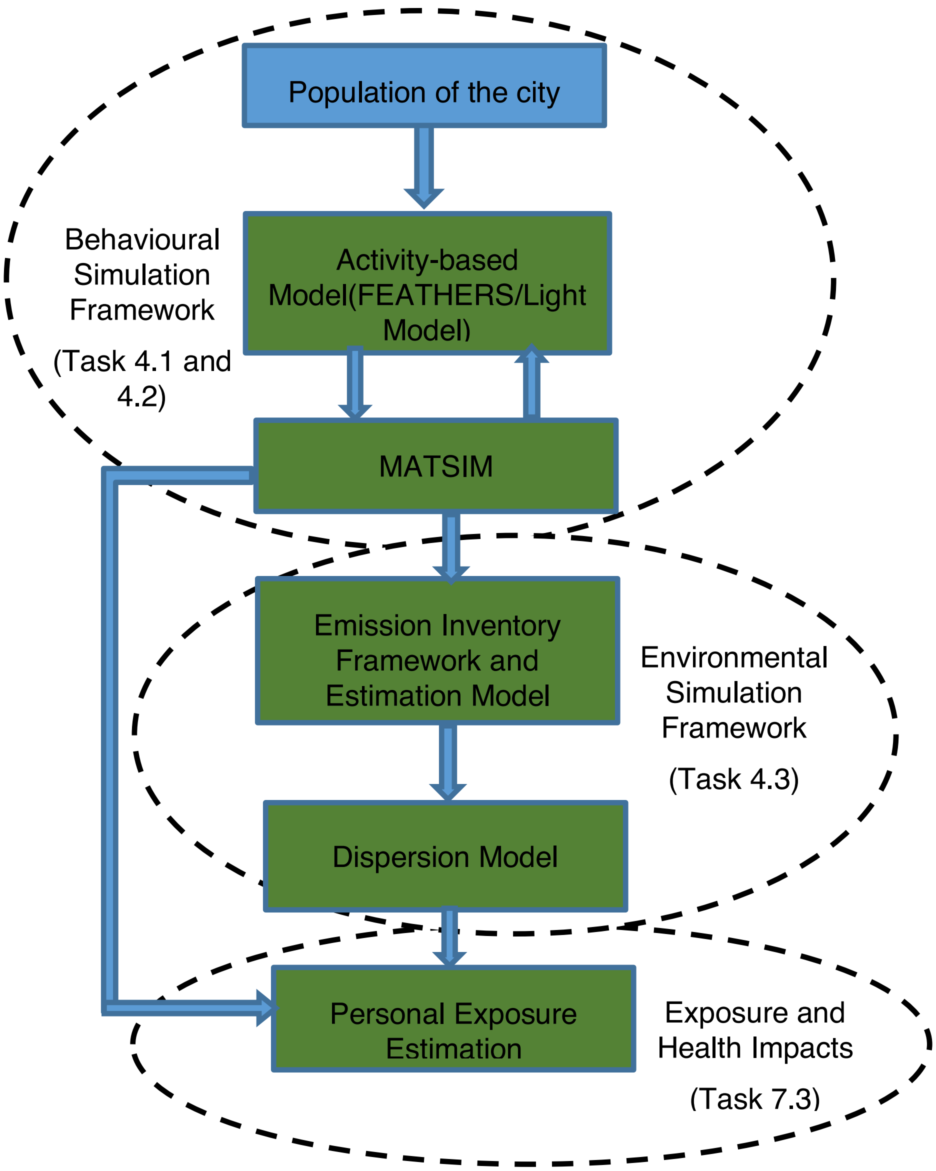


Figure 1: Overall Simulation Framework

Figure 1 describes the flow of data and different models that are implemented in the framework to obtain the desired output. It also points out the different tasks in relation to a particular component to explain the bigger picture.

3.2 Detailed Framework- Behavioural simulations

In this section, we explain the behavioural simulation framework in some detail, so that the results provided in the next section can be understood in a better manner.

The first important step is to generate a population of a particular city for which simulations need to be executed. As the detailed census data is usually not available due to privacy reason, the population is generated using some aggregate data. The data is usually known as zonal marginal, where aggregated socio-economic characteristics of the population in small spatial units are given, such as

- number of females and males in each zone
- number of individuals in each age category
- number of workers, cars in a household etc.

This data is used along with some seed data of the individual and household structure of the region in an algorithm known as iterative proportional updating (IPU) to first find the relationship so that personal and household characteristics are matched in the seed data and zonal marginal. On this basis, persons and households are drawn from those matched in order to generate the synthetic population [*Cho et al., 2014a*]. In the case of each selected city, this data was available to an extent, and algorithm is used to generate the synthetic population with reasonable accuracy.

The next major step is to estimate models within FEATHERS (an activity-based model). This model takes a variety of input data to estimate models. These datasets are detailed personal activity-travel diaries, skim matrices (that contains zone to zone travel times, travel cost with respect to mode and time periods of the day) and zone-based land use data. The sub-models within FEATHERS are trained with these datasets in a decision tree modelling framework. These sub-models include day pattern, number of work episodes, home-based tours, activity duration for primary and secondary activities of the tour, destination choice for the activities and mode choice for primary and secondary activities of the tour. All models are structured in a hierarchical manner, so that the decision from upper layer models are also transferred to the lower level models [*Baqueri et al., 2019*]. When these models are simulated by using a synthetic population, it generates an entire day-activity travel schedule for the individuals. In the case of Flanders region (Hasselt is part of Flanders), we have availability of such rich datasets and therefore, we estimated FETAHERS model. Furthermore, the model outputs are further adjusted with the availability of detailed activity-travel diary records from smartphone application from the individuals in Hasselt city, to obtain the accurate prediction of activity-schedules for Hasselt population. In the cases of Bologna and Vantaa, a light version of activity-based models are developed because of unavailability of such datasets. The model segments the population based on a few characteristics and compared it with the obtained schedules of similar population segments of Flanders region. Then it draws an activity sequence from these schedules. These activity sequences are further enriched with other scheduling dimensions (such as activity duration, modes, departure times etc.) based on the activity-travel diary data recorded from Bologna and some published travel research from Vantaa and its surrounding region. Some consistency checks are performed to see the travel mode shares, trip distance and time-of-day distributions are consistent with existing trends in the available aggregate data. The output of the activity-based model is then used as input to MATSIM by incorporating another procedure to obtain node-based activity locations from zonal-based locations. The node is part of the network used to perform MATSIM simulation.

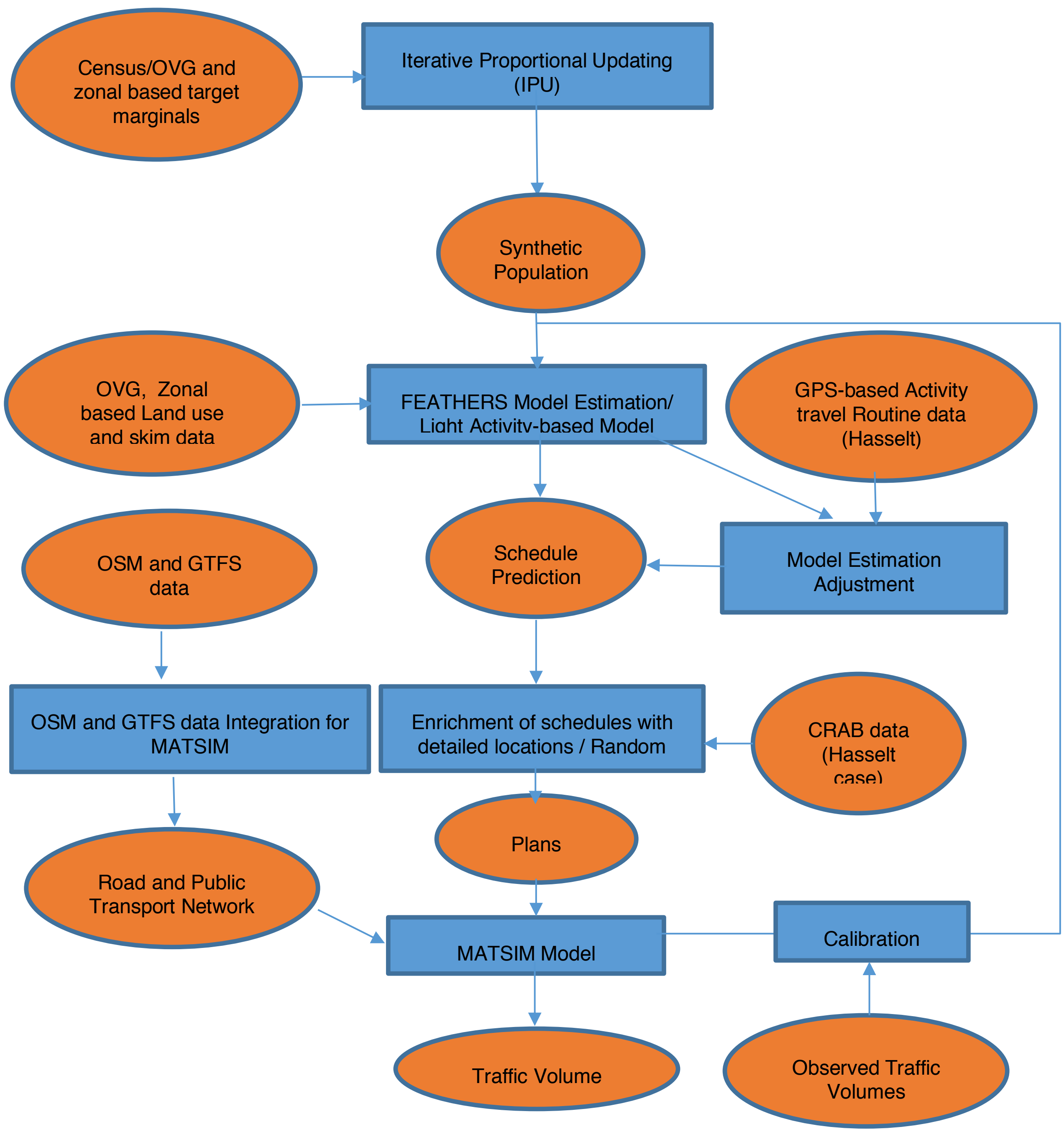


Figure 2: Integrated Behavioural Simulation Framework- Prototype

Another major step is to develop inputs for MATSIM in the form of a road network and also public transport network. The road networks for each city is obtained from OSM and then along with GTFS data, bus stops are mapped into the road network. For this purpose, an algorithm is developed based on the principle of minimising the total trip distance for the bus operators. The algorithm is explained in detail in [*Vuurstaek et al., 2018*]. The schedules from FEATHERS/light activity-based model and road/public transport network data is then provided to MATSIM for execution. MATSIM usually provides results after around 250 simulation runs. The output of MATSIM is then processed further in the form of zonal skim matrices to again provided to FEATHERS for generation of another set of schedules. However, it is not possible with the light version of activity-based model because of its data-driven nature. In addition to this, MATSIM output in the form of network traffic volumes are to undergo in a calibration framework to produce more consistent outputs. This is only done for the base case. The calibration framework is based on the ordinary least square type and uses simultaneous perturbation stochastic approximation (SPSA) algorithm [*Lu et al., 2015*] to optimise parameters within MATSIM framework. Figure 2 explains the flow of data from one component to another of the behavioural simulation framework and this should be considered as a prototype model.

4 Execution of Simulations - Results

This section presents the core of this deliverable. Results from the behavioural simulation framework are presented and explained in this section. We start from the Hasselt case and then move towards Bologna and then Vantaa.

4.1 Hasselt case

Hasselt is one of the urbanised Arrondissements in the Limburg province of Belgium. Hasselt Arrondissement is a combination of 17 municipalities including Hasselt city. The total population of the Arrondissement is around 0.43 million in 2018 and out of this 77,000 individuals are residents of Hasselt city. Hasselt city is also the capital of Limburg and is therefore, often be visited by individuals from the surrounding region for a variety of administrative issues. The total area of the Arrondissement is 906 square km, while Hasselt city has an area of around 102 square km with a population density of 750 inhabitants per square km. Figure 3a and 3b represent Hasselt Arrondissement and Hasselt city as part of the Limburg province of Belgium.

(a) (b)

Figure 3: (a) Hasselt city in red, within the Limburg province in Belgium. (b) Hasselt Arrondissement in red in the Limburg province of Belgium.

In Hasselt, variation in terms of meteorological conditions can be observed during the year. The average minimum temperature in February 2018 was reported as -1.0°C. In February, the amount of rain is normal with an average of 40 mm. This month is also known as a chilly month with the average wind speed of 17 km per hour in year 2018. In July 2018 average maximum temperature was 28°C which was the highest average temperature during any month. The maximum average rainfall in any month last year was recorded in January i.e. around 150 mm.

4.1.1 Mobility context of the city

Hasselt city is at the junction of important traffic arteries from several directions. The most important motorways are the European route E313 (Antwerp-Liège) and the European route E314 (Brussels-Aachen). The old town of Hasselt is enclosed by two ring roads. The outer ring road serves to keep traffic out of the city centre and main residential areas. The inner ring road, the "Green Boulevard", serves to keep traffic out of the commercial centre, which is almost entirely a pedestrian area. There are also important traffic arteries to Tongeren, Sint-Truiden, Genk, and Diest. The road network of the Hasselt is illustrated through figure 4. In the last two decades, car ownership has significantly increased in the area which causes problems like traffic congestion and air pollution. During the peak hours congestion can be seen on the routes connecting E313 and E314 with the outer ring and then to inner ring.

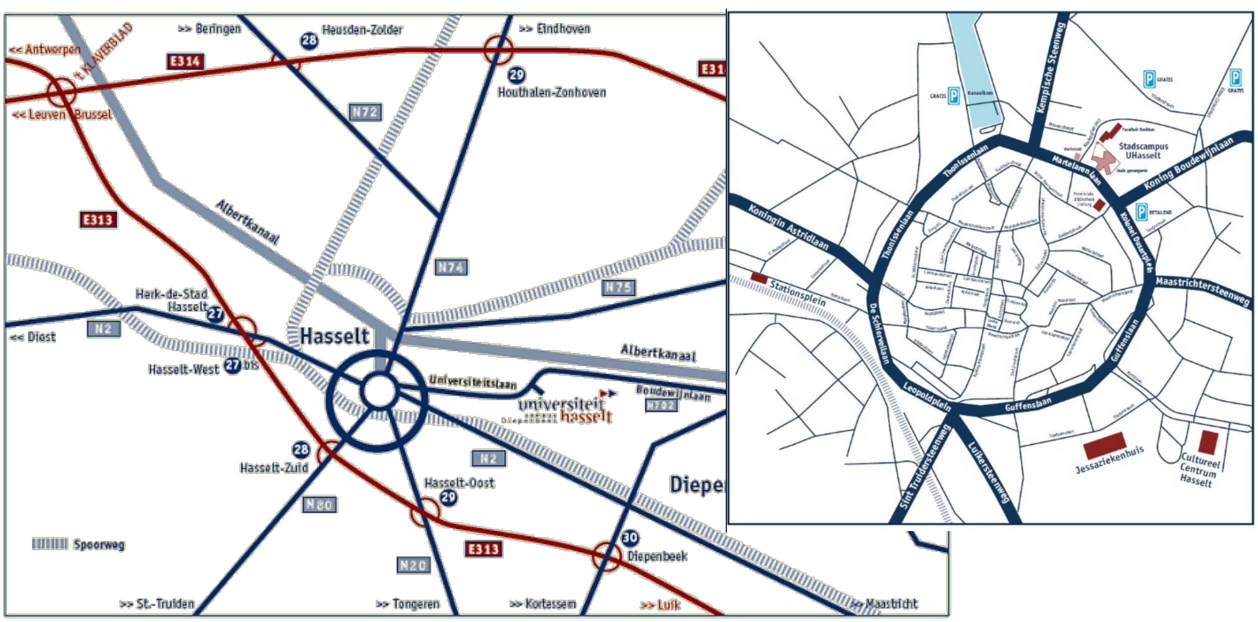


Figure 4: Hasselt city and surrounding areas connection through a road network

In Hasselt, 73 percent of the total trips are performed using a car. For a trip distance of around 8 to 10 km, the bicycle has the 2nd largest share after the car, which is the result of adopting a bicycle oriented policies by the city administration such as the development of relevant infrastructure (i.e. segregated bicycle lanes, bicycle priority streets, bicycle parking facilities), the availability of bike sharing schemes and the increase in parking cost in the inner core areas. However, in the inner core region, there are streets which still allow car movements despite some of the shopping streets which are completely pedestrianized. There are more than 8 large car parking areas as shown in figure 5 (having a capacity of more than 100 cars) surrounding the inner ring, which facilitates citizens to park their cars and then walk around the inner city region for shopping or other activities.

Public transport is available and a major transport hub is located near the Hasselt train station. There is only one operator (*Delijn*) providing the bus-based public transport services within the Hasselt Arrondissement. However, bus service is not very frequent except a few routes that cover Hasselt train station and Hasselt University campus located in Diepenbeek (a small town near Hasselt city).

Figure 5: Parking Location near/ on inner ring of Hasselt

In the recent past "Fietslus Groene Boulevard" project was launched with the aim to increase bicycle safety on the smaller ring. The cycle path of the Green Boulevard was interrupted in a number of places by obstacles and the cycle route was not equally clear everywhere. This caused confusion and unsafe situations. The combination with uncomfortable cobblestones ensured that many cyclists use the bicycle path on the outside of the ring in the opposite direction. City administration in collaboration with the Roads and Traffic Agency have started the construction of an uninterrupted bicycle loop on the inside of the Green Boulevard. Keeping in view the riding comfort several cobbled strips, such as the Van Veldekeplein, are replaced by comfortable pavements as illustrated in the figure 6 [*Stad_Hasselt, 2019*].

Figure 6: Uninterrupted bicycle loop on the inside of the Green Boulevard in Hasselt

4.1.2Base case calibration - Results

This sub-section presents the base case results of the mobility pattern in Hasselt after performing the simulation in the developed behavioural simulation platform described in section 3.2. The main results are as follows:

4.1.2.1 Synthetic Population

Based on the marginal totals (zone marginal/target marginal) and seed data in the form of personal activity-travel diaries with household and personal based socio-economic factors, a synthetic population is generated for the entire Flanders regions that contains around 2386 zones (subzones as Traffic analysis zones) using IPU algorithm. Within Hasselt boundaries, there are 23 such zones. It should be noted that the IPU algorithm can be run in parallel for each zone provided that the correct data is fed to the algorithm. The simulation took an average of around *84 seconds* to generate the population of a particular zone. This simulation time is highly dependent on the number of individuals being generated in each zone. Figure 7, illustrates the process being followed for a particular zone of Hasselt.

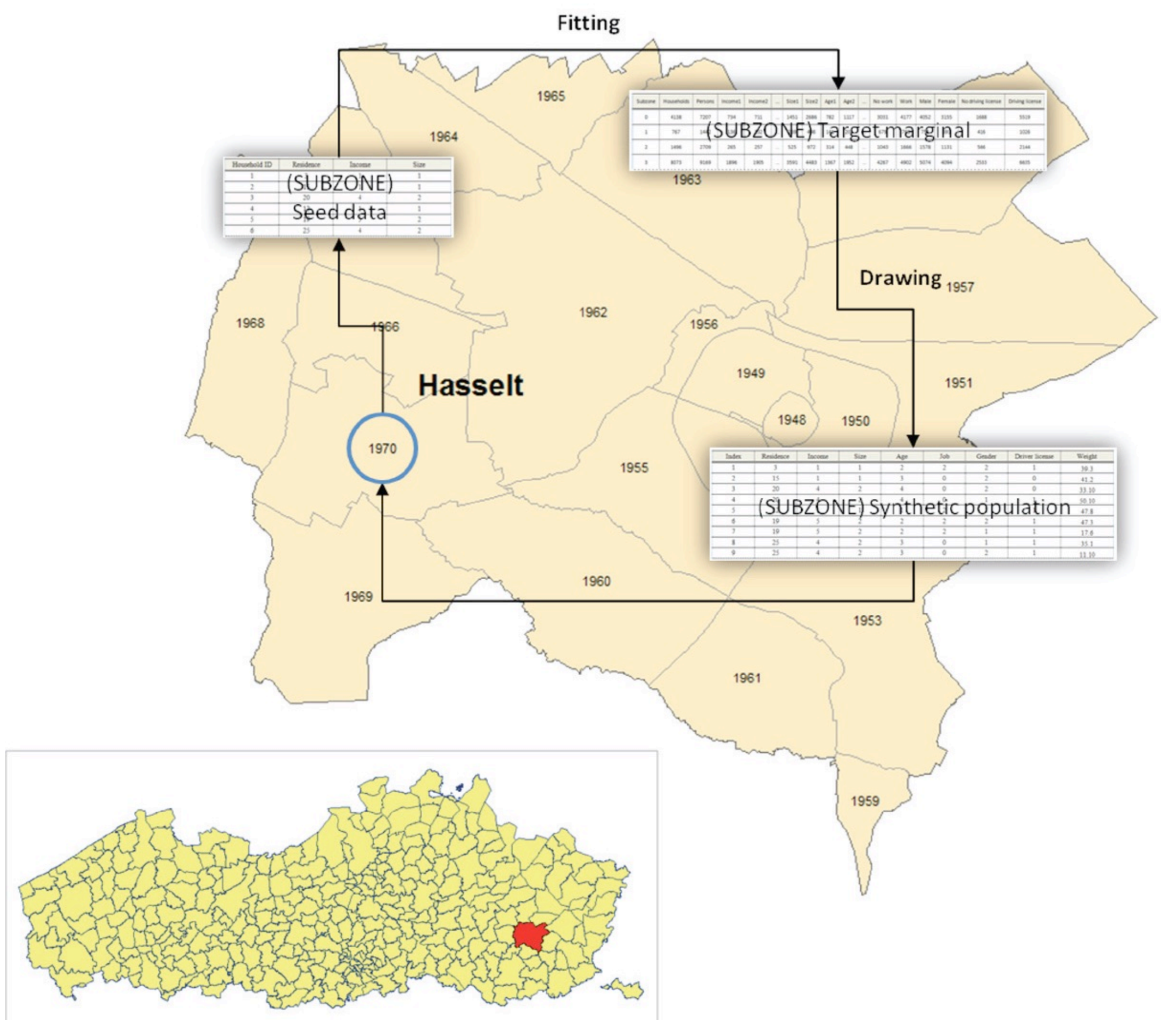


Figure 7: Hasselt Zones and IPU based population generation process along with location with Hasselt in Flanders region

Based on the consistency check as described in deliverable 4.3, available target marginal and the same statistics obtained from the generated synthetic population is calculated for each zones in the form of Standard root mean square error (SRMSE). Figure 8 provide the plot for such values for all subzones of the Flanders that also include zones of the Hasselt city. It can be noted that SRMSE values are around zero for each zone, as the highest value noted is 0.0028. This shows that synthetic population is matching the target marginal very well [*Cho et al., 2014a*]. The population generated using IPU is following the statistics available for year 2017 for Flanders region.

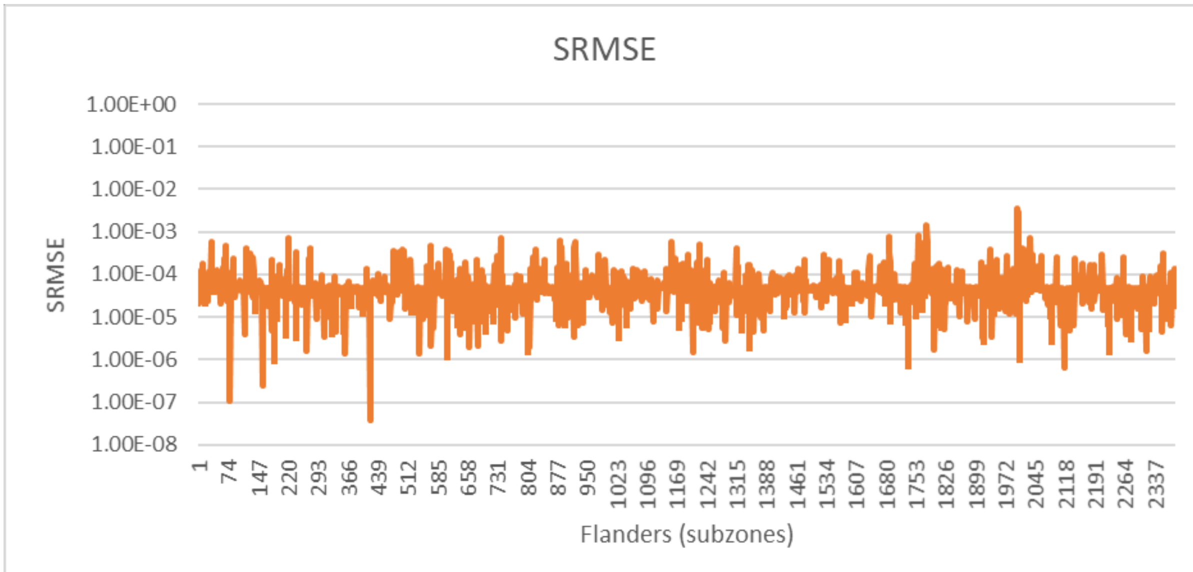


Figure 8: Goodness of fit (SRMSE) for each Zone

4.1.2.2 FEATHERS and MATSIM Outputs

FEATHERS and MATSIM can produce a large variety of results in relation to mobility aspects of every individual in the population. Here, we are presenting results which are aggregated in nature and also representing key mobility features of the city. These results are provided after the calibration of outputs with available traffic volume data for the Flanders. As described in deliverable 4.3, we followed a calibration framework that optimises link capacities (within a specified range for each road category, parameters within the config.xml file of MATSIM mostly mode choice related params) to match the predicted car traffic (in vehicles/hr) from MATSIM with available data on important links of entire Flanders (this data is available for around 400 links of Flanders, and within Hasselt road network traffic volume is available for only 20 locations). The objective function is of OLS type and SPSA algorithm is used to minimise the objective function. The RMSE is also calculated at each calibration iteration and the results are shown in figure 9. Around 50 calibration iterations are performed and within each calibration iteration, 250 iterations of MATSIM are performed. The MATSIM simulations are performed by selecting a geographical region that includes Hasselt city. In this manner, only those individuals from the entire Flanders population are considered that has at least one activity location within the geographical region. This means all Hasselt population is included in the simulation process along with those individuals who are not residing at Hasselt but their schedules predicting an activity location within that region. Through this option, all external trips within Hasselt region is also captured, which is of prime interest. Each MATSIM simulation run (that include 250 iterations) is performed in 612 minutes.

The calibration took around little more than 20 days of a server machine (3.50 GHz with 12 cores) to run those 50 iterations. Figure 9 presents the performance of the calibration framework. The staring value of RMSE is 1.8 and after 50 iterations it has been lowered to 0.15, which can be considered sufficient for such a complex calibration framework [*Lu et al., 2015*]. Further lower values are desirable, but given the time limits we restrict the calibration simulation to be 50 as there seems to be very little improvement if we go for more iterations. The performance graph is not smooth which can be attributed to the stochastic nature of the SPSA algorithm.

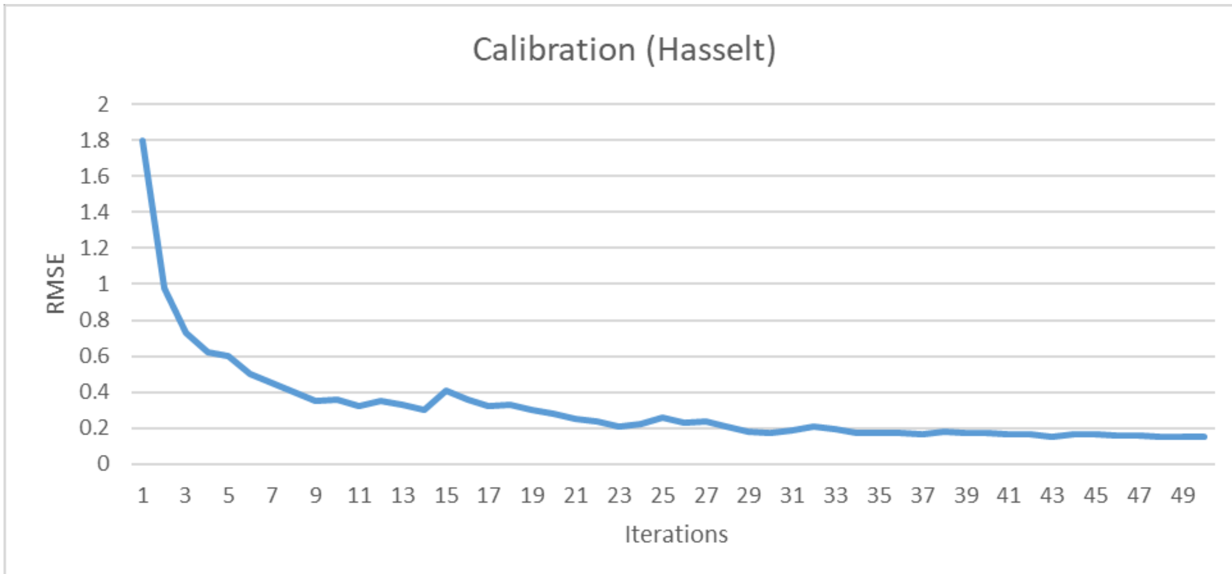


Figure 9: Performance of the Calibration framework

The traffic volume (including freight traffic and public transport) for the morning peak hour can be seen from figure 10 for the reduced road network (representing only Hasselt city premises). Most of the roads contain volume in between 150 to 1500 vehicle/hr (which is lower than the capacity limits), or lesser. However, there are several links which are in yellow and orange colour, clearly showing that traffic volume in the outer ring in rush hour is more than the capacity limits. The traffic volume is more especially at the main junctions of outer ring and the point where the outer ring is connected to the E313 motorway ramps (in the southern part of the outer ring) that connect Hasselt with other major cities of Belgium (such as Brussels, Antwerp, Liege etc.). It should be noted that at the inner ring of the Hasselt, there is significant traffic, however, usually this is considered as a green boulevard. Furthermore, all the major radial roads connecting the inner ring also have significant traffic volume. Most of these major radial roads are connected to links that contain schools. Furthermore, these connecting roads are attracting traffic from the residential roads in between the inner ring and outer ring, these residential roads have lesser traffic compared to the major radial roads that provide smooth connection between inner ring and outer ring.

Figure 11 presents the daily variation of traffic for a weekday (when both directional traffic is combined together) with respect to traffic volume in the peak hour (8 am-9 am). The morning peak is squeezed in comparison to evening peak. The evening peak starts from around 1430 hrs and keep on increasing until it reaches at its maximum point at 1700 hrs. The reason for the early rise of the evening peak is because of the school end time which is usually at around 1515 hrs in Flanders regions.

The outputs mentioned in figure 10 and 11 are important input for emission and dispersion models.

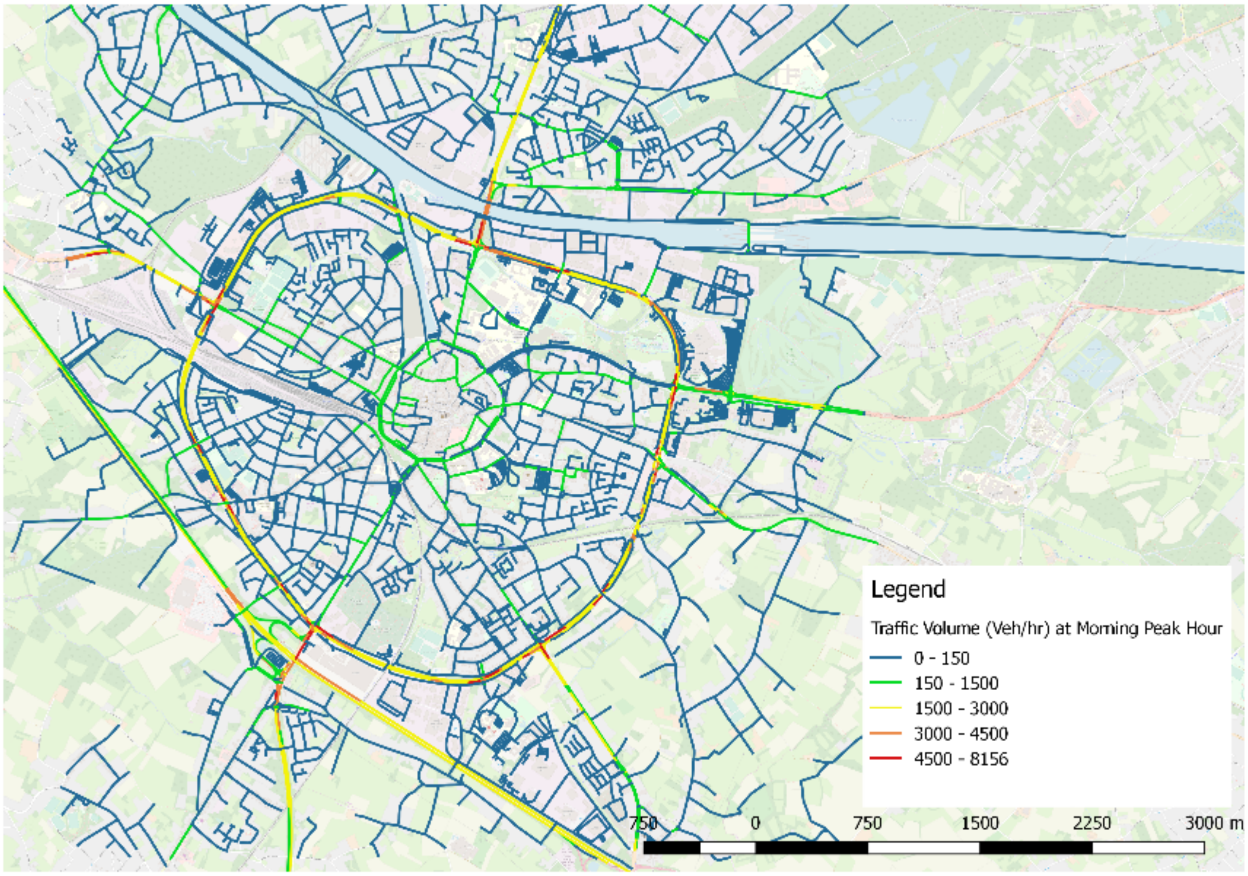


Figure 10: Morning peak hour traffic volume (vehicles/hr) on reduced Hasselt Network

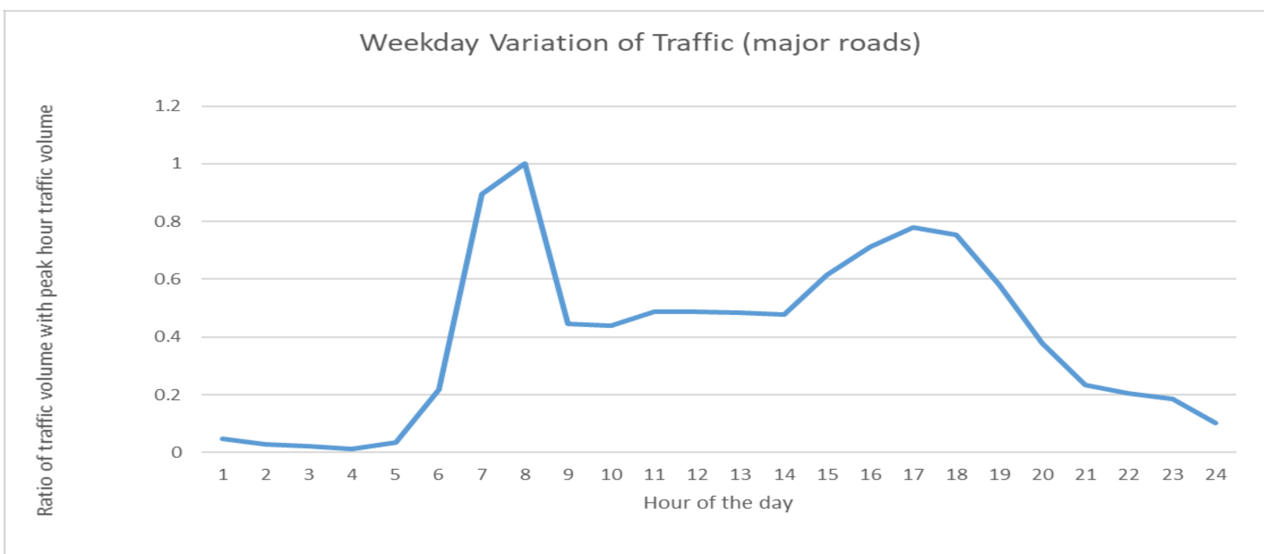


Figure 11: Weekday traffic variation with respect to peak hour traffic volume on major roads

Based on the outputs, we found that there are on average 2.63 person trips per day. Figure 12 presents the travel mode used as a main mode for the tours performed by individuals in the synthetic population. Main mode of the tour indicates that most of the trips of tour are conducted using a particular mode and also the distance covered is higher for such mode. For example, in a single trip to work from home a person can use bicycle/walk to reach at a bus stop to collect the bus to his work location. There may be multiple modes involved, however, the graph below can be interpreted as the main mode of the travel which is bus. Figure 12 clearly indicates that more than 70% of the individuals are using car (either as a driver or car passenger) and around 12% are using bicycles. Public transport (in the form of bus) usage is significantly low, mainly due to higher waiting times (less frequency of buses). Mostly it is used by individuals travelling for education purpose (i.e. students), or are falling under low income or high age categories. Other travel modes include taxi and motorcycles/scooters etc.

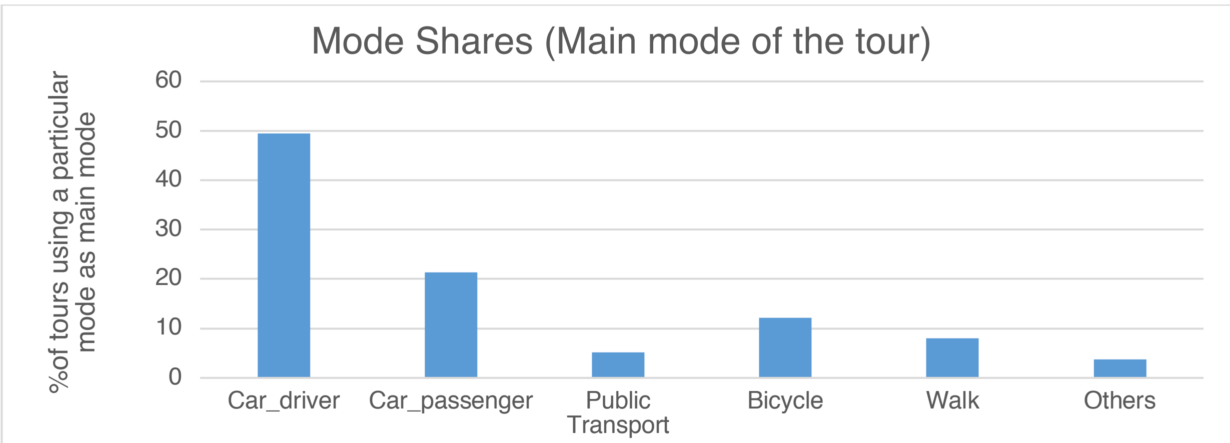
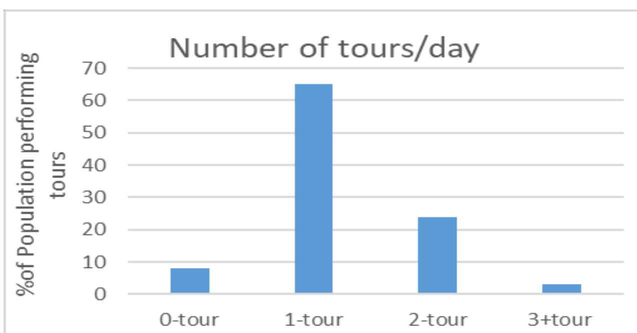
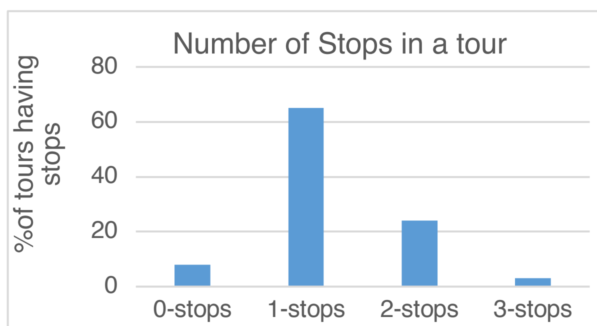


Figure 12: Mode shares as main travel mode of the tour





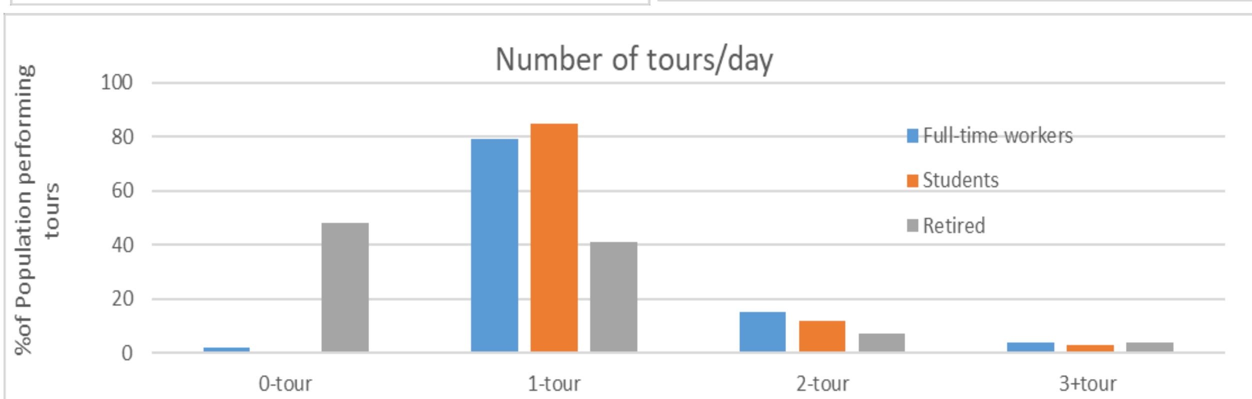


Figure 13: Tour pattern distribution among the population (Hasselt)

Figure 13 presents the distribution of individuals (%) in the population based on number of tours performed in a day and number of stops in each tour. Furthermore, it provides this distribution for type of individual in the population. It can be clearly seen that more than 40% of the retired individuals stay at home the whole day and only a few workers are also staying at home (maybe they are availing work from home opportunity). A plenty of similar outputs can be shown with respect to different socio-economic properties of the individuals in the population. This is useful to identify the impact of a particular policy on different segments of the population, so that more appropriate policy could be designed for different population segments. As we also keep track of these individuals on the road network, so this would give richer framework to make an appropriate estimation of exposure.

4.1.3Policy Scenario 1 – Car Traffic Restrictions

This policy has been found most effective in relation to bring positive environmental impacts. The policy is mostly implemented in many cities of the world by restricting access of diesel cars, or allowing access by paying certain fees (congestion charge zone). In order to raise awareness, Hasselt city organised an event on an annual basis in the city where for a single day inner ring and all roads encompass the inner ring are completely banned for cars. Keeping this as the context, we tested an intervention where 319 links in the road network are completely restricted to access from car. However, the usual bus routes are kept intact. This intervention has been implemented in the behavioural simulator by restricting car access to these roads by introducing a very high penalty to car drivers in the MATSIM simulation platform. In addition, not only change in routes are allowed within MATSIM but also through the integrated framework, mode, activity duration, activity sequence, omission of activity from the schedule and departure times are also allowed to be changed. In this way not only impacts on other links of the road network can be accessed but at the same time, it can be estimated whether individuals have shifted their mode choice or other scheduling dimensions in reaction to that intervention.

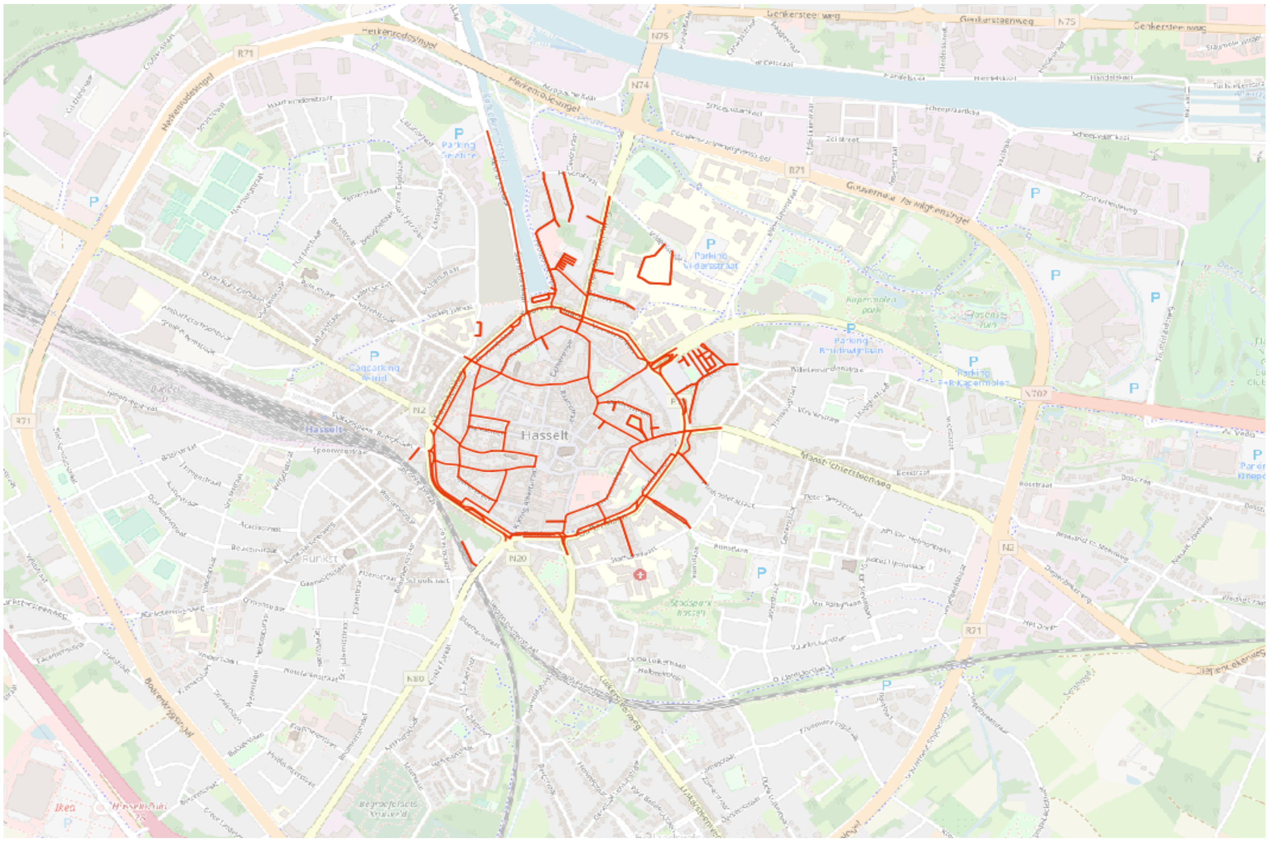


Figure 14: Restricted Car-access links in the Hasselt road network (inner ring and other surrounding links)

The policy is implemented by incorporating changes in config.xml file of MATSIM, where another component is added which is usually used to test road pricing policies [*Horni et al., 2016b*]. As we completely want to restrict car access to those identified links in the road network, therefore, the tolls to travel on to these links are mentioned as a very high number. So that utility of choosing a route that contains any of such links is a very low value compared to other routes in the network, or it may also cause change in travel mode or some other scheduling dimension. In figure 14, links are highlighted in red, where car access is restricted. Figure 15 provides the similar outputs as shown in figure 10 (the base case) and both figures can be compared to see changes in terms of traffic volume for the morning peak hour.

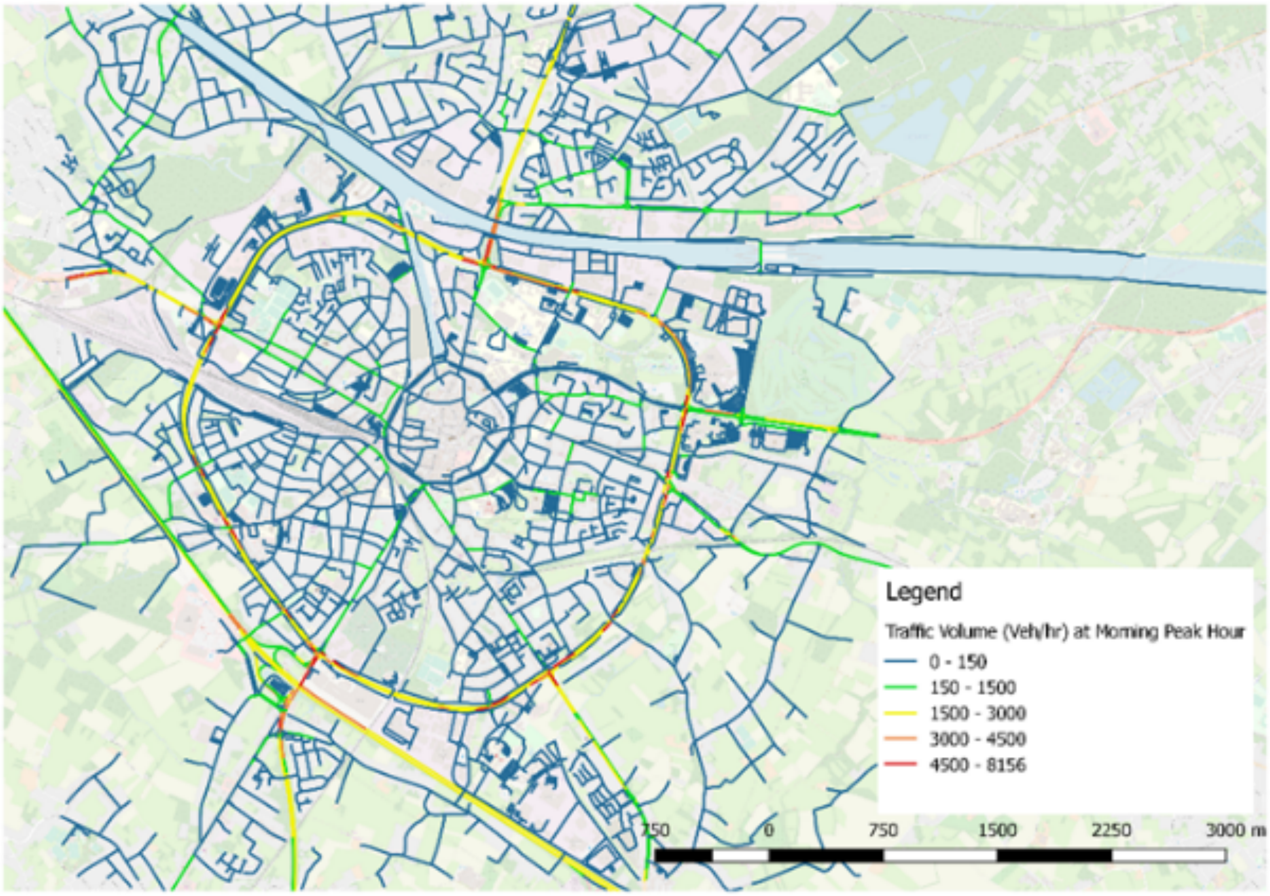


Figure 15: Morning peak hour traffic volume (vehicles/hr) on reduced Hasselt Network- Car Restricted Policy

It can be observed that the inner ring is now in lowest category of traffic volume (the traffic volume is only due to the buses on those restricted links). Other major roads that connect traffic from inner ring to outer ring are in the 2nd lowest category (where traffic volume is still under capacity limits). However, the close examination of values of traffic volume on these radial roads revealed that traffic volume is much lesser on these roads compared to the base case. This is because only the local residents are now using these radial connectors to go towards out ring to find the best possible route to their destination. Furthermore, there is no notable difference found on motorways and other primary arterial roads. In addition to this, we observed the following major changes:

a) Several drivers have detoured their routes as they are now using longer routes in comparison with the base case where car drivers were using more direct routes. It is noted that the travel time of the car drivers on an average has been increased by 9%.
b) Due to the introduction of very high penalty for using the inner ring, 22% of the car trips have reduced where the destination was the inner core zone of the city.This has been distributed as 11% to public transport, 7% to bicycle and 4% to walking. Furthermore, around 6 - 7% of individuals have changed their location of activities from inner city area to other areas in Hasselt city.
c) The majority of the individuals that have changed their travel mode because of this policy belong to the retired and student population.

Figure 16 presents the overall mode share differences between the base case and this policy. The largest difference in percentage points (2.1%) are noted for car passenger use followed by car drivers, and it is translated in terms of use of more buses and then bicycles. In relation to absolute numbers, PT trips increased from 10,150 to 14,385 trips because of this policy (i.e. a difference of 4,235 trips in a day) and car_driver and car_passenger trips decreased from 1,38,200 to 1,31,370 daily trips (i.e. a decrease of 6,830 car trips/day). This is a reasonable decrease in car traffic compared to the size of Hasselt city, and may be helpful in improving the air quality.

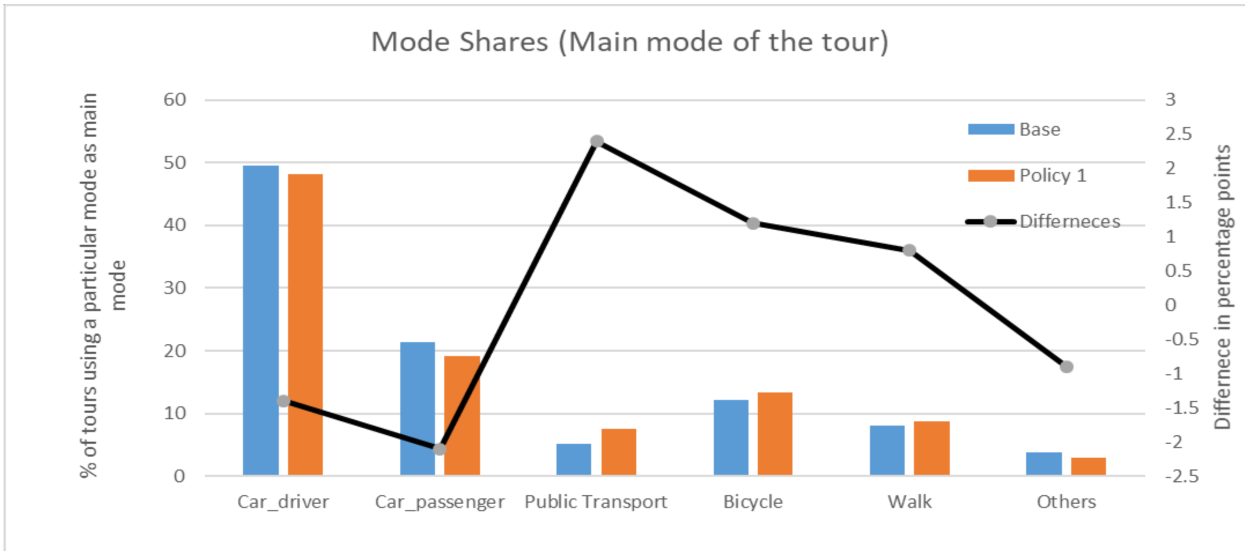


Figure 16: Mode shares as main travel mode of the tour (along with differences with base case)

4.1.4 Policy Scenario 2 – Enhancement of Bus Services

In relation to Policy 2, there is a relatively less concentration of Hasselt city on investments and subsidies for bus-based public transport in the city. As a result, operators have reduced their bus fleet to a significant extent and recently most of the bus routes are re-designed. More than 80% of the households have car ownership and PT is mainly used by low-income individuals, students and senior citizens. All these categories of citizens also have to pay less fare in comparison with other classes. Additionally, children under 12 years of age are enjoying free ride on the bus. To encourage use of public transport, Hasselt city council are now extending this facility to individuals up to 20 years [*Stad_Hasselt, 2019*]. However, in current situation, only 6% of tours have their main mode of travel based on PT, and one of the prime reasons is the less frequency (higher waiting times) of the buses. In total, within Hasselt city, there are around 50 bus routes including 22 routes that are dedicated for serving areas within Hasselt and other bus routes that are serving part of the area of Hasselt and continues towards other surrounding cities (such as Genk, Tongeren, Sint-Truiden, Masseik and even Maastricht (a city in Netherlands) etc.). In peak hours during regular weekdays (also school days), only a handful routes have a frequency of 5 minutes (routes serving Hasselt university campus at Diepenbeek), and some have frequency of an hour as well. However, during the non-peak hours the frequency of the buses is low (around an hour), and therefore individuals tend towards other modes of travel. There is a single operator Delijn that operate the buses. There is also a smart phone application from Delijn, which not only provide the schedule of bus services but also a functionality to pay as you go, if individuals do not have their regular bus passes. A single journey fare is a bit expensive if paid by cash as compared to electronic payment via smartphone, the fare difference is almost 40% [*Dlijn, 2019*]. In addition to this, there are monthly, 3 monthly and a yearly passes available for low income individuals, where basic health insurance companies covers the expenses of the bus travel. Apart from this, there are several employers within the region that provides bus fare subsidies to their employees. Public transport users mostly perceived the bus service as less reliable especially in non-peak hours and sometimes in peak-hour as well. Furthermore, it has been also realised that the bus routes have a very less coverage and at the same time a quite low frequency in places where most of the university students are living.

Based on this context, a scenario was implemented in the microsimulation platform by increasing the frequency of buses. We increased the frequency of around 50% of the current bus routes by double and by 25% for other 50% bus routes. Those bus routes where the bus service is frequent such as within 5-10 minutes in peak hours, these bus routes are not enhanced. Based on this, we have estimated that the bus fleet size requirement will be increased by 35% and at the same time *Delijn* may need to employ more bus drivers and other ground staff. This is a significant investment. The most crucial component to run this policy is the mode choice model within FEATHERS and MATSIM. Within the mode choice model, the PT utility contains a waiting time variable, whose values are changed during the execution of this policy scenario.

The results indicate that this change increased the PT mode share by only 4.8% percentage points (i.e. the overall share of PT for this scenario is 10%). Because of this scenario, car use has been reduced but it is not significant as the majority of the bicycle and on-foot travelers have shifted their mode to PT rather than car users. Figure 17 provides a clearer summary of the changes in mode share distribution in this situation. In absolute terms, PT trips increases from 10,150 to 19,520 (i.e. an increase of 9,370 trips in a day), however this increase is at the cost of decrease in bicycle trips from 23,815 to 20,496 and walking trips from 15,616 to 13,100. Car traffic is reduced only 1.8 percentage points, which is around 3,000 trips in magnitude. The major reason could be that even with low waiting times, bus is still not an attractive travel alternative for individuals who are captive car users.

This policy has not rendered results as expected, and therefore, to encourage use of PT it is also necessary that some other car-based interventions are to be implemented, such as an increase in car use tax and parking cost etc. Furthermore, we also produced an output in terms of traffic volume to visualise changes in the road network. Figure 18 provides these results. In comparison with the base case, no significant changes are visualized within the city road network. The inner ring road and radial roads are having similar car traffic in the peak hour as noted in the base case. This indicates that changes in the car traffic have been occurred in the non-peak hours.

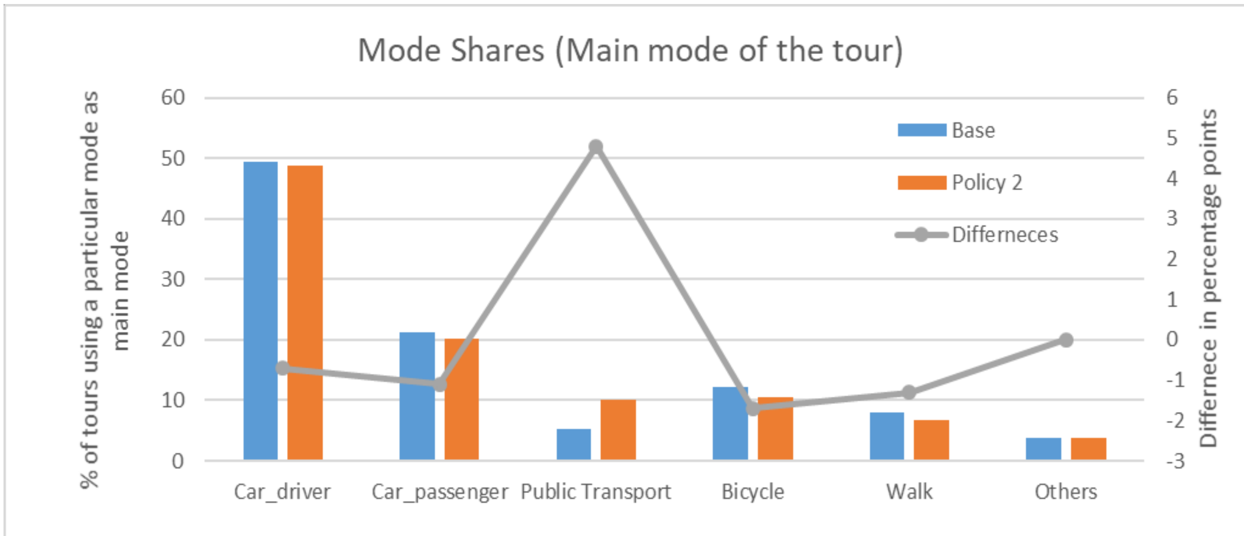


Figure 17: Mode shares as main travel mode of the tour (along with differences with base case)

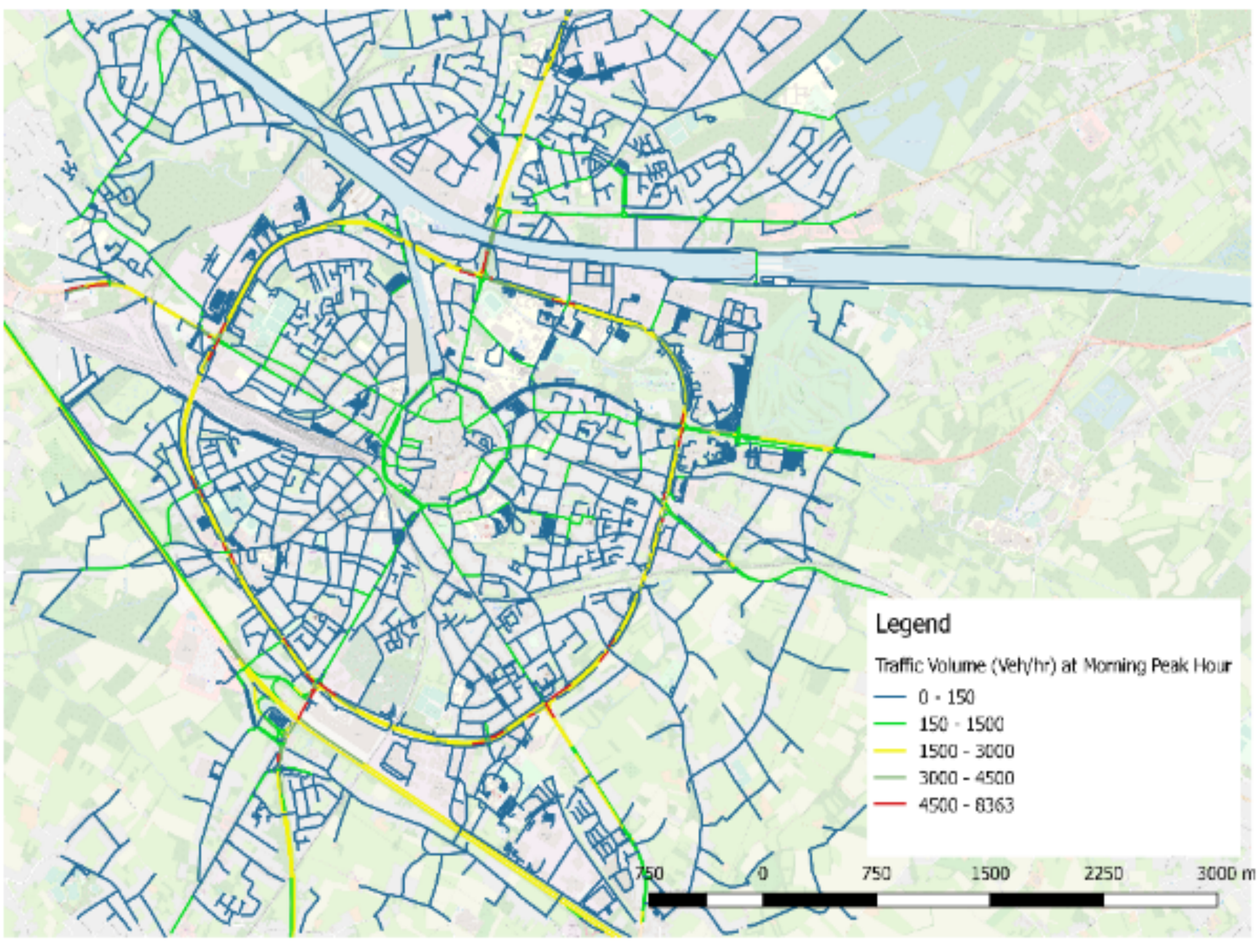


Figure 18: Morning peak hour traffic volume (vehicles/hr) on reduced Hasselt Network - Bus Frequency Enhancement)

4.2 Bologna case

Bologna is the seventh largest densely populated city in Italy. It is located in northern Italy at the foot of the Apennines and between the rivers Reno and Savena. It is the capital and largest city of the Emilia-Romagna Region with population of 388,567. It has population density of 2766 per km² [*CityPopulation, 2019*]. The municipality of Bologna is subdivided into six administrative boroughs as shown in figure 19. Bologna has a very important and busy crossroad for both road and rail due its unique location. The international airport of Bologna further enhances city characteristic as a transportation hub. It is also known as a university town as Bologna has one of the oldest universities in the Western world with around 85,500 students [*de Ridder-Symoens and Rüegg, 2003*]. Bologna has a humid subtropical climate. The average maximum monthly temperature for the year 2018 was reported in July and August i.e. 33 °C. The amount of rainfall is recorded more in August (94 mm) as compared to July (42 mm). In February 2018, average minimum temperature was 3°C which was lowest average temperature during any month. The maximum average rainfall in any month in last year was recorded in February i.e around 227 mm.

Figure 19: Location of Bologna and its Administrative divisions

4.2.1 Mobility context of the city

As Bologna has an industry related to machinery, electronics and food so it attracts a lot of people making it an important hub for road and rail transport in the northern region of Italy. Due to this Bologna also have a seventh busiest Italian airport for passenger traffic (8 million passengers handled in 2017). Bologna central train station is also very busy due to the city's strategic location as a crossroad between north-south and east-west routes. It serves 58 million passengers annually. By road it is accessible via the A1 from Milan, the A22 and E35 from Verona and the A13 from Venice as shown in figure 20.

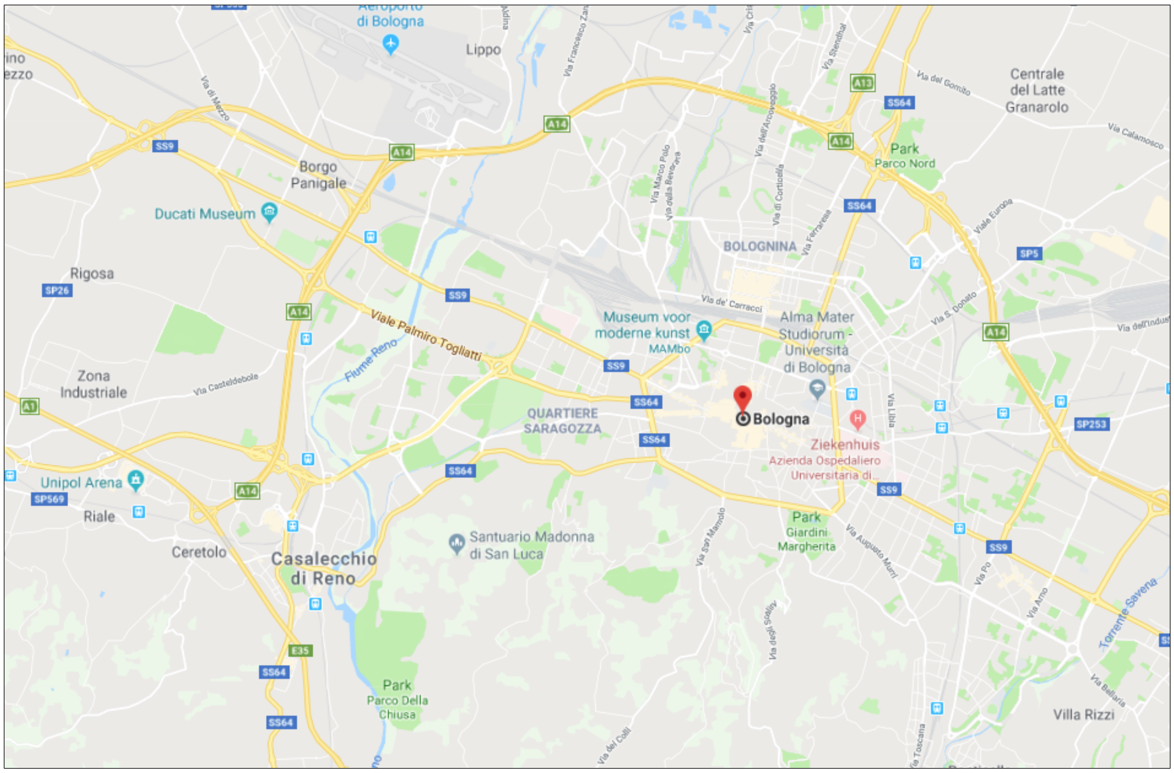


Figure 20: Bologna Road Network

Due to the industrial and educational zone, lot of commuters enter/ leave the city and create traffic congestion specially on the approach road to the cities on peak hours. Although the city is served by a large network of public bus lines, including trolleybus lines, operated since 2012 by Trasporto Passeggeri Emilia-Romagna SpA (TPER) but still highest mode share for transport in the city is by car i.e. 35%. And then by public transport i.e. 26% [*Barrett, 2018*]. The average amount of time people spend commuting with public transit for example to and from work, on a weekday is 53 min. 9% of public transit riders ride for more than 2 hours every day. The average amount of time people wait at a stop or station for public transit is 12 min, while 16% of riders wait for over 20 minutes on average every day. The average distance people usually ride in a single trip with public transit is 5.4 km, while 7% travel for over 12 km in a single direction [*Moovit, 2019*].

The historic city of Bologna is surrounded by a ring road (8 km in length) that is further connected with highways approaching from north south and east west of Italy. Most of the historic, administrative and educational buildings such as Piazza Maggiore (Palazzo D'Accursio, Salaborsa Library, Palazzo Podestà and Palazzo Re Enzo), Basilica of San Domenico, University district (Alma Mater Studiorum - Università di Bologna) etc are located near the city centre so during the day, lot of traffic flow towards the center using connecting and ring roads. Due to this congestion occurs at various spots during peak hours. City has a large network of bus and trolley bus based public transport system operated by TPER. All the buses start and end their trip at a point just outside the ring road near a train station.

Keeping in view the increasing traffic volume on roads approaching toward city centre, the city of Bologna is taking measures and designing policies to tackle this problem. As shown in figure 10 more than 10 parking areas below are created for the commuters who come via car to visit the city center and surrounding area for performing various activities. The inner core of the city is also made traffic free and one can visit that area only by foot or bike as illustrated by the green area in the road network in figure 21).

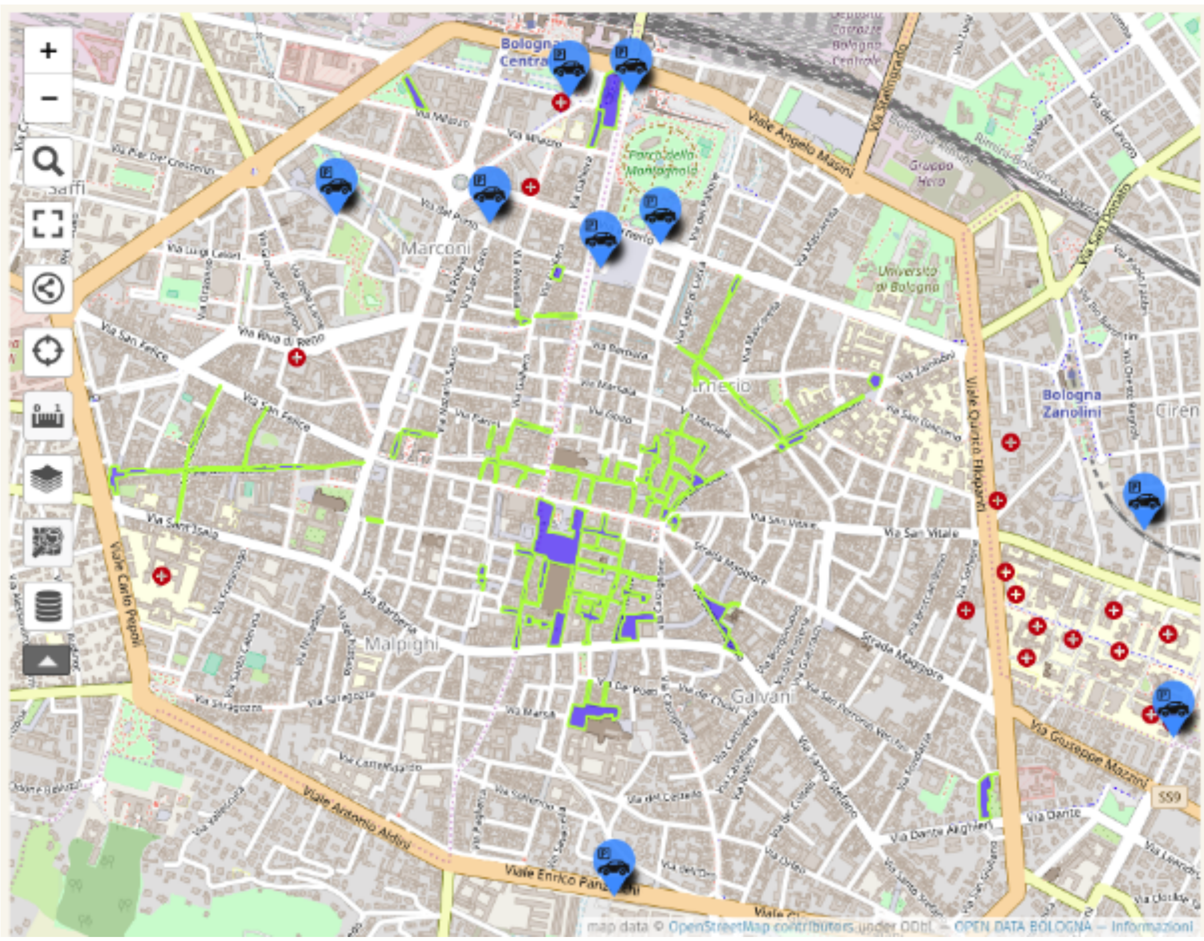


Figure 21: Bologna ring road network with parking spaces and motor vehicle free routes (source: [Comune_di_Bologna, 2019])

The city administration has also defined Limited Traffic zone (ZTL) which is a large area located within the historic centre of Bologna. In this zone the movement of motor vehicles is subject to limitations, everyday from 07:00 am to 08:00 pm. Particular types of vehicles such as buses, bicycles, mopeds (two, three, four wheels), vehicles of hotel customers, vehicles equipped with a special access ticket, validated and displayed on the vehicle can enter this area. Within ZTL there are some areas only accessible by pedestrians for 24 hours.

There is also special mobility conditions in the so-called "T" which is located in the heart of the historic centre of Bologna, in an area of great tourist and monumental interest that is also one of the most lively commercial areas of the city. Its name derives precisely from its geographic conformation, as there are three roads representing an inverted T.

The "T" zone includes the following three links:

1. Via Rizzoli (except for the semi-roadway that leads from Via Calzolerie to Piazza della Mercanzia)
2. Via Ugo Bassi (except for the semi-roadway that from Piazza Malpighi leads to Via Testoni and from Via Nazario Sauro to Via Marconi)
3. Via Indipendenza (from the intersection with Ugo Bassi and Rizzoli up to the intersection with Righi and Falegnami)

The "T" is controlled 24 hours a day by the RITA remote control system. From Monday to Friday (excluding mid-week holidays) no personal vehicles except bicycles, mopeds and electric (two and three-wheeler) can enter the “T” zone. Every weekend, from 8:00 am to 10:00 pm on Sundays and all holidays from 8:00 am to 10:00 pm, the Zona T (via Rizzoli, via Indipendenza and via Ugo Bassi) is open only to pedestrians and bicycles.

In October 2008, the "Zona Universita" is formed by the areas of Fine Arts and Belmeloro, located north and south of Via Zamboni respectively, for now excluded from the provision. In the university area, 24 hours a day, seven days a week, access to cars and motorbikes (both motorcycles and mopeds) is prohibited. Access control is ensured by the video cameras located at via Bertoloni and via Belmeloro.

The promotion of bicycle use as an alternative to motor vehicles is one of the most significant commitments for sustainable development, contributing to the reduction of emissions of polluting gases into the atmosphere and to the decongestion of urban traffic. To encourage the reduction of car use, it is essential to create a continuous, safe and well-recognizable network of cycle connections, as well as integrating it with other forms of mobility. In this regard municipal administration of Bologna is focusing on completion and continuity of the itineraries, starting from the Historic Center and first suburbs. Recently 8.4 km of bike path along the ring of the Viali is constructed as shown in figure 11, which acts as a fundamental hinge between all the radial paths that connect the suburbs to the city centre [*Comune_di_Bologna, 2019*].

Figure 22: Bicycles ring road - Porta Maggiore - Viale Carducci (Source: [Comune_di_Bologna, 2019])

4.2.2Base case calibration- Results

This sub-section presents the base case results of the mobility pattern in Bologna after performing the simulation in the developed behavioural simulation platform described in section 3.2. The main results are as follows:

4.2.2.1 Synthetic Population

Based on the marginal totals (zone marginal/target marginal) and with the availability of seed data in the form of recorded personal activity-travel diaries with household and personal based socio-economic factors, a synthetic population is generated for the city of Bologna. It should be noted that the seed data is only available for around 20 individuals from the entire Bologna. Furthermore, the attributes in the zonal marginal are also limited such as gender, age categories, and family size within the household for around 2,333 census sections in Bologna. We considered that spatial unit as an analysis zone. This is a much better resolution of spatial units compared to Hasselt city. The IPU algorithm is run in parallel to generate the population for Bologna. A particular zone (census section) took an average of around 36 seconds to generate its population. It is run in similar format as illustrated in figure 7 for the Hasselt case. However, the only difference is that the seed data is assumed same for each census section.

Based on the consistency check as described in deliverable 4.3, available target marginal and the same statistics obtained from the generated synthetic population is calculated for each zone in the form of Standard root mean square error (SRMSE). Figure 23 provides the plot for such values for all census sections of Bologna. It can be noted that SRMSE values are below 0.1 for most zones, as the highest value noted is 0.27. This shows that synthetic population is matching the target marginal to a reasonable extent as for only a few zones (4 zones) the error is in the range of 20% to 27% [*Cho et al., 2014a*]. The population generated using IPU are following the statistics available for the year 2016 for Bologna.

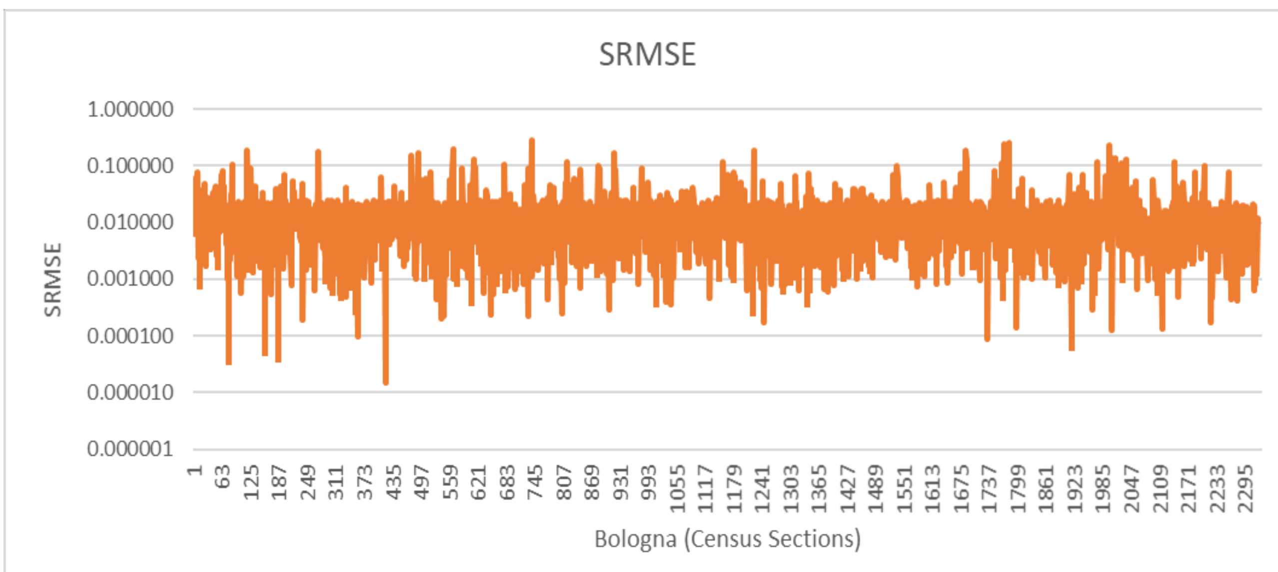


Figure 23: Goodness of fit (SRMSE) for each Zone

4.2.2.2 Simulation Outputs and Calibration

The light version of activity-based model and MATSIM can produce a large variety of results in relation to mobility aspect of every individual in the population. Here, we are presenting results which are aggregate in nature and also representing key mobility features of the city. These results are provided after the calibration of outputs with available traffic volume data for the Bologna. As described in deliverable 4.3, we followed a calibration framework that optimizes link capacities (within a specified range for each road category, parameters within the config.xml file of MATSIM mostly mode choice related params) to match the predicted car traffic (in vehicles/hr) from MATSIM with available data. For Bologna, the links counts are available for another calibrated network that includes only major roads. We are using a more detailed network available from OpenStreetMaps, so that we can appropriately map the bus stops for all bus routes within the area. Furthermore, the link counts available for the Bologna network contains total link volume (combining both directional flows). Because of the different resolution of the two networks, we followed a slightly different approach for the calibration. We have marked the grids (based on horizontal and vertical lines to form a number of square boxes as a mesh) on both networks and matched the traffic volume by summing all links falling in a respective square box of the mesh (This is shown in figure 24 as a snap shot for a given Bologna network). In total these square boxes are 5078 (excluding those in which there is no link). The objective function is again an OLS type and the SPSA algorithm is used to minimize the objective function. The RMSE is also calculated at each calibration iteration and the results are shown in figure 25. Around 50 calibration iterations are performed and within each calibration iteration, 250 iterations of MATSIM are performed.

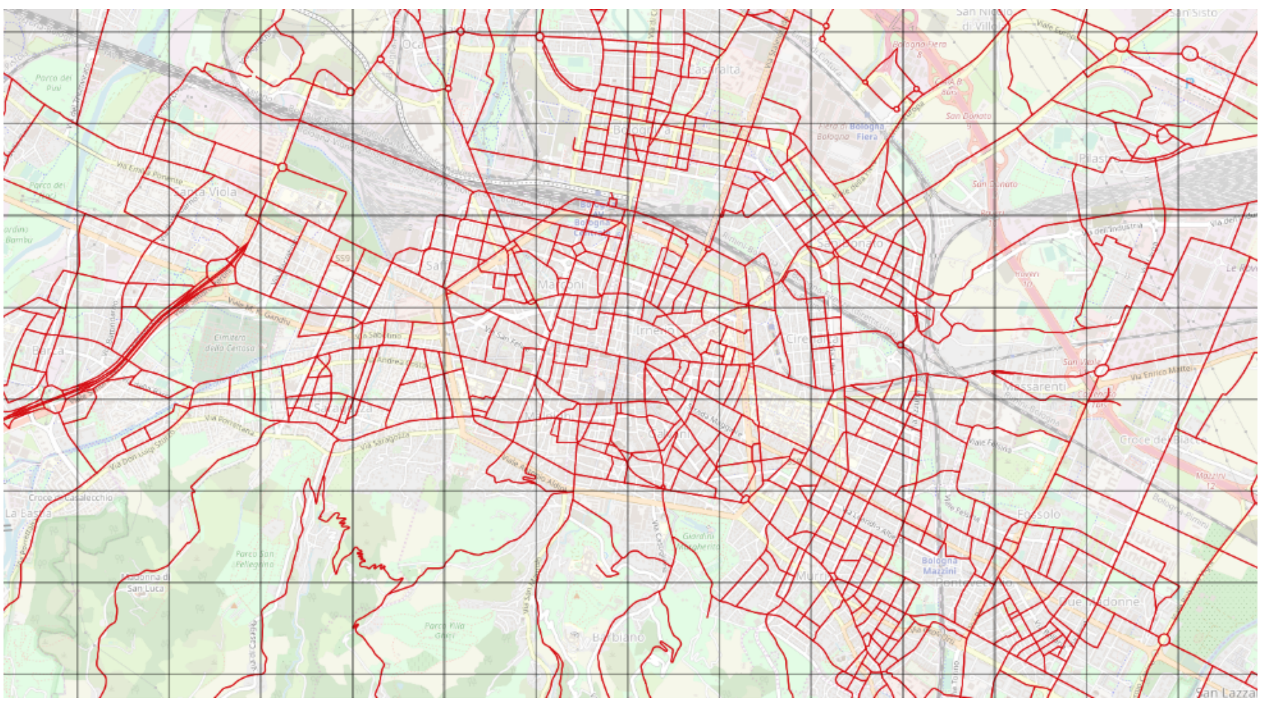


Figure 24: Mesh over the given Bologna network

The MATSIM simulations are performed by selecting a 20% population of Bologna in order to keep check on simulation run time. The final output is expanded for the entire population. Each MATSIM simulation run (that includes 250 iterations) is performed in 432 minutes. The calibration took around little more than 15 days of a server machine (3.50 GHz with 12 cores) to run those 50 iterations. Figure 25 presents the performance of the calibration framework. The staring value of

RMSE is 2.4 and after 50 iterations it has been lowered to 0.26, which can be considered sufficient based on the availability of the datasets, especially in relation to schedules that are generated from light version of the activity based model[*Lu et al., 2015*]. The undulations within the calibration framework are attributed to the stochastic nature of SPSA.

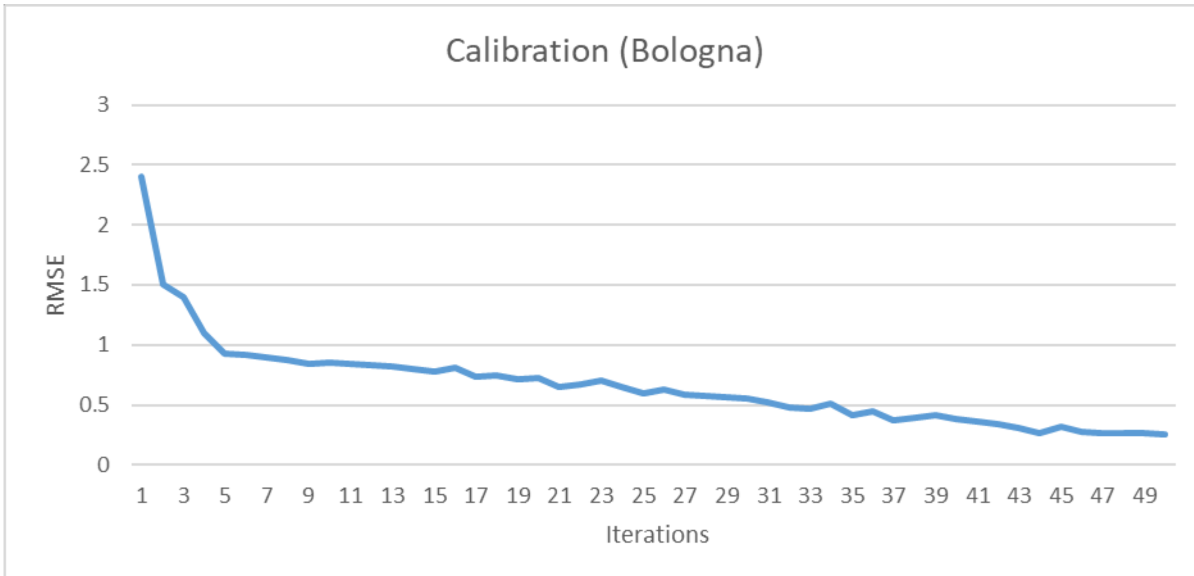


Figure 25: Calibration framework performance

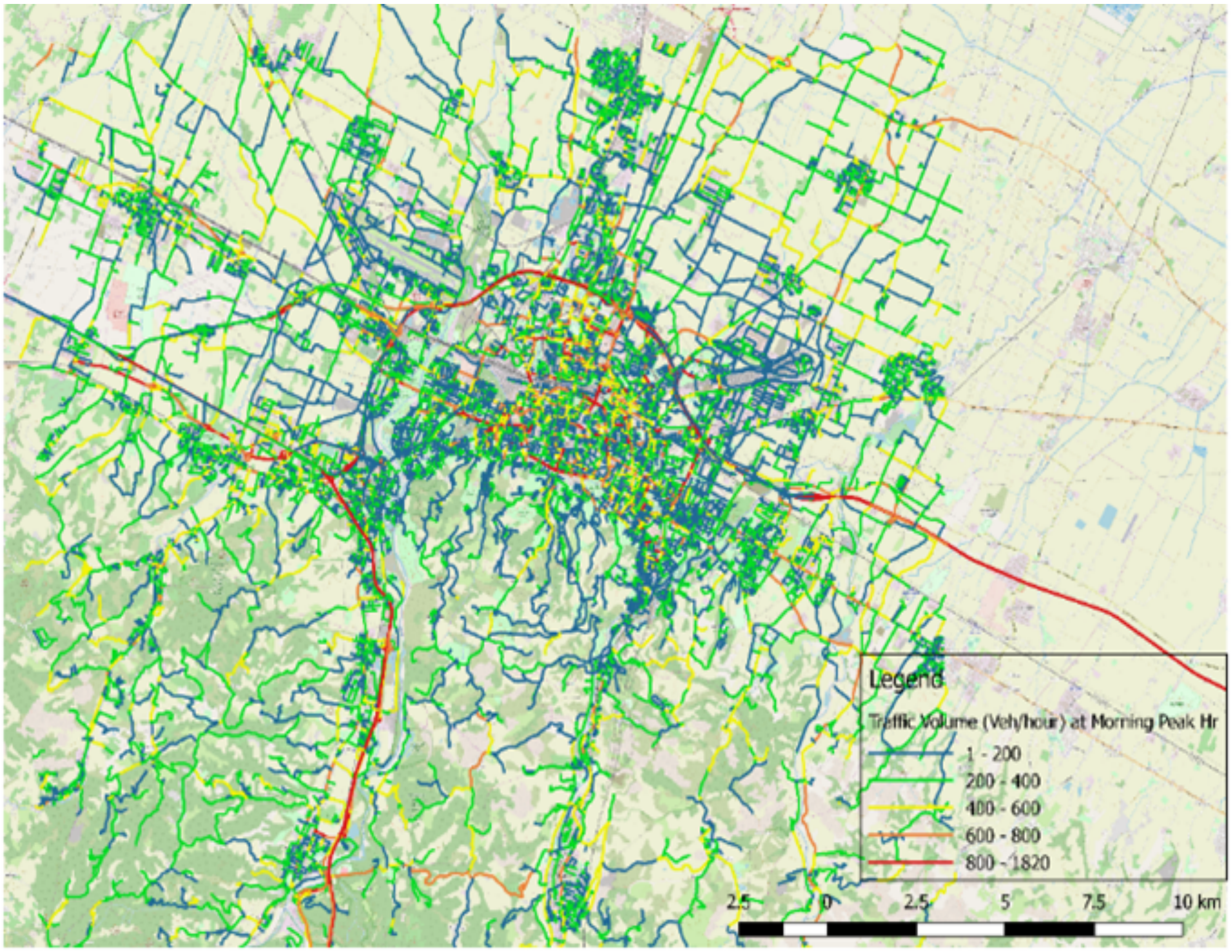


Figure 26: Morning peak hour traffic volume (vehicles/hr) on Bologna Network

The traffic volume (including freight traffic and Public transport) for the reduced road network (representing Bologna premises) during the morning peak hour can be seen in figure 26. The motorway marked in red can easily be visualised around which the city road network is located. Furthermore, there is lesser traffic in outskirt of the city and it is increasing around the main ring of the city. It is difficult to visualize each individual link on the road network. We also provide the mode shares obtained from the travel schedules in figure 27. Unlike Hasselt case, individuals in Bologna are using PT, bicycles and walking (contributed towards active mode of travel) as their main mode of travel, which is around 58% of the total due to the highly connected and frequent public transport network and progressive policies to encourage sustainable mobility (i.e. encouraging bicycles and walk). Figure 28 shows tour pattern distribution of individuals in Bologna. Compared to Hasselt, more individuals are performing two and three tours in a day. In addition, tours are more complex (having 1 or more intermediate stops). Also retired population is more mobile in comparison to Hasselt case.

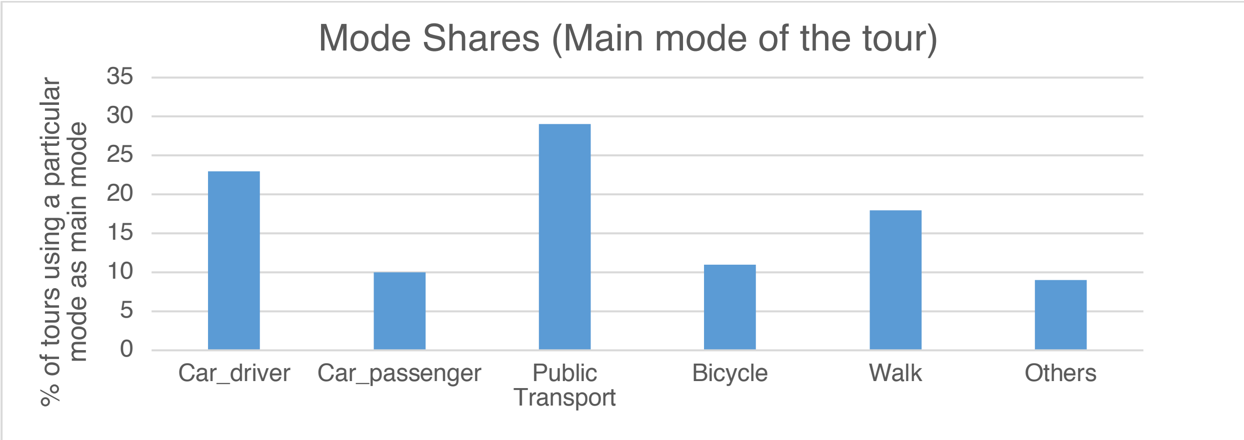


Figure 27: Mode share based on the tours

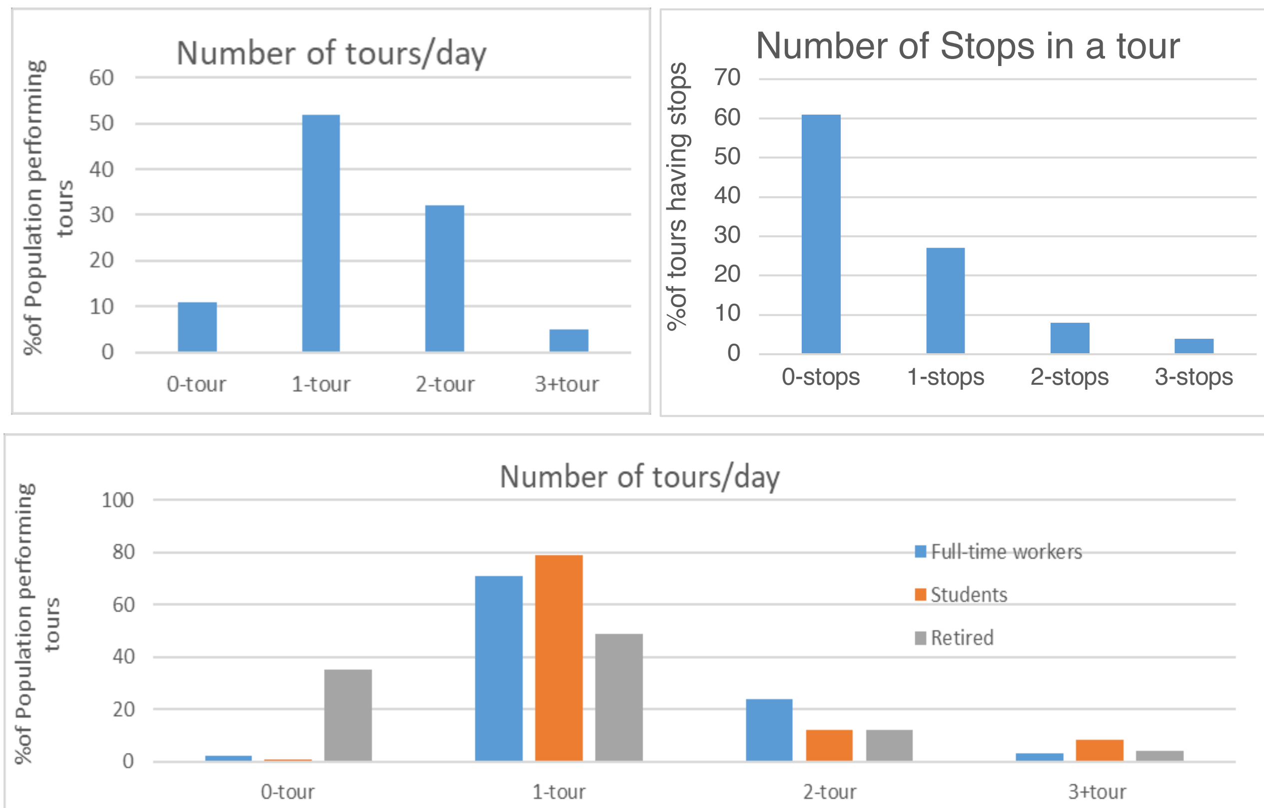


Figure 28: Tour pattern distribution among the population (Bologna)

4.2.3 Policy Scenario 1 – Car Traffic Restrictions

Because of the most effective nature of this policy in relation to improve air quality, car traffic restrictions are simulated for Bologna as well. As in sub-section 4.2.1, it is already mentioned that there are number of links which are already car free within the core region of Bologna. In this policy, we have extended that network of car free links, in order to see what improvements can be achieved in terms of air quality. Keeping this as the context, we tested an intervention by restricting 1024 links (this includes those which are already car free links) in the road network to access by cars. However, the usual bus routes are kept intact and electric cars can travel to these links. This intervention has been implemented in the behavioural simulator by restricting car access to these roads by introducing a very high penalty to car drivers in the MATSIM simulation platform [*Horni et al., 2016a*]. In addition, not only change in routes are allowed within MATSIM but mode, activity duration, activity sequence, omission of activity from the schedule, departure times choices are also allowed to be changed. In this way not only impacts on other links of the road network can be accessed but at the same time, it can be estimated that whether individuals have shifted their mode choice or other scheduling dimensions in reaction to that intervention.

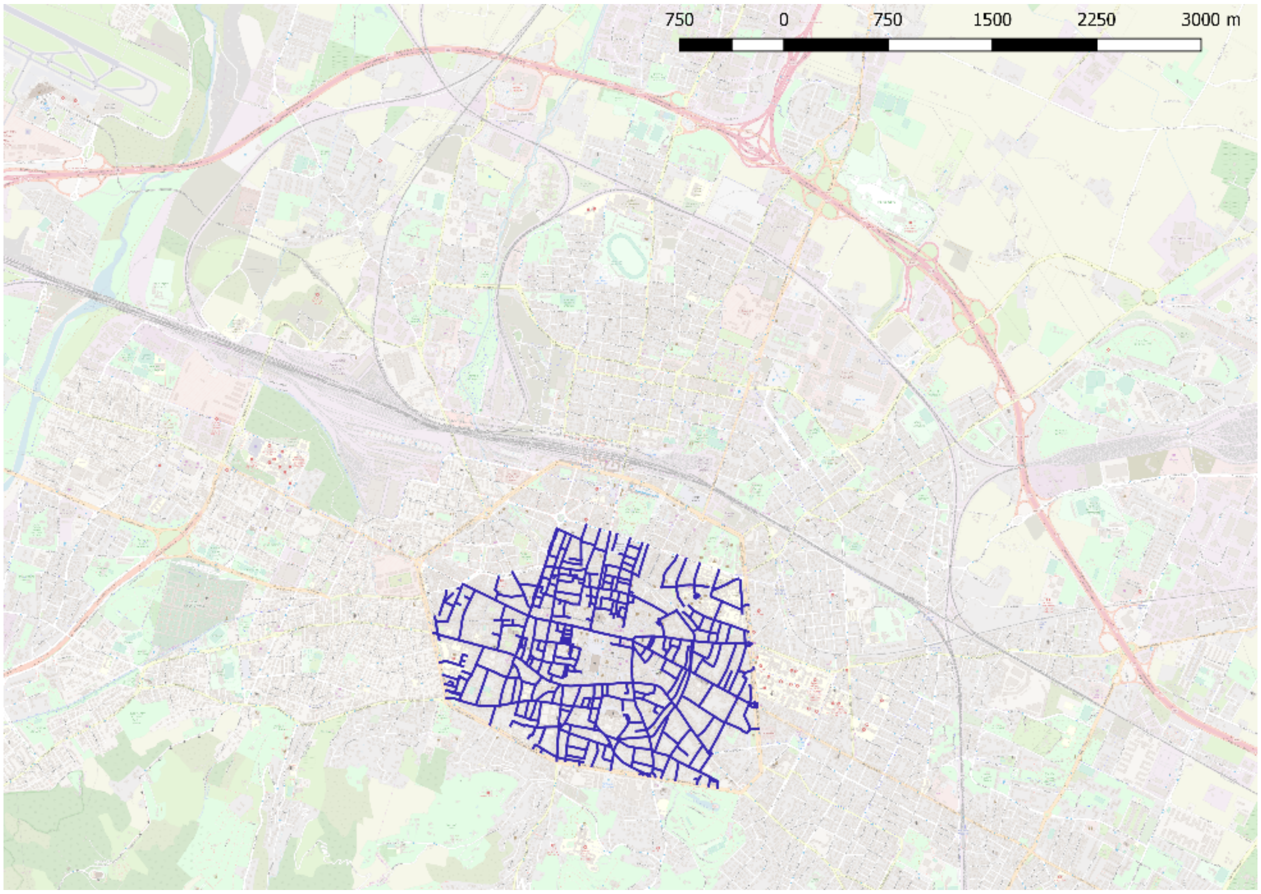


Figure 29: Restricted Car-access links in the Bologna road network (links inside the ring)

The policy is implemented by incorporating changes in config.xml file of MATSIM, where another component is added which is usually used to test road pricing policies. As we completely want to restrict car access to those identified links in the road network, therefore, the tolls to travel on to these links are mentioned by a very high number. So that utility of choosing a route that contains any of such links is a very low value compared to other routes in the network, or it may also cause change in travel mode as well or some other scheduling dimension. In figure 29, links are highlighted in blue, where car access is restricted. Figure 30 provides the similar outputs as shown in figure 26 (the base case) and both figures can be compared to see changes in terms of traffic volume for the morning peak hour.

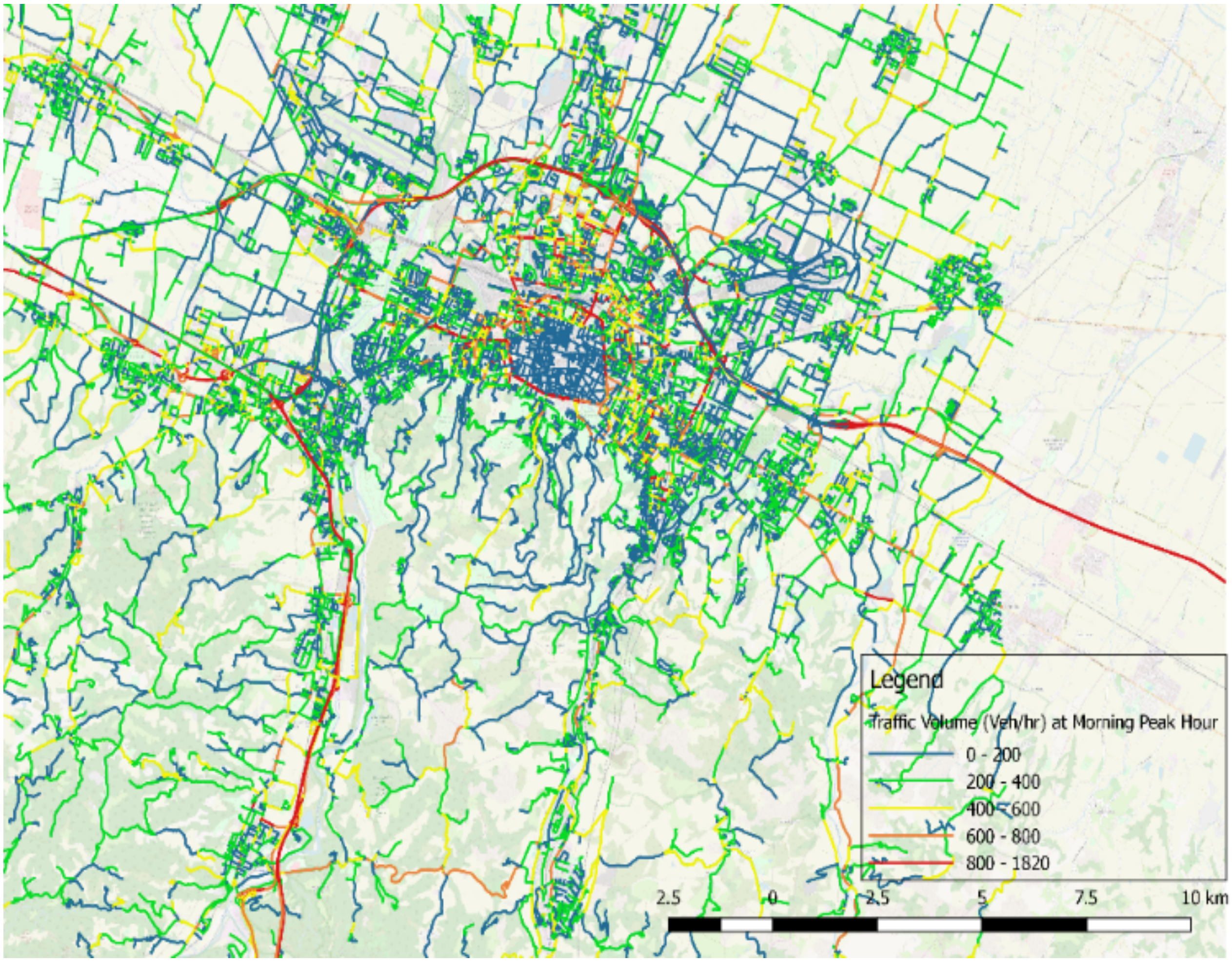


Figure 30: Morning peak hour traffic volume (vehicles/hr) on reduced Hasselt Network- Car Restricted Policy

The comparison of figure 30 with the base case (figure 26) has revealed contrasting results compared to the case of Hasselt. All the roads where car traffic is restricted have very low traffic volume (first category), however, the traffic volume on the ring road has significantly increased. This is because in the case of Hasselt, the inner ring road itself is restricted for car access, and therefore, that situation causes no connectivity with other major roads. In the case of Bologna, only links inside the ring roads are restricted for car access, and therefore, the situation does not cause any significant loss of connectivity of the road network. Individuals visiting locations inside the ring road can still travel on the ring road to park their vehicle at a decent location. Moreover, car traveller who can previously use links inside ring road to cross the ring are now detouring by moving on the ring road to reach to their destination. Furthermore, there was no notable difference found on motorways and other primary arterial roads. In addition to this, we observed the following major changes:

a) Several drivers have detoured their routes as they are now using longer routes in comparison with the base case in which car drivers were using more direct routes. It is noted that the travel time of the car drivers on an average has been increased by 13%.
b) Due to the introduction of very high penalty for using the road inside the ring, 10% of the car trips toward inner city have reduced. This 10% of car trips have been distributed as 8% to PT, 1% to bicycle, and 1% to walking. Furthermore, around

2% of individuals have changed their location of activities from inner city area to other areas in Bologna

c) The majority of the individuals that have changed their travel mode because of this policy belong to student population and low-income categories.

Figure 31 presents the overall mode share differences between the base case and this policy. The largest difference in percentage points (-1.3%) are noted for car passengers, followed by car drivers and other mode users, and it is translated in terms of use of more buses and then bicycles. In relation to absolute numbers, PT trips are increased from 0.337 million trips/day to 0.360 million trips/day trips because of this policy (i.e. a difference of 23000 trips approximately in a day). Car_driver and car_passenger trips are decreased from 0.382 million trips/day to 0.358 million trips/day (i.e. a decrease of 25000 trips/day). This is a significant decrease in car trips/day due to the strict nature of this policy.

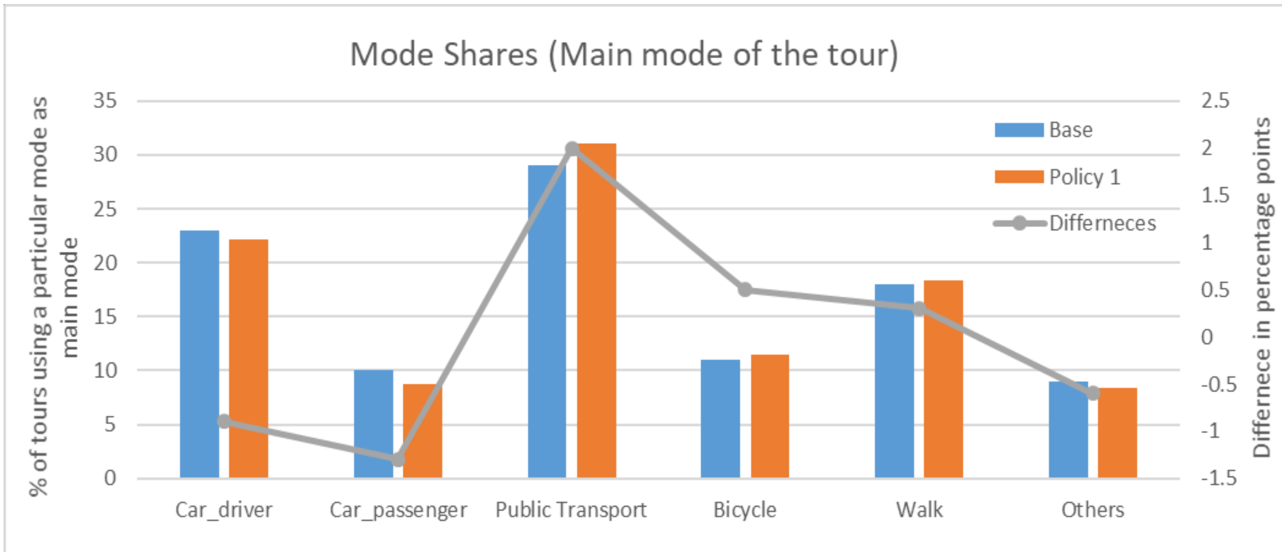


Figure 31: Mode shares as main travel mode of the tour (along with differences with base case)

4.2.4 Policy Scenario 2 – Activity-timing Restrictions

Due to the already significant use of public transport (compared to Hasselt city) and also the recommendations of stakeholders (Partners in Bologna), the second policy scenario tested for Bologna is based on restricting the opening hours of shops/markets. In Bologna, shops are usually open from Monday to Saturday from 09:00-13:00 hrs and after a lunch break from 15:30 - 20:00 hrs. Thursday is an unusual day when shops are closed in the afternoon. Some large supermarkets however open till 21:00 hrs in the night [*WTG, 2016*]. In the base scenario, we followed this schedule for thirty-minute shopping activities. For shopping activities of less than 30 minutes, there are no restrictions applied for open and end times within the base case. It is assumed that these shopping activities are based on the local shops/night or day shops which can be carried out during reasonable hours of the day (starting from 6:00 am to 2:00 am in the night).

For this particular policy, we ran a simulation by setting out open times for shopping from 1000 hrs in the morning to 2000 hrs in the night. Therefore, only opening times are changed primarily to reduce morning peak traffic on the road network. It should be noted that within the simulation framework only those individuals who are performing shopping activity for duration larger than 30 minutes will be effected from this change. However, individuals who are going for work activity within these shops/malls/market are not affected by this change, as work activity within the simulator does not have further distinctions in relation to location where this activity are performed.

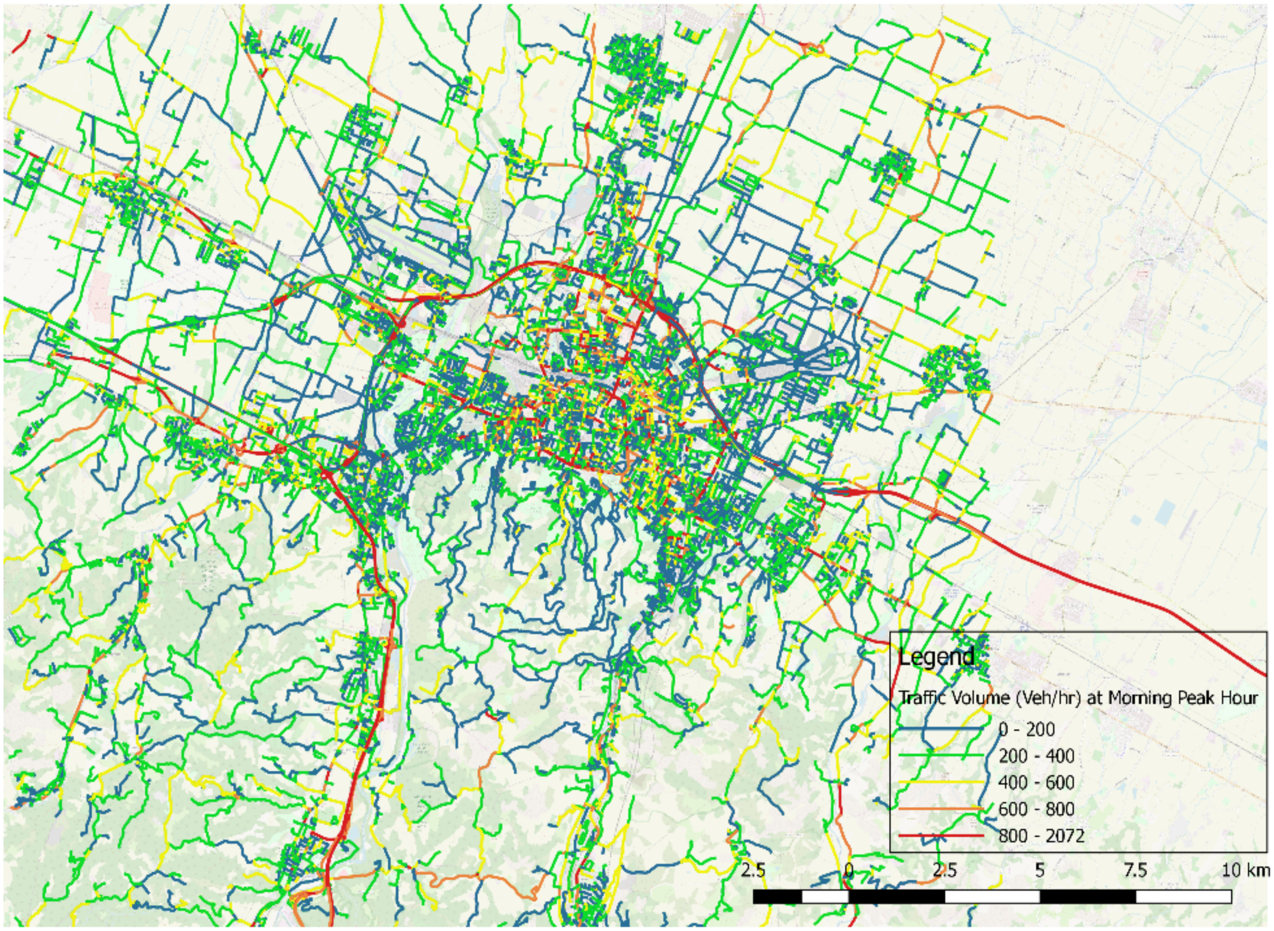


Figure 32: Morning peak hour traffic volume (vehicles/hr) on reduced Hasselt Network- Restricted Activity Timing Policy

Figure 32 presents the similar output as presented for the base case in figure 26 (i.e. morning peak traffic volumes on the road network). The comparison in terms of visualization shows no significant differences probably because the target group (those individuals who are performing shopping activity of more than 30 minutes) count is lower in the morning period. However, we have identified a few differences by looking closely on traffic counts for links inside and around the ring where there are large supermarkets/malls and where shops are located. The following are the observations:

a) The links close to the ring roads have a lesser amount of traffic volume in comparison to base case. This difference is varying around 6% - 9% lesser in relation to base case.
b) It is found that females with age greater than 30 years and retired individuals are involved in shopping activities greater than 30 minutes during the morning peak period in the base case. In the policy simulation, 70% of such tours have their departure times shifted to later time period. It should be noted that we have defined departure times based on 15-minutes interval within MATSIM departure times. Figure 33 presents the distribution of starting times of such shopping activity for all segments of the population.

c) No significant change in mode share is noted because of this policy. The low traffic volume on certain roads may be because of shifting the start time of shopping activities.
d) We also did not found any significant change in the overall shift in the morning peak period due to this policy.

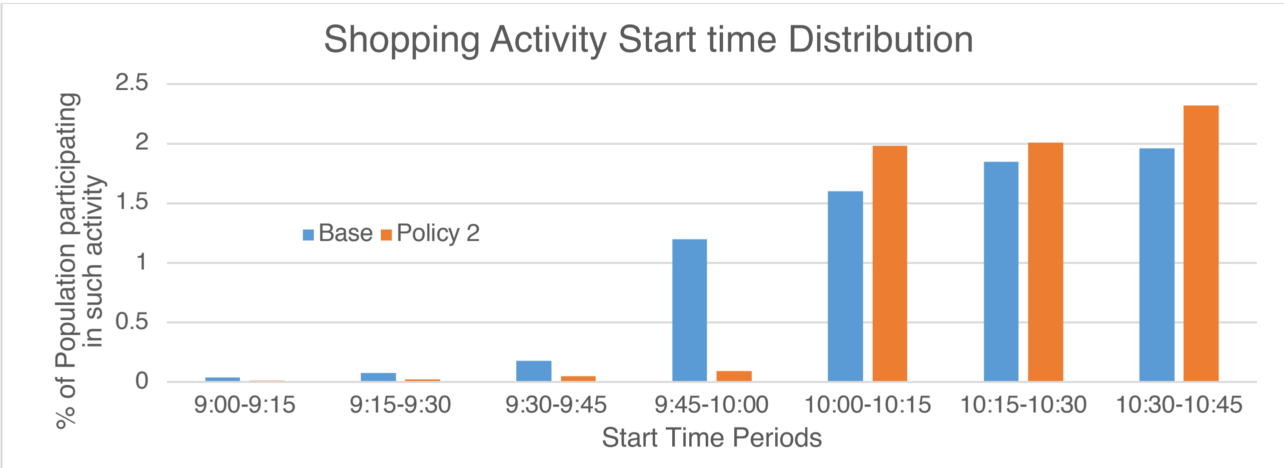


Figure 33: Shopping activity start time distribution

The policy has some impact, but its significance in relation to emission and air quality is quite low. However, it may cause significant differences in terms of improving the comfort level of commuters who are usually using PT as their usual mode as those affected by this policy mostly travel by public transport. Because of their shift in terms of activity start time at a later time period, therefore, their departure time from previous activity (in most cases it is home) are also shifted to later time periods. Therefore, congestion in the buses may have reduced at these times.

4.3 Vantaa case

Vantaa is a 4th largest municipality and city of Finland with 225,682 inhabitants. It is a part of capital region together with Espoo and Kauniainen and located beside Helsinki as shown in figure 34 . In Vantaa majority of the people speak Finnish language i.e. ± 95%. Vantaa has a total area of 238 km² with population density of 947 individuals / square km. Helsinki-Vantaa airport which is the largest Finnish airport served around 19 million passengers in 2017, ten percent more passengers in 1 year [*FINAVIA, 2019*]. Due to proximity of the airport many logistics and production companies are primarily located in Vantaa which attracts a lot people from surrounding municipalities for work. Vantaa also has a university named as Laurea University of Applied sciences having a student body of around 8000 students. All these factors have contributed in the rapid development of the area and put Vantaa in the list of big cities of Finland. Vantaa has a humid continental climate with severe winters and no dry season. The average maximum monthly temperature for the year 2018 was reported in July i.e. 24 °C and the average rainfall recorded in the same month is 74 mm. In February 2018 average minimum temperature was -9°C which was the lowest average temperature during any month. The maximum average rainfall in any month in last year was recorded in September i.e. around 112 mm.

Figure 34: Location of Vantaa as a part of Helsinki Capital region

4.3.1 Mobility context of the city

Vantaa is a big transportation hub as it has a largest airport with lot of logistic companies working around it. Helsinki city centre is only 30 minutes away from Vantaa airport which resulted in a lot of commuters enter and leave the city daily. Tikkurila Station, located in Vantaa is one of the busiest railway stations in Finland. Most of the trains leaving from Helsinki Central Railway Station go through Tikkurila, including Allegro, the train going to St. Petersburg (Russia). Most of the main roads (Ring Road III, Tuusulanväylä, Hämeenlinna motorway) shown in figure 35 run through Vantaa and result in a huge traffic volume passing through the city.

In Vantaa, the most used mode of transport is car i.e. 68 percent of the total following the active modes which is 25 percent and least by public transport [*Barrett, 2018*]. Even though the city has a strong public transport system managed and run by HSL (Helsinki Region Transport) but still private cars have strong influence on the city planning. In Helsinki region, Public transport consists of route networks of different modes of transport. Metro is the main strength of the transport network, complemented by bus services and also by tram services in the inner city of Helsinki. But still there is a need to make public transport more attractive in Vantaa and future policies should be designed that help to increase the modal share of public transport. The strategies/ policies based on the following points can be helpful in this regard:

- Reduce the appeal of driving in a city by implementing low speed and car free zones
- Increase parking facilities around the main shopping zone
- Establish infrastructure for cycling such as segregated bike lanes

- Introduce car and bike sharing schemes in the city

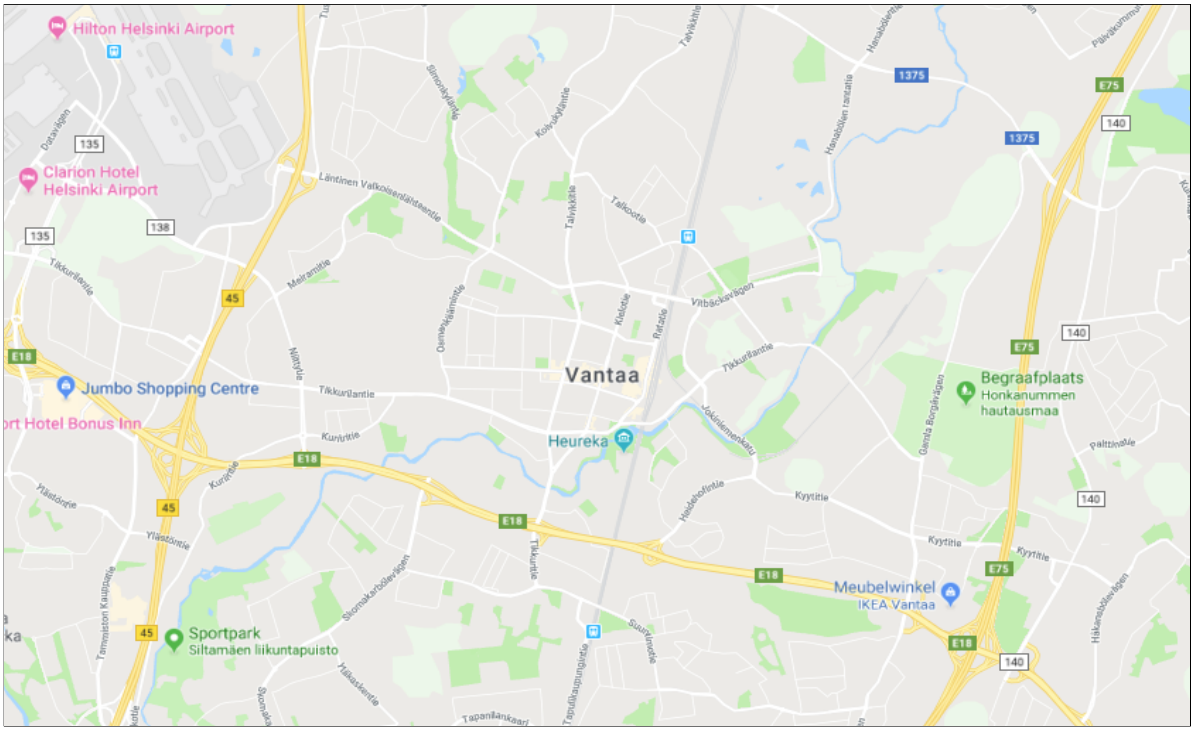


Figure 35: Vantaa Road Network

4.3.2Base case calibration- Results

This sub-section presents the base case results of the mobility pattern for Vantaa after performing the simulation in the developed behavioural simulation platform described in section 3.2. The main results are as follows:

4.3.2.1 Synthetic Population

The synthetic population is generated using IPU algorithm based on the marginal totals (zone marginal/target marginal) for a total of 60 districts of Vantaa using seed data borrowed from Flanders personal travel survey. For these 60 districts, there are a variety of socio-economic variables available (e.g., gender, age categories, employment type, household type, education status, and occupation). We have developed population for 60 districts, which seems too less to be considered as traffic analysis zones. However, this marginal totals are available only for these spatial units. A particular district took an average of around 121 *seconds* to generate its population. It has been executed in similar a format as illustrated in figure 7 for the Hasselt case. However, the only difference is that the seed data is assumed same for each district. Figure 36 presents these 60 districts for Vantaa. Airport runways can also be clearly seen from the figure within district Lentokenttä. The significantly less number of zones (in terms of district) can affect the performance of activity location choices, however, this is the best we can do given the availability of data.

Based on the consistency check as described in deliverable 4.3, available target marginal and the same statistics obtained from the generated synthetic population is calculated for each zones in the form of Standard root mean square error (SRMSE). Figure 37 provides the plot for such values for all districts of Vantaa. It can be noted that SRMSE values are below 0.1 for most zones, as the highest value noted is 0.22. This shows that synthetic population are matching the target marginal to a reasonable extent even though we have used the seed data from Flanders regions [*Cho et al., 2014b*]. The population generated using IPU are following the statistics available for the year 2016 for Vantaa. In total more than 0.2 million persons are generated with a variety of socio-economic/demographics properties of the person. For these 60 units (now we will termed as zones), we assigned the home locations randomly using POI density.

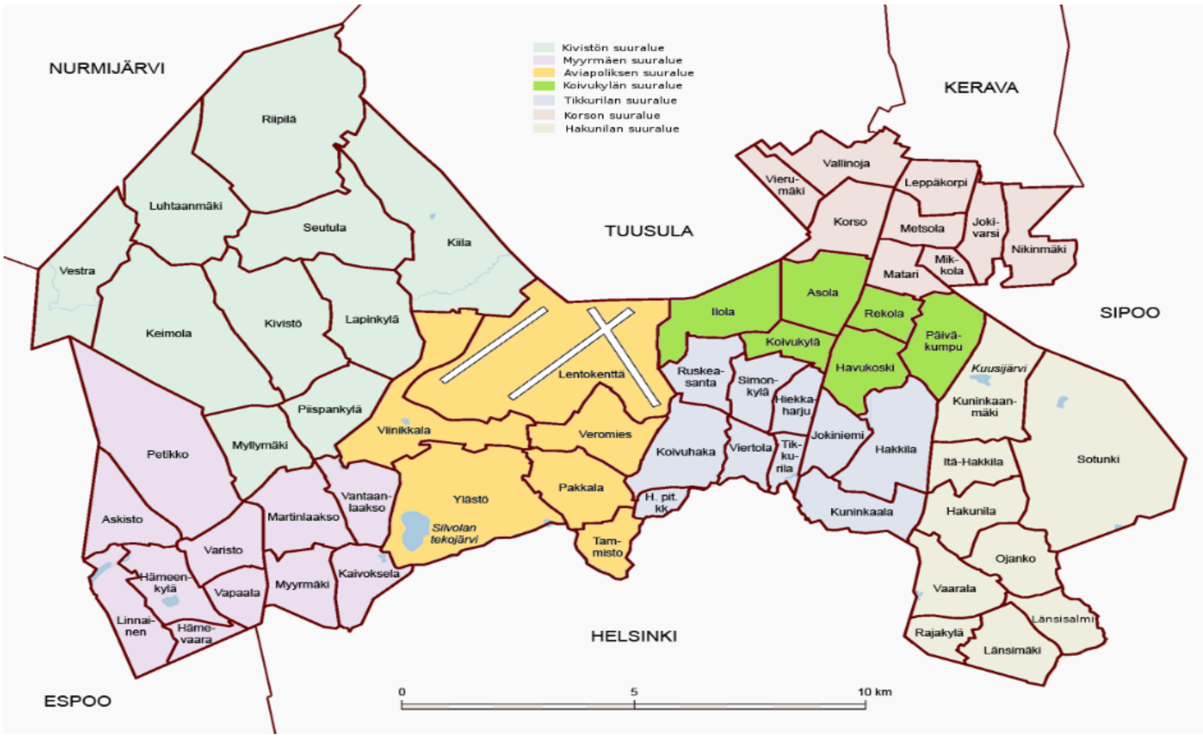


Figure 36: Vantaa Road Network

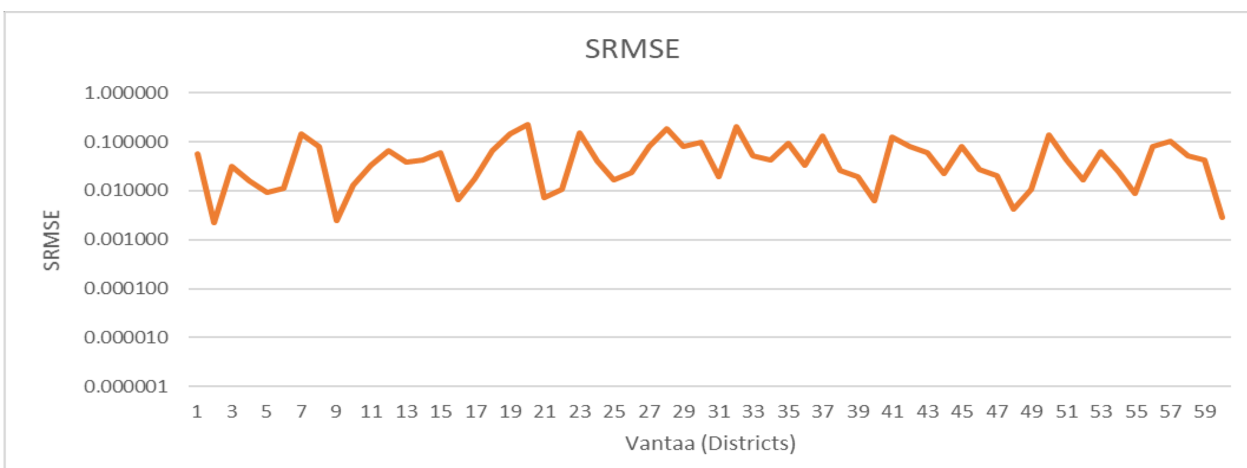


Figure 37: Goodness of fit measure for Vantaa synthetic Population

4.3.2.2 Simulation Outputs and Calibration

The light version of activity-based model and MATSIM can produce a large variety of results in relation to mobility aspects of every individual in the population. Here, we are presenting results which are aggregated in nature and also representing key mobility features of the city. These results are provided after the calibration of outputs with available travel time matrix data for different modes in rush hour (available from [*ARG, 2019*]). This data is available for year 2018. The entire Helsinki region, for which Vantaa is also a part is divided into 13231 grids, and each grid is then considered as a zone (from each grid centre point travel time to another grid centre point is provided based on different mode and time period). We have used part of this data set in a way that grids are overlaid to the Vantaa road network used for MATSIM simulation. A node from the MATSIM network is mapped to a respective grid, and we found out travel time of car traffic in rush hour between several node-to-node pairs. This node-to-node pair travel times are compared with grid-to-grid travel times in the available data. We made a threshold that at least 10 trips node-to-node travel time from MATSIM can be taken as an average for comparison with available data. We found around 543 such node-to-node pairs to formulate an OLS type objective function for calibration purpose. Figure 38 present the MATSIM network on the available grid cells shape file for Helsinki region. Again, the SPSA algorithm is used to minimise the objective function. The RMSE is also calculated at each calibration iteration and the results are shown in figure 39. Around 50 calibration iterations are performed and within each calibration iteration, 250 iterations of MATSIM are performed.

The MATSIM simulations are performed by selecting a 30% population of Vantaa in order to keep check on simulation run time. The final output is expanded for the entire population. Each MATSIM simulation run (that include 250 iterations) took around 531 minutes. The calibration took around little more than 18 days of a server machine (3.50 GHz with 12 cores) to run those 50 iterations. Figure 39 presents the performance of the calibration framework. The staring value of RMSE is 3.1 and after 50 iterations it has been lowered to 0.31, which can be considered sufficient based on the availability of the datasets, especially in relation with schedules that are generated from light version of the activity based model [*Lu et al., 2015*]. The undulations within the calibration framework is attributed to the stochastic nature of SPSA. It should also be noted that the locations of activities are randomly assigned within the larger zone geometry within Vantaa compared to the zone geometry available for Hasselt and Bologna. It should be noted that along with simulation parameters, we have added a certain percent of external traffic on the road network to match the travel times in the two outputs. This is because Vantaa is closely connected with other surrounding regions and also with Helsinki region and there are plenty of individual who are visiting Vantaa for various purposes. Figure 40 presents the morning rush hour traffic volumes on Vantaa road network. The motorway marked in red can be easily visualised around which the city road network is located. It is difficult to visualize each individual link on the road network. We also provide the mode shares obtained from the travel schedules in figure 41. The average trips per day per person is around 3.03 (slightly more than Bologna). Like Hassett, individuals in Vantaa are using cars for their travel. However, after car related modes the walk and bicycles are more used compared. Figure 42 shows tour pattern distribution of individuals in Vantaa. Compared to Hasselt, more individuals are performing two and three tours in a day. In addition, tours are more complex (having one or more intermediate stops).

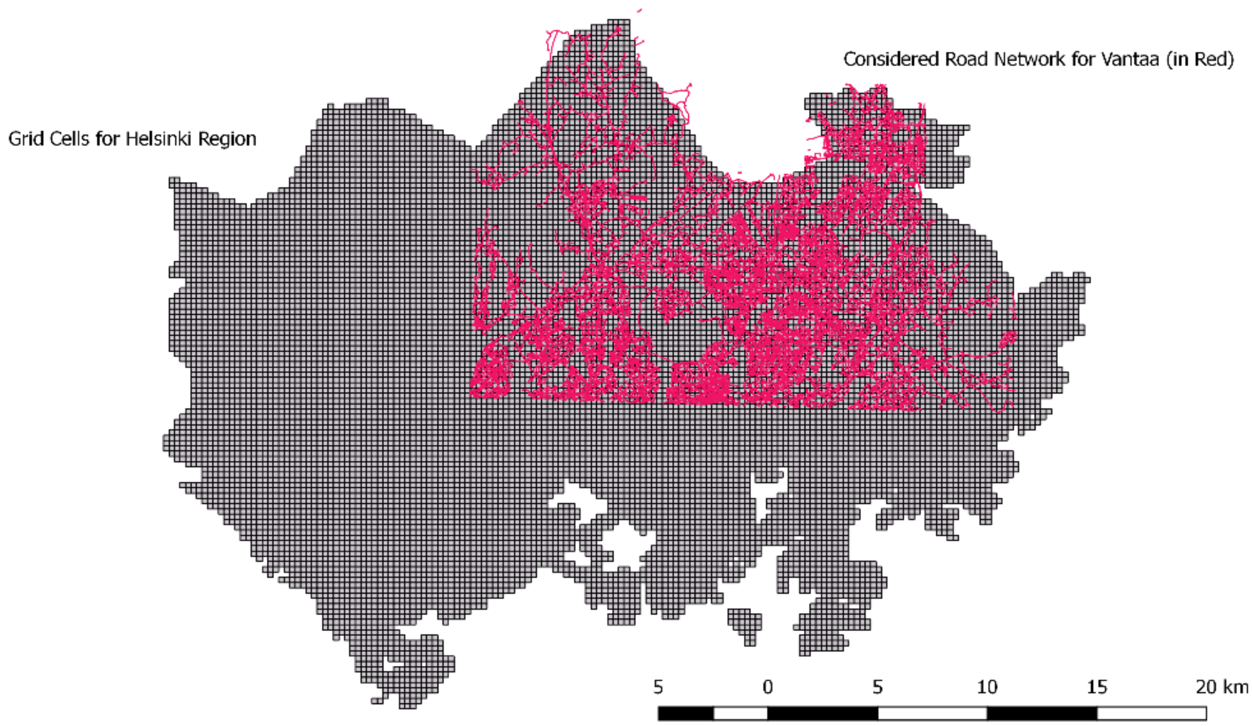


Figure 38: Considered Road Network for Vantaa on top of Grid Cells for Helsinki Region for which Travel times are available

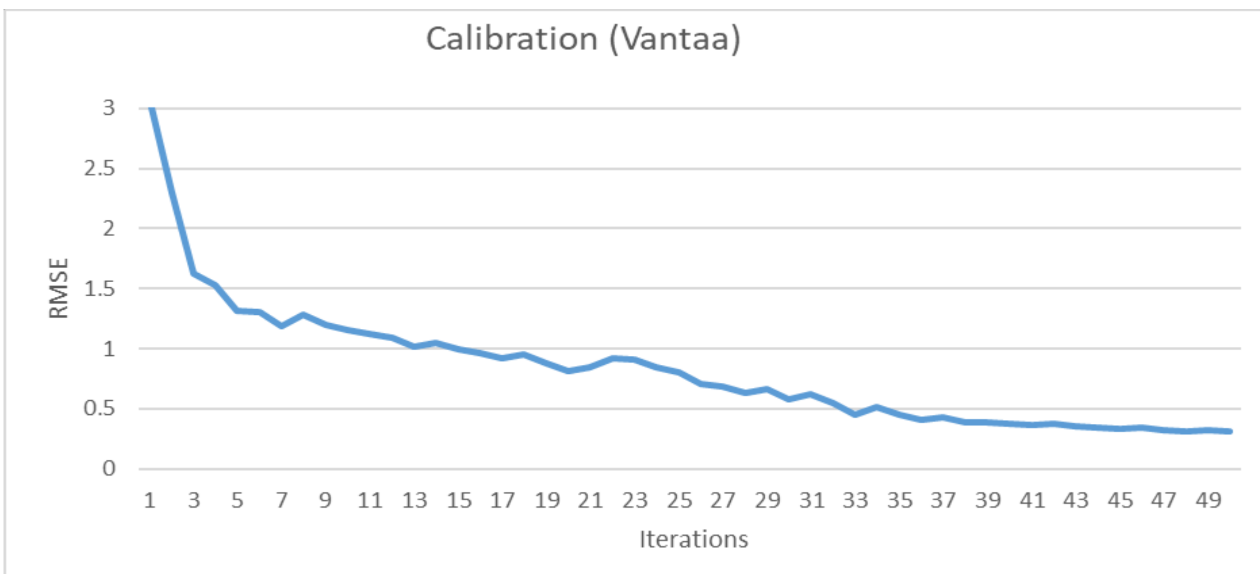


Figure 39: Performance curve of the calibration of travel time in Vantaa

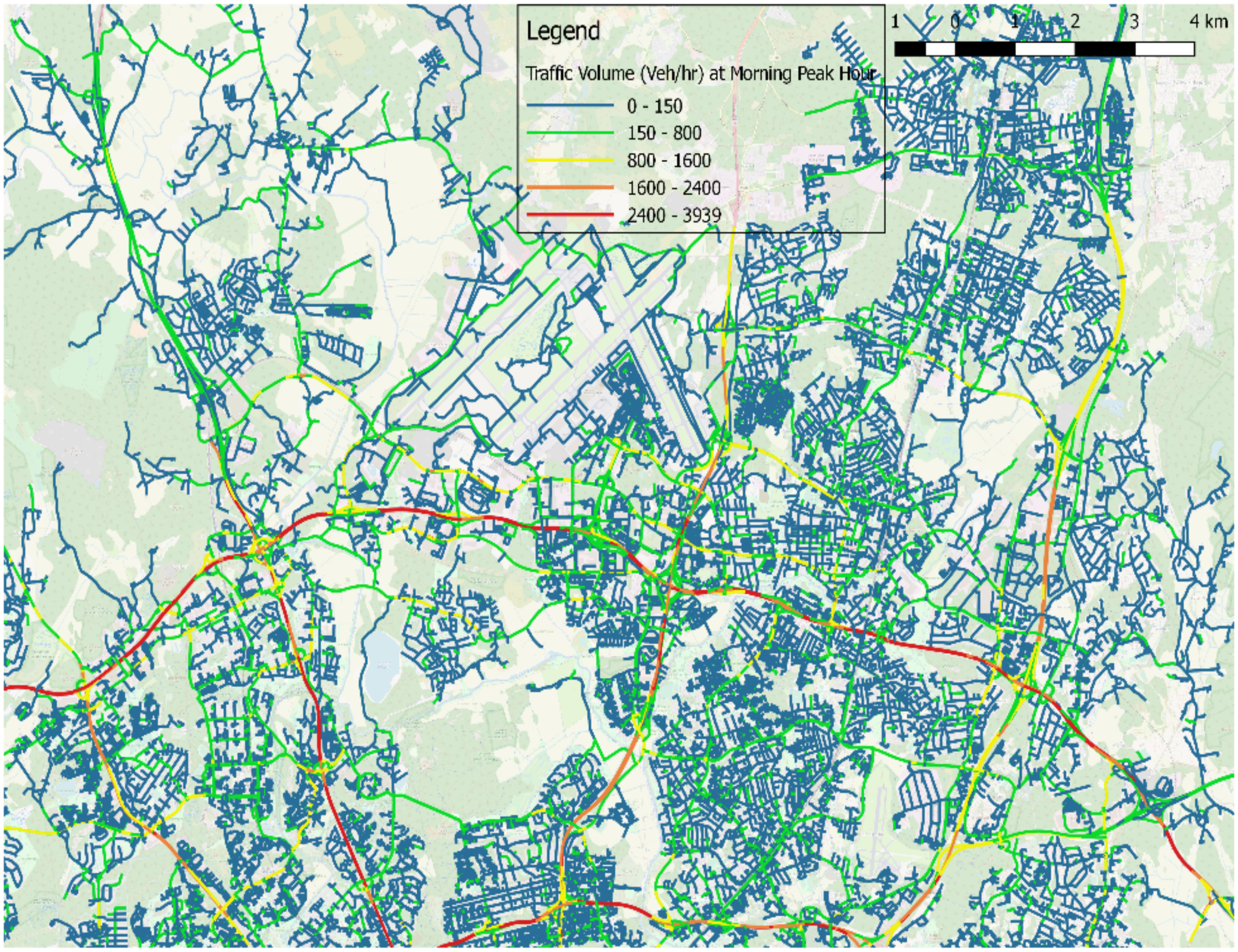


Figure 40: Morning peak hour traffic volume (vehicles/hr) for Vantaa Network

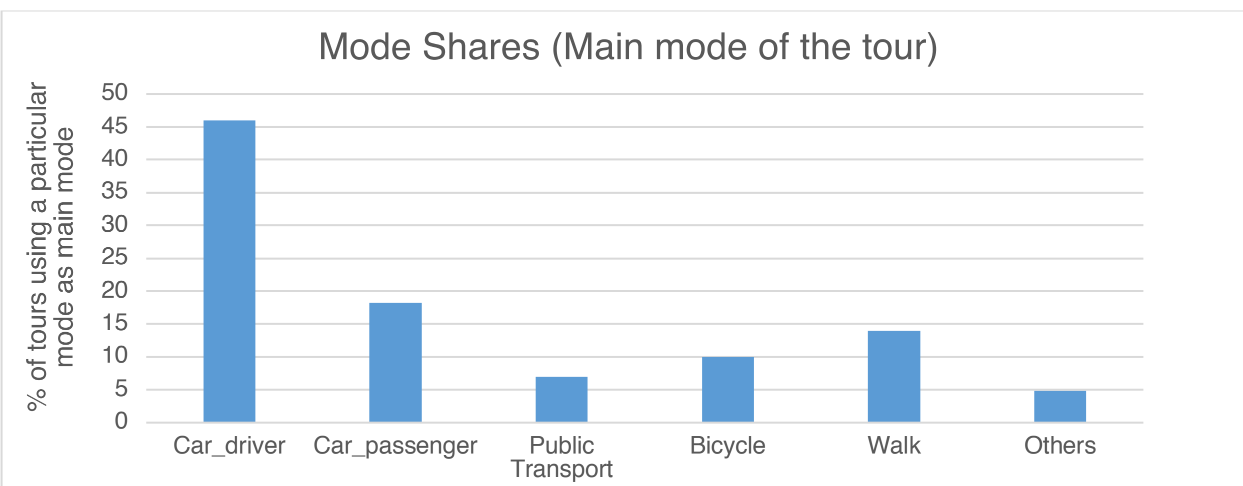


Figure 41: Modal shares for the main mode of the tour (Vantaa)

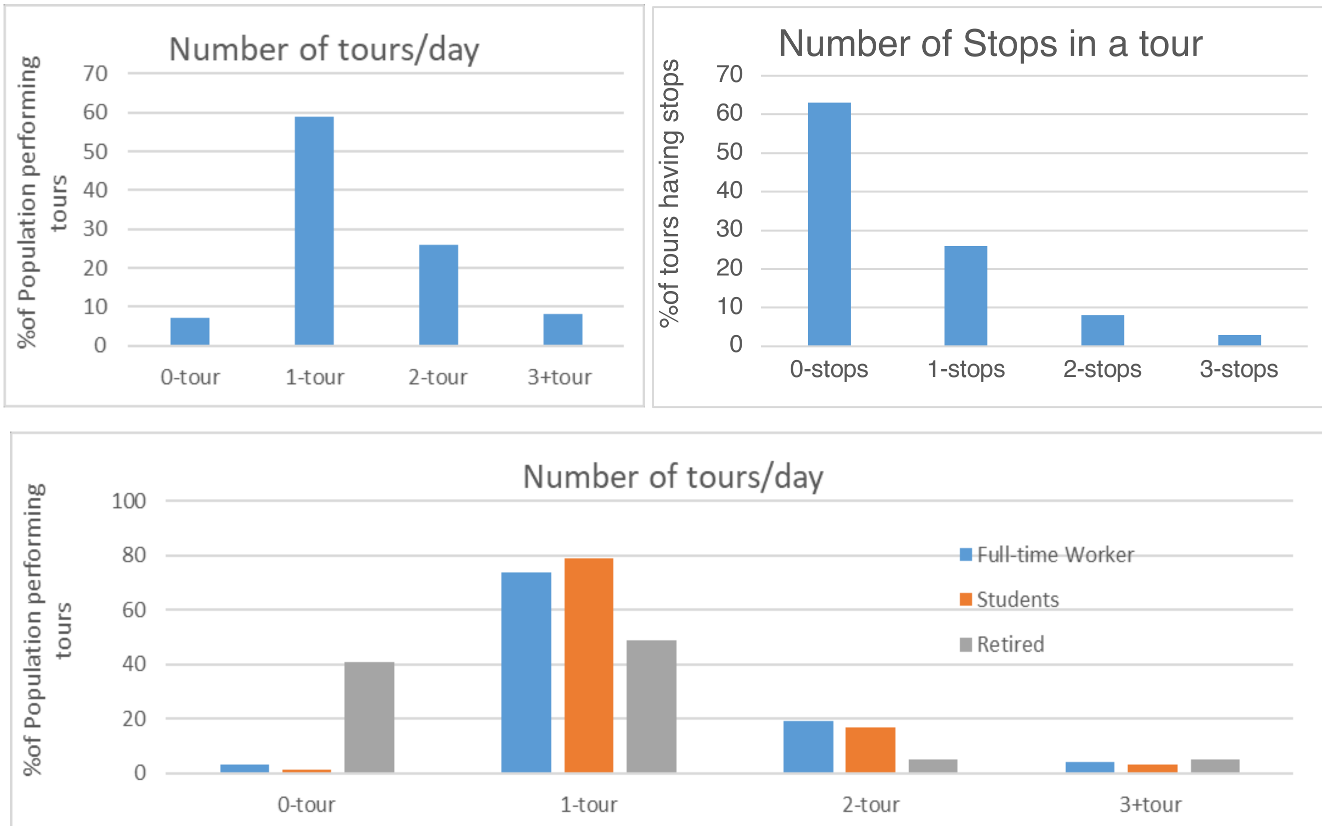


Figure 42: Tour pattern distribution among the population (Vantaa)

4.3.3Policy Scenario 1 – Car Traffic Restrictions

This policy of car traffic restrictions has been found most effective in relation to bring positive environmental impacts. It is mostly implemented in many cities of the world by restricting access of diesel cars, or allowing access by paying certain fees (congestion charge zone). Given the city dynamics and recent efforts to use active modes of travel, Vantaa city also want to assess the impacts of restricting car access to inner city near the train station of Tikkurila. Along with the connectivity to railway station, the region contains shopping malls, hypermarket, library, schools, district court, small playgrounds areas, and various other points of interests such as restaurants etc. This region is quite busy especially during rush hours. Based on the recommendation of our partners, we tested an intervention in which 682 links within the inner city area are banned for car traffic. However, public transport can circulate on the roads with their usual routes and frequency. This intervention has been implemented in the behavioural simulator by restricting car access to these roads by introducing a very high penalty to car drivers in the MATSIM simulation platform. In addition, not only change in routes are allowed within MATSIM, but also through the integrated framework, mode, activity duration, activity sequence, omission of activity from the schedule, departure times are also allowed to be changed. In this way, not only impacts on other links of the road network can be accessed but at the same time, it can be estimated that whether individuals have shifted their mode choice or other scheduling dimensions in reaction to that intervention.

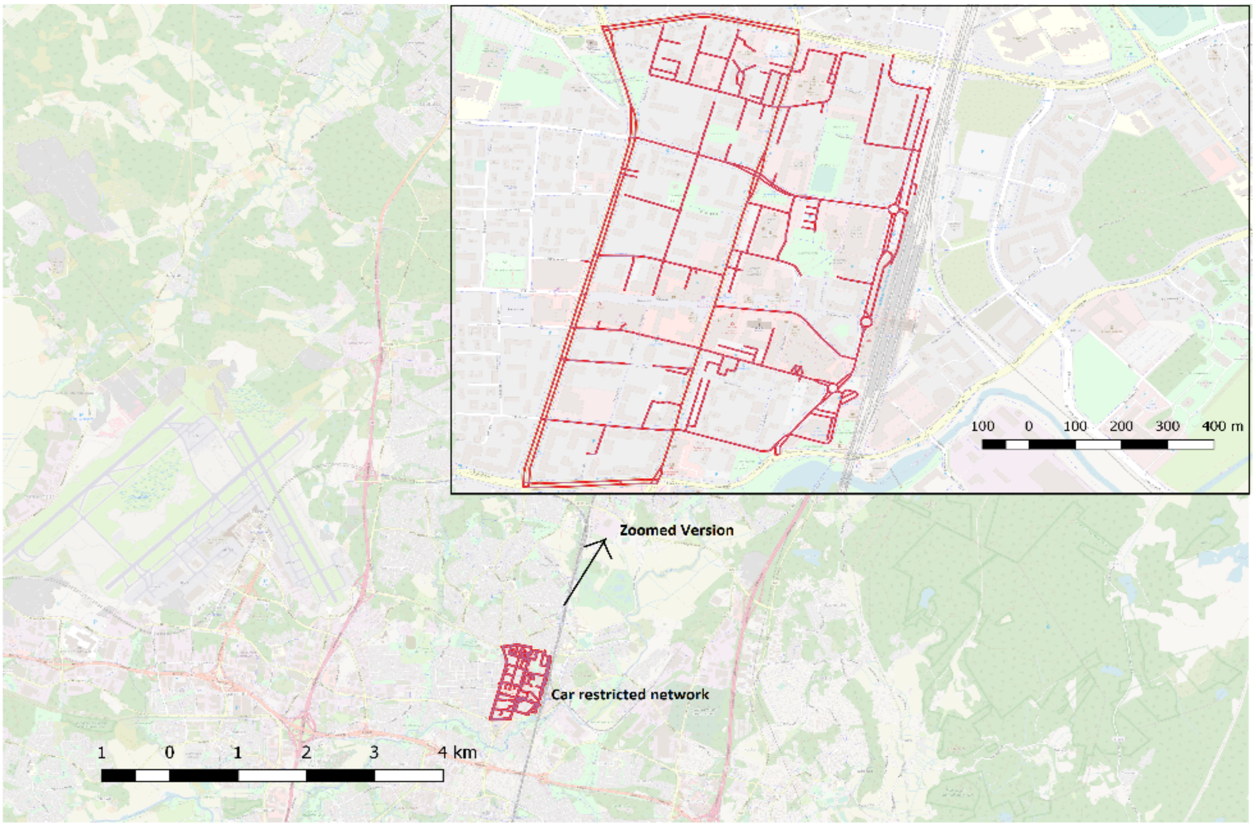


Figure 43: Restricted Car-access links in the Vantaa road network

The policy is implemented by incorporating changes in config.xml file of MATSIM, where another component is added which is usually used to test road pricing policies. As we completely want to restrict car access to those identified links in the road network, the tolls for travel on to these links are therefore classified as a very high. So that utility of choosing a route that contains any of such links is a very low value compared to other routes in the network, or it may also cause change in travel mode as well or some other scheduling dimensions. In figure 43, links are highlighted in red, where car access is restricted. Figure 44 provides the similar outputs as shown in figure 40 (the base case) and both figures can be compared to see changes in terms of traffic volume for the morning peak hour.

It can be observed that car restricted links are in lowest category of traffic volume (the traffic volume is only due to the buses on those restricted links). Other major roads that connect traffic to major outer roads have volumes slightly greater than observed in the base case. This trend is similar to the trend noted for Bologna. This is because there are several routes available to individuals because of the grid nature of the network. In Hasselt case, we noted different trends because the outer ring of Hasselt provides much better connectivity with faster speed and therefore, car traffic on the road network between the inner and outer ring is reduced due to such policy. Furthermore, there was no notable difference found on motorways and other primary arterial roads. This indicates that the effects in relation to traffic pattern on routes are of localised nature. In addition, we observed the following major changes:

a) Several drivers have detour their routes as they are now using longer routes in comparison with the base case in which car drivers were using more direct routes. It is noted that the travel time of the car drivers on an average has been increased by 13%.

b) Due to the introduction of very high penalty for using the restricted links, most of the trips where the destination is the inner core zone of the city, 16% of the car trips have reduced. This 16% of car trips have been distributed as 9% to PT, 3% to bicycle and 4% to walking and 1% to other modes of travel. Furthermore, around 3-4% of individuals have changed their location of activities from inner city area to other areas in Vantaa city.

c) The majority of the individuals that have changed their travel mode because of this policy belong to the female population, non-worker class and students.

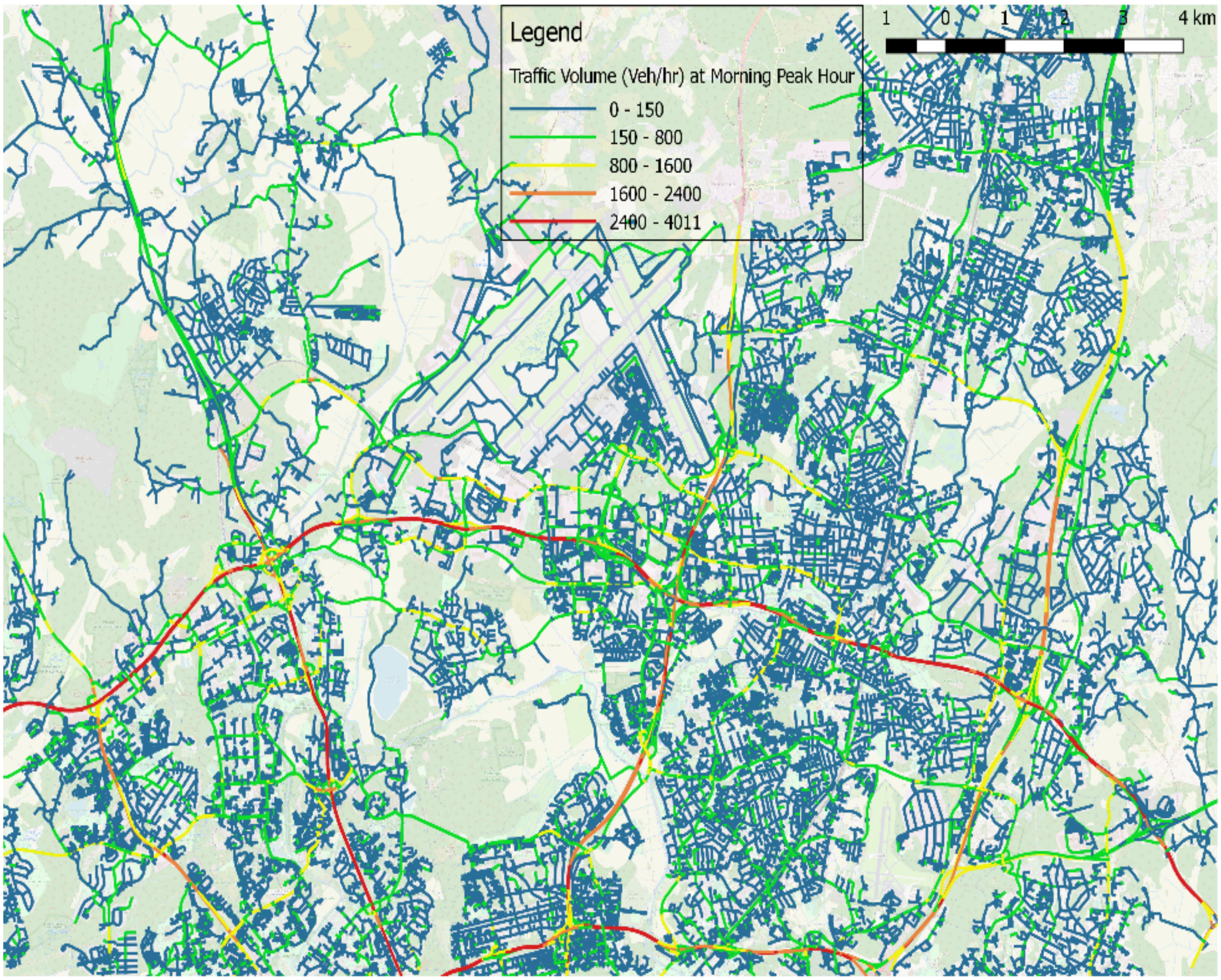


Figure 44: Morning peak hour traffic volume (vehicles/hr) on reduced Vantaa Network- Car Restricted Policy

Figure 45 presents the overall mode share differences between the base case and this policy simulation. The largest difference in percentage points (0.7%) are noted for car passenger use followed by car drivers, and it is replaced by the use of more buses and then bicycle and walk. In relation to absolute numbers, PT trips increased from 47,150 to 51,650 trips because of this policy (i.e. a difference of 3,500 trips in a day). Car_driver and car_passenger trips decreased from 437,683 to 429,000 daily trips (i.e. a decrease of 9,000 car trips/day). This is a reasonable number of decrease in car traffic compared to the size of restricted network, and may helpful in improving the air quality at a neighbourhood scale (i.e. within the vicinity of the train station).

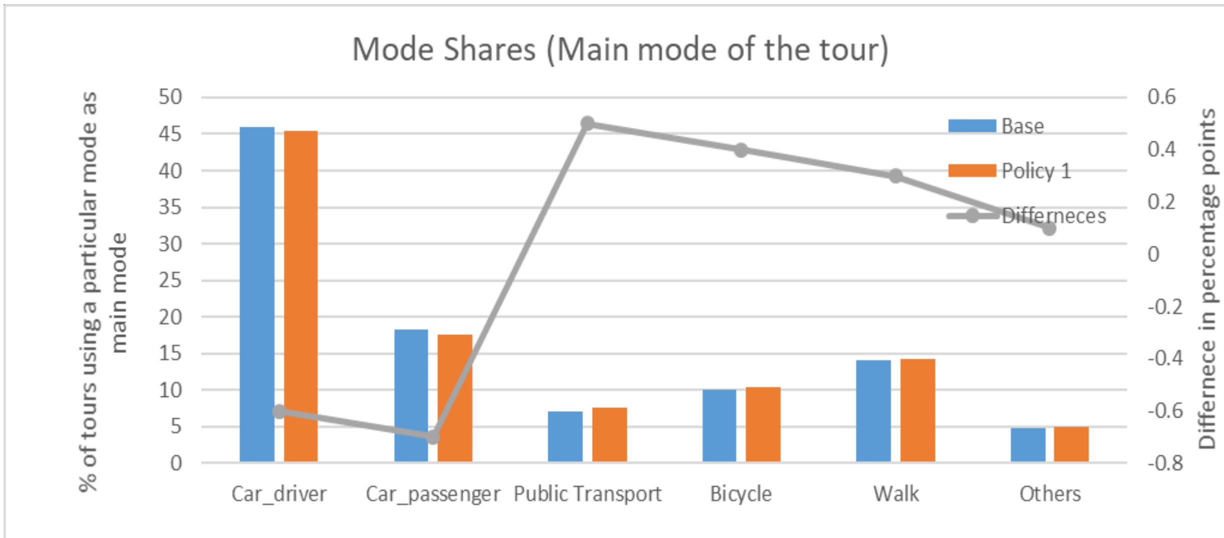


Figure 45: Mode shares as main travel mode of the tour (along with differences with base case)

4.3.4 Policy Scenario 2 – Enhancement of Bus Services

In relation to Policy 2, there are a variety of measures taken to encourage use of public transport within the Helsinki region. This includes the enhancement of bus services, fare reduction and their collection system, new routes, and multimodal connectivity of Vantaa with surrounding regions. Within Helsinki city, the situation has improved a lot due to the dense public transport network. However, Vantaa city is lagging behind in the increasing use of bus service. Based on this context, a policy is investigated to increase the frequency of a few PT routes (identified by the city). The routes for which the frequency must be enhanced are as follows:

Table 1: PT routes and their frequency details in existing conditions

Line No.	Region	districts served	Remarks on Current Frequency
335	Myyrmaen Suuralue	Askisto, Linnainen, Hameenkyta Varisto, Martinlaakso, Myyrmaki, Vapaala, Petikko	20-30 minutes (Morning rush hour) and it goes upto 1 hour in non-peak times
571	Tikkurilan suuralue, Avaipoliksen suurealue, Myyrmaen suuralue	Tikkurila, Viertola, H. pitt. Kk, Pakkala, Yiasto, Vantaanlaakso, Martinlaakso, Myyrmaki, Vapaala,Hameenkyta ,Varisto	15 minutes (Morning rush hour) and it goes upto 30 hour in non-peak times
572K	Hakunilan suuralue, Tikkurilan suuralue, Avaipoliksen suurealue, Myyrmaen suuralue	Lansimaki, Rajakyta, Vaarala, Hakunila, Kuninkaala, Tikkurila, Viertola, H. pitt. Kk, Pakkala, Vinikkala, Vantaanlaakso, Martinlaakso, Myyrmaki	20-30 minutes (Morning rush hour) and it goes upto 1 hour in non-peak times

574	Koivukylan suuralue, Tikkurilan suuralue, Avaipoliksen suurealue, Myyrmaen suuralue	Asola, Koivukyla, Simonkyla, Koivuhaka, Veromies, Vinikkala, Vantaanlaakso, Martinlaakso, Myyrmaki	30 minutes (rush hour) and it goes upto 1 hour in non-peak times
575	Tikkurilan suuralue, Avaipoliksen suurealue, Myyrmaen suuralue	Tikkurila, Viertola, Koivuhaka, Veromies, Vinikkala, Vantaanlaakso, Martinlaakso	30 minutes, serve morning rush hour, then afternoon time till evening 6 pm.
P train	More details in figure 46		Every 10 minutes: Monday-Friday 9am-7pm, Saturday 9am-4pm Every 15 minutes: Monday-Friday 7pm-10pm, Saturday 7am-9am and 7pm-10pm, Sunday 10am-10pm Every 20 minutes: Monday-Friday 4am-6am and 10pm-midnigth, Saturday 5am-7am and 10pm-midnigt, Sunday 5am-10am and 10pm-midnight
I train	More details in figure 46		

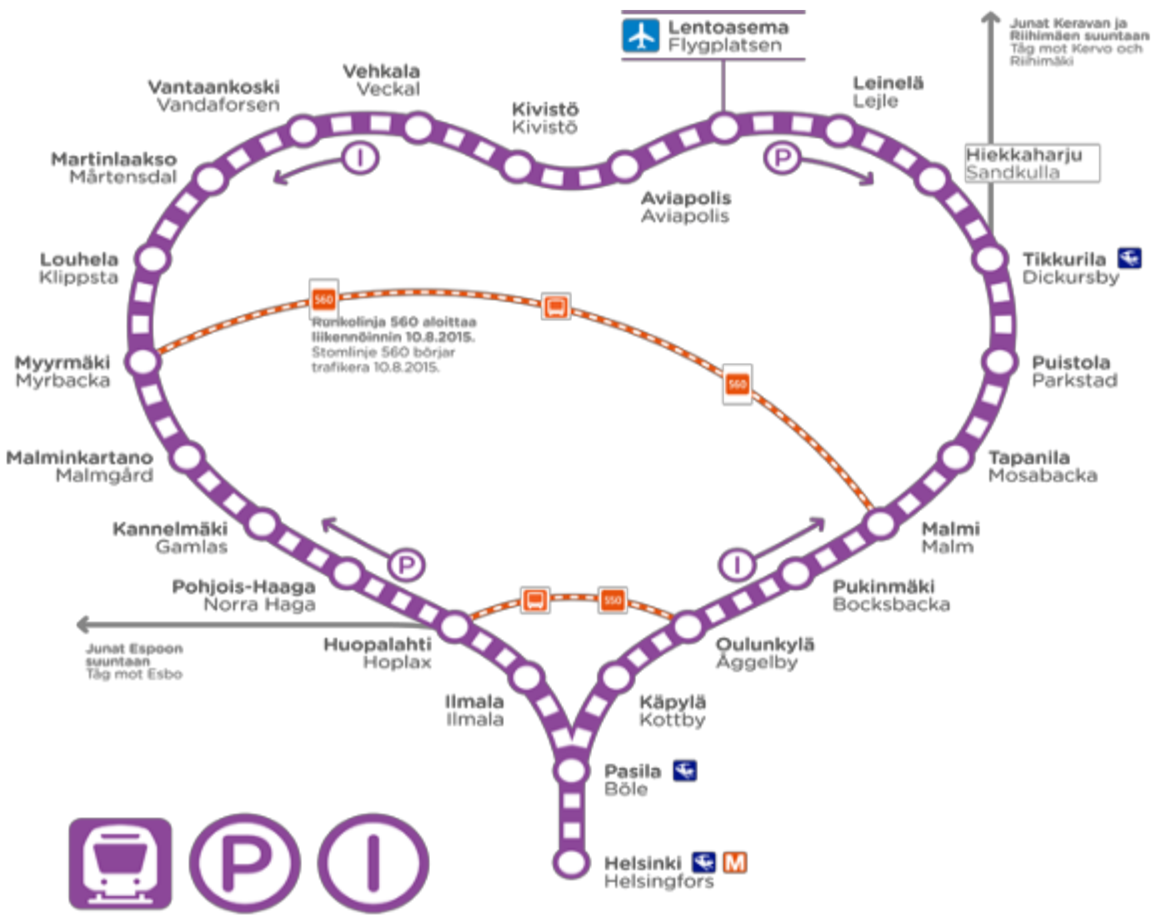


Figure 46: P and I trains coverage (Ring Rail Lines) in HSL region (source: https://www.hsl.fi/en/ringrailline)

Given the details mentioned in table 1 and figure 46, it is evident that ring rail lines (P and I train) frequency is already on the higher side (i.e. it is available every 10 min) and they connect Vantaa very efficiently with Helsinki city. Therefore, we did not increase the frequency of these ring rail lines any further in our policy scenario. However, for all bus routes mentioned in table 1, we have simply doubled the frequency in rush hours and non-peak hours. The most crucial component to run this policy in the simulator is the mode choice model within MATSIM. Within the mode choice model, the PT utility contains a waiting time variable, whose values are changed during the execution of this policy scenario.

The results indicate that this change increased the PT mode share by only 2% percentage points (i.e. the overall share of PT for this scenario is 9%). Because of this scenario, car use has been reduced but it is not significant as the majority of the bicycle travelers have shifted their mode to PT rather than car users. Figure 47 provides the clearer summary of the changes in mode share distribution in this situation. In absolute terms, PT trips increased from 47,150 to 60,785 (i.e. an increase of 13,635 trips in a day), however this increase is at the cost of decrease in bicycle trips from 68,000 to 60,000. Car traffic is reduced only 0.6 percentage points, which is around 4000 trips in magnitude. The major reason could be that even with low waiting times, bus service is still not an attractive travel alternative for individuals who are captive car users as it has been noted for Hasselt case as well.

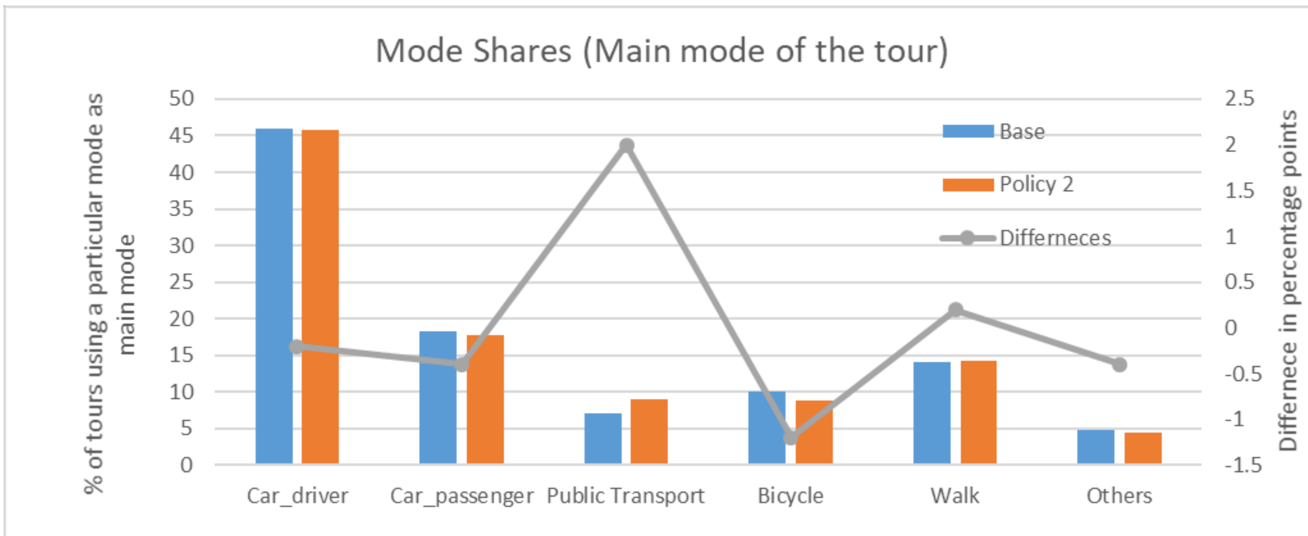


Figure 47: Mode shares as main travel mode of the tour (along with differences with base case)

This policy has not rendered results as expected. In order to encourage use of PT, it is also necessary that some other car-based interventions are to be implemented, such as an increase in car use tax and in parking cost etc. Furthermore, we have also produced output in terms of traffic volume to visualise changes in the road network. Figure 48 provides these results. In comparison with the base case, no significant changes are visualised within the city road network. Most of the roads are having similar car traffic in the peak hour as noted in the base case. This also indicates that changes in the car traffic have occurred more in the non-peak hours.

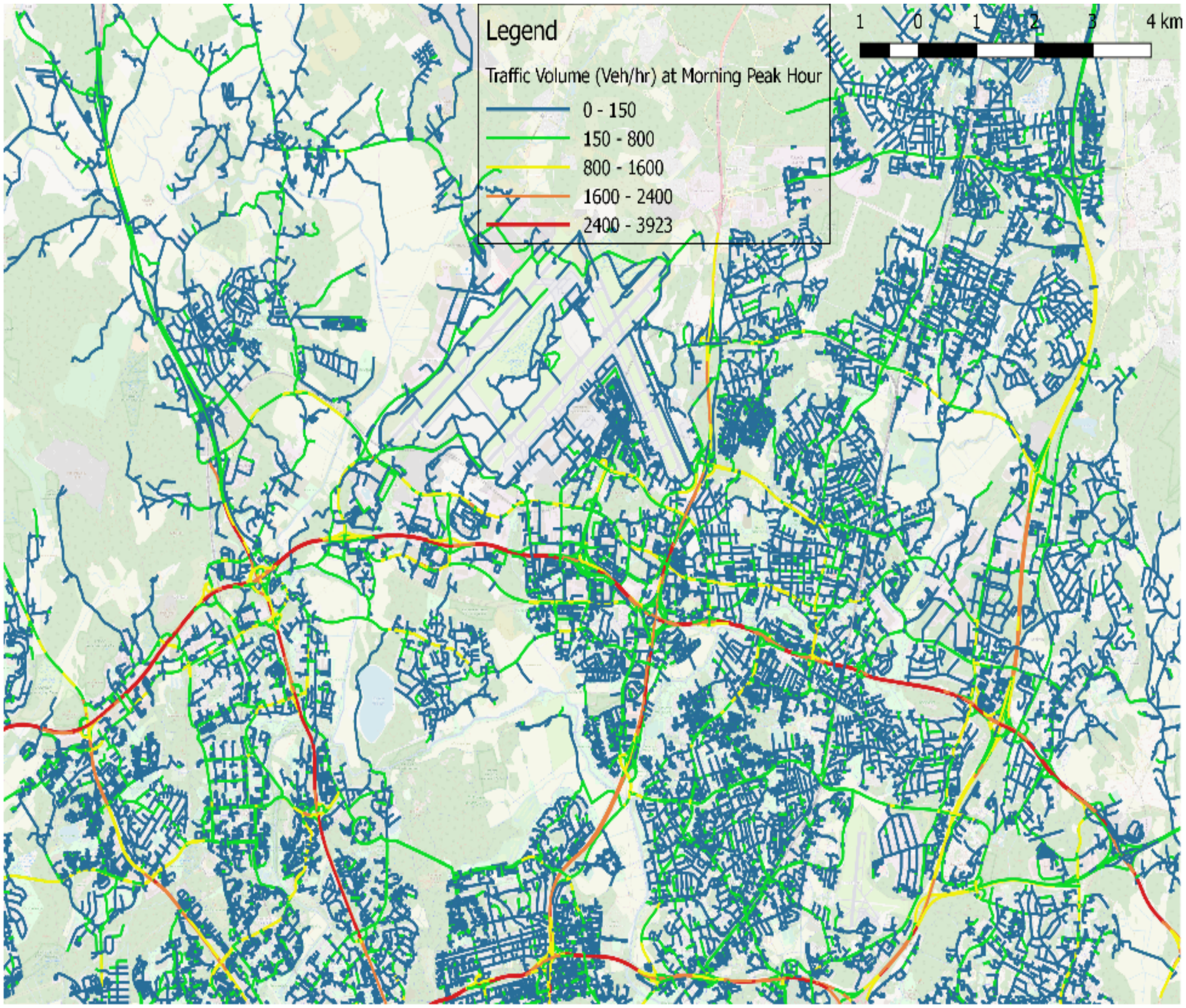


Figure 48: Morning peak hour traffic volume (vehicles/hr) on reduced Vantaa Network- Bus Frequency Enhancement)

5 Integration of Results in other Deliverables

This section presents discussion on further advancement of the output presented in section 4. For each city these outputs along with the shape files are provided to UNIBO, to obtain estimation of emission and then use those results in the dispersion model to estimate impact on the pollution concentrations in the base case and also in relation to policy scenarios tested for the three cities. The results and necessary discussion on this can be seen in the deliverable 4.5. This section further discussed on the results in terms of the uncertainty of the results mentioned in section 4 and also discuss the way forward to obtain estimation of exposure.

5.1 Discussion on the Uncertainty of behaviour simulation results

There are a number of sources of uncertainty of the simulation framework, such as input data, model parameters, simulation methodology and the modelling structure, and the approach followed to obtain the required results. It is not the scope of this task to measure these uncertainties in the results, however, the authors of this deliverable have conducted a similar study in case of Singapore, where activity-based modelling procedure is used to simulate the entire population of Singapore. This study [*Petrik et al., 2018*] investigated the parameter and simulation type uncertainties in a similar simulation platform used to obtained behavioural simulation results. The results showed that the order of magnitude of all considered kinds of uncertainty strongly depend on how frequently the alternative is predicted in the choice process. We discussed the uncertainty in predicted modal shares, as for all the policy scenarios discussed above we have given that statistics a special importance because of their significance in environmental analysis. We provide results from that study that gives an idea about the magnitude of uncertainty presented in the results shown in section 4.

The study of [*Petrik et al., 2018*], in relation to simulation uncertainty (often regarded as simulation error in the literature) estimated modal share percentage uncertainty (in the form of standard deviation) within the range of 0.04% for car traffic. This indicates that the mean values of mode share for car in per cent (as reported for three cities in this deliverable) can subject to a standard deviation of 0.04%. Apart from this simulation error, the analyses also reported parameters uncertainty. This is done by varying a parameter of the model in a systematic way (i.e. using the concept of multivariate distribution). That analysis obtained a parameter uncertainty for car traffic in the range of 0.4%. In relation to policy scenarios, in which the results are reported for the difference from the base case, we have seen that the percentage point differences are quite lower (i.e. in the range of 1-2%). It is therefore important that this magnitude of uncertainty should also be taken care of while interpreting the effect of policy scenarios.

5.2 Integration framework for Personal exposure measurements

As also explained in the deliverable 4.3, individual exposure to pollutants will be estimated as part of task 7.3 of WP 7. The MATSIM outputs obtained in this report are not only in the form of traffic volume, but also obtained as a complete itinerary of individuals in the synthetic population. This output can easily be displayed on a GIS platform, which represents a complete itinerary of individuals starting from home to coming back home at a later time period. The information can easily be converted into a format similar to GPS-based trajectory data of an individual. On the other hand, outputs of deliverable 4.5 (from UNIBO) provide ambient pollution concentration maps at a certain spatial resolution. The critical process involves in this algorithm is matching pollutant concentration data with activity-travel plans to assess dynamic exposure of a person.

The framework employed here is similar to the one used in deliverable 4.1 and also reported in [*Ahmed et al., 2018*]. This is done by assigning each x.y pair of the obtained trip trajectory to the respective grid-based pollutant concentration zones in order to get the exposure at that point with respect to time. Exposure of a trip and activity is calculated by taking summation of the time someone spends in different pollutant concentration categories i.e. low, moderate, high, and very high. To explain it further in case of an activity exposure, the spatial location from the predicted output along with the timestamp for each activity is available for each individual. For that particular location and duration of activity at a given time period, changes in the pollutant concentration categories are determined and time spent within each category is noted. The procedure is repeated for all activities individuals have performed in a given day. The results are aggregated for time spent in each category of pollutant concentration. In relation to a trip, each trip is decomposed in several segments on the basis of their association with a particular grid of the pollutant concentration data. For that duration of the trip in a given time period, pollutant concentration category belong to that grid is assigned. The process is repeated for all segments of the trip, and then for a particular trip, time duration spent for each category of the pollutant concentration is determined. The process is repeated for all trips individuals have performed in a given day. Once duration distributions for trips and activities are available for each individual, it is then further aggregated to represent the overall exposure of activity-travel behaviour in a given day. The appropriateness of the exposure estimation mainly depends on the granularity of the pollutant concentration maps (e.g. their space-time resolution). The higher the space-time resolution, the more appropriate will be the exposure estimate of the individual in the synthetic population.

6 Conclusions

The focus of this deliverable is mainly to briefly describe the prototype behavioural simulation model and the results obtained by performing those simulations with a few policy scenarios for the three selected cities. Hasselt case behavioural simulation framework is more detailed and comprehensive. At the same time, the implementation of such a framework is time-consuming. Therefore, a light activity-based model is presented that uses simplified data for Bologna and Vantaa. Use of MATSIM in the simulation framework provides flexibility to employ a range of policy scenarios and at the same time, the results are as detailed as possible to obtain the impact of policies on a disaggregate level.

The base case scenarios for Hasselt, Bologna and Vantaa are calibrated well enough with the error ranging from 0.15 to 0.3. It has been found that policies in relation to restricting car traffic is more effective in terms of reducing traffic from the network and also shifting of car drivers/passenger to other modes of travel. This is in line with the results reported in other similar studies. The enhancement of bus infrastructure in relation to increase the frequency and also tweaking activity start time (changing open and end times) are not able to significantly reduce car traffic. Especially, improvement of bus infrastructure causing shifting of bicyclist towards public transport, which is an undesirable result of the policy if the objective is to improve sustainability and environment. It is therefore, important that these policies are to be implemented together to have more appropriate effect. Deliverable 4.5 presents the further use of the results reported in this deliverable to estimate emission and pollutant concentrations.

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