Modelling Impacts of Mobility Hubs in Residential Areas

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MODELLING IMPACTS OF MOBILITY HUBS IN RESIDENTIAL AREAS

by

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PREFACE

In September 2019, I started my master's degree in Transport and Planning(T&P) track in Civil Engineering Department at TU Delft. The academic journey at TU Delft has been a rollercoaster ride with lots of ups and downs, especially with the courses shifting to the online platform due to COVID-19. The wide range of courses offered in the T&P programme helped me explore different topics in the field of transportation and to select my specialization on 'Transport Networks'.

After finishing most of my courses, I approached Maaike Snelder in February 2021 to choose an interesting topic related to transport networks for my master's thesis. In a short meeting, I was briefed about several topics researched at TNO by Maaike and Marike van der Tuin. During the discussion in the meeting, the concept of mobility hubs caught my eye and eventually became my master's thesis topic.

I started my thesis internship at TNO in the mid of April 2021 after all the administration process, with Marieke being my company supervisor. I would like to thank Marieke for introducing me to this thesis topic and for guiding me in the right direction whenever I was stuck in the thesis, both in terms of concept and modelling. I would like to thank Maaike for linking me to TNO for my thesis. I would like to thank Bachtijar and Eleni from TNO for ensuring that my internship at the company was hassle-free from the start concerning the administration side. I would also like to thank the SUMS department of TNO for allowing me the opportunity to pursue my thesis internship at the company.

I would like to take this opportunity to also thank my thesis committee members from TU Delft. I thank Adam Pel, my thesis chairperson, who guided me since the start of the thesis, from forming the thesis committee to solving my doubts when stuck in modelling. I thank Gonçalo Correia, my daily thesis supervisor, who constantly motivated me and helped me find my way through concepts. I thank Natalia Barbour, my external thesis supervisor, who helped me with constructive feedback to improve my report and helped me identify key details that I was missing out on while conducting the research.

Even though I doubted myself at several points during this journey, there was always a constant motivation from back home. I would like to thank my family, Saravanan (father), Subapriya (mother), and Nikil (brother), for believing in me and helping me through my tough times.

I would like to also thank my friends here in the Netherlands and back in India who helped in me different ways along this rollercoaster journey. I thank Medha for ensuring my well being over the years and for reading my report several times & suggesting various improvements that could be made. Karthikeyan, Arjun, Hem, Ganesh, Roshan, Navin, Darshan, and Sanjay, who all were like a family away from home from the start of my new beginnings in the Netherlands. I thank them for their continuous support and presence in this period. I thank my classmates Nischal and Raunaq, who helped me a lot when I struggled with courses and for their support over these years. I thank Chendur and Rahul, my bachelor's college friends, who kept checking on me during different phases of my master's degree and helped me with my thesis report. I would finally like to thank Stavros for the insightful points highlighted on topics during discussions and the random fun conversations we had during coffee and lunch breaks as interns.

Mukil Prasath Saravanan
Den Haag, March 2022

EXECUTIVE SUMMARY

In the Netherlands, the number of passenger cars has been increasing at a faster pace than that of the adult population. The high number of cars occupying space often leads to parking demands. The introduction of shared modes in addition to public transport and active modes are currently on the rise. To improve the accessibility to different transport modes and reduce private car usage, city planners have introduced the concept of mobility hubs.

At a mobility hub, all sorts of mobility come together: public transport, shared bikes, shared cars, and parking places for private vehicles. Additionally, facilities such as repair, eating, shopping and logistic pick-up points are added to increase the attractiveness of the hub.

Based on stated-preference surveys and expert interviews, it was identified that mobility hubs could change people's travel behaviour in the region where it is located. As a result, these mobility hubs could play a vital role in the functioning of cities in which they are located and could have an impact on traffic flows and traffic conditions in the network. Also, the introduction of new modes at the mobility hubs could have an impact on the environment. However, these studies only provided insights and were insufficient to assess the mobility hub's impact on the transport network. As a result, this research aims to study the impact of a mobility hub on the transport network in which it is placed.

The focus area was on residential zones as the parking demand in such zones is increasing the pressure on residents to switch to different modes, and these hubs could play a key role in providing alternative transport options.

For the aim and focus of the study, the following main research question was framed:

"What is the impact on the transport network usage caused by a mobility hub in a residential area?"

To help answer the main research question, it was essential to understand the concept of a mobility hub for a residential area and explore different ways to help assess impacts on a whole transport network.

For this study, "A residential area focuses predominantly on housing function while being supported for daily needs by the presence of small scale functions like transportation, retail and business." Using this definition as the base, the broad classification of typologies of mobility hubs was explored to identify the typology suitable for a residential area. The classification type "Neighbourhood mobility hub" was deemed suitable. Several studies gave different descriptions of the components available at neighbourhood mobility hubs. Based on these descriptions, in this research, a neighbourhood mobility hub is defined as

"A central location in the residential area that provides at least one shared transportation option such as shared cars or shared bikes to its residents as an alternative to private vehicles with retail services, public transportation and other facilities being optional elements".

It was further found that for a residential area, a station-based vehicle sharing system is suitable for the shared modes present at the hub, where the mobility hubs act as the station.

To incorporate the mobility hubs into transport models, the pre-specified mode chain modelling technique was identified to be suitable as trips via a hub were found to be of multi-modal nature. As the transport modes available in each mobility hub varies, a generalized way to

introduce hubs into the four-step transport model was defined. The hubs were introduced into the model in the form of a new transport mode called "Hub-Travels". The new mode - "Hub-Travels", further consists of different transport mode-combinations based on the mobility hub's available mode options.

The key areas of focus in the four-step transport model for making this introduction were identified as the travel resistances/level of services input, trip distribution step, modal split step, and trip assignment step. Based on the key areas of focus in the four-step model, the adjustments that have to be made for these steps while incorporating mobility hubs with shared modes are defined. The level of service is generated for the new mode "Hub-Travels", which acts as an input for the simultaneous trip distribution and modal split step. The origin-destination (O-D) matrices per mode or per mode-chain are generated in this step, taking into account the best hub choice for different mode combinations. The mode combinations O-D matrices are segregated per trip leg and used as inputs for trip assignment. The trip assignment step assigns the route choice over the different modes and acts as a feedback to the level of service. A representation of the adjustment steps in the key focus areas is shown below in Figure 1.

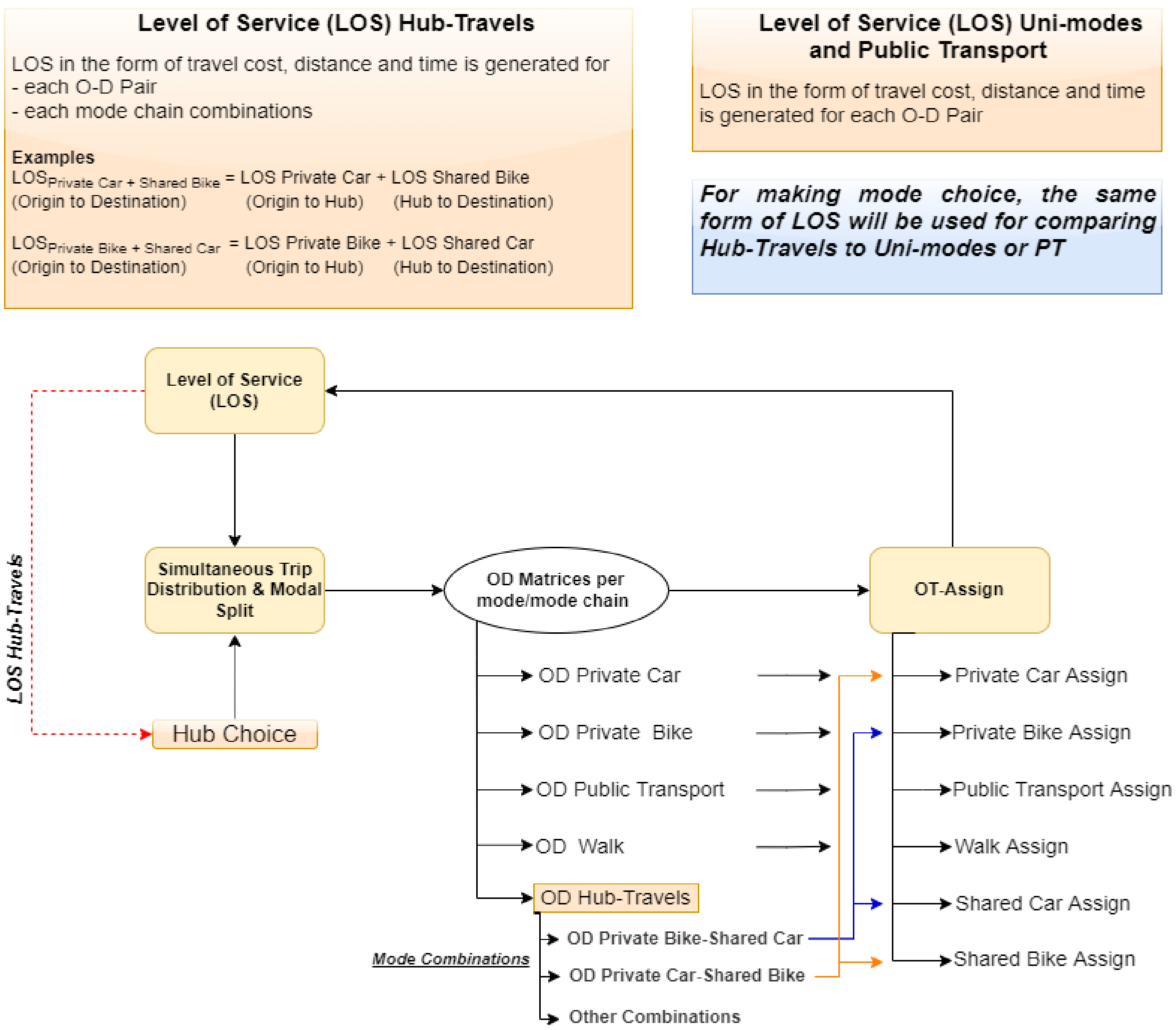

Figure 1: Adjustments to the four-step framework for incorporating mobility hubs with shared modes based on the area of focus

Using the adjustments methodology as the base, the existing transport network of the city of Delft was explored as a case study to try and incorporate mobility hubs. Two scenarios, one with mobility hubs and one without, was used for comparison. The adjustments made for modelling each of the scenarios are explained elaborately. The hubs were modelled in the identified residential zones of Delft, and shared modes such as bikes and cars were introduced to the model.

The introduction of the seven mobility hubs in the Delft network led to an overall decrease in uni-modal trips by 7% and public transport trips by 14.7%. It was also observed that across all the trip purposes in the scenario with mobility hubs in the Delft network, the total number of uni-modal and public transport trips reduced compared to the scenario without mobility hubs. The newly introduced mode-combination options compensated for the reduction in uni-modal and public transport trips in the presence of mobility hubs in the network.

The total vehicle kilometres and total time travelled was observed to increase across private cars and shared cars combined in the network for all trip purposes in the scenario with mobility hubs. With the introduction of seven hubs, there was an overall increase in kilometres and time travelled for cars (private and shared combined) in the network by 3.4% and 6.2%, respectively.

With regard to the total kilometres and total time travelled across private bikes and shared bikes combined, similar findings to that of the car network stated above were observed. The kilometres and time travelled increased by 2.3% and 2.2% respectively for private and shared bikes.

The proportion of arrivals at the mobility hubs by different transport modes was found to be more by private bikes and walk while for the departures from hubs the proportion was more varied over the different modes.

There was no significant change in the car congestion levels in the transport network of Delft with the introduction of mobility hubs that considers both private and shared cars. There were minor reductions in congestions only on a few links.

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ABBREVIATIONS

LOS	Level of Service
O-D	Origin-Destination
VKT	Vehicle Kilometres Travelled
P2P	Peer to Peer
B2B	Business to Business
B2C	Business to Consumer

1. INTRODUCTION

In the Netherlands, the number of passenger cars has been increasing at a faster pace than that of the adult population. As of January 2020, there were over 7.6 million privately owned cars (CBSa, 2020) which accounts for over one car for every two persons. The increase in usage of cars is not only constrained to the Netherlands but applies to the majority of the countries in the world. The European Union averages 569 passenger cars per 1000 inhabitants (ACEA, 2021). The high number of cars occupy space on the road and also uses up space while being parked both at home and destination (Natuur & Milieu, 2020). Even though the number of cars being used is high, the average occupancy of a car is only around 1.5 persons per car (CSS, 2021). As a result, several cities are introducing new shared modes such as shared cars, bikes and scooters in addition to public transport and active modes of transportation to reduce the usage of private cars.

To make the cities more accessible by connecting the different transport options, city planners introduced the concept of mobility hubs. At a mobility hub, all sorts of mobility come together: public transport, shared bikes, shared scooters, shared cars, and parking places for private vehicles. Additionally, facilities such as repair, eating, shopping and logistic pick-up points are added to increase the attractiveness of the hub. The representation of a mobility hub is shown in Figure 2.

Figure 2: Representation of a mobility hub (ShareNorth, 2021)

As mobility hubs are a developing concept, research on this topic is currently on the rise. The majority of the research which currently exists on this topic is from grey literature. The concept of mobility hubs is still very broad and has different typologies and component classification based on the area where it is introduced. The articles and documents which have been published regarding mobility hubs have also focussed mainly on cities with high people movement. However, the parking demand in residential areas is causing a lot of pressure on residents to switch to different modes. Mobility hubs in such residential areas could play a key role in providing alternative transport options to residents and improving accessibility.

There are more studies related to mobility hubs based on stated preference surveys and interviews with experts in the field of transportation compared to pilot studies. From these surveys and interviews, it is observed that people are willing to change their travel behaviour based on the available transport options and facilities at the hub. As a result, these mobility hubs could play a vital role in the functioning of the cities in which they are located. These hubs could have an impact on the transport network like traffic flows, modal split, and parking in the surrounding areas. Also, the introduction of new transport modes at the mobility hubs can have an impact on the environment. However, based on surveys and interviews alone, interpreting the impacts the hubs can cause is not possible because there are network effects, and the demand is not even. Thus, it becomes essential to research the mobility hub's overall impact on a whole network level.

To study the potential impacts of mobility hubs on the network level it is necessary to introduce and integrate the elements of mobility hubs with the transport network. However, research on integrating such mobility hubs in transport models is still missing and is identified as a key area of research to be done.

1.1. Research Scope and Objective

This research aims to study the impact of a mobility hub on the transport network in which it is placed and integrate mobility hubs in transport models. The impact is assessed in terms of travel behaviour, traffic conditions and sustainability in this research. The integration of hubs into transport models is considered at an aggregate level using macroscopic simulation and is based on the four-step transport model. This research focuses on mobility hubs located in residential areas and excludes other areas such as city centres, education and working centres.

It is assumed that the mobility hubs can be located anywhere in the network if the zone is classified as a residential area, i.e., the optimal location for the hub in the network is not considered. It is also assumed that the shared vehicles at mobility hubs are always available for users to use, i.e., the fleet size of shared vehicles at the hubs is not considered.

1.2. Research Questions

Based on the objective and the scope of research, the main research question formulated is as follows:

"What is the impact on the transport network usage caused by a mobility hub in a residential area?"

To answer the main research question, the following sub-research questions are formulated:

1. What typology of mobility hub is needed for a residential area? And what are the components that are required in the hub?
2. What is the methodology for introducing mobility hubs with shared modes in aggregate transport models?
3. How to model mobility hubs in an existing transport model?

1.3. Report Structure

The structure for the remaining report is as outlined below.

Chapter 2 covers a brief overview of the existing literature on the topics of mobility hubs, shared modes and the vehicle sharing systems that are used, multi-modal trips and existing transport models. These topics are used to understand the concepts for conducting the research and to identify the gap in the literature.

Chapter 3 acts as the base for answering the first sub-question. It elaborates on mobility hubs in residential areas and the usual travel behaviour which is seen in the presence of hubs. The chapter also identifies the suitable typology for mobility hubs in residential areas along with the key components needed in it. The vehicle sharing system which can be implemented in a residential area is also discussed.

Chapter 4 focuses on the four-step transport model and explains a generalized adjustment methodology that can be followed to incorporate mobility hubs with shared modes in aggregate transport models. This chapter helps answer the second sub-question.

Chapter 5 gives a brief overview of the Delft transport network on OmniTRANS, and it explains the steps followed to model mobility hubs with shared modes in the Delft transport network in the form of a case study based on the adjustments stated in chapter 4. This chapter is used to answer the third sub-question.

Chapter 6 presents the results that were obtained on simulation of the Delft network case study, and Chapter 7 discusses the obtained results from the Delft network simulation in terms of travel behaviour, traffic conditions and sustainability.

Chapter 8 provides the conclusions that were drawn from the research along with the limitations. Finally, recommendations for future research are stated.

The report structure and connection between the different chapters in the report is shown in Figure 3.

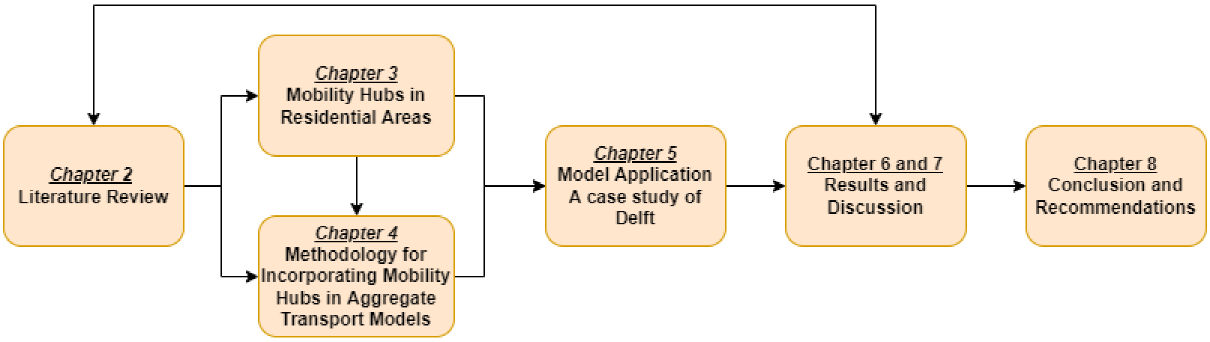

Figure 3: Report structure and connection between chapters

2. LITERATURE REVIEW

A literature review is first performed to help identify the unresolved problems on the research topic and the gaps in knowledge. The literature study in this chapter focuses on mobility hubs, shared modes, transport models and multi-modal trips. At the end of the chapter, the research gap which still exists will be discussed.

2.1. MOBILITY HUBS

Mobility hubs are a developing concept; therefore, limited studies exist on the topic of mobility hubs. The literature study for this concept includes grey literature like reports and documents from the research of regional planning commission & transport operators (Metrolinx, 2008; Urban Design Studio, 2016; Aono, 2019; CoMoUK, 2019; SEStran, 2020), case studies of mobility hubs from different cities and master theses (Blad, 2021; van Gerrevink, 2021). First, the various definitions used to describe a mobility hub are examined, followed by the various typologies of mobility hubs and, finally, the components available at a mobility hub. This review further acts as the base for chapter 3.

Definitions

From the literature, it is noticed that there isn't a fixed definition for mobility hub, and various definitions have been used in different documents and reports to describe it. Some of the referred to definitions of mobility hubs in different studies are as follows:

- "Mobility hubs are places of connectivity where different modes of transportation from walking to high-speed rail come together seamlessly and where there is an intensive concentration of employment, living, shopping and/or recreation." -Metrolinx (2008)

- "Mobility hubs provide a focal point in the transportation network that seamlessly integrates different modes of transportation, multi-modal supportive infrastructure, and place-making strategies to create activity centres that maximize first–mile last-mile connectivity." - Urban Design Studio (2016)

- Mobility hubs are a place to promote connectivity through different sustainable modes that are integrated seamlessly. - Aono (2019)

- Mobility hubs are a place that should be recognizable, offering different connected transport modes to benefit and attract travellers while having an addition of facilities. - CoMoUK (2019)

- "A Mobility Hub is a recognisable and easily accessible place which integrates different transport modes and supplements them with enhanced facilities, services and information aimed at encouraging more sustainable travel, creating sense of place and improving journeys and travel choices" - SEStran (2020)

- "The mobility hub is a place where multiple sustainable transport modes come together at one place, providing seamless connection between modes, additionally offering shared mobility, possibly including other features, ranging from retail, workplaces to parcel pick-up points." - Blad (2021)

Several other definitions also exist for mobility hubs. However, from the various definitions described above and those available online, the common themes or keywords mobility hubs concerned its location, purpose, modes, and available services & facilities. The terms sustainable modes and facilities at the hub have been recently incorporated into the definitions. So based on the existing definitions and literature, for this research, the definition used is:

"A mobility hub is a place where all sorts of mobility come together: public transport, shared bikes, shared scooters, shared cars, and parking places for private vehicles. Additionally, facilities such as repair, eating, shopping and logistic pick-up points are added to increase the attractiveness of the hub."

Typology of Mobility Hub

From literature studies, it is observed that the typology of mobility hubs varies. It can be based on the mobility hubs' geographical location (Goudappel & APPM, 2020), the scale of operation (Urban Design Studio, 2016; Goudappel & APPM, 2020; PBOT,2020), urban context (Engel-Yan & Leonard, 2012; Shared Use Mobility Center, 2018; CoMoUK, 2019; Goudappel & APPM, 2020), transportation function (Engel-Yan et Leonard, 2012) and services offered at the mobility hub (PBOT,2020). As the focus of the thesis is on residential areas, the urban context will be of significant focus.

Based on the urban context and geographical location, distinction of a hub can be made into four zones(Figure 4): Inner-city location (A), urban residential area (B), peripheral zone urban region (C) and regional centres/rural zone (D) (Goudappel & APPM, 2020). The typologies of hubs in other literature studies are distinguished similarly in terms of urban context: city, residential and regional.

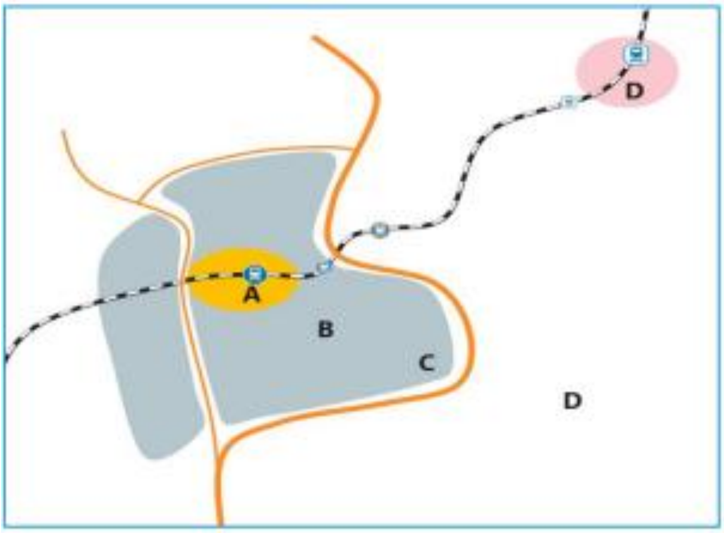

Figure 4: Geographical location zones (Goudappel & APPM, 2020)

PBOT (2020) classifies the mobility hubs into four types (Figure 5): major hubs(city), mid-size hubs(city), minor hubs(residential\regional) & mini hubs (residential\regional). In terms of its land use and transportation context, the hubs are allocated to centres and corridors, categorised into different types.

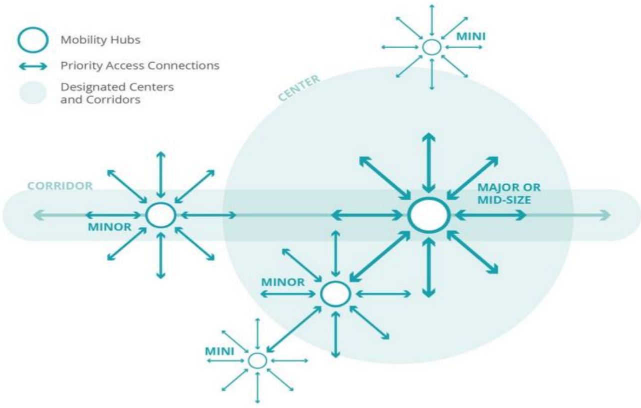

Figure 5: Typology of mobility hubs by PBOT(2020)

Typologies of mobility hubs based on users and urban context can be ranged into six types (CoMoUK, 2019) –

1. **Large interchanges/City hubs** – for a high number of passengers starting/ending/ transferring between modes (city).
2. **Transport corridor, Smaller interchanges/Linking hubs** – for local area residents connecting to main network services (regional).
3. **Business park/New housing development hubs** – for high density of users connecting to main network services (regional).
4. **Suburbs/Mini hubs** – for low density of people with high private car ownership (residential)
5. **Small market town/Village hubs** – for local area residents to connect to main network services (regional)
6. **Tourism hubs** – for visitors and residents in rural areas for improving connectivity (regional)

According to Urban Design Studio (2020), mobility hubs are classified into three tiers: Neighbourhood (small & for low-density areas; residential), Central (in a more urban area; city), and Regional (large & for high-density areas; regional). This report also states the vital, recommended and optional amenities for each tier.

van Gerrevink (2021), for better visualization and understanding of the typologies of mobility hubs categorised the different hubs based on the scale of operation, urban context and scale of geographical location into one table, as shown in Figure 6.

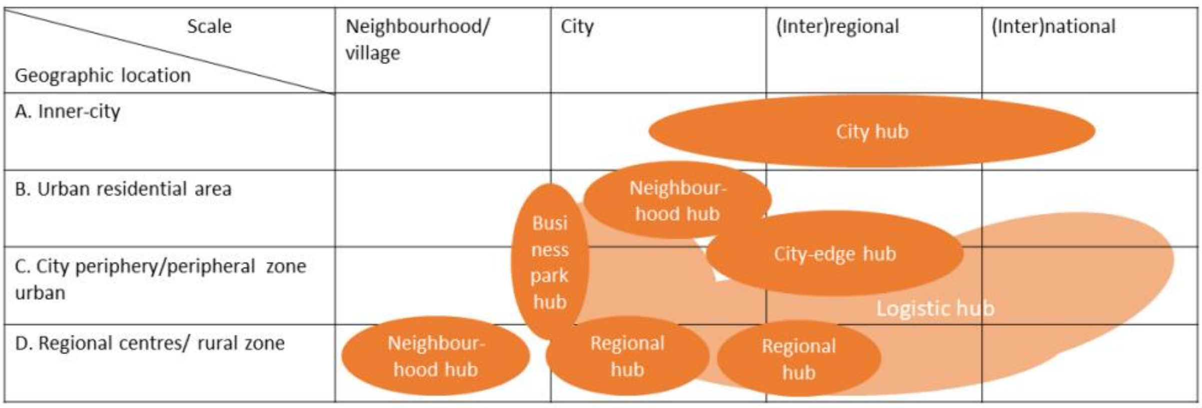

Figure 6: Categorisation of mobility hubs (van Gerrevink. 2021)

Components in a Mobility Hub

There is no universal approach to implement or design mobility hubs, but there is a need for consistency in how they are implemented for people to recognise them (SEStran, 2020). The components and elements present at the mobility hub also vary.

SANDAG (2017) identified that a wide variety of services and amenities can be included in a mobility hub and classified them into five categories:

1. **Transit Amenities** – Waiting area, Real-time travel information & Transfer zones.
2. **Pedestrian Amenities** – Crossings & Walkways.
3. **Bike Amenities** – Bikeways, Bikeshare, Bike parking.
4. **Motorized Services & Amenities** – Scooter share, Car share, Micro transit, Electric vehicle charging, Smart parking, Dedicated transit lanes.
5. **Support Services & Amenities** – Wayfinding, Package delivery, Mobile retail services.

CoMoUK (2019) categorised the components present at mobility hubs into four types (Figure 7) –

1. **Mobility Component: Public Transport –** Bus, Tram, Rail
2. **Mobility Component: Non-Public Transport** – Car share, Bike share, E-scooters
3. **Mobility Related Components** – Bike parking, Bike repair, Electric vehicle charging
4. **Non-Mobility & Urban Realm Improvement Components** – Wi-Fi, Phone charging, waiting area, package delivery lockers, cafes.

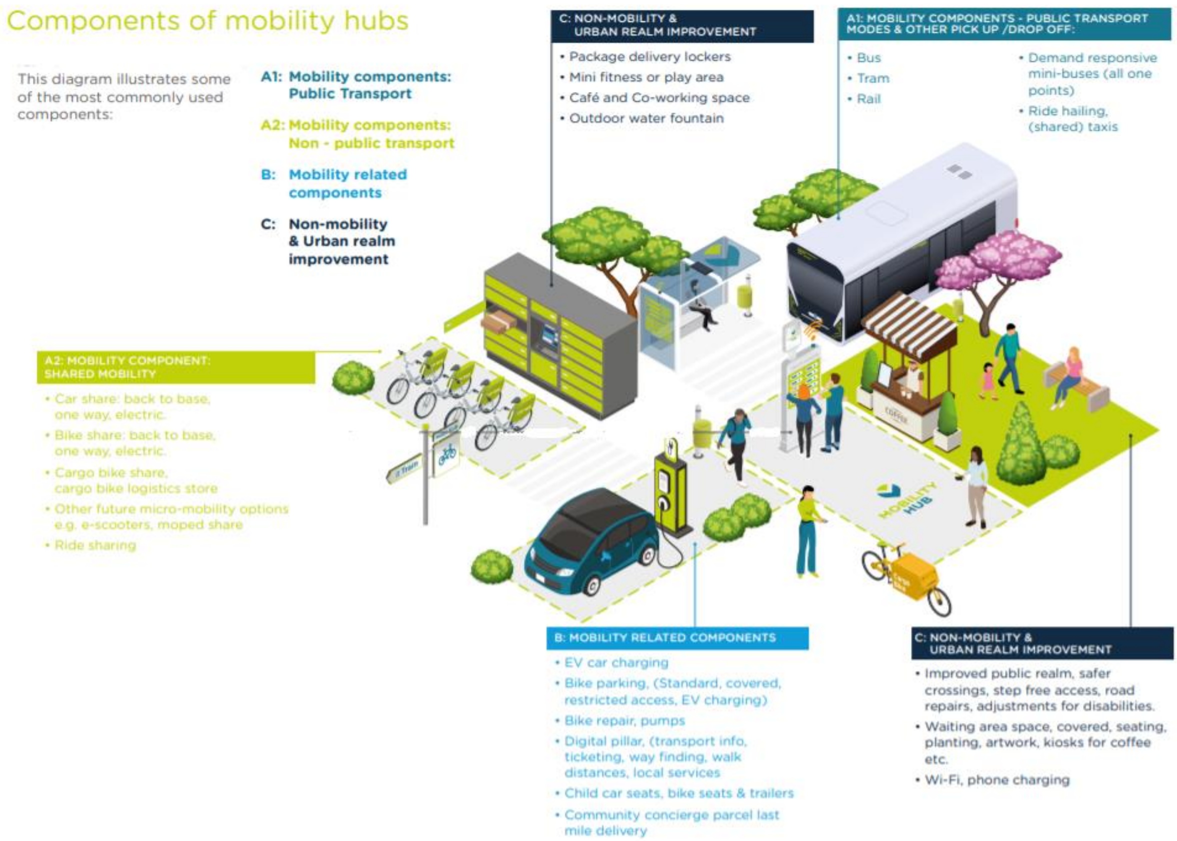

Figure 7: Components of mobility hub (CoMoUK, 2019)

A simpler categorisation of the components in mobility hubs is done by SEStran (2020), where the components are categorised into mobility-related and non-mobility related components. The components present in each category are unique based on the hub location, need in the area, and available funding.

Different case studies (Aono, 2019; CoMoUK, 2019; RI.SE 2020) of regions where the mobility hubs have been implemented already also indicate that the variation of components depends on the location, availability of resources, and the objective for which the hub is built.

2.2. Shared Modes

From the literature studied in Section 2.1, it is observed that the shared modes are a vital component of mobility hubs. This section focuses on the commonly used shared modