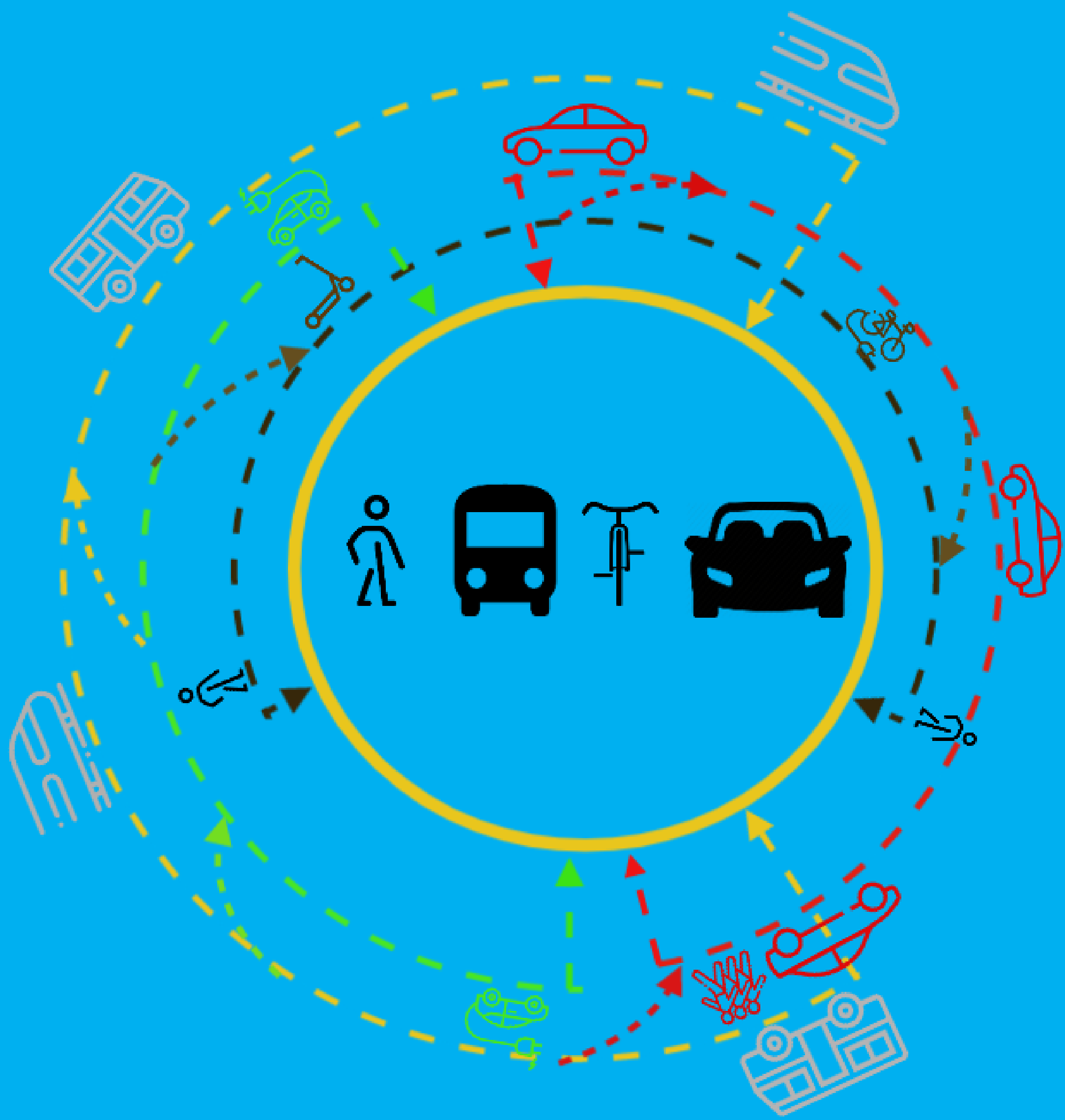
Analysing Mobility Hubs using Microsimulation Travel Demand Model

The case of OCTAVIUS

Raghu Tippabhatla



TU Delft

dat mobility

ANALYSING MOBILITY HUBS USING MICROSIMULATION TRAVEL DEMAND MODEL

A thesis submitted in partial fulfillment of the requirements for the degree of

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by

Raghu Tippabhatla

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ACKNOWLEDGMENT

This thesis written in partial fulfillment of the requirements for the degree of Master of Science, has been carried out in the past ten months. The research was conducted for the transport consultancy firm DAT.Mobility, a part of Goudappel Coffeng. The research involves with the feasibility study of the microsimulation travel demand model while modelling future mobility hubs. My motivation to carry out this research lies in my passion for the future. "The past is always tense, the future perfect".

I believe that the research will encourage transport planning professionals to understand the scope of mobility hubs along with microsimulation travel demand models and its ability to model future travel behaviour. The evolution of transport hubs to Mobility hubs will impart changes in travel behaviour and with this research I aim to demonstrate the extent to which microsimulation travel demand models can model these potential changes in travel behaviour.

Firstly, I would like to thank Luuk Brederode and DAT.Mobility, for giving me the opportunity to work in a practical environment, without your constant support this thesis would not have been possible. It was a great pleasure and privilege working with you. You inspired me throughout the duration of the thesis. I would also like to thank your colleagues, Bernike and Tanja who provided constant support during the initial stages, giving me the required information regarding the model and helping me understand the whole concept of microsimulation.

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To the reader, I would like you to be inspired by the research and I wish my research will be useful for the future work.

Enjoy the Read.

Raghu Tippabhatla
Delft, November 2020

EXECUTIVE SUMMARY

City leaders and planners need to handle transport networks strategically, as the world increasingly urbanizes, to ensure that the changing needs of city dwellers and travellers are met. Moving from A to B is a vital part of the life of almost every person, and current transport networks that rely heavily on the use of cars are simply not set up in many cities to cope with the growing population. Related to rising levels of emissions and declining sources of energy, transport is one of the most pressing problems we face as we plan and maintain our cities. Ultimately, shifting mobility patterns influence many other facets of urban life, such as economics, the world of work and citizen health and well-being, and in tandem, shifting habits will eventually influence citizens' preferences for commuting. In order to meet traveller requirements, those in charge of operating transit systems must be brave and flexible enough to implement creative new solutions. In addition, an excellent transport system will improve the productivity of a city, draw talent, build a productive economy and contribute to its success relative to other cities. Therefore, as we rethink and re-imagine our approach to transport, preferring creativity and multi-sector cooperation, it is argued that a flexible, forward-thinking approach to transport is vital cities(Mathieu Lefevre, 2020).

The traditional transport hubs are shaping into the idea of the mobility hubs with the advent of multiple vehicle-sharing forms, such as bike sharing and car sharing. In addition, a gradual shift in the culture of consumption towards more usage and less ownership, as well as the shared economy supported by internet platforms and mobile apps, allows easy access to multiple daily mobility choices, especially in urban environments. The Mobility hubs seek to merge conventional public transport with these new shared services which has the potential to serve as a solution to the first/last mile problem within the public transport and will allow operators increase their ridership.

PROBLEM STATEMENT

Transport demand models are used to forecast future travel demand but consider the same travel behaviour as that of today. Mobility Hubs have the potential to change the travel behaviour of travellers and travel demand models should not only be able to forecast the future travel demand but also take into consideration the potential changes in travel behaviour due to the mobility hubs. This study deals with a microsimulation travel demand model, OCTAVIUS.

RESEARCH GOAL, RESEARCH QUESTION AND RESEARCH OUTLINE

The research objective is to identify the possibility of modelling potential changes to travel behaviour due to the implementation of mobility hubs within Microsimulation Travel Demand Model, OCTAVIUS. The model will also provide insights on the ability of microsimulation demand model while incorporating potential travel behaviour which is expected to be induced due to mobility hubs.

The research question for this thesis is formulated as follows:

Main Research Question

To what extent can microsimulation travel demand models can capture the potential changes in travel behaviour due to the implementation of Mobility Hubs?

Sub Research Questions

- What are the potential changes in travel behaviour that could be observed due to the implementation of mobility hubs?
- How do travel demand models deal with the potential changes in travel behaviour related to mobility hubs?
- What are the possibilities of modelling potential changes in travel behaviour due to mobility hubs within microsimulation travel demand model, OCTAVIUS?

The research questions are answered by first investigating the literature regarding Mobility Hubs and the potential changes to travel behaviour due to Mobility Hubs. Secondly, the capacity of travel demand models will be investigated while modelling such changes to travel behaviour, drawing the benefits and drawbacks of different travel demand models. Further, the latest microsimulation travel demand model, OCTAVIUS, will be introduced. Finally, the possibility of modelling potential changes to travel behaviour due to mobility hubs within OCTAVIUS will be explored by the means of a Case study in the Almere Region.

The Mobility Hubs under investigation are a concept for the future and scientific literature regarding mobility hubs is still scarce. Pilot studies on mobility hubs such as in the case of Interreg (2019) will result in the collection of data which could provide insights on the practical application of mobility hubs and the underlying theories which will provide a better representation of the mobility hub concept.

LITERATURE REVIEW ON MOBILITY HUBS AND TRAVEL DEMAND MODELS

The literature review was carried out in three stages, the first stage identified the potential changes to travel behaviour that might be induced due to the mobility hubs and its mobility services which was done by observing 3 mobility hubs namely, the case of Utrecht, the case of Greater Toronto and the case of San Diego. In all the cases, the first attribute of mobility hubs regards to the use of shared mobility services as first/last mile mode such as shared-bikes on the activity end for the traveller, the second function of mobility hubs regards to the use of shared modes as an alternative to public transport such as shared-cars and micro-transit systems. The use of shared services as either as a feeder mode to public transport or as an alternate to public transport, are the two main functions of mobility hubs, i.e. Multi-modality (feeder mode), Multi-modality (main mode).

Further, the third function of the mobility hubs observed mainly within the case of San Diego is the ability to carry out multiple activities near or within the mobility hub region. With additional mobility services and transit oriented development, mobility hubs have the potential of becoming a major destination to carry out activities such as shopping for groceries and clothes or watching movies or meeting a client for business etc at one location. The attribute of allowing travellers to carry out multiple activities generates the function of multi-activity destination. Overall, these functions have the potential to induce changes to travel behaviour of the travellers.

The second stage aimed at investigating the capacity of travel demand models while implementing mobility hubs and the above mentioned mechanisms. It was identified that conventional demand models lack the ability to model complex travel behaviour (Bhat and Koppelman, 2014; Timmermans et al., 2002; Vovsha, 2019). Most research suggest that microsimulation models should be investigated while modelling complex travel behaviour due to their flexibility while modelling such behaviour. Further, behavioural, structural and computational advantages related to microsimulation travel demand models over traditional demand model were identified (Vovsha, 2019).

The last stage aimed at identifying the location of mobility hubs within the transport system and literature suggested that mobility hubs must be in or near major transit stations, in order to serve its purpose. This also demonstrates the use of shared mobility services as a first/last mile mode. The case study done on the Greater Toronto and Hamilton Area indicated that mobility hubs perform higher where public transport infrastructure is already available. The low performing mobility hubs are in places where there is less or no public transport infrastructure. From the review done on the three mobility hubs it was quite evident that the concept of MaaS will play a major role. This is mainly due to the fact that MaaS allows the travellers seamless travel options combining different modes of transport under one platform. In the case of mobility hubs, MaaS has the potential of combining traditional public transport with shared mobility services. The concept of e-Hubs being carried out by 15 partnership countries as mentioned in the review is very much like that of Mobility hubs, which is currently under pilot study (Ratti, 2017; Jittrapirom et al., 2017).

MODEL INTRODUCTION

At DAT Mobility, a recent development in the field of transport demand models is taking place. The new microsimulation travel demand model, namely, OCTAVIUS is currently under development. Compared to regular microsimulation models the OCTAVIUS guarantees that the agents/individuals behave according to the choice models. The OCTAVIUS is applicable to strategic applications where the model user is mainly interested in the difference between a reference situation and a scenario that includes policy measures to be evaluated. The model is currently applied on the region of Almere. To keep the executive summary comprehensive, OCTAVIUS will be briefly elaborated.

The framework of the OCTAVIUS model is illustrated in figure 0.1. The OCTAVIUS model is mainly divided into 4 stages. The first stage is the population synthesizer which generates a synthetic population for the whole study area. The second stage is the Tour Generator which uses a discrete choice model to estimate the tour characteristics of each individual. The third stage is the destination choice model which estimates the destination for each individual for each mode within the tour estimated in the tourgenerator. The final stage is the Mode Choice Model, which estimates the probability of each mode, for the corresponding destination, for each individual. For each stage within the model except the population synthesizer, a Variance Reduction Technique is used to simulate discrete choices for each individual.

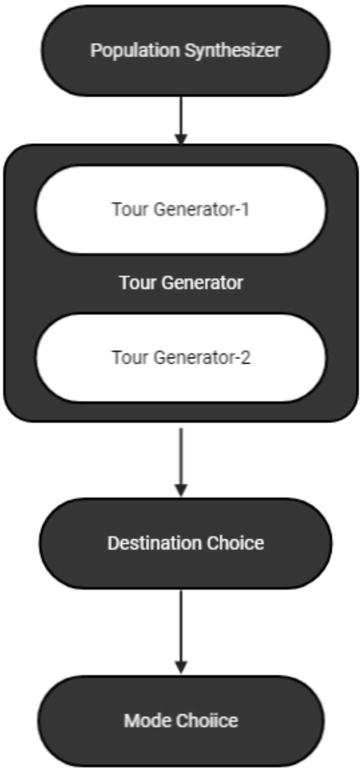

Figure 0.1: The OCTAVIUS framework

CASE STUDY ON THE REGION OF ALMERE

In the model application, two schemes were implemented namely, the mobility service scheme and mobility hub activities scheme. Both schemes aimed at replicating the characteristics of the mobility hub and its corresponding change in travel behaviour for two-trip and three-trip tours using public transport.

The mobility service scheme aimed at replicating the travel behaviour using mobility services, though the major assumption is that the entire tour (both two-trip and three-trip tour) is carried out using public transport. Within the two-trip tour, it was assumed that the travellers travelling to and from the mobility hub use mobility services and hence have faster travel times compared to traditional public transport as they don't have to wait for the vehicle and directly access it. Within the three-trip tour, a distinction was made between primary and secondary activities being performed at the hub location. The first distinction assumed that the primary activity is performed at the hub location and travellers would reach the hub using bike or by walking, from where they would perform the secondary activity at another location using the mobility services. Although mobility hubs would allow travellers to perform multiple activities at the hub location, due to model complexity it was not realised within the model application. The second distinction assumed that after performing the primary activity, the traveller would perform the secondary activity at the hub location. In this distinction, it was assumed that for the entire tour, travellers would use mobility services, as in the case of two trip tours.

The mobility hub activities scheme aimed at replicating the nature of increased activities at the mobility hub. The literature study suggested that mobility hub aims increasing various activities within its location, namely, Work, Business, Shopping and Social Recreational (Metrolinx, 2011; Gemeente Utrecht, 2018; RTP, 2019).An increase of 20% of these activities at the hub location was assumed. The 20% increase in the land use activities was given to the mobility hub zones only when travellers performed the above-mentioned activities. The corresponding change in the utility function for the mobility hub zones was formulated and was applied within the model.

Both schemes were applied within the model separately to identify independent impact of each scheme on the overall travel demand. Although a combined effect on travel demand could be observed in real life due to both increase in land-use activities and multiple mobility services.

CONCLUSIONS

The case study of OCTAVIUS showed the benefits of using microsimulation models compared to traditional demand models. Considering individual characteristics,the microsimulation model provides much better behavioural accuracy compared to traditional models. But while modelling mobility hubs the microsimulation model could not incorporate intermediate usage of stops and including constraints to impart the desired travel behaviour is still difficult.

Although the model performed in-line with the expectations which indicates the fact that the model is capable of handling different scenarios, adding the required constraints pertaining to mobility hub concept was not possible. Hence implementing constraints which were required to inherent the desired travel behaviour of mobility hubs were not realized. Though microsimulation models are considered to be the future of travel demand modelling, the need for data requirement is very high in such cases. The OCTAVIUS model is one of the few microsimulation travel demand models that is currently used for the strategic application of travel demand. The constraints require identification of proper methodology to be included within the model framework.

Finally, it can be concluded that currently, to a very limited extent can we model the potential changes in travel behaviour due to mobility hubs within microsimulation demand models. The potential changes to travel behaviour could only be implemented implicitly within the model. With the availability of data on various mobility services, data on travellers perception, methodology to implement constraints within the model framework, the implementation could then be extended within the microsimulation model. It can be stated that microsimulation models have the potential to model such changes but research is still required.

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ACRONYMS

GTHA Greater Toronto and Hamilton Area 4
PT Public Transport 4
OViN Onderzoek Verplaatsingen in Nederland 20
CBS Central Agency for Statistics 20
KiM Knowledge Institute for Mobility Policy 20
ASC Alternate Specific Constant 21
VRT Variance Reduction Technique 18
CDF Cumulative Distribution Function 26
AV's Automated Vehicles 4
EV's Electric Vehicles 4
KPI's Key Performance Indicators 4
IPF Iterative Proportional Fitting 20

1 INTRODUCTION

Mobility hubs are agglomerations of transportation modes, like conventional public transport and emerging shared mobility services in well-defined locations, delivering improved mobility for travellers and incentives them to use different modes of transport besides the individual motorized modes (Anderson et al., 2017; Gemeente Utrecht, 2018; RTP, 2019).

Mobility hubs are the result of a variety of policy constraints aimed at delivering benefits, such as expanding the area, increasing the use of public transit, densifying the inner city or increasing regional connectivity. However, the ultimate goal of mobility hubs is to enhance the quality of transport for future generations (Gemeente Utrecht, 2018; Metrolinx, 2011; RTP, 2019).

The traditional transport hubs are shaping into the idea of the mobility hub with the advent of multiple vehicle-sharing forms, such as bike sharing and car sharing. In addition, a gradual shift in the culture of consumption towards more usage and less ownership, as well as the shared economy supported by internet platforms and mobile apps, allows easy access to multiple daily mobility choices, especially in urban environments (Martin and Shaheen, 2011).

The change in the consumption culture of more using and less owning will induce new travel behaviour, for example, a person can make use of multiple shared services while performing multiple activities within the entire travel duration, which is quite different than using same mode to perform multiple activities within travel duration.

With the inclusion of mobility hubs and mobility services through jurisdictions within their regional transport plans, focus needs to be paid to the modelling of mobility hubs and mobility services within transport models. Modelling transport on both demand and supply side is critical and necessary for forecasting travel demand and supplying policymakers and transport planners with useful knowledge on the impact of mobility hubs and mobility services (Jittrapirom et al., 2017; Kamargianni et al., 2019).

On the demand side, transport demand models estimate the complexities of travel demand based on individual decisions on day-today activities, changes in land use, and so forth. The supply side focuses on the modes of transport offered and covers both design and operations, such as fleet size management and empty ride allocation. This research mainly focusses on the demand modelling of mobility hubs and incorporating the corresponding travel behaviour within travel demand models.

Conventional models were aggregated in nature while modelling travel demand, and the four-step modelling method was the dominant approach, for example, the gravity model. Advancements in the field resulted in a shift from aggregate models to disaggregate models. Disaggregate models use disaggregated data on individual travel between zone. The fundamental difference between aggregate and disaggregate models is that the disaggregate models are constructed using data at the individual/household level rather than zonal averages as perceived within aggregate models. Further, the behavioural inadequacy of both aggregate and disaggregate models contributed to the development of microsimulation models.

Microsimulation is increasingly assuming a major role in the advancement of demand-modelling practice. At the same time, it is attracting growing attention from the larger transportation-planning community. Theoretically, the microsimulation concept is based on the individual (or household) unit of behaviour. However, the microsimulation process is capable of generating discrete choices of the individual (trip purpose, destination, mode, time of day) rather than an array of probabilities for a population segment associated with each available alternative. The ability to simulate travellers individually allows for consideration of complex linkages across multiple trips, ultimately resulting in a better estimation of real-world travel behaviour (Vovsha, 2019).

The research will be carried out with the outline as illustrated in figure 1.1.

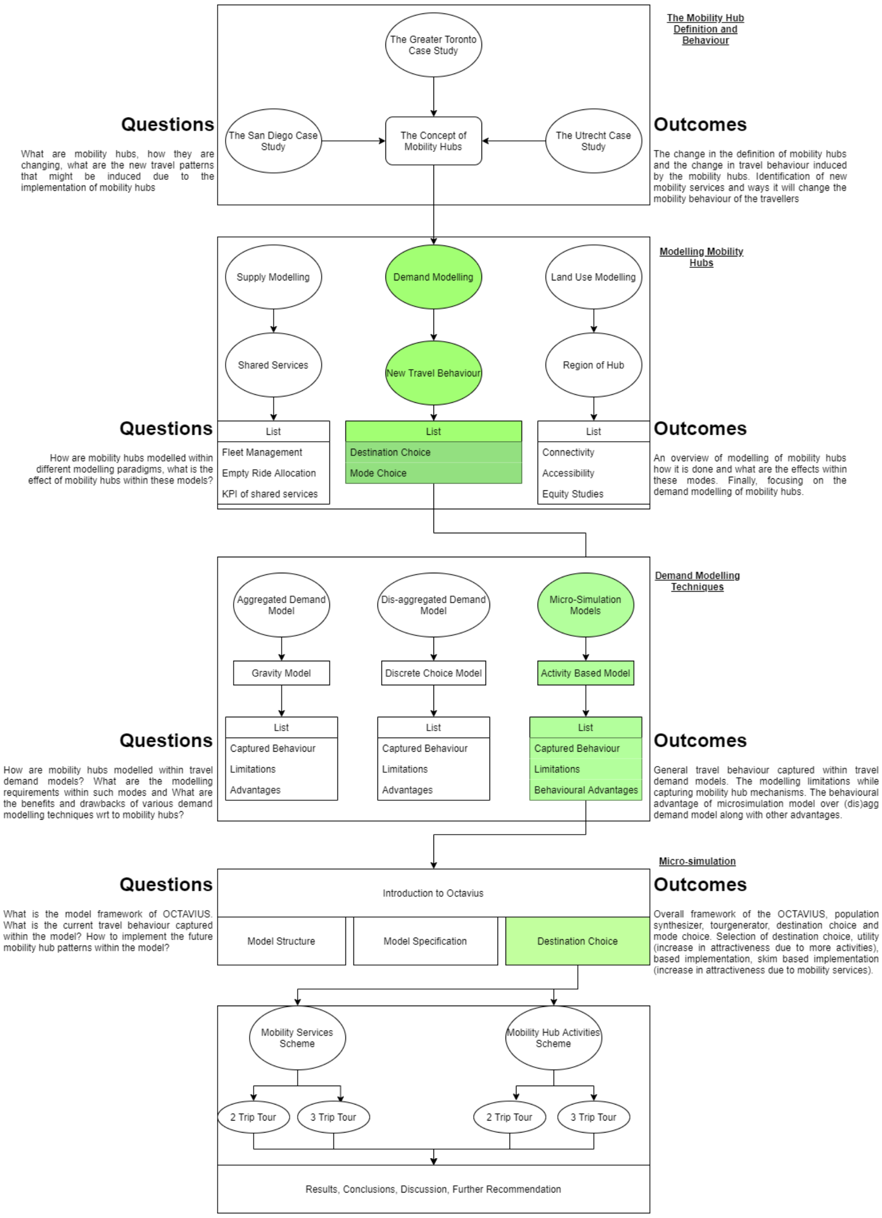


Figure 1.1: Thesis Outline

1.1 PROBLEM STATEMENT

According to Wikipedia, "a transport hub is a place where passengers and cargo are exchanged between transport modes". Transport hubs mainly involve public transport such as train stations, rapid transit stations, airports etc. In some cases the hubs are used as a central point for change in direction of the travel and in other cases a change in mode. The hubs provide a multitude of options for the travellers to reach their desired destinations although all destinations might not be accessible with all modes.

The idea of a mobility hub is relatively new compared to transport hubs, primarily because, with the advent of new mobility technologies such as ride-sharing and vehicle-sharing, as discussed by numerous scholars, mobility hubs seek to merge conventional public transport with new shared services (Martin and Shaheen, 2011; Miramontes et al., 2017; Gerben, 2018). Concepts such as the e-Hubs, which are close to the idea of mobility hubs, focus exclusively on mobility services and do not aim at integrating mobility services with conventional Public Transport (PT) (Interreg, 2019).

In addition to mobility services, mobility hubs also seek to enhance the degree of activities that could be carried out in and around the location of the mobility hub, primarily due to improved accessibility due to additional mobility services. Mobility hubs can become an attractive destination because of its dual nature, providing multiple mobility services and increased opportunities for activities.

Existing literature suggests that studies on mobility hubs mainly focus on the land-use impact of the mobility hubs, where these hubs are located near an existing transit station since the infrastructure is already available. Studies done by (Eliot et al., 2019; Ratti, 2017; Elshater and Ibraheem, 2014; El-Amine et al., 2017; Metrolinx, 2011), suggest that with the implementation of mobility hubs, the accessibility of the hub region increases, thus, increasing the attractiveness of hub region and public transport, creating a link between the residents and the jobs that could be carried out at the hub (Metrolinx, 2011; Ratti, 2017). These studies also indicate the fact that mobility hubs could provide solution for the first/last mile problem within the public transport due to increase in the accessibility.

Other literature regarding mobility hub and mainly the mobility services are focused on the supply side of these mobility services. Although there are many mobility services available, these researches mainly focus on car-sharing, ridesharing/ride-hailing and bike-sharing. These studies are aimed at estimating the fleet size requirement, empty ride allocation and Key Performance Indicators (KPI's) for such services. In addition to mobility services, technologies such as Automated Vehicles (AV's), Electric Vehicles (EV's), and the shared economy have attracted considerable attention recently. MaaS is argued to help improve the attractiveness of shared mobility, and the same can be expected in the case of mobility hubs (Yale Z Wong et al et al., 2018).

Research on the mobility hub and its impact on network usage is still scarce within conventional demand models. Two available researches on mobility hubs within travel demand models were carried on Greater Toronto and Hamilton Area (GTHA) and Merwedekanaal Zone in Utrecht. Research on GTHA indicates an increase in the overall mobility hub demand and where as research on Merwedekanaal Zone indicated that the travel demand was satisfied using different modes favoured by policy makers such as reduction in car usage of the region (Hut, 2019; Ratti, 2017) . However, in the case study of GTHA, linear regression models were used to forecast the mobility hub demand. The main disadvantage with such models relates to the fact that it assumes same travel behaviour before and after the implementation of hub. Further, in the case of Merwedekanaal Zone, mobility hubs were implemented within a trip-based gravity model, additional constraints were added to impart multimodal and parking behaviour for the travellers which are expected due to the implementation of mobility hub.

Thus, transport demand models should not only be able to forecast the future travel demand but also take into consideration the potential changes in travel behaviour due to the mobility hubs whilst fitting in an existing modelling framework from which the mathematical properties of its solutions are known.

In summary, Mobility hubs are a part of the future and it is important to identify the potential changes in travel behaviour associated to it. These potential changes in the travel behaviour must be included within transport demand models while analysing mobility hubs. Further, within transport demand modelling, the microsimulation of travel demand seems to be the most promising solution. The microsimulation model under consideration is known as OCTAVIUS, currently being developed at DAT.Mobility. As such microsimulation travel demand models are still under development, the research problem could be summarized into 3 main points:

- Mobility hubs are a part of the future and with more municipalities across the globe are aiming to realise it, the potential changes in travel behaviour due to mobility hubs must be investigated.
- Travel demand models must be able to incorporate the changes in travel behaviour while modelling future mobility hubs.
- Given the advancements in the field of travel demand modelling, it is necessary to investigate the ability of microsimulation models while modelling the potential changes in travel behaviour.

1.2 RESEARCH QUESTION

To what extent can microsimulation travel demand models can capture the potential changes in travel behaviour due to the implementation of Mobility Hubs?

Sub Questions:

- What are the potential changes in travel behaviour that could be observed due to the implementation of mobility hubs?
- How do travel demand models deal with the potential changes in travel behaviour related to mobility hubs?
- What are the possibilities of modelling potential changes in travel behaviour due to mobility hubs within microsimulation travel demand model, OCTAVIUS?

1.3 SCIENTIFIC AND SOCIETAL RELEVANCE

The scientific significance of this study is that it will help to recognize the potential of microsimulation travel demand models while modelling mobility hubs and associated potential travel behaviour. It will also build a case for a move from conventional aggregated travel demand models to dis-aggregated microsimulation travel demand models. It may also be used as a starting point for understanding the effect of mobility hubs on the transport network.

The societal relevance of this research is that it could benefit transport planners understand the potential changes in travel behaviour, in the case of mobility hubs, which could be used in accessibility and equity studies of mobility hubs in the future. Further, with an appropriate level of detail, the research would improve the quality of ex-ante studies of mobility hubs.

1.4 RESEARCH METHODOLOGY AND THESIS OUTLINE

The research methodology can be divided into 5 parts.

1. Literature review on Mobility hubs and Modelling of Mobility hubs

   This section will be covered within chapter 2 of the report. As the main aim of the research is to check to what extent can we apply the mobility hub concept within microsimulation transport demand model, the literature review will form the base of understanding the mobility hub concept and the potential changes in travel behaviour associated with it. The literature review will also investigate the current modelling practices of mobility hubs. Further, the literature will provide insights while modelling potential changes in travel behaviour within travel demand models, providing various benefits and limitations of travel demand models. Finally, the potential of using microsimulation w.r.t behavioural, statistical, and computational efficiencies will be laid.

2. Introduction to Microsimulation Travel Demand Model: OCTAVIUS

   This section will be covered within Chapter 3 of the report. With the increase in the computational efficiency of models, traditional demand models are having shifted the focus from aggregated macroscopic models to much finer dis-aggregated microscopic models. At DAT mobility, a microsimulation travel demand model is under development, named OCTAVIUS. The OCTAVIUS model uses personal characteristics of travellers to estimate travel decisions at every point of travel for every individual.

3. Application of mobility hubs within Microsimulation travel demand model, OCTAVIUS

   This section will be covered within Chapter 4 of the report. The section deals with the implementing the mobility hub scenario within the microsimulation travel demand model, OCTAVIUS. Currently the model runs on the region of Almere which has 630 zones and more than 160,000 inhabitants. This section would also guide through the modelling specifications of the OCTAVIUS model and the underlying assumptions required while modelling mobility hubs within the OCTAVIUS model.

4. Analysing mobility hubs within OCTAVIUS and Identifying modelling implications of Microsimulation Travel demand model

   This section will be covered within chapter 5 of the report. The section deals with analysing the mobility hubs implemented within the OCTAVIUS model. The change in the demand levels will be discussed and final conclusions will be made on the effect of mobility hub on the transport networks. Further the modelling implications faced during the implementations and points for further research will be laid in the final section.

5. Conclusions, Discussions and Future Recommendation

   The final chapter will first answer the research questions formulated in chapter 1. The ability of microsimulation travel demand model, OCTAVIUS to capture the potential changes in travel behaviour induced due to the mobility hubs will be discussed. Further, recommendations for the future will be laid in context to both mobility hubs and OCTAVIUS.

1.5 RESEARCH SCOPE AND LIMITATIONS

The research deals with analysing mobility hubs and the potential changes in travel behaviour due to these hubs, within microsimulation travel demand model together with demonstrating the modelling capacity of microsimulation demand model while modelling the potential changes in travel behaviour due to mobility hubs. The demand modelling of mobility hubs would further help the research on the supply modelling of mobility services taking into account the potential changes in travel behaviour due to the mobility hubs which is currently ignored in the supply modelling of mobility services. The research could be used to demonstrate the benefits of using disaggregated microsimulation demand models compared to traditional aggregated demand models.

The main limitation of this research is the validity of the estimated travel demand of the mobility hubs. As mobility hubs are considered as a concept for the future and do not exist, the research would not be able to use actual data on different aspects of the mobility hub but rather assumed values, thus making it difficult to validate the effect of mobility hub on travel demand. Further, there is a possibility that mobility hubs could be completely different from what it is expected to be in this research. The potential changes in travel behaviour needs to be further analysed using stated and revealed preference studies which would provide information on how mobility hubs could be perceived by travellers.

2 LITERATURE REVIEW

The literature review is done in three sections, section 2.1 is a formal review of mobility hubs, section 2.2 review of mobility hubs within transport demand models. and finally section 2.3 is a review on Mobility Hubs specifications within transport models.

Section 2.1 would investigate different mobility hubs aimed by different jurisdictions across the globe and the potential changes in the travel behaviour due to these hubs. Mobility hubs can be seen across countries like Canada, The US, Italy, Finland, Germany and The Netherlands. The fact that the mobility hubs are either future-oriented, as in the case of the United States and the Netherlands, or are in pilot studies with minimal infrastructure, as in the case of Germany and Finland, remains the key problem when researching mobility hubs. Literature on most of these mobility hubs cannot be considered as scientifically significant as most of them are proposals by their respective jurisdictions. For this research only three mobility hubs will be investigated which have been previously mentioned within scientific studies, namely, the case of Utrecht Merwedekanaal Zone (The Netherlands), the case of San Diego Mobility Hub (The United States) and the Regional Road Transport plan of the Greater Toronto and Hamilton Region (Canada). Investigation of these mobility hubs would help in laying out the potential changes in travel behaviour which will be further used in Chapter 4.

Section 2.2 would investigate the modelling of mobility hubs within different demand models. As the focus of this research is Microsimulation Travel Demand Model, the potential of such models with regards to behavioural and computational efficiencies will be investigated.

Section 2.3 would investigate the mobility hubs specifications such as the locations of mobility hubs and its types. Most of the mobility hub studies deal with the land-use impact of mobility hubs. These studies reveal the importance of placement of mobility hubs within the transport network. Further, the relevance of Mobility-as-a-Service within Mobility hubs will be investigated. The relevance of MaaS would enable to identify different mobility services that could be provided at the mobility hub. This section mainly deals with literature where, this is mainly done to investigate the desired locations of mobility hubs and to identify the role of MaaS within the Mobility Hub framework.

2.1 A FORMAL REVIEW OF MOBILITY HUBS AROUND THE WORLD

In general a hub is defined as "the central or main part of something where there is most activity"(Cambridge dictionary). This means that the hub is the central part of any system where most activities take place. Within the transport network, hubs are locations which have a higher connectivity to other locations making it place of high importance within the transport network.

In Urban context, the hub concept is the network of urban corridors that link and cross in and around a city or town. Hub functions, namely, interchange with other modes of public transport, where traffic exchanges across several modes of transportation (Bell, 2019).

Transport hubs are in place since the inception of air travel but have been widely used within road transport network as railway stations, compared to which the notion of mobility hub is quite recent. The inclusion of mobility services within the hub apart from traditional public transport forms the concept of mobility hubs.

The mobility services such as vehicle-sharing and ride-sharing which are expected to be within the mobility hubs will provide flexible travel options to the traveller compared to transport hubs which provide public transport services on fixed routes/paths. The inclusion of mobility services will enable travellers to reach destinations from the hub, which were previously not accessible using transport hubs. The flexibility of mobility hubs is expected to impart changes in travel behaviour of travellers.

The following sub-sections will investigate the potential changes in travel behaviour across three mobility hubs, namely, the case of Utrecht Merwedekanaal Zone (The Netherlands), the case of San Diego Mobility Hub (The United States) and the Regional Road Transport plan of the Greater Toronto and Hamilton Region (Canada). The services provided by these mobility hubs will be looked upon to get an idea about the potential changes in travel behaviour.

2.1.1 The Case of Utrecht: Merwedekanaal Zone

The municipality of Utrecht appointed the Merwedekanaal Zone as an inner urban development area and aims at realizing 9000 houses in the former industrial site.

The realization of a mobility policy that reduces the development of car traffic in the region is the most important condition for being able to build 9,000 homes in the Merwedekanaal region. This includes attractive paths for walking, cycling and public transit, a major decline in the number of parking spaces in the city and the provision of a car-sharing scheme, the mobility hubs shall encourage various mobility choices and promote safe urban living and zero-emission modes, would be a key feature. The largest mobility hubs will contain a variety of options: inhabitants will be able to easily unlock a shared bike with their mobility subscription, they will have access to a high-quality and frequent bus connection, possibly a tram in the future, with several stops at the border of the area, they can collect their postal packages in special package walls, so that the postman's van won't have to drive through the area, they will have effortless access to shared cars in the parking garages and there will be a physical mobility store for the customer service and to pick up e-bikes and cargo-bikes (Gemeente Utrecht, 2018).

The aim of the mobility hub is to reduce the number of cars within the Merwedekanaal region. This is achieved by providing attractive walking and cycling paths in the region. Further, the mobility hubs would allow travellers to park their personal bikes at the mobility hub and travel further either by public transport or shared-car. In situation where travellers reach the mobility hub by walk, travellers with subscription have the option to use a shared-bike available at the mobility hub apart from public transport and shared-car. The mobility hubs would allow travellers to choose from a much wider shared mobility options rather than traditional public transport.

The mobility hub would allow the municipality to provide more housing to the population in the Merwedekanaal Region. The whole focus is to allow travellers to use personal modes such as bike or shared modes such as shared-bike and shared-car along with public transport and reduce the usage of personal cars in the region.

2.1.2 The Case of Greater Toronto and Hamilton Area: The Regional Transport Plan

The regional transport plan for the greater Toronto and Hamilton area was visioned by Metrolinx. According to their RTP, mobility hubs would play the key role in developing region of Toronto and Greater Hamilton Area. The mobility hub would help smaller towns across the Toronto Region namely, Durham, Halton, Peel and York in becoming urban growth centres. The mobility hub is defined as a place of connectivity, where different modes of movement, from walking to high speed rail would come together seamlessly along with an increasing attractiveness due to intense concentration of employment, living, shopping and recreational activities. A mobility hub is easily accessible for those who begin or end their trip on foot or riding bicycles. It is a place where the transit rider is treated like a coveted consumer, with choices about how he or she moves around the region. It is a safe, convenient, attractive place in which the city interacts with its transit system (Metrolinx, 2011).

Within the regional transport plan, the mobility hubs are categorised as Primary, Secondary and Tertiary hubs. The primary hubs are locations of significant regional city centres, the secondary hubs are the locations of major activity centres such as shopping malls and educational institutions and the tertiary hubs are all the major transit stations such as stations with high demand for public transport which are not included in the previous categories. One major similarity between the three categories is that all these hubs are located near to a transit station, making public transit more attractive to travellers. Further, being city centres primary hubs will attract more demand due to the availability of more activities. Activities such as buying groceries (shopping), visiting a barber and watching movies (recreational) could be carried out at these hubs. The secondary and tertiary hubs are mainly used as means to increase the demand for public transport. Although activities such as work could be carried out at secondary hubs. Along with public transport, allocation for pedestrians and shared-bikes is provided (Metrolinx, 2011)

Further mobility services such as station based vehicle sharing and ridesharing are available at each mobility hub. A Station based vehicle sharing system which connects these mobility hubs, allowing travellers multiple alternatives to travel apart from public transport. Travellers can reach the desired destination either by public transport or shared bikes, whereas travellers can access mobility hubs using public transport, shared bikes and station based vehicle sharing systems (in case where a traveller has to travel between the mobility hubs).

The key characteristics of the mobility hub include:

- Hosts one or more modes of higher-order transit (such as train, metro, tram and bus)
- Shall provide parking for personal modes such as personal bike or shared bike and shared cars.
- Has land available for different types of development in and around mobility hub.
- Provision of multiple activities such as shopping and recreational.

With these key characteristics, mobility hubs would become a place not only for the transfer between modes but will also be a place to carry out multiple activities such as shopping for groceries, having a haircut or even watching a movie.

Traditional transport hubs were considered as place of transfer between modes only but with much efficient land-use, mobility hubs would induce a shift in travel behaviour of undertaking multiple activities within the mobility hub zone (Metrolinx, 2008).

2.1.3 The Case of San Diego: The Regional Transport Plan

The 2021 Regional Plan included mobility hubs as the key in achieving various transport and land-use issues for the region of San Diego. Within the regional plan, Mobility hubs would serve as the communities with high concentration of people, destinations and travel choices. They would offer on-demand travel options supporting infrastructure that enhance connections to high-quality Transit Leap services while helping people make short trips around the community on Flexible Fleets. Mobility Hubs can span one, two, or a few miles based on community characteristics and are uniquely designed to fulfil a variety of travel needs while strengthening the land-use value (Sandag, 2019).

Similar to the case of Greater Toronto and Hamilton Area discussed in section 2.1.2, the mobility hub in the region of San Diego focuses mainly on walking and shared biking as the feeder mode to the mobility hub. The hub would be located at or near the transit location in-order to improve the transit ridership and reduce the levels of road traffic congestion in and near the hub location. Compared to the mobility hubs discussed in 2.1.1 and 2.1.2, the San Diego Mobility Hub is visioned with much more futuristic mobility services, such as rideables, micro-transit, E-bikes, on-demand rideshare. Each mobility hub is designed specifically for the surrounding community it serves, ultimately making it easier for residents, employees, and visitors to use transit to travel to and from home and work, with a wide variety of destinations in between. A mobility hub area includes not just the transit station itself but all those services and destinations that are accessible within a 5-min on shared-bike, or drive using shared services to/from transit. Compared to traditional transport hub, the mobility services would increase the accessibility of the mobility hub to the nearby regions which is illustrated in figure 2.1.

Along with these services, high importance is given to the pedestrians and people using bikes. This would imply that travellers would reach the hub either by walk or bikes and leave the hub using either public transit or mobility services such as shared-car, micro-transit and rideables. This would allow travellers access multiple destinations in or near the hub location, depending on the type of mode chosen.

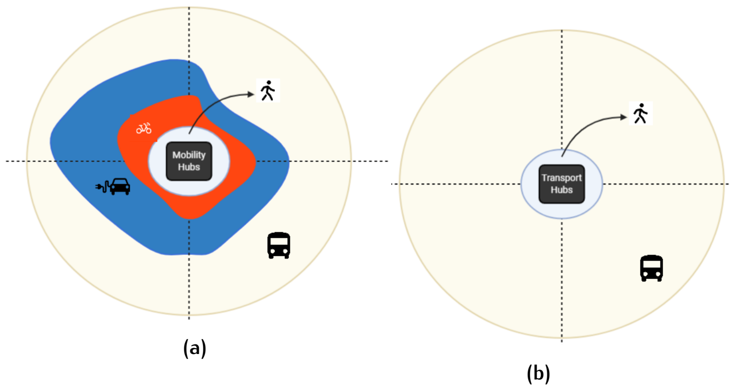


Figure 2.1: Accessibility of to carry out activities due to (a) Mobility hub(b) Traditonal Transport Hub

Apart from the mobility services, high importance is also given to other amenities such as wayfinding, package delivery, mobile retail services and universal transportation account. These features are similar to what is offered within the Mobility-as-a-Service scheme (García et al., 2020).

Potential Changes to Travel Behaviour

The mobility hubs investigated in sections 2.1.1, 2.1.2 and 2.1.3 are mainly focused on offering multiple mobility services together with traditional public transport and optionally provide an opportunity to carry out activities at the mobility hub (considering better land-use and transit oriented development as seen in the case of GTHA and San Diego). To further understand the potential changes in travel behaviour, the mobility services could be categorised into two categories based on the purpose of use, as shown in table 2.1.

Type of Mobility Service	Service Purpose
Shared-bikes, e-bikes, rideables	First/last mile mode from the hub.
Shared-car, Micro-transit, Ride-share	Alternative to public transport

Table 2.1: Mobility services based on purpose of use.

Mobility services such as shared-bikes, e-bikes and rideables which are available at the mobility hub are promoted to be used as first/last mile solution for the activity end for the travellers, for example, travellers reaching the mobility hub using public transport could use shared-bikes to reach their office. Whereas for the home-end travellers would still have to use personal modes or PT to reach the mobility hub, as the mobility services would be only available at the mobility hub. Further, in cases where travellers use personal modes to reach the hub, the personal mode will have to be parked at the mobility hub adding an additional parking function of the mobility hub.

Mobility services such as shared-cars (either free-floating or station based), micro-transit or ridesharing (in case of San Diego) are promoted to be used as an alternative to public transport which is mainly beneficial for travellers who would consider using shared car rather than public transport. It is also safe to assume that travellers using shared-bikes, e-bikes and rideables would travel for shorter distances compared to travellers using shared-cars. A list of mobility hub functions is shown in table 2.2.

Mobility Hub Functions	**Description**
Multimodality (feeder mode)	Ability to use shared services (such as shared-bike) as first/last mile mode (activity-end)
Multimodality (main-mode)	Ability to use shared services (car-sharing, micro-transit) at the hub in place of public transport
Multi-Activity Destination	Ability to perform multiple activities within the same location
Additional Function	Travellers using personal modes to access hub
Parking	Ability to park personal mode at the mobility hub.

Table 2.2: Mobility hub Functions

Due to the complex nature of these hubs and the underlying functions, transport demand models must incorporate constraints in-order to impart the desired travel behaviour, which would help various stakeholders understand the impacts of the hubs on the transport system. Required constraints persisting to each mobility hub function are listed in table 2.3

Mobility Hub Functions	**Required Constraints**
Multimodality (feeder mode)	• Vehicle Availability Constraint • Pick-up/Drop-off Constraint
Multimodality (main-mode)	• Vehicle Availability Constraint • Pick-up/Drop-off Constraint • Subscription Constraints (in cases when subscription is required)
Multi-Activity Destination	• Intrazonal Constraints
Additional Function	Travellers using personal modes to access hub
Parking	• Return Trip Constraint • Parking Constraints

Table 2.3: Mobility hub Functions and required constraints

2.2 REVIEW OF TRANSPORT DEMAND MODELS IN THE CASE OF MOBILITY HUBS

Transport demand models have evolved from static to dynamic capturing travel behaviour in terms of time-dependent conditions and information, and from an aggregate to a disaggregate representation of travel, focusing on the heterogeneity of individual traveling (Ben-Akiva et al., 2007).

Transport modelling is important and essential for estimating travel demand and offering valuable information to policy makers and transport planners. During the years, several modelling approaches have been explored and formulated. In travel demand modelling, conventional models were aggregate in nature and the dominant approach was the four-step modelling process. Dissatisfaction with trip-based models due to the behavioural inadequacy of this approach has led to the emergence of disaggregate forecasting models (Bhat and Koppelman, 2014).

Moving to activity-based approach, new aspects are of crucial importance: integrity, inter-dependencies between trips of the same trip chain or household, higher temporal and spatial aggregation and a strong behavioural basis, as engaging in an activity in fact 'represents' a dynamic interaction of household needs, tasks, and constraints(Ettema and Timmermans, 2003). One of the first types of activity-based models were the constraints models, examining the feasibility of agendas with a great emphasis on the role of spatial-temporal constraints on daily travel behaviour. Then, the second approach in activity-based modelling was the econometric one, based on discrete choice models and on the principle of utility maximisation to model pattern formation. Though these models can capture complex travel behaviour by considering inter-dependencies between trips of the same trip chain but are computationally inefficient.(Bhat and Koppelman, 2014; Timmermans et al., 2002).

Further, the potential of microsimulation has made a huge impact in the field of demand modelling. Microsimulation are considered as an extension to disaggregate models and not as an alternative. The main difference between both models being the ability to simulate trip makers on an individual basis allows for complex linkages across multiple trips, ultimately resulting in a better estimation of real-world travel behaviour.

Microsimulation models are considered to have several major advantages over standard models. Firstly, microsimulation allows modellers to improve the behavioural realism of travel demand models. Explicitly modelling individuals in households allows for exploration of a chained or hierarchical structure of travel decisions as well as objective time–space constraints on a daily-activity agenda. Further, when constraints are introduced into the modelling framework at the destination choice stage, competition over attractions arises(Vovsha et al., 2002). This implies that within traditional models such as the 4-stage modelling, implementing constraints leads to increased computational times and some cases might lead to mathematical instability of the model, for example, in the case of Implementing mobility hub within a multi-constrained trip based gravity model, lead to the loss of entropy maximization for a particular mobility hub function of parking (Hut, 2019). In the case of mobility hubs investigated in the previous section, potential constraints were identified. According to Vovsha, inclusion of such constraints within traditional aggregated models is not sufficient and given the potential of microsimulation models, the application of constraints within them shall be investigated. One major drawback of microsimulation models persists to the availability of data. The microsimulation models are highly dependent on data quality and data availability.

Considering scope of this research the extent to which mobility hubs could be modelled within Microsimulation Travel Demand Model, namely, OCTAVIUS will be investigated.

2.3 REVIEW OF MODELLING MOBILITY HUBS

2.3.1 Mobility Hubs within Land-Use Models

The integration of land-use planning, and transport planning is as the keystone of a sustainable transport planning (Banister, 2008; Cervero et al., 2009).The concept of mobility hub revolves around the same notion of integrating land-use planning (which would provide more job opportunities) and transport planning.

In the previous sub-section of the review of mobility hubs, it can be observed that all the mobility hubs were in and around the transit stations. This is mainly because the infrastructure already exists and can be further developed while realising mobility hubs. The hubs would attract services and in large scale, these hubs can change people flows and thus have impact on planning land use concerning both residential and industrial zones (Kamargianni et al., 2019).

For the Greater Toronto and Hamilton area, accessibility studies done by Ratti showed that the highest performing hubs were located at major transit stations whereas the least performing hubs were largely underdeveloped. The mobility hubs which were deemed successful are also located in the core of Toronto, thus, resulting in sufficient demand to sustain local transit (Ratti, 2017).

2.3.2 Relevance of Mobility-as-a-Service

With the current pace in the field of Mobility-as-a-Service, mobility hubs are not far away from realisation. The concept of e-Hubs is in the phase of pilot studies done by 15 partnership countries (Interreg, 2019). Also, the goal of MaaS schemes is to encourage the use of public transport services, by bringing together multi-modal transportation and allowing the users to choose and facilitating them in their intermodal trips. The whole concept of Mobility hubs linking mobility services to public transit and the potential of MaaS could be the driver in realization of mobility hubs. Further, the mobility hubs would allow travellers use the mobility services available at the hub and mainly benefit for the activity end of the traveller. With MaaS, at the home-end, the travellers could also use mobility services such as free-floating shared-bikes and shared-cars to reach the hub or any other desired location. Travellers could then use these services to reach the hub and would eliminate the use of personal modes. (Jittrapirom et al., 2017)

MaaS aims at integrating a number and variety of new on-demand transportation services that have appeared in the transportation arena. Among these, shared services, namely car-sharing and bike-sharing. The free-floating configuration of these shared services (the car or bike can be left at the destination and not necessarily at the initial pick-up point), is the one that allows for more flexibility and, therefore, the most suitable for the case of Mobility hubs (Jittrapirom et al., 2017; Landínez, 2018; García et al., 2020).

2.4 CONCLUSION

The literature review was done in three stages, the first stage identified potential changes to travel behaviour that might be induced due to the mobility hub and its mobility services. From table 2.1 it is quite evident that mobility hubs would allow travellers flexible travel options along with public transport while accessing and leaving the hub. Further, due to the shared mobility services, mobility hubs will allow travellers to perform multiple activities in and near the mobility hub region. This was largely ignored within traditional transport hubs. Thus, three main functions of the mobility hub were observed and the potential constraints were identified in table 2.3.

The second stage of literature allowed us to identify drawbacks of aggregate, disaggregate 4-stage models and activity-based models while modelling such changes in potential travel behaviour (Timmermans et al., 2002; Bhat and Koppelman, 2014; Vovsha, 2019). Most research suggest that new microsimulation models shall be investigated while modelling complex travel behaviour such as usage of shared services for both first/last mile, as an alternative to public transport and allowing traveller to carry out multiple activities at one destination (mobility hub functions in table 2.2), due to their flexibility while modelling such behaviour. Based on the statements regarding the benefit of microsimulation by Vovsha, for this case study, a microsimulation demand model, namely, OCTAVIUS will be investigated to identify the potential of microsimulation model while modelling potential changes to travel behaviour due to mobility hubs. Though there are several microsimulation demand models available, this study will deal only with OCTAVIUS.

Finally, while investigating different models where mobility hubs were implemented, location of mobility hubs within the transport system was identified and literature suggested that mobility hubs must be in or near major transit stations in order to serve its purpose. The case study done on the Greater Toronto and Hamilton Area indicated that mobility hubs perform higher where public transport infrastructure is already available. The low performing mobility hubs are in places where there is less or no public transport infrastructure. The locations of the mobility hubs near the transit stations shall be used while modelling mobility hubs within transport demand models.

3 MODEL INTRODUCTION

Analysing and understanding of individual travel behaviour is the cornerstone of travel demand models. Aspects such as rich segmentation of individuals and activities along with time-space constraints is largely ignored in macroscopic models (Vovsha, 2019).

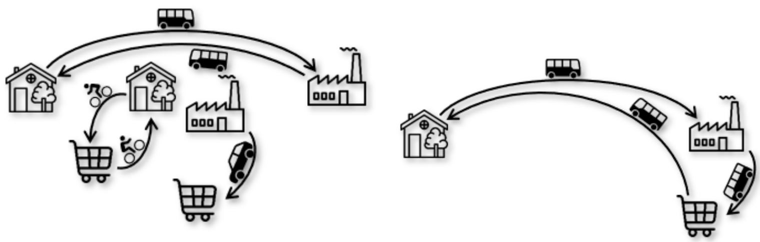
As observed in chapter 2 mobility hubs have the potential to change the travel behaviour of the travellers given the fact that mobility hubs are aimed at providing multiple mobility services along with public transport together along with the option to carry out multiple activities within the mobility hub zone. Travel Demand Models must also be able to capture the potential change in travel behaviour due to the mobility hubs while analysing mobility hub demand. Existing literature investigated in section 2.2 suggests that simplified macroscopic (such as aggregated macroscopic modes such as the trip-based and tour-based models or even disaggregated models) are not flexible enough to portray such changes in mobility (Ben-Akiva et al., 2007; Vovsha, 2019).

At DAT Mobility, a recent development in the field of transport demand models is taking place. The new microsimulation travel demand model, named, OCTAVIUS is currently under development. Compared to regular microsimulation models the OCTAVIUS model guarantees that apart from the quantization error the probabilities from the macroscopic behavioural models that it uses are always exactly met by their discrete representation at the level of the zone/segment combination. The model is applicable to strategic applications where the model user is mainly interested in the difference between a reference situation and a scenario that includes policy measures to be evaluated. The model is currently applied on the region of Almere. Section 3.2 will provide a brief introduction to the OCTAVIUS model. Section 3.3 will describe different stages involved within the model followed be the discussion on each stage within the model framework.

3.1 INTRODUCTION TO MICROSIMULATION TRAVEL DEMAND MODEL:OCTAVIUS

The OCTAVIUS model is aimed towards estimating future complex travel behaviour that considers individual characteristics at each decision point within the entire travel duration of each individual. The model aims at representing complex travel behaviour as illustrated in figure 3.1, the figure represents a three trip tour, where the traveller carries out two activities within the entire travel duration using different modes on different legs during the tour. The same tour represented using a trip-based gravity model and a tour-based gravity model can be illustrated in figure 3.2a and figure 3.2b.

Figure 3.1: Potential Travel Behaviour to be Captured within OCTAVIUS



(a)

(b)

Figure 3.2: Travel behaviour captured in (a) Trip based Model (b) Tour based Model

Apart from general benefits of using microsimulation travel demand models as discussed on 2.2, the OCTAVIUS model is able to simulate discrete choices using a Variance Reduction Technique (VRT). The VRT and its underlying impacts on the model will be further discussed in sub-section 3.2.5.

3.2 FRAMEWORK OCTAVIUS

As the OCTAVIUS model is still under development, the model is a subject to constant changes and improvements. Within the case study an earlier and simpler version of the model was used compared to the latest version. For the sake of this case study the components of the model will be explained based on the earlier version and not based on the latest version.

The framework of the OCTAVIUS model is illustrated in figure 3.3. The model is mainly divided into 4 stages. The first stage is the Population Synthesizer which generates a synthetic population for the whole study area. The second stage is the Tour-Generator which uses a discrete choice model to estimate the tour characteristics of each individual. The third stage is the Destination Choice Model which estimates the destination for each individual for each mode within the tour estimated in the tour-generator. The final stage is the Mode Choice Model, which estimates the probability of each mode, for the corresponding tour undertaken by each individual. Each stage within the model uses the Variance Reduction Technique to simulate discrete choices for each individual. Each stage will be explained in detail in the following sub-sections.

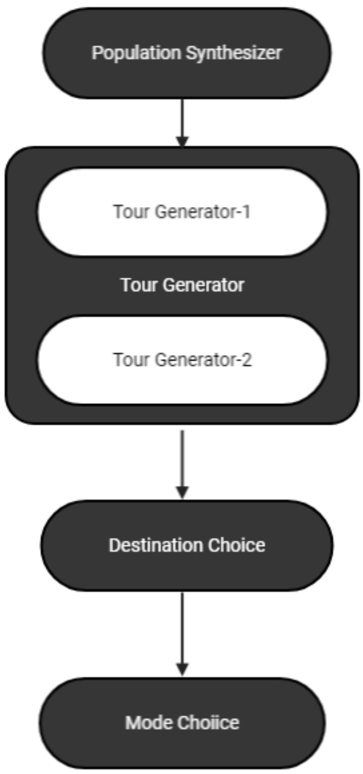


Figure 3.3: OCTAVIUS Framework

3.2.1 Population Synthesizer

The Population synthesizer works in two phases, known as, the fitting stage and the allocation stage as illustrated in figure 3.4. The fitting stage is generally used to compute an aggregated representation of the target population and the allocation stage is used to perform the dis-aggregation of the fitted data. The zonal and household totals are obtained from CBS-Buurt (https://cbsinuwbuurt.nl) whereas the distribution over person and household segments are obtained from the OViN data collected between 2010-2017. Onderzoek Verplaatsingen in Nederland (OViN) is a survey by the Dutch institution Central Agency for Statistics (CBS) that gathers all statistical information about the Netherlands. Specifically, OViN yearly produces a data set storing reports of movements by Dutch people. Respondents receive a questionnaire and are asked to fill out their made trips together with its specifications. This results in sample of the Dutch population (about 0.25% filled in a questionnaire), after which the samples are scaled to approximate the trips of the whole population. Furthermore, the household composition is obtained from Knowledge Institute for Mobility Policy (KiM) (https://www.kimnet.nl/mobiliteitspanel-nederland)

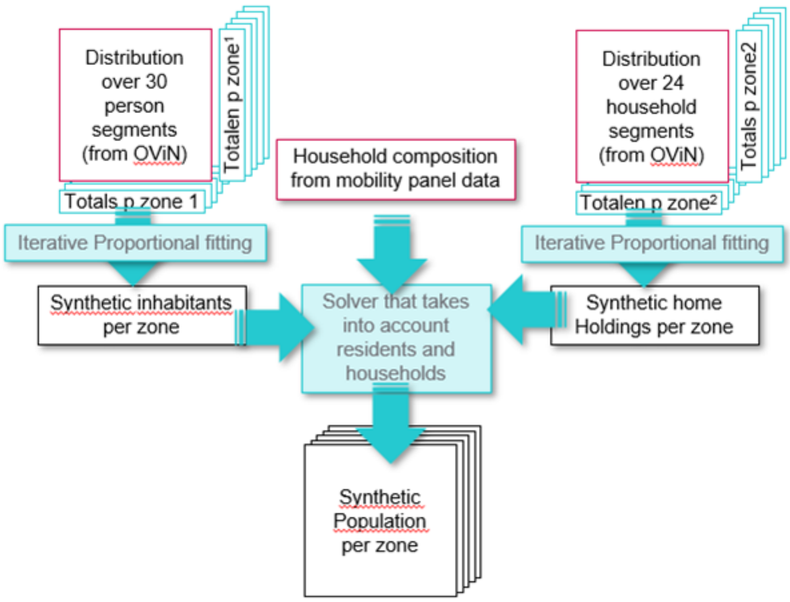


Figure 3.4: Framework of Population synthesizer, Source:DAT Mobility

The Zonal totals at person level are given across three dimensions, social participation (Student, working, other), Age Range (0-17, 19-29, 30-44, 45-64, 65+) and Gender (male, female). The zonal totals at household level are given across two dimensions, Household size and Number of cars per household.

During the fitting stage the model uses Iterative Proportional Fitting (IPF) for both person level and household level, which calculates number of persons per zone and number of households per zone. The allocation is done using a mixed inter linear programming solver to draw out a synthetic population per zone from a data source containing a representative sample of household and person characteristics with each individual having characteristics such as zone id, age, social participation, gender, household id, household size and number of cars within the household.Thus, by the end of the simulation, the population synthesizer produces a synthetic population, representative for the whole study area.

3.2.2 Tour-Generator

The population synthesizer provides agents having characteristics as mentioned in section 3.2.1. This data is then used to estimate the number of tours each person makes.

In general, the entire tour-generator is considered as a single block within the model framework. But within the OCTAVIUS version used for this case study, the tour generator is used in a hybrid form i.e. divided into two parts, where the first part estimates the number of tours each person undertakes, whereas the second part estimates the tour characteristics for each individual. This is done in order to align the number of trips with actual trip counts for the case of Almere. This is achieved by calibrating the Alternate Specific Constant (ASC) for the tour-generator-1 with that of an aggregated model, after which the tour-generator-2 is simulated. Such calibration is not usually required for other applications of the model, as the model is currently under development, this step ensured consistency with the estimates of the tour-generator. The Tour-Generator is used to estimate the tour characteristics for each individual, such as number of tours, length of tours, primary and secondary purposes within tours and sequence of purposes within tours.

Tour Generator 1

The general idea behind the tourgenerator-1 is to estimate the number of tours undertaken be every individual. A person has a freedom to make n number of tours within a day, but in-order to model such situations suitable data is required. The data used in this case is obtained from OViN. Table 3.1 shows the percentage of tours obtained between 2010-2017.

Number of Tours per day	% of Tours	Cumulative
0 Tours	16.81%	16.81%
1 Tour	49.6%	66.46%
2 Tours	25.4%	91.87%
3+ Tours	8.13%	100%

Table 3.1: Percentage of Total Tours for years 2010-2017, Source:CBS

Currently the model is used to estimate maximum of 2 tours for each individual, this is mainly because 2 tours constitute 91.87% total tours. Thus, each individual can undertake 0,1 or 2 tours at maximum. Restricting the model to only 2 tours per individual, eliminates approximately 8% of the tours which are generally observed in reality. Eliminating 8% of the total tours might not have considerable impact on estimates of total tours but this might have impact on total number of trips to be estimated in tour-generator-2 which requires further research.

For every individual having characteristics such as age, gender, social participation, urbanity of the zone (specified explicitly based on the location each person is living in), number of cars within the household and household size, these attributes are then considered as parameters. The significance of the estimated parameters are checked using Student-T test, which are then used to calculate the probability of choosing one of the three available choice situations. Finally, for each choice situation VRT is applied to let each individual choose one discrete option, before the moving ahead with tour-generator-2

Tour Generator 2

For each individual, the Tourgenerator-2 estimates, number of trips within the tour, purpose of trips and sequence of purposes. This will then be used to identify the destination for each individual in the destination choice.

The choice tree for the complete setup of the tourgenerator is illustrated in figure 3.5.

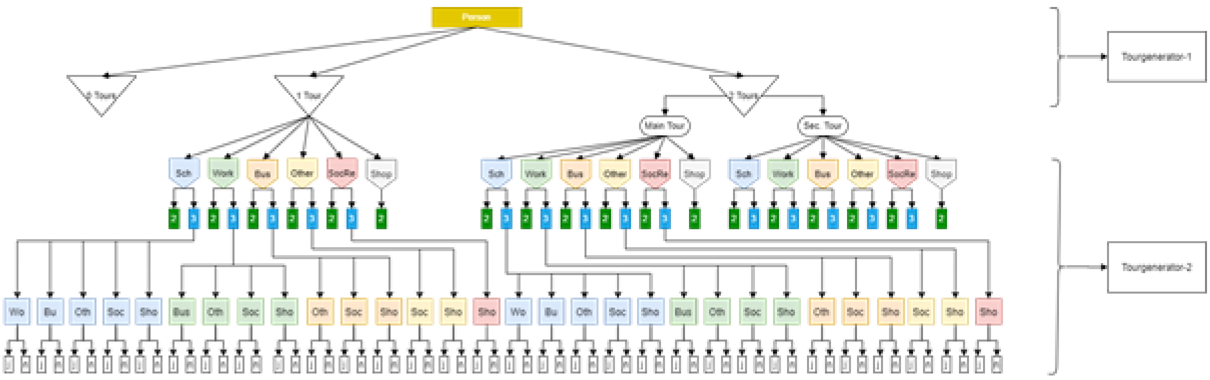


Figure 3.5: Overview of Tour Generator Choice Tree

The first stage of the tourgenerator-2 is to estimate the primary purpose of each tour. Using the OViN data, 6 main purposes were identified. These purposes are School, Work, Business, Other, Social Recreational and Shopping. Thus, for every choice of number of tours selected in the tourgenerator-1, will be extended with these 6 choices. Again, a VRT is applied to let each individual choose one discrete option before moving on to the next choice situation, i.e. number of trips within the tour.

These alternatives are estimated using the same set of parameters (age, gender, social participation etc.) used in the tourgenerator-1. The probability of each alternative is calculated using a multinomial logit model and every individual is then assigned one of the six available alternatives.

After the estimation of the first/primary purpose, the tree is extended to estimate the length of each tour for every primary purpose i.e. number of trips within the tour. Usually an individual can make n number of trips within a tour but in order to model the number of trips within a tour it is assumed that every person can make a maximum of 3 tours. This is because most tours have a maximum trip length of 2 following with a trip length of 3. The trip length distribution obtained from OViN is illustrated in table 3.2.

Tour Length	% of Tours	Cumulative %
1	0.92%	0.92%
2	76.15%	77.07%
3	16.25%	92.39%
4	5.24%	97.64%
5	1.50%	99.14%
6	0.53%	99.67%

Table 3.2: Tour Length Distribution for year 2010-2017 Source:CBS

Again the VRT is applied to let each individual choose a discrete choice for the selection of number of trips within a tours. Now, After the selection of number of tours and number of trips within the tour, for tours with trip length 2 imply that travellers carry out only one activity within the entire travel duration, whereas for tours with trip length 3 implies that travellers carry out two activities within the entire travel duration.

From the choice tree represented in figure 3.5 it can be seen that each choice of primary purpose has limited number of alternatives for the secondary purpose. For example, for the primary purpose ”School” the travellers can choose from 5 alternatives for the secondary purposes, whereas for primary purpose ”Work”, travellers can choose from 4 of the remaining alternatives. Similarly, for primary purpose of ”Business” has 3 alternatives, ”Other” has 2 alternatives and ”Social Recreational” has only one alternative. Such hierarchy is applied to determine the primary and secondary activities and also to eliminate multiple situations for travellers for choosing the same alternatives in the choice tree. Again, the VRT is applied to let each agent/individual choose a discrete choice for the selection of the secondary purpose.

For tours with length 3, it is required to estimate the sequence of purposes, as the traveller carry out two activities within the entire travel duration. If an individual is estimated to choose “Yes”, then the secondary purpose is carried before the primary purpose (implies ”secondary purpose first”) and if the person chooses “No”, the primary purpose is carried out before the secondary purpose(implies ”primary purpose first”). This can be illustrated using an example of carrying out ”Work” as primary purpose and ”Shopping” as secondary purpose and the situation when traveller selects ”Yes” in figure 3.6a and the situation when the traveller selects ”No” in figure 3.6b .

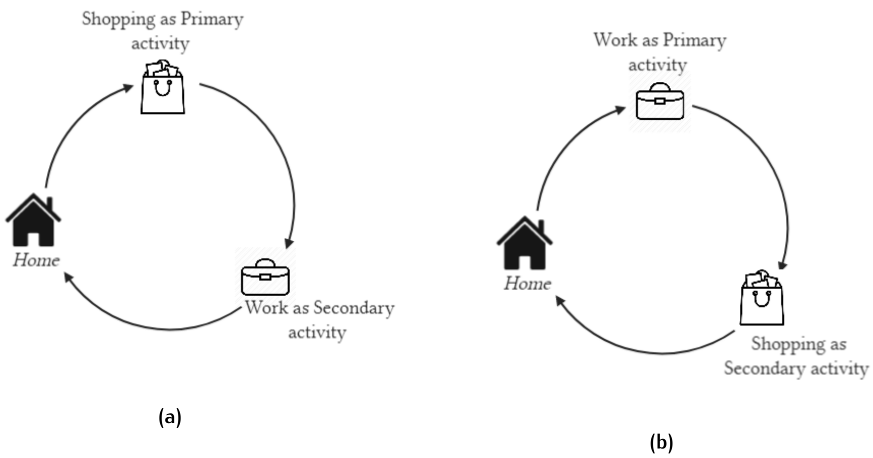


Figure 3.6: Example of doing 2 activities within the tour (a) If a person chooses ”Yes” (b) If a person chooses ”No”

3.2.3 Destination Choice

The destination choice modes is used to estimate the destination for every purpose chosen within the tour-generator for every person and every mode. This can be illustrated using figure 3.7.

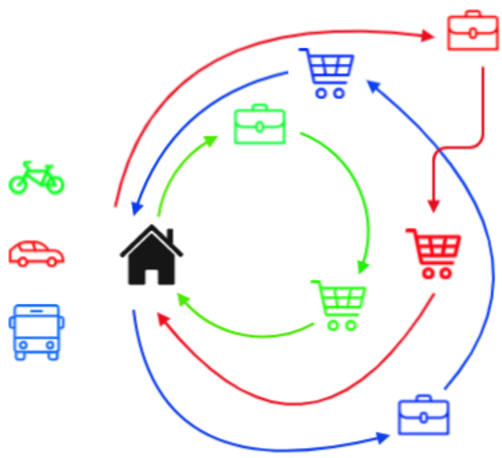


Figure 3.7: Estimation of destination for each mode within a 3-trip tour

Figure 3.7 represents a 3-trip tour where the primary purpose is "Work" and the secondary purpose is "Shopping" and an appropriate destination is chosen for modes, bike, car and public transport. Given the respective utility functions, typically, for mode bike, destinations closer to the origin are chosen by the traveller, for mode car and public transport, relatively farther destinations are chosen.

In order to find suitable destination for every purpose within a tour, the destination choice model generates a 3-purpose combinations or ***hij*** combinations. The ***hij*** represents the purposes carried out by the traveller, where "h" is activity on known location of origin, "i" is activity on unknown location to be estimated by the destination choice model, "j" is activity on known location of activity performed after "i". The probability of each destination is calculated using equation 3.1

$$P_{i|h,j} = \frac{exp(V_{i|h,j})}{\sum_{i'} exp(V_{i'|h,j})} \tag{3.1}$$

With Utilities:

$$V_{i|h,j} = \beta(t_{hi} + t_{ij}) + \ln(m_i) \tag{3.2}$$

Where,

t_{hi}: travel time from h to i in min
t_{ij}: travel time from i to j in min
m_i: Socio-economic activities at i
β: parameter combination: (h_{type}, i_{type}, j_{type}, a_{mode}, b_{mode})

The β parameter is estimated per parameter combination of h_{type}, i_{type}, j_{type}, a_{mode} and b_{mode}. The formulation of ***hij*** combination will be discussed in the next section. The a_{mode} and b_{mode} represent the mode used to travel from h to i and i to j respectively. Within the current model while calculating the utility of destination "i" given the location of "h" and "j", the a_{mode} is considered to be the same as b_{mode}. This represents the fact that the entire tour is carried out using the same mode such as PT-PT, Car-Car, Bike-Bike. The destination choice model will calculate the utilities of each destination for each mode. Further, combinations such as Car-PT, Bike-PT and so on were not estimated within the current version of the model.

Formulation of hij Combination

The main assumption while formulating various purpose combinations is that the tour undertaken by each person will start and end at home. For modelling tours with two trips, this is a straightforward approach, i.e. each person will start at Home, carry out the main/primary purpose and then return to Home. Thus, creating a ***hij*** combination of Home(h)>Primary Purpose(i)> Home(j). It can be represented using an example of tour with "Work" being the primary purpose. Thus, resulting with an ***hij*** combination of Home>Work>Home.

For tours with length 3, the formulation of ***hij*** is done using the decisions estimated for the sequence of purposes simulated in the last step of tour-generator-2 as mentioned in 3.2.2. This results in 2 ***hij*** combinations for a 3-trip tour.

In such situations the first ***hij*** combination corresponds to the situation where "h" and "j" are Home, where as "i" is either the location of primary activity (if person chooses "No" in the last stage of Tourgenerator) or the location of secondary activity (if person chooses "Yes" in the last stage of Tourgenerator). Again the VRT is applied after each application of a choice model on a ***hij*** combination.

After each individual is assigned the the location to carry out the first activity, within the second ***hij*** combination, "h" is assigned to the location of first activity chosen by the individual within the first ***hij*** combination (as it is already estimated), "j" is assigned to "Home" and "i" is estimated for the location of second activity within the tour (NOTE: it can either be a primary or a secondary activity, depends on the sequence of purposes). The location of second activity within the tour is conditional to the location of first activity. This might not be the case in reality, as the traveller chooses both locations at once, given the fact that the traveller already knows where he will travel within a tour.

NOTE: As the model is still under development the utility function in equation 3.2 are simplistic in the current model as it only considers travel time and socio-economic activities as variables. Including more variables would only increase the accuracy of the estimates.

While calculating the utilities for bike, the zones nearer to the person's origin will have a higher probability whereas for the utilities for car, the zones farther to the person's origin would have higher probability. This can also seen in figure 3.7.

Thus, for each mode a a destination (for 2-trip tours) or 2 destinations (for 3-trip tours) are assigned and the probability of choosing this destination or these destinations for the considered tour are calculated. Further, While using a lot of zones the Variance Reduction Technique doesn't work for more than 6 alternatives and to avoid such situations the zones are aggregated at various levels, where each level has 6 alternatives to choose from. The utilities and probabilities for every zone are summed on every aggregation level. Thus, a person chooses one of the alternatives on every aggregation level till the final zone is chosen. After the destination choice the mode choice model estimates the probability of each mode for every tour made by each traveller.

3.2.4 Mode Choice

The mode choice is quite straightforward process which uses a multinomial logit model to determine the probability of every mode (for the entire tour with that mode) for every traveller given the total number of modes. The aim of the mode choice model is to provide the probabilities of each mode for every agent for the entire tour. The probabilities are calculated using equation :

$$P_{m|c} = \frac{exp(V_{m|c})}{\sum_{m'} exp(V_{m'|c})} \tag{3.3}$$

With Utilities:

$$V_{m|c} = \beta_{m1} t_{c,m} + \beta_{m2} X_{m2} + .. + \beta_{mn} X_{mn} + logsum_{c,m} \tag{3.4}$$

Where,
$t_{c,m}$: travel time spent reaching the set of destinations with mode m (min)
$X_{m2}..X_{mn}$: explanatory variables (such as car availability)
$logsum_{c,m}$: average attractiveness of set of destinations
$\beta_{m1}..\beta_{mn}$: parameters for each mode

The mode choice model is the last stage of the OCTAVIUS after which the results are used in various assignment models but are not a part of the current model framework. Further the VRT could be applied for each choice situation within the mode choice model but is currently ignored. This is because the assignment models that follow up on the mode choice model are all macroscopic. So they don't require discrete choices but can handle (or even expect) matrices with fractions of trips.

In cases where the model requires to add an additional choice model after the mode choice (for example the departure time choice) VRT must be applied to the mode choice results as the mode choice model will not be the last stage of the OCTAVIUS framework.

3.2.5 The Variance Reduction Technique

Except the population synthesizer, every stage of current version of the OCTAVIUS estimates the probabilities of alternatives using a multinomial logit model. The probabilities are arranged within a Cumulative Distribution Function (CDF) from which agents are then assigned the alternatives using Halton draws (quasi-random draws). Within regular microsimulators, the choices are assigned using pseudo-random draws (such as the monte carlo draws). Assigning choices using pseud-random draws results in discretization error. The use of quasi-random draws, in the case of OCTAVIUS, the Halton Series leads to a uniformly filled space between 0-1, compared to randomized draws reduces the discretization error of the whole system.

As the name suggests, the aim of the VRT is to reduce the variance generated at every decision point. The technique helps in checking if the estimated values are equal to that of the market shares (probabilities of alternatives multiplied by agents, hence: for each alternative the number of agents that chooses it relative to the total number of agents in the choice situation.). The VRT chooses a discrete solution that per zone of origin, eliminates the stochastic noise and only leaves with quantaization error inherent to all microsimulation models. After the generation of Halton series, the values are assigned to the agents and their decisions are estimated. These estimates are then compared to market shares to check for deviations. If deviation exists new replications of a new halton sequence (being either a sequence based on another prime and/or a shuffle of a previously used sequence) are used to assing the choice alternatives to agents. This process is repeated until the estimated shares are close to the market shares. The process of repetitions is termed as replications which is fixed to reduce computational time. More replications indicates more accurate results. Although the number of replications does not depend on the number of agents. Further, in rare instances even after 2000 replications an optimal solution is not found, in such cases the best solution found so far is used.

4 MODEL APPLICATION

This chapter deals with the application of potential travel behaviour induced due to the mobility hubs within the OCTAVIUS model. This chapter would help answering key questions as, to what extent can we model the future mobility hub and its functions within OCTAVIUS and to demonstrate the (in)abilities of OCTAVIUS to capture relevant functions as discussed in chapter 2.

From the literature review, it was identified that mobility hubs have three major and one additional function as mentioned in table 2.2. Further potential constraints were identified for each mobility hub function in table 2.3. The implementation within the OCTAVIUS model will aim at replicating the mobility hub functions.

The following sub-sections would introduce the region of Almere, a brief description of its demographics and the model specifications for this case study. The implementation of mobility hub will be applied within the destination choice and the model output on the destination choice will be discussed further in chapter 5.

4.1 THE CASE OF ALMERE

Almere is the newest city in the Netherlands. As of 2019 Almere is home for 207,904 inhabitants and is a planned city and municipality in the province of Flevoland, Netherlands, bordering Lelystad and Zeewolde. Almere is connected to the motorways A6 and A27.

In chapter 2 it was identified that the mobility hubs are located mainly near the transit stations of the region. Almere has 6 major railway stations, for the sake of this case study, each station is assumed to be a mobility hub allowing travellers to carry multiple activities and access to multiple mobility services. The region of Almere and the transit stations are depicted in Appendix A

In chapter 2 a distinction on shared mobility services was made based on the purpose of use in table 2.1. The mobility services generally used as first/last mile mode include share-bikes, e-bikes and rideables whereas the mobility services used as an alternative to public transport usually include shared-car, micro-transit and On-Demand transit and has the potential to accommodate future emerging technologies such as Automated vehicles.

Within the current framework of the OCTAVIUS model, the constraints listed in table 2.3 regarding the mobility hub functions listed in table 2.2 are not included and adding constraints to impart desired travel behaviour was not possible. This is mainly due to lack of methodology for implementing constraints within such model. While investigating microsimulation models only OCTAVIUS was considered and being a model under development concrete methodology on the application of constraints was not available. Research is still required to identify the suitable methodology for the application of various constraints.Lack of constraints regarding mobility hub in the model lead to the use of multiple assumptions for implementing the mobility hub functions, these assumptions will be explained in the next section.

Within the current model, two schemes are implemented. The first scheme, namely, mobility hub activities scheme is aimed at replicating the multi-activity destination function of the mobility hub. The second scheme, namely, mobility services scheme is aimed at replicating the multimodality (feeder) and multimodality (main mode) functions of the mobility hubs (Table 2.2).

4.2 MODEL ASSUMPTIONS AND SPECIFICATIONS

4.2.1 Model Specification

Within the OCTAVIUS model, the population synthesizer does not consider location characteristics, whereas the tour generator only considers the level of urbanisation on the home-location which can be considered as a person/household property, hence, no direct zonal relationships are included in neither population synthesizer nor tour-generator. The effect mobility hub could be observed only within the destination choice model. The destination choice model as discussed in 3.2.3, where each destination is selected based on the travel time and land use activities.

While assigning the destination, travellers do not have the knowledge regarding the mobility hub. Hence while applying both schemes, the utilities for the mobility hubs zones, are recalculated and the choices are made again.

As discussed in section 3.2.2, the tour-generator currently takes into account only 2-trip and 3-trip tours. Considering higher trip-lengths might be more useful for the case of mobility hubs. But the current implementation is done considering 2-trip and 3-trip tours only.

Within the tours a distinction is made for both two-trip and three-trip tour and further utility calculations will be explained in detail in the following sub-section. A a flow chart of the of the distinction and the further implementation of schemes is illustrated in figure 4.1:

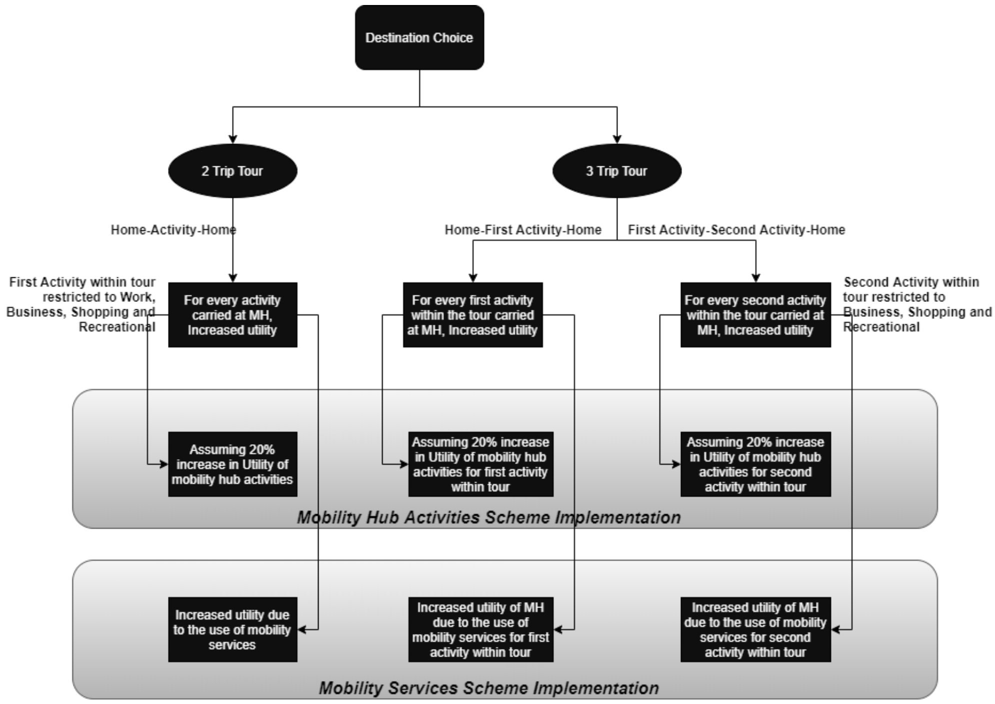


Figure 4.1: Framework for Mobility Hub Implementation within OCTAVIUS

4.2.2 Model Assumptions

Since mobility hubs and the mobility services are a part of the future and no actual data is available for the case of mobility hubs, model assumptions are required. These assumptions simplify the concept of mobility hub while implementing mobility hub in the model. The assumptions which are considered for the implementations for both schemes are listed below. Scheme specific assumptions will be discussed within respective scheme implementation sections.

- **Assumption on Mobility Hub Location:**
  From the literature it was identified that mobility hubs along with mobility services aim at increasing the public transit ridership. Therefore, the first assumption is that mobility hubs shall be in zones along with transit lines. This applies for both schemes to be implemented within the model.

- **Assumption of Public Transport Mode:**
  Within the current model there are 4 main modes are considered, these modes are Car, Bike, Public Transport (PT) and Car Passenger (CarPass). Now, while implementing mobility hub, data w.r.t multiple mobility services is required which is currently unavailable. Therefore, the mobility services are not implemented as an additional mode but are implicitly included within the public transport mode. The destination choice model estimates the destination for every activity within the tour and for each mode separately. While implementing both schemes the effect of mobility hub is assumed to be only for public transport mode. Although this is not true in real life, as people using other modes will also be affected by the inclusion of mobility hubs. The OCTAVIUS model currently lacks the constraints (Table 2.3) required to explicitly model mobility hubs along with unavailability of data, implementations are done only for public transport mode. Further, assumption on the public transport modes will be discussed within section 4.3 and 4.4.

- **Assumption on Mobility Hub Activities:**
  As Mobility hubs aim at increasing activities such as Work, Business, Shopping and Social Recreational (Metrolinx, 2011; RTP, 2019), from the 6 purpose

categories within OCTAVIUS mentioned in 3.2.2, it is assumed that the number of activities that could be undertaken for purpose "School" and "Other" will not be included within the mobility hub zone. One major dis-advantage is that this might not happen in real life scenario and people undertaking such activities are free to use the mobility services provided by the mobility hub.

4.3 THE MOBILITY HUB ACTIVITIES SCHEME IMPLEMENTATION

The mobility hub activities scheme aims at replicating the multi-activity destination function of the mobility hubs. The function allows traveller to carry out multiple activities within the same location of the mobility hub. For such travel behaviour intrazonal constraints are required, which is not implemented within the model. The model allows travellers to carry out only one activity at any given location. Thus, for the purpose of implementing the increase in the activity levels of the mobility hub, it is assumed that there will be 20% increase in the mobility hub activities. This still implies that mobility hubs will allow only one activity at the mobility hub location which is not realistic. By increasing the number of activities that can be carried out at the hub, the overall attractiveness of the mobility hub will increase.

Although, this scheme will allow to check the demand levels of the mobility hub due to increase in the land-use activities of the mobility hub. A distinction has to be made between two trip and three trip tours. Another assumption for this scheme is that travellers use traditional public transport to reach the mobility hub destination.

2 Trip Tour

In 2-trip tours travellers perform only one activity in their entire schedule. If the activity (must be a mobility hub activity) is to be carried out at the mobility hub zone, the utility of the mobility hub zone is increased by 20% on the land use part of the utility function. The corresponding equation of the utility is:

$$V_{MH|h,j} = \beta(t_{h-MH} + t_{MH-j}) + \ln(1.2 * m_i) \tag{4.1}$$

Where,
$t_{\text{h-MH}}$: travel time from home to Mobility hub using public transport (min)
$t_{\text{MH-h}}$: travel time from mobility hub to home using public transport (min)
m_i: socio-economic activities at Mobility Hub
β : parameter per combination (h: Home, i: MH, j:Home, PT,PT)

The increase 20% to the socio-economic activities at the mobility hub aims at increasing the overall utility of the mobility hub only for activities such as Work, Business, Shopping and Social Recreational. This is illustrated using figure 4.2 The calculation of probability for the mobility hub destination remains same as mentioned in section 3.2.3.

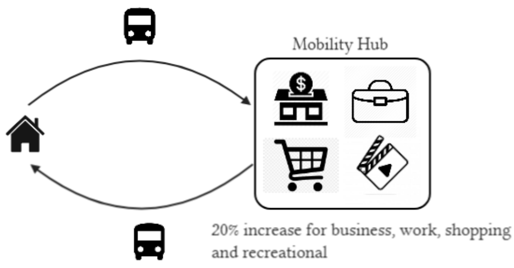


Figure 4.2: 2 Trip Tour with increased activities due to mobility hub

3 Trip Tour

Within the 3 trip tour, a distinction is made corresponding to the first activity and second activity within the tour. This distinction is made due to the model structure, where the entire 3-trip tour is split into 2 ***hij*** combinations. As illustrated in figure 4.1, for the first activity within a tour carried at the mobility hub, increase of 20% activities is restricted to Business, Work, Shopping and Recreational. For the second activity within a tour carried at the mobility hub, the increase of 20% activities is restricted to the same purpose but without work. Here, it is assumed that people who carry out their second activity within the tour at the mobility hub, do not undertake "Work", but rather use it for activities such as grocery shopping, haircut, amenities shopping etc.

For the tour where first activity is performed at the mobility hub location the utility for the first part of the tour is given a 20% increase in the socio-economic activities. For the tour where the second activity is performed at the mobility hub location, the utility for the second part of the tour is given a 20% increase in the socio-economic activities. The utility for the case where traveller performs first activity within the tour at the hub will remain same as of equation 4.1. The corresponding scenario is depicted in figure 4.3

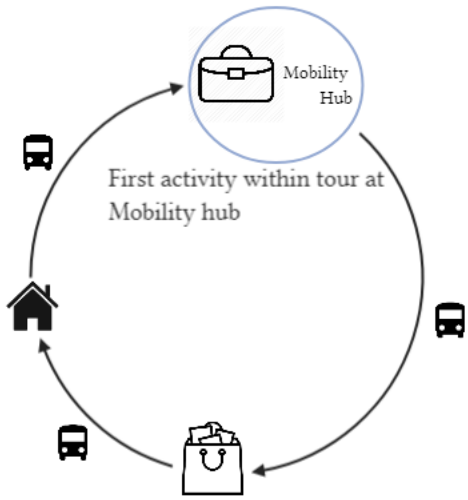


Figure 4.3: Example showing "work" activity undertaken at hub and shopping an another location with mode PT

Here, it is considered that the traveller undertakes the first activity within the 3-trip tour at the mobility hub and the second activity within the tour is carried out at other location. In reality, mobility hubs would allow the travellers to perform both activities within the same location. But this is not realised in the current situation.

Now, if the traveller performs the second activity within the 3-trip tour at the mobility hub, this is illustrated using figure 4.4. Again the utilities are calculated using equation 4.1

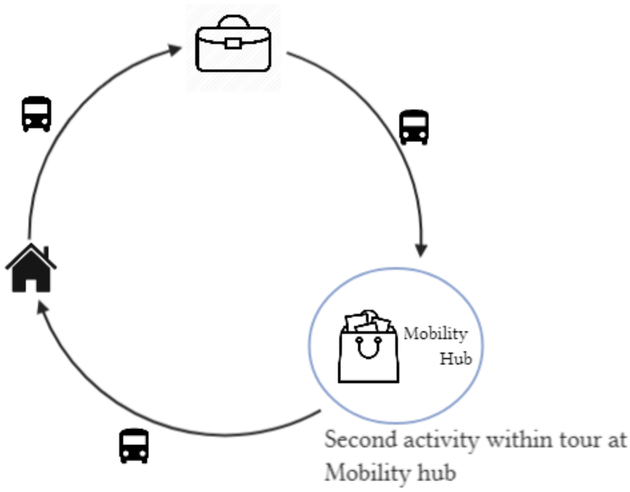


Figure 4.4: Example showing "Shopping" activity undertaken at hub and work at another location with mode PT

Here, it is considered that after performing the first activity travellers use the mobility hub to perform the secondary activity within the tour.

For all instances of increase in attractiveness of the mobility hub location, the probability of the mobility hub zone is calculated using the same multinomial logit function used within the original destination choice in section 3.2.3

4.4 THE MOBILITY SERVICES SCHEME IMPLEMENTATION

The mobility service scheme is aimed at replicating two functions of the mobility hub, i.e. multimodality (feeder mode) and multimodality (main mode). Using shared modes requires constraints such as pick-up/drop-off constraints, vehicle availability constraints or in some cases subscription constraints. To implement such constraints within the OCTAVIUS framework, the constraints shall be investigated individually. Along with the assumptions in the beginning of this chapter, it is assumed that these mobility services are in abundance and would not face capacity issues.

Similar to the distinction regarding 2-trip and 3-trip tour in section 4.3 a distinction between 2-trip and 3-trip tours is made within the mobility service scheme, it is assumed that only within a 2-trip tour, travellers would use mobility services to and from the mobility hub considering the fact that MaaS would allow the use of mobility services at the home-end of the traveller. For example, a MoBike is available at the home location to access the hub. Such situations might not be seen in reality and might be completely different.

Within the 3-trip tour travellers would reach the mobility hub using personal mode such as bike and would carry out the remaining journey using mobility hub service. This is applicable only to situations where travellers perform their first activity within the tour at the mobility hubs. The main reason for such assumption was to capture the additional parking function of the mobility hub, where people can park their personal modes and use the mobility hub services for the remainder of their tour. The parking function would also induce an additional trip from the location of the second activity within the tour to the hub, this would allow mode consistency within the tour. The parking function is illustrated using figure 4.5:

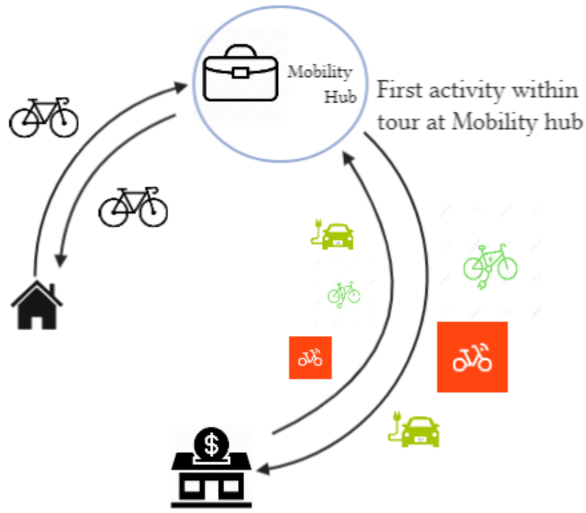


Figure 4.5: An Example, where first activity is carried at hub using personal mode, and the remainder of the journey is carried using mobility services

For the 3-trip tours, the parking function is included implicitly within the public transport trips and no additional trip was added to the tour. The drawback will be discussed later.

2 Trip Tour

In the case of two-trip tour using the hub as the location of activity and mode as public transport, it is assumed that trips to and from the hub will be carried using mobility services.

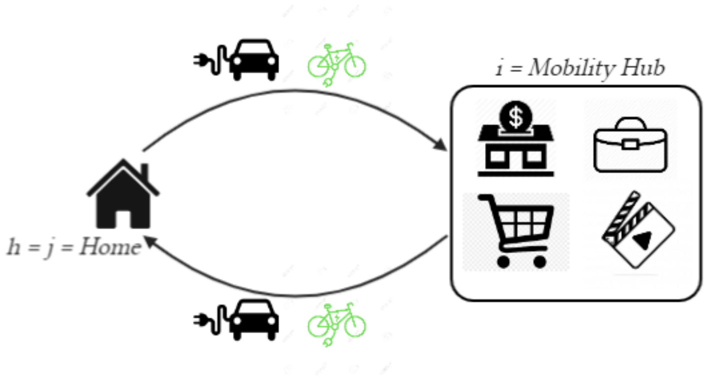


Figure 4.6: Representation of 2 trip tour to the mobility hub using mobility services

In the above graph, the first and final destination is home whereas the intermediate location of the activity is the hub locations. The pictures in the hub location indicate the activities restricted to the mobility hub. The utility of the mobility hub is calculated using equation 3.1 but the main difference being different travel times indicated in green:

$$V_{MH|h,j} = \beta(t_{h-MH} + t_{MH-j}) + \ln(m_i) \tag{4.2}$$

Where,
$t_{h\text{-}MH}$: travel time from location of first activity within the tour to Mobility hub using mobility services (min)
$t_{MH\text{-}j}$: travel time from mobility hub to home using mobility services (min)
m_i: socio-economic activities at Mobility Hub
β : parameter per combination (h: Home, i: MH, j:Home, PT,PT)

The green travel times indicate the travel time using mobility services scheme. It was assumed that the mobility services will be faster than traditional public transport. The faster travel times for mobility services used in this case are the travel times for car from the mobility hub to the respective destination. It is assumed that mobility services have the same level of service as that of a private car. Such strong assumptions were only required to demonstrate the usage of the mobility hubs. In reality the travel times could be equal to the in-vehicle times of public transport. (NOTE: Only travel times from the mobility hub zones were changed whereas the travel times of the remaining zones were kept same as that of public transport. This ensured that utilities for other zones was not affected.) The probability of choosing the mobility hub is calculated using equation 3.1.

3 Trip Tour

In general, the 3-trip tour has two situations. The first situation corresponds to the first activity within the tour carried out at the hub as illustrated in figure 4.5 and second situation corresponds to the second activity within the tour carried at out at the hub. It is expected that the mobility hub would allow both activities to be carried out in the location of the mobility hub zone (implying the multi-activity destination function), in-order to demonstrate such situations, intrazonal constraints are required. Research on intrazonal constraints and integrating it within such microsimulation frameworks is still required and therefore have not been realised within the current implementation.

For the situation where the first activity within the 3-trip tour is carried at the hub. This situation can be illustrated using figure 4.7.

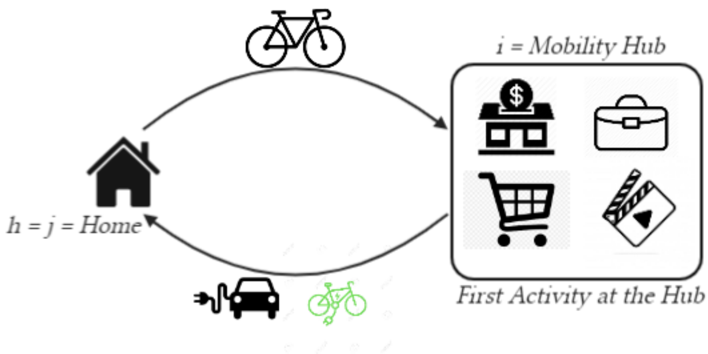


Figure 4.7: Representation of first part of 3 trip tour where first activity is carried at the hub

In the first part of the three-trip tour, it is assumed that travellers reach the mobility hub using personal mode such as bike or walk. The utility for such situations is calculated as follows:

$$V_{MH|h,j} = \beta(t_{h-MH} + t_{MH-j}) + \ln(m_i) \tag{4.3}$$

Where,
$t_{h\text{-}MH}$: travel time from location of first activity within the tour to Mobility hub using personal modes (min)
$t_{MH\text{-}j}$: travel time from mobility hub to home using mobility services (min)
m_i: socio-economic activities at Mobility Hub
β : parameter per combination (h: Home, i: MH, j:Home, PT,PT)

The corresponding probability of the mobility hub location is calculated using equation 3.2:

As the traveller uses mobility services to carry out the second activity within the tour, the travel time considered from hub to the home location is that of mobility services. This will be clearer after explaining the second part of the three-trip tour where the first activity is carried at the mobility hub which can be illustrated using figure 4.8

Now, the second activity within the tour is carried out using mobility services available at the mobility hub, where the first activity was undertaken, and the travellers use the mobility services to reach home. Hence, while estimating the utility of the first activity the travel time from the hub to the home was considered using mobility services. Though in reality travellers would return to the hub location to pick their personal bike which is currently not realised. Further research is required for

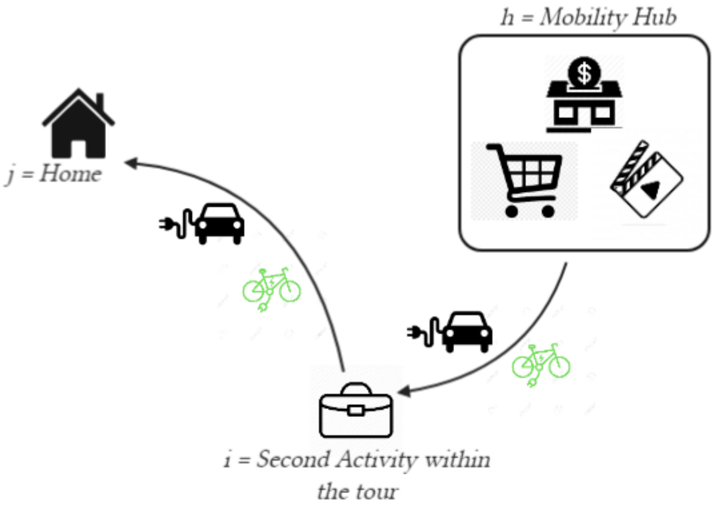


Figure 4.8: Second Part of 3 trip tour where first activity is carried at the mobility hub

vehicle pick-up and drop-off constraints for the mobility services and parking and return trip constraints on the personal mode. These constraints are currently omitted within the model.

Now, for the situation when the second activity within the tour is carried out the mobility hub location, it is assumed that the traveller would use conventional public transport till they reach the mobility hub to carry out the second activity within the tour. From where the traveller would use mobility services at the mobility hub to reach home. The following graph represents the first part of the situation when the second activity within the tour is carried out at the mobility hub.

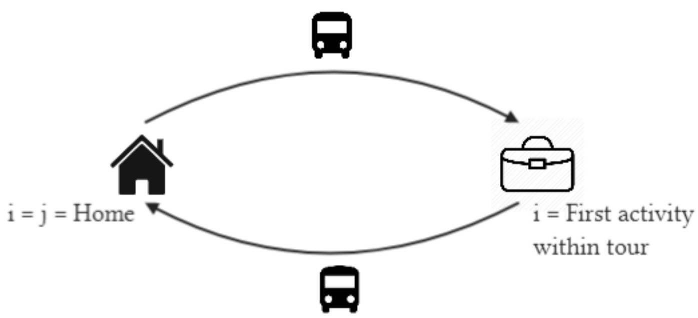


Figure 4.9: Representation of first part of 3 trip tour where first activity is carried out.

The second part of the tour where the second activity within the tour is carried out at the hub can be illustrated in figure 4.10:
The secondary activity at the hub is restricted to Shopping, Business and Social recreational. The utility of the mobility hub location is calculated as follows:

$$V_{MH|h,j} = \beta(t_{h-MH} + t_{MH-j}) + \ln(m_i) \quad (4.4)$$

Where,
$t_{h\text{-}MH}$: travel time from location of first activity within the tour to Mobility hub using public transport (min)
$t_{MH\text{-}j}$: travel time from mobility hub to home using mobility services (min)
m_i: socio-economic activities at Mobility Hub

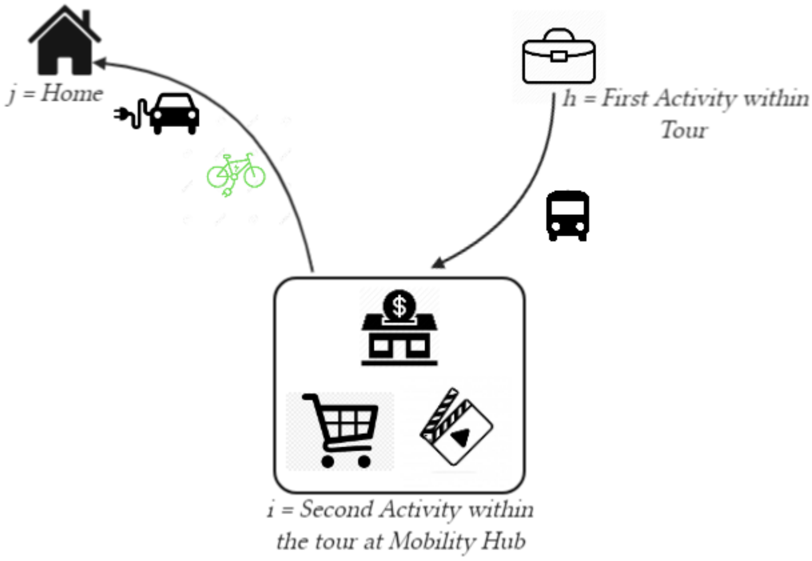


Figure 4.10: Representation of second part of 3 trip tour where second activity is carried out at the mobility hub

β : parameter per combination (h: Home, i: MH, j:Home, PT,PT)

One minor drawback of this situation is that the utility of the location of the primary activity is also increased due to the use of mobility hubs but considering the fact that mobility hub increases the attractiveness of the nearby regions(Anderson et al., 2017; Elshater and Ibraheem, 2014; Keenan, 2012).

4.5 MODE CHOICE

The mode choice model is applied for both implemented schemes. No explicit changes were made to the mode choice model while estimating the mode choice for both schemes. The mode choice model uses the same formulation as mentioned in section 3.2.4 which uses a multinomial logit model to determine the probability of every mode (for the entire tour with that mode) for every traveller given the total number of modes which results in matrices with fraction of trips (3.2.4). In order to identify discrete choices made by each individual the VRT is again applied after the mode choice model which results in each individual choosing one mode, given the four alternatives.

4.6 conclusion

In the model application, two schemes are implemented namely, the mobility hub activities scheme and the mobility service scheme. Both schemes aimed at replicating the mobility hub functions and its corresponding change in travel behaviour.

Although, the mobility hub activities scheme aimed at implementing the multi-destination function of the mobility hub, the ability to carry multiple activities within the mobility hub location was not achieved. The increase of 20% in mobility hub activities still resulted in travellers carrying out only one activity at the mobility hub. Though the model is capable of adding intrazonal constraints, it was identified during the final few days of internship and was not applied. It is possible to add intra-zonal constraints within the current framework of the OCTAVIUS model. Though further research is required on the level of each mobility hub activity.

Unfortunately, the model currently lacks the potential constraints for multimodality as a feeder and main mode functions (Table 2.3), the constraints are required to be further investigated and the methodology to implement such constraints within OCTAVIUS are required. Further due to lack of data availability on different shared services along with the fact the there is no concrete evidence on the exact number or type of shared service that will be available at the mobility hub didn't allow different shared services to be included as a separate modes within the model. The current implementations followed the same travel behaviour as that of the model although the potential changes in the travel behaviour were modelled implicitly within mode public transport. Mobility hubs are required to be modelled explicitly using different modes within transport demand models which was not achieved with the current implementation.

Further, the usage of different modes on different legs of the trip within the tour is not yet realized within the model. This is again due to the lack of data availability on mode combinations which are used to estimate the β parameter in the destination choice (3.2.3).

Both schemes were applied within the model separately to identify independent impact of each scheme on the overall travel demand. Although a combined effect on travel demand could be observed in real life due to both increase in land-use activities and multiple mobility services.

5 MODEL OUTPUT

The model output will be discussed in two sections. In section 5.1 each individuals with the changes in destination and mode choice will be analysed where as in section 5.2 aggregated results will be analysed.

5.1 INDIVIDUAL RESULTS

In the general application of the model, the VRT was not applied within the mode choice model (3.2.4). In order to identify the changes made by each individual the VRT was applied for the implementation in order to have discrete choices made by each individual. Further the changes in travel behaviour could be observed only within the mobility services scheme. Within the mobility hub activities scheme, the increase in utility resulted in higher demand to mobility hub zone and therefore only aggregated results will used.

5.1.1 Analysing the Mobility Service Scheme

The mobility services scheme aimed at replicating the multimodality functions of the mobility hubs. It was assumed that mobility services would have the same level of service as that of a private car, implying faster travel times, but for travellers using mobility hubs as a destination within the tour. Further, a person carrying out a three-trip tour where if the first activity within the tour is carried out at mobility hubs using mode public transport in the implementation implies that, the person reaches the mobility hub using personal mode after which the person will use mobility services such as shared car as an alternative to public transport for the remaining part of the tour(Figure 4.7, 4.8). Where as within the three-trip tour if the person carries out the second activity within the tour at the mobility hub using mode public transport implies that the person uses public transport to reach the mobility hub location, from where the mobility services such as bike-sharing could be used as a last-mile mode(Figure 4.9,4.10).

Though the model could trace each individual, to demonstrate the microscopic nature of the model, only 10 individuals are chosen. In figure C.1, two tables represent mobility services scheme. In the figure, the first table represents travellers who carry out the second activity within the tour at the mobility hub. The second table represents travellers who carry out the first activity within the tour at the mobility hub. In both tables, the column in blue colour represents the mobility hub destination.

In the case where travellers perform the second activity within the tour at the mobility hub location and use the mobility services as first/last mile mode, the purpose carried out at the hub is mainly Social-Recreational. It can also be observed that travellers mainly change their mode from personal mode to public transport. This is mainly due to the higher level of service of public transport assumed in the case of mobility hubs.

In the case where travellers perform the first activity within the tour at the mobility hub location and use the mobility services as an alternative to public transport, the purpose carried out at the hub mainly shopping. Further travellers change their mode mainly from car to public transport. This is again due to the higher level of service of public transport assumed in the case of mobility hubs.

The analysis of individuals is done to demonstrate the microscopic nature of the model and the effect mobility hubs on the travellers choices. In most cases where travel demand models are used, aggregated results are still preferred over individual results as the aggregated results are capable of showing the impact of any policy measure on a larger scale compared to individuals.

5.2 AGGREGATED RESULTS

In this section aggregated results are analyzed as the model contains more than 200,000 individuals, aggregated results will be useful for identifying the impact of the implementation within the destination choice. Though, the model is capable of tracing individual travellers as seen in section 5.1 it could be useful mainly in situations where each mobility service is applied as an independent mode, tracing individuals would allow better analysis of each mobility service.

5.2.1 Analysing the Mobility Hub Activities Scheme

As discussed in chapter 3, within the destination choice model, the model estimates a destination for each mode, for each activity within the tour and for each traveller. The model is run for 4 main modes, namely Car, Bike, Public Transport and Car Passenger. For each mode, a suitable destination is selected within the destination choice model.

The mobility hub activities scheme was implemented based on the fact that mobility hubs would provide more activity opportunities compared to traditional transport hubs. From the literature review it was identified that mobility hubs mainly facilitate work, shopping, business and social recreational activities, providing services like grocery shopping, movie theatres, offices etc. Within the model this was implemented within the destination choice model and the land use component of the mobility hubs was given a 20% increase for the mobility hub activities.

While comparing both schemes, the first indications at the trips and tours, to and from the mobility hub show that mobility services has more impact on the attractiveness of the mobility hub compared to that mobility hub activities.

Mode	Base Case	Mobility hub Activities Scheme
Car	1091	1091
Bike	1685	1658
Public transport	1520	1925
Car Passenger	1381	1381
Total	5677	6055

Table 5.1: Total Trips to the the Mobility hubs

The total number of public transport trips to the mobility hubs has increased from 1520 to 1925. Compared to other modes which have no increase. This is inline with the implementation, which only provided the increase in the utility to public transport trips, hence other modes have no change. Further the total number of trips to the mobility hub increased from 5677 to 6055. Together the rise in the number of trips to the hub indicate that 20% increase in attractiveness of the location has considerable impact on the total trips to the hub.

Mode	Base Case	Mobility hub Activities Scheme
Car	1062	1062
Bike	1765	1765
Public transport	1485	1901
Car Passenger	1402	1402
Total	5714	6130

Table 5.2: Total Trips from the mobility hub

Similar to that of total trips to the hub, the total trips from the hub for mode public transport increased from 1485 to 1901 for the mobility hub zones. The difference between the change in total trips to and from the hub due to the implementation is quite negligible. This suggests that the results are inline with the implementation.

Mode	Base Case	Mobility hub Activities Scheme
Car	113	113
Bike	150	150
Public transport	109	130
Car Passenger	120	120
Total	492	513

Table 5.3: Mobility hub chosen as the location of first activity within the 3 trip tour

The total number of travellers who choose the hub as the location to perform the first activity within the tour has only increased from 109 to 130 and can be termed as negligible. Although within the models the total number of 3 trip tours is quite low. The values indicate that increase in the number of mobility hub activities at the mobility hub is mainly beneficial for travellers carrying two trips within a tour. Mobility hub as a location of secondary activities also indicate a similar story. The increase in the estimated values of mobility hub chosen as a location of secondary activity is quite low and indicates the fact that increasing 20% in the land-use activity results in higher use of the mobility hubs by travellers undertaking 2-trip tours.

Mode	Base Case	Mobility hub Activities Scheme
Car	70	70
Bike	153	153
Public transport	67	100
Car Passenger	82	82
Total	372	405

Table 5.4: Mobility hub chosen as the location of second activity within the 3 trip tour

5.2.2 Analysing the Mobility Services Scheme

The mobility services scheme aimed at replicating the multimodality functions of the mobility hubs. It was assumed that mobility services would have the same level of service as that of a private car, implying faster travel times, but for travellers using mobility hubs as a destination within the tour. The situation is compared with base scenario when no mobility hub was implemented. This allows us to identify the change in the demand levels for the mobility hub zones.

Mode	Base Case	Mobility Services Scheme
Car	1091	1091
Bike	1685	1658
Public transport	1520	2790
Car Passenger	1381	1381
Total	5650	6920

Table 5.5: Total Trips to the the mobility hub

Total trips to the mobility hub represent the total trips that have been estimated to reach the hub. As the main assumption for both schemes is that all trips to and from the mobility hub zone are carried out using public transport, the number of trips estimated to reach the hub is same for modes other than public transport. Due to the mobility services the mobility hub was assumed to be more attractive for travellers and the total trips to the mobility hubs increased from 1520 trips to 2790 trips. Compared to the mobility hub activities scheme, the mobility service scheme showed higher number of trips.

Mode	Base Case	Mobility Services Scheme
Car	1062	1062
Bike	1765	1765
Public transport	1485	4237
Car Passenger	1402	1402
Total	5714	8466

Table 5.6: Total Trips from the mobility hub

For the total trips from the hub, the number of trips leaving the hub location has increased from 1485 to 4237 trips which is higher than that of total trips to the hub. Due to the multiple mobility services available within the mobility hub zone, this gives us the first indication that mobility hubs and its services have higher possibility of becoming a major multimodal transport hub given the assumptions made within the implementation.

Mode	Base Case	Mobility Services Scheme
Car	113	113
Bike	150	150
Public transport	109	183
Car Passenger	120	120
Total	492	566

Table 5.7: Mobility hub chosen as the location of first activity within the 3 trip tour

Based on the statistics obtained from CBS, the percentage of 3 trip tour is quite low compared to 2 trip tours. The 3 trip tours contribute to only 17% of the total tours whereas 2 trip tours contribute to 76% of the total tours. This is can be seen from the table as there are not many 3 trip tours compared to the total number of trips to and from the hub. During model implementation, a distinction was made within the three-trip tour regarding the primary and secondary purposes. If a traveller carried out primary purpose within the mobility hub zone, it was assumed that the traveller would reach the hub using either bike or walk, from where the traveller would use the mobility services. Now due to the use of slower mode compared to the mobility services for the first part of the trip, the total number of three trip tours using mobility hub as the location for primary purpose has not increased compared to that of secondary purpose. Though, 74 more 3 trip tours are now carried out at the mobility hub location.

Mode	Base Case	Mobility hub Services Scheme
Car	70	70
Bike	153	153
Public transport	67	346
Car Passenger	82	82
Total	372	651

Table 5.8: Mobility hub chosen as the location of second activity within the 3 trip tour

Finally, the use of mobility hub as the secondary activity destination within the 3-trip tour is more interesting compared to the primary activity at the mobility hub. The mobility service scheme has an increase of almost 300 3-trip tours indicating the fact that mobility hubs could be a location of performing secondary activity. This also indicates that mobility hub must be researched for performing multiple activities at the mobility hub location as this is one of the key characteristics of mobility hubs.

5.3 CONCLUSION

The analysis is done only on the destination choice results and though the results show an increase in the demand of mobility hubs due to the implementation of the mobility hub schemes, the increase is a result of increased utilities of the mobility hubs due to the implementations. Although the change in the demand levels of the mobility hubs are inline with the implemented schemes, which suggests that the model handles changes to considerate levels. Another major drawback of the implementations persists to the fact that the changes were implicit in nature, implying, that the inclusion of mobility services was within mode public transport and a new mode as mobility service was not created explicitly. This was done due to two reasons, first, unavailability of the data parameters regarding mobility services and secondly, adding constraints to the model required more elaborate methodology. Further work is required on identifying the methodology to implement the constraints that impart the mobility hub functions within the model. The possibilities to add constraints within the current version of the model are very low.

6 CONCLUSIONS, DISCUSSIONS AND FURTHER RECOMMENDATIONS

6.1 CONCLUSIONS

The aim of this research was to identify to what extent microsimulation travel demand models can deal with the potential changes in travel behaviour due to the implementation of mobility hubs. This section will first answer the sub research questions followed by the main research question. Further discussions will be made in section 6.2 on potential changes to travel behaviour mobility hubs, the possibilities of modelling such changes within microsimulation travel demand model: OCTAVIUS and Applied implementations within OCTAVIUS and finally further recommendations on mobility hubs and microsimulation demand models will be discussed in section 6.3.

6.1.1 Potential Changes To Travel Behaviour due to Mobility Hubs

The first sub-research question was formulated as: What are the potential changes in travel behaviour that could be observed due to the implementation of mobility hubs?

Mobility hubs along with mobility services has the potential to change the travel behaviour of travellers. The major impact will be mainly due to the shared mobility services. The shared services based on the purpose of use had two functions, i.e. Multimodality (feeder mode), where travellers would use the shared services such as shared bike as a first and last mile mode on the activity end, second, multimodality main mode, where travellers would use shared services such as shared-car as an alternated to public transport.

Further, the mobility services will enable people to access regions in and near the mobility hub, which has the potential to increase the mobility hub accessibility as depicted in figure 2.1. Most jurisdictions stated that mobility hubs shall not only be considered as a place of transfer of modes but also as a location to carry out multiple activities (Metrolinx, 2011; RTP, 2019). Situations where people carry out multiple activities within the same zone, leads to the function of multi-activity destination, where travellers can perform more than one activity at the mobility hub destination.

The main drawback within the mobility hub persists to the fact that travellers still have to either walk or use personal bike to reach the mobility hub. The use of personal bike creates an additional parking function of the mobility hub. In section 2.3.2 it was identified that MaaS could eliminate the parking function considering the fact that it would provide first/last mile solution for the home-end of the travellers as well. But overall the literature review allowed to identify the main functions of the mobility hubs shown in table 6.1.

Mobility Hub Functions	Description
Multimodality (feeder mode)	Ability to use shared services (such as shared-bike) as first/last mile mode (activity-end)
Multimodality (main-mode)	Ability to use shared services (car-sharing, micro-transit) at the hub in place of public transport
Multi-Activity Destination	Ability to perform multiple activities within the same location
Additional Function	Travellers using personal modes to access hub
Parking	Ability to park personal mode at the mobility hub.

Table 6.1: Mobility hub Functions

6.1.2 Modelling of Mobility Hubs within Travel Demand Models

The second sub-research question was formulated as: How do travel demand models deal with the potential changes in travel behaviour related to mobility hubs?

Transport modelling is important and essential for estimating travel demand and offering valuable information to policy makers and transport planners. Although existing transport demand models are capable of handling current travel behaviour, demand models such as the aggregated models and dis-aggregated models are not flexible to capture travel behaviour related to mobility hubs. Both aggregated and dis-aggregated trip based demand models require several constraints while modelling travel behaviour related to mobility hubs (Timmermans et al., 2002; Bhat and Koppelman, 2014). Adding multiple constraints within conventional models is comparatively difficult to add to the mathematical foundation of these models. In the case of mobility hubs, mobility services requires different constraints based on the functions such as pick-up and drop-off constraints, vehicle availability constraints, subscription constraints (in cases where subscription is required) etc. Models require these constraints in-order to impart the desired travel behaviour.

Microsimulation models seem to be more efficient compared to traditional models, mainly due to the behavioural accuracy of models (Vovsha, 2019). Further, microsimulation models consider individual characteristics which are ignored within conventional demand models. Explicitly modelling individuals in households allows for exploration of a chained or hierarchical structure of travel decisions as well as objective time–space constraints on a daily-activity agenda.

The OCTAVIUS model followed the same principles of regular microsimulation models and is deemed to be a fit for modelling potential changes in travel behaviour due to the mobility hubs. The ability of OCTAVIUS to model tours allowed to model multiple activities. For the case of mobility hubs carrying out multiple activities was a key consideration.

Traditional travel demand models are not capable of handling potential changes to travel behaviour. Implementing mobility hubs within such models can lead to biased travel behaviour and the model would lose the mathematical foundation. Microsimulation travel demand models seem to be the only only option while considering shared mobility services and multiple activities within a tour.

6.1.3 Modelling of Mobility Hubs within Microsimulation Travel Demand Model: OCTAVIUS

The third sub-research question was formulated as: What are the possibilities of modelling potential changes in travel behaviour due to mobility hubs within microsimulation travel demand model, OCTAVIUS?

The possibilities of adding the mobility hub functions and the required constraints within the OCTAVIUS model is still limited. Given the three main and one additional function of the mobility hubs the possibilities are show in table 6.2

Mobility Hub Functions	**Possibility within OCTAVIUS**
Multimodality (feeder mode)	Not Possible
Multimodality (main-mode)	Note Possible
Multi-Activity Destination	Possible, Not Implemented
Additional Function	
Parking	Possible, Not Implemented

Table 6.2: Mobility hub Functions and the possibility within OCTAVIUS

The current implementation within the OCTAVIUS model, didn't impart the desired travel behaviour due to the mobility hubs rather made implicit changes within the current framework of the model. Adding constraints within the current framework is still difficult and requires a concrete methodology. For the multi-activity destination function, adding intra-zonal trip constraints was possible but due to time limit it was not achieved. Further, to impart the parking function, return trip constraints are required which were difficult to incorporate within the current model structure. Although putting constraints on individuals was deemed easier compared to aggregates, microsimulation models have to be investigated further.

The implementation was mainly carried within the destination choice of the OCTAVIUS model for both schemes. The results were analysed on the estimation of number travellers choosing the mobility hub zone as a destination. A graph comparing both schemes with the base case can be made on the total number of trips to and from the hub for mode public transport.

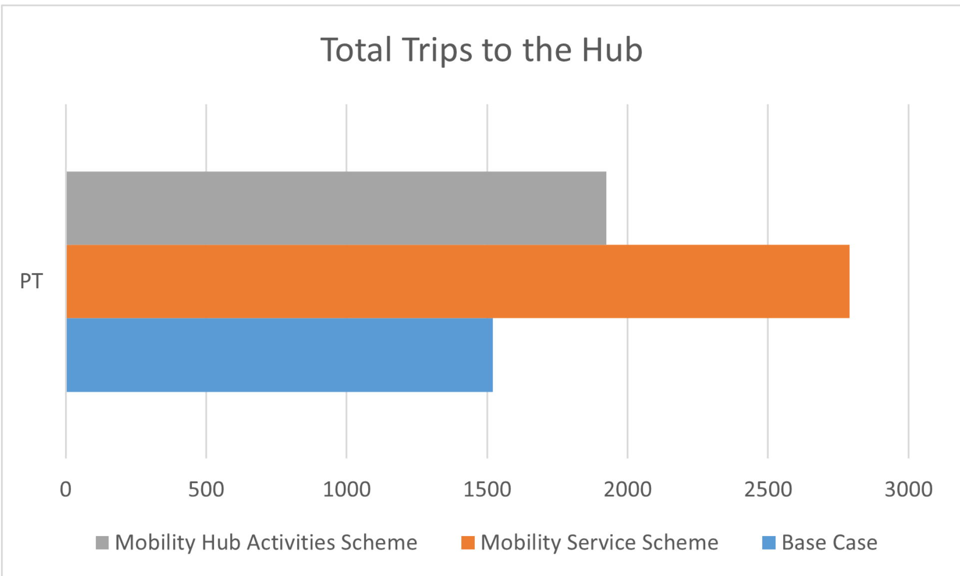


Figure 6.1: Total Trips to Mobility Hub

For both schemes, it was assumed that only public transport users would consider mobility hubs as an attractive destination and the results indicate the same. It was also assumed that the trips to and from the hub would remain same for other modes as these travellers would not consider mobility hubs as an attractive option. Further, the mobility service scheme resulted in higher trips to and from the hub and this is due to the assumption that mobility hubs would provide multiple mobility services, which are assumed to be faster compared to traditional public transport.

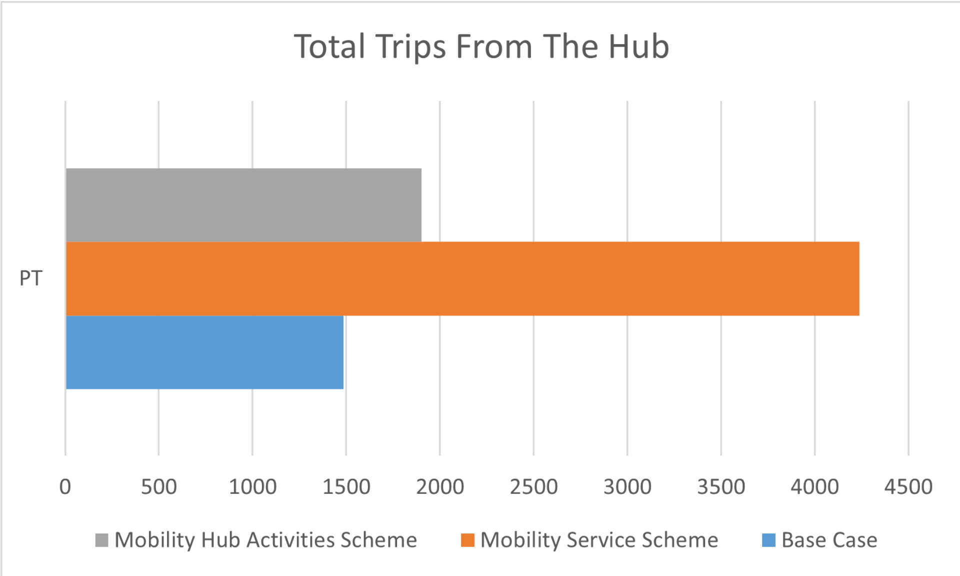


Figure 6.2: Total Trips From Hub

The graphs indicate that mobility hubs are considered as more attractive destination when it is assumed that mobility hubs provide mobility services. Also, there is no considerable increase in both graphs when it is assumed that mobility hubs provide more opportunities for activities. The increase in number of activities is more attractive for travellers undertaking a 2-trip tour rather than a 3-trip tour. The results indicate that while assuming mobility hubs provide multiple mobility service, it becomes a more attractive place for carrying out secondary activities, such as shopping, social recreational and business. Further research is required to outline the types and characteristics of these mobility services that would be available within mobility hub.

6.1.4 Final Conclusion

The main research question was formulated as: To what extent can microsimulation travel demand models deal with the potential changes in travel behaviour due to the implementation of Mobility Hubs?

The case study of OCTAVIUS showed the benefits of using microsimulation models compared to traditional demand models. Considering individual characteristics, the microsimulation model provides much better behavioural accuracy compared to traditional models. But while modelling mobility hubs the microsimulation model could not incorporate intermediate usage of stops and the unrealistic tour compositions when using mobility hubs show serious limitations as well.

For the case of mobility hubs, the mobility services and mobility hub activities had to be implemented implicitly within the models. Implying that the travel behaviour regarding mobility hubs was considered to be same as that the model is based on. Although the model performed in-line with the expectations, the model still lacks the flexibility desired in the case of potential travel behaviour due to mobility hub functions. Provision to implement constraints which were required to inherent the desired travel behaviour of mobility hubs were not realized. This is mainly due to four reasons, first, the availability of literature on mobility hubs and mobility services is still scarce, concrete evidence on potential changes in travel behaviour is still required to implement such situations. Secondly, availability of data on mobility services to be implemented as an additional mode is not available. Third, the model still under development and the considered variables at each decision point are naive. With time, the model will be able to consider much more variables compared to when the research is carried out. Finally, within the destination choice model, the model estimates the destination for each mode for each activity within the tour and for each person and is currently restricted to only 2-trip and 3-trip tours. Adding constraints in such situations becomes very difficult and a methodology must be identified in order to implement such constraints given the framework of OCTAVIUS.

Though microsimulation models are considered to be the future of travel demand modelling, the need for data requirement is very high in such cases. The OCTAVIUS model is one of the few microsimulation travel demand models that is currently used for the strategic application of travel demand. Microsimulation models such as OCTAVIUS are still under development or are mainly used within academic studies. Further, the scope of adding constraints is needed to be researched upon.

Further, as this research deals with only one microsimulation model, which, to a very limited extent can model the potential changes in travel behaviour due to mobility hubs within microsimulation demand models. The potential changes to travel behaviour could only be implemented implicitly within the model. With the availability of data on various mobility services and data on travellers perception, the implementation could then be extended within the microsimulation model.

Finally, similar implementations are possible to be carried out implicitly within traditional aggregated model, but evidence of such implementations are not many and it is required to investigate. Similar research of implementing mobility hubs using other microsimulation models is still required in-order to completely understand the potential of microsimulation models while modelling mobility hubs. So far, it can be stated that microsimulation models do have the potential to model such changes as in the case of mobility hubs but research on understanding travel behaviour due to mobility hubs and modelling such behaviour in microsimulation models using a methodology of adding constraints is still required.

6.2 DISCUSSIONS

This section provides a discussion about the conclusions. Section 6.2.1 provides a discussion regarding Mobility Hubs. Section 6.2.2 discusses the potential of microsimulation travel demand model, OCTAVIUS.

6.2.1 Mobility Hubs

Mobility hubs and its services are a concept for the future and hence the such implementations within travel demand models are only based on several assumptions. With the arrival of MaaS and technologies such as AV's, mobility hubs have the potential of becoming even more attractive but the underlying functions of these mobility hubs must be investigated. The mobility services were assumed implicitly within public transport and the travellers had the option to choose from 4 modes rather than 8 or 10. This was done mainly due to unavailability of data regarding mobility services.

Though, most jurisdictions (in this case municipality of Utrecht, San Diego and Toronto) vision mobility services to be an answer to major transport related issues such as, inner city densification, congestion and pollution. Only the positive impact of the mobility services are considered whereas issues such as infrastructure requirement, capacity management, vehicle maintenance are largely ignored.

Scientific research on mobility hub is still scarce and research on travellers preferences will enable to further understand on possible travel behaviour before actually implementing within travel demand models. Most mobility hubs investigated within this research are mainly proposals by their respective jurisdictions and with further research on mobility hubs, decisions regarding their implementation can take pace.

6.2.2 Potential of Microsimulation Travel demand models

The aim of the research was to identify to what extent can microsimulation travel demand models can capture the potential changes in travel behaviour due to mobility hubs. For this study only the OCTAVIUS model was used. Within the current implementation of mobility hubs schemes within the model several assumptions were required due to lack of availability of data, lack of mobility hubs in real life. Concrete evidence on mobility hubs and its underlying travel behaviour are still required to be researched upon.

In section 2.2 it was stated that microsimulation models such as OCTAVIUS model has the potential to handle the potential changes in travel behaviour, though inability to include constraints only allowed the mobility hubs to be implemented implicitly within the model structure. Further, two possible constraints could be implemented within the the model, but it is not guaranteed whether they could be completely implemented.

Within the implementation only the positive impact of mobility services and mobility hub activities are considered. Impacts such as unavailability of shared vehicles, individual demand for shared vehicles were not considered. Moreover, travellers perception regarding these shared services requires more elaborate research. Further, impact of shared services used as access and egress modes is still under research.

Regarding the mobility services, constraints such as the pick-up and drop-off and vehicle availability constraints are comparatively hard to be implemented within the such models.

6.3 FURTHER RECOMMENDATIONS

While implementing mobility hub schemes within the microsimulation travel demand model, OCTAVIUS, possibilities of adding constraints were identified. Although, these constraints were not implemented within the current model applications, it is worth to research them for future applications of mobility hubs.

6.3.1 Intrazonal Trip Constraint

The intrazonal trips are short trips for which the origin and the destinations are same. They are not usually considered within demand models, firstly because they are shorter trips generally, it is widely believed that intrazonal trips are mostly non-motorized trips such as walking, secondly, they are not always considered in the estimation of a model since they do not appear on a network in centroid-to-centroid travel and it is also presumed that their exclusion does not affect model results (Bhatta and Larsen, 2011; Demissie et al., 2019). As discussed in previous sections, one of the mobility hub function is to allow multi-activity destination, which requires intrazonal constraints. Providing additional utilities for such trips within the OCTAVIUS model could lead to desired travel behaviour. Further, the ability of the mobility hubs to provide multiple mobility services, there is high degree of chance of having more intrazonal trips for the mobility hubs. Earlier, in the literature review it was identified that mobility hubs could be used as a transfer point and a place to do multiple activities. Therefore, further research on the intrazonal trips within the mobility hubs could be the way for showing the benefits of the mobility hubs.

6.3.2 Destination and Mode Choice for the Case of OCTAVIUS

After the implementation of mobility hub schemes within the OCTAVIUS mode, the mode choice model was also applied to check the overall effect on the modal split of the Almere region. It was identified that even though mobility hubs seemed to be an attractive destination due to the mobility hub schemes, while modelling mode choice these trips to the hubs were ignored by the travellers and the overall modal split remained same. The mode choice results didn't yield the desired results and as it was beyond the scope of study, were not included in the output analysis. Although the model split can be seen in Appendix B.

In the chapter 3, it was stated that for every traveller a suitable destination was estimated for every available mode (within the destination choice model). Even though the destination choice model estimated more trips to and from the hub, while applying the mode choice model, the desire mode was not selected, this could mainly be due to two reasons, first the travellers who selected mobility hub as a destination might live far from the mobility hub zone, secondly, while calculating the utility for each mode within the mode choice, the average attractiveness of the mobility hub zone was not increased for public transport. It might be possible that such effects are observed only in this case study, as the applied implementations were implicit and were based on assumptions. To make sure that such instances do not occur, the relation between the destination choice model and the mode choice model must be researched further, specially for the application of OCTAVIUS.

BIBLIOGRAPHY

Karl Anderson, Samuel D. Blanchard, Derek Cheah, and Drew Levitt. Incorporating equity and resiliency in municipal transportation planning: Case study of mobility hubs in Oakland, California. *Transportation Research Record*, 2653(1): 65–74, 2017. ISSN 21694052. doi: 10.3141/2653-08.

David Banister. The sustainable mobility paradigm. *Transport Policy*, 15(2):73–80, 2008. ISSN 0967070X. doi: 10.1016/j.tranpol.2007.10.005.

Daniel Bell. Intermodal Mobility Hubs and User Needs. 2019. doi: 10.3390/socsci8020065.

Moshe Ben-Akiva, Jon Bottom, Song Gao, Haris N. Koutsopoulos, and Yang Wen. Towards Disaggregate Dynamic Travel Forecasting Models. *Tsinghua Science and Technology*, 12(2):115–130, 2007. ISSN 10070214. doi: 10.1016/S1007-0214(07)70019-6.

Chandra R Bhat and Frank S Koppelman. Activity-Based Modeling of Travel Demand 3 ACTIVITY-BASED MODELING OF TRAVEL DEMAND. (March), 2014. doi: 10.1007/0-306-48058-1.

Bharat P. Bhatta and Odd I. Larsen. Are intrazonal trips ignorable? *Transport Policy*, 18(1):13–22, 2011. ISSN 0967070X. doi: 10.1016/j.tranpol.2010.04.004. URL http://dx.doi.org/10.1016/j.tranpol.2010.04.004.

Robert Cervero, Olga L. Sarmiento, Enrique Jacoby, Luis Fernando Gomez, and Andrea Neiman. Influences of built environments on walking and cycling: Lessons from Bogotá. *International Journal of Sustainable Transportation*, 3(4):203–226, 2009. ISSN 15568318. doi: 10.1080/15568310802178314.

Merkebe Getachew Demissie, Santi Phithakkitnukoon, and Lina Kattan. Trip Distribution Modeling Using Mobile Phone Data: Emphasis on Intra-Zonal Trips. *IEEE Transactions on Intelligent Transportation Systems*, 20(7):2605–2617, 2019. ISSN 15249050. doi: 10.1109/TITS.2018.2868468.

Samar El-Amine, Stéphane Galland, Ansar Ul Haque Yasar, and Abderraffiaa Koukam. Demand for Agent-Based Transportation Models & Social Behavioral Challenges. *Procedia Computer Science*, 113:210–216, 2017. ISSN 18770509. doi: 10.1016/j.procs.2017.08.351. URL http://dx.doi.org/10.1016/j.procs.2017.08.351.

Raymond Eliot, Christina Hong, Mathias Hughey, and Independent Study. Creating Mobility Hubs to Connect Transportation Modes. 2019.

Abeer M. Elshater and Fatima Ibraheem. From Typology Concept to Smart Transportation Hub. *Procedia - Social and Behavioral Sciences*, 153:531–541, 2014. ISSN 18770428. doi: 10.1016/j.sbspro.2014.10.086. URL http://dx.doi.org/10.1016/j.sbspro.2014.10.086.

Dick Ettema and Harry Timmermans. Modeling Departure Time Choice in the Context of Activity Scheduling Behavior. *Transportation Research Record*, (1831): 39–46, 2003. ISSN 03611981. doi: 10.3141/1831-05.

José Roberto Reyes García, Gadi Lenz, Steven P. Haveman, and Gerrit Maarten Bonnema. State of the art of mobility as a service (MaaS) ecosystems and architectures-an overview of, and a definition, ecosystem and system architecture for electric mobility as a service (eMaaS). *World Electric Vehicle Journal*, 11 (1), 2020. ISSN 20326653. doi: 10.3390/WEVJ11010007.

Gemeente Utrecht. Mobiliteitsconcept voor Merwede. 2018.

G T J Gerben. Car-Sharing in Activity- Based Models. (March), 2018.

Douwe Hut. Implementation of Mobility Hubs in a multi-constrained gravity model. 2019.

Interreg. eHUBS - Smart Shared Green Mobility Hubs — Interreg NWE. *NW Europe*, 2019. URL http://www.nweurope.eu/projects/project-search/ehubs-smart-shared-green-mobility-hubs/.

Peraphan Jittrapirom, Valeria Caiati, Anna Maria Feneri, Shima Ebrahimigharehbaghi, María J. Alonso-González, and Jishnu Narayan. Mobility as a service: A critical review of definitions, assessments of schemes, and key challenges. *Urban Planning*, 2(2):13–25, 2017. ISSN 21837635. doi: 10.17645/up.v2i2.931.

Maria Kamargianni, Lampros Yfantis, Jakub Muscat, Carlos Lima Azevedo, and Moshe Ben-Akiva. Incorporating the Mobility As a Service Concept Into Transport Modelling and Simulation Frameworks. *Transportation Research Board 98th Annual Meeting*, (18):1–23, 2019.

Andrew S Keenan. Using Ontario's development permit systems to implement Metrolinx's Mobility Hubs in the Greater Golden Horseshoe (Major Research Paper). 2012.

Godoy J. D. Landínez. Unraveling the Dynamics of MaaS. 2018. URL http://repository.tudelft.nl/.

Elliot Martin and Susan Shaheen. The impact of carsharing on public transit and non-motorized travel: An exploration of North American carsharing survey data. *Energies*, 4(11):2094–2114, 2011. ISSN 19961073. doi: 10.3390/en4112094.

Mathieu Lefevre. Moving cities forward: shaping a better urban future. pages 1–11, 2020.

Metrolinx. Green Paper #2 Mobility Hubs: Development of a Regional Transportation Plan for the Greater Toronto and Hamilton Area (for consultation). pages 1–54, 2008. URL www.metrolinx.com.

Metrolinx. MOBILITY HUB GUIDELINES For the Greater Toronto and Hamilton Area. (September):164, 2011. URL http://www.metrolinx.com/en/regionalplanning/mobilityhubs/mobility{_}hubs{_}guidelines.aspx.

Montserrat Miramontes, Maximilian Pfertner, Hema Sharanya Rayaprolu, Martin Schreiner, and Gebhard Wulfhorst. Impacts of a multimodal mobility service on travel behavior and preferences: user insights from Munich's first Mobility Station. *Transportation*, 44(6):1325–1342, 2017. ISSN 15729435. doi: 10.1007/s11116-017-9806-y.

Nicole Ratti. Not all hubs are created equal: An analysis of future mobility hubs in the Greater Toronto Area. 2017.

SanD RTP. 2021 Regional Plan MOBILITY Vision for the San Diego Region. 2019.

Sandag. Mobility Hub Features Catalog REGIONAL MOBILIT Y HUB IMPLEMENTATION STR ATEGY. 2019.

Harry Timmermans, Theo Arentze, and Chang-hyeon Joh. Analysing space-time behaviour : new approaches to old problems. 2:175–190, 2002.

Vovsha. *Decision Economics. Designs, Models, and Techniques for Boundedly Rational Decisions*, volume 805. Springer International Publishing, 2019. ISBN 978-3-319-99697-4. doi: 10.1007/978-3-319-99698-1. URL http://link.springer.com/10.1007/978-3-319-99698-1.

Vovsha, Eric Petersen, and Robert Donnelly. Microsimulation in travel demand modeling: Lessons learned from the New York best practice model. *Transportation Research Record*, (1805):68–77, 2002. ISSN 03611981. doi: 10.3141/1805-09.

David A Hensher Yale Z Wong et al, Corinne, and Mulley. Emerging transport technologies and the modal efficiency framework: A case for mobility as a service (MaaS). 2018.

A THE REGION OF ALMERE

The region of Almere has 6 major transit stations, for this case study each station is considered to be a Mobility Hub. Within the following table the name of the stations and the corresponding zones within the OCTAVIUS model are shown:

Station Name	Zone Number
Almere Poort	389
Almere Muziekwijk	90
Almere Centrum	111
Almere Parkwijk	202
Almere Buiten	272
Almere Oostvaarders	261

Table A.1: Station Name and Zone number within the OCTAVIUS model

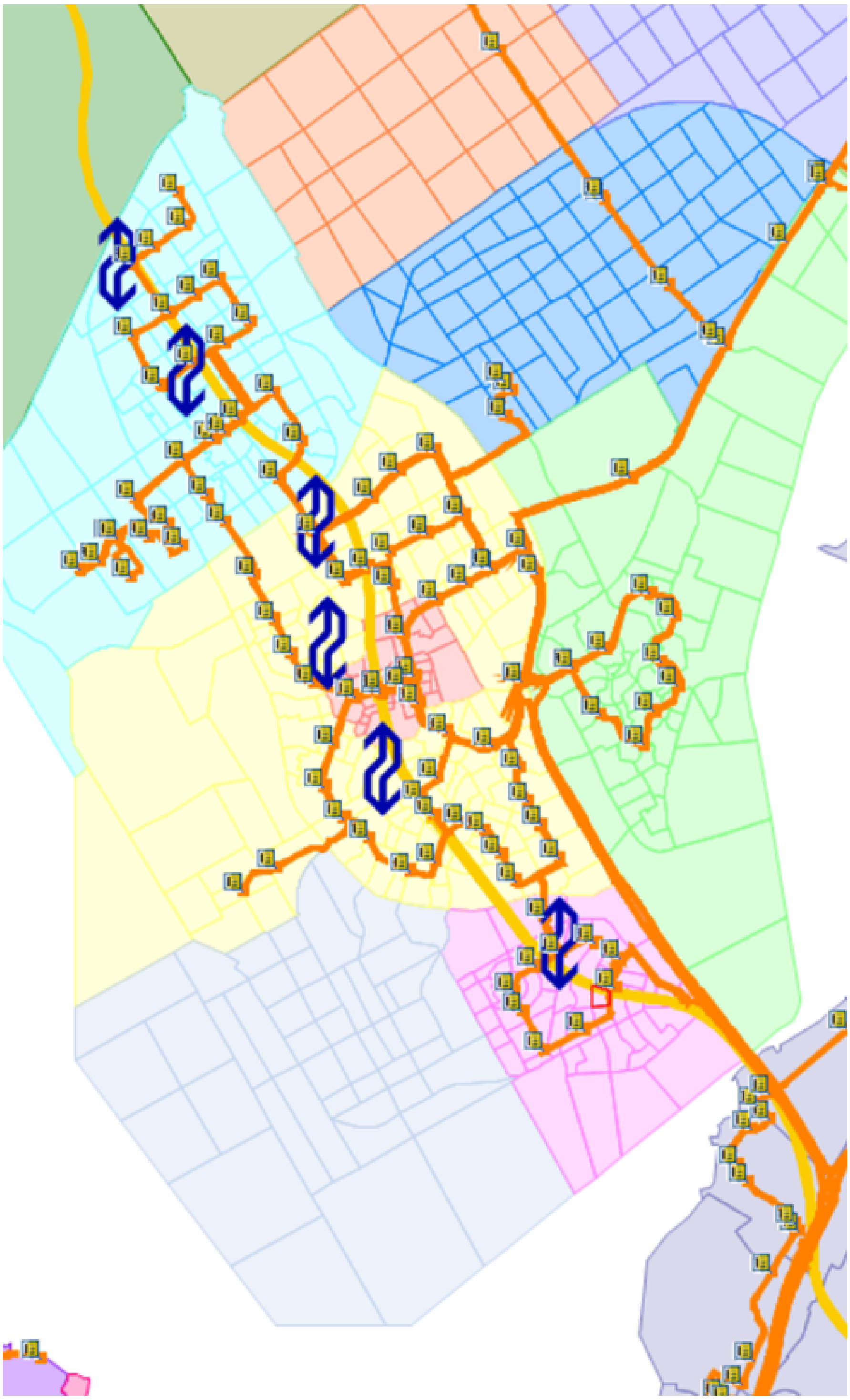


Figure A.1: Map of Almere with where transit stations are considered as mobility hubs

B | OVERALL MODAL SPLIT

Modal Split for Mobility Services Scheme												
Zone Number	Car-NHB	PT-NHB	Bike-NHB	CarPass-NHB	Car-HB	PT-HB	Bike-HB	CarPass-HB	Car-Total	PT Total	Bike-Total	CarPass-Total
90	5.72	2.32	8.71	1.17	73.03	23.93	47.05	17.71	78.75	26.25	55.77	18.87
111	0.00	2.03	2.03	0.13	4.53	7.00	9.44	0.67	4.53	9.03	11.47	0.80
202	357.40	223.75	309.01	103.68	1568.73	769.46	1575.65	475.93	1926.13	993.21	1884.66	579.61
272	16.11	3.48	16.94	3.94	342.74	141.96	322.17	98.27	358.84	145.44	339.11	102.22
261	10.81	5.29	14.04	3.61	558.22	205.91	521.28	210.11	569.03	211.20	535.32	213.72
389	17.96	2.02	30.42	6.51	266.94	108.27	307.58	80.45	284.90	110.29	338.00	86.97

Modal Split for Mobility Hub Activities Scheme												
Zone Number	Car-NHB	PT-NHB	Bike-NHB	CarPass-NHB	Car-HB	PT-HB	Bike-HB	CarPass-HB	Car-Total	PT Total	Bike-Total	CarPass-Total
90	5.02	3.26	8.71	1.16	74.13	25.55	46.83	17.67	79.14	28.82	55.55	18.83
111	0.59	1.58	2.03	0.13	3.89	5.88	9.47	0.67	4.47	7.46	11.50	0.80
202	376.25	227.67	308.99	103.71	1574.59	917.30	1586.86	477.75	1950.85	1144.96	1895.86	581.46
272	15.72	4.47	17.04	3.98	344.82	154.06	321.08	98.22	360.54	158.53	338.12	102.20
261	10.56	5.68	14.55	3.64	561.26	195.86	521.14	210.55	571.82	201.54	535.69	214.19
389	18.50	1.07	30.39	6.51	268.95	135.07	309.39	80.82	287.45	136.14	339.78	87.33

Modal Split for Base Case												
Zone Number	Car-NHB	PT-NHB	Bike-NHB	CarPass-NHB	Car-HB	PT-HB	Bike-HB	CarPass-HB	Car-Total	PT Total	Bike-Total	CarPass-Total
90	5.89	2.69	8.91	1.28	73.56	35.07	58.51	24.83	79.45	37.76	67.42	26.11
111	0.46	2.47	2.15	0.45	5.64	195.88	13.95	2.8	6.1	198.35	16.1	3.25
202	431.18	260.98	352.46	121.71	1574.27	908.3	1594.86	482.36	2005.45	1169.28	1947.32	604.07
272	15.79	3.65	17.45	4.45	347.96	161.87	346.56	110.92	363.75	165.52	364.01	115.37
261	10.68	5.89	16.58	4.54	601.33	266.39	698.2	307.55	612.01	272.28	714.78	312.09
389	25.42	2.14	36.74	8.97	299.47	247.87	508.23	167.23	324.89	250.01	544.97	176.2

Figure B.1: Model Split for Base case, Mobility hub activities and Mobility hub services scheme

C INDIVIDUAL DESTINATION AND MODE CHOICE

Mobility Hub as a Location of Second Activity (Mobility Service as First/Last Mile Mode)									
Person ID	Purpose-1	Purpose-2	Person Origin	Destination for first activity (base)	Destination for second activity (base)	First Activity (Implementation)	Destintaion for Second Activity	Mode Choice	Mode Choice Base Case
123159	Work	Social Recreational	270	268	267	174	272	PT-PT-Shared Bike	Car
128393	Work	Social Recreational	273	277	272	277	272	PT-PT-Shared Bike	Bike
171671	Shopping	Social Recreational	354	344	362	245	261	PT-PT-Shared Bike	Bike
2818	Shopping	Social Recreational	12	174	206	245	261	PT-PT-Shared Bike	PT
59533	Shopping	Social Recreational	134	174	120	174	90	PT-PT-Shared Bike	Bike
95648	Shopping	Social Recreational	226	311	372	245	202	PT-PT-Shared Bike	Car
66807	Shopping	Social Recreational	146	174	82	245	202	PT-PT-Shared Bike	Bike
5151	Shopping	Social Recreational	14	47	54	245	202	PT-PT-Shared Bike	Car
189808	Shopping	Social Recreational	394	186	143	186	111	PT-PT-Shared Bike	Car
193563	Shopping	Social Recreational	400	404	413	245	272	PT-PT-Shared Bike	Car

Mobility Hubs as a Location of First Activity (Mobility services as an aletnative to PT)									
Person ID	Purpose-1	Purpose-2	Person Origin	Destination Zone for First Activity (Base)	Destination Zone for Second Activity (Base)	Destination Zone for First Activity	Destination Zone for Second Activty	Mode Choice	Mode Choice base case
74160	Work	Shopping	156	111	174	111	174	Bike-Shared Car-Shared Car	PT
95847	Work	Shopping	226	83	211	272	245	Bike-Shared Car-Shared Car	Car
53652	Work	Social Recreational	123	317	156	111	156	Bike-Shared Car-Shared Car	Car
120640	Work	Social Recreational	267	273	267	272	267	Bike-Shared Car-Shared Car	Car
31913	Work	Social Recreational	83	80	83	389	83	Bike-Shared Car-Shared Car	CarPass
51686	Social Recreational	Shopping	117	153	118	202	174	Bike-Shared Car-Shared Car	Bike
59506	Social Recreational	Shopping	134	267	245	202	174	Bike-Shared Car-Shared Car	PT
65805	Social Recreational	Shopping	145	72	92	202	245	Bike-Shared Car-Shared Car	Bike
68968	Social Recreational	Shopping	151	100	174	389	186	Bike-Shared Car-Shared Car	Bike
95420	Social Recreational	Shopping	226	339	311	202	245	Bike-Shared Car-Shared Car	CarPass

Figure C.1: Tracing 10 agents for the multimodal function of mobility hubs

COLOPHON

This document was typeset using LaTeX. The document layout was generated using the arsclassica package by Lorenzo Pantieri, which is an adaption of the original classicthesis package from André Miede.

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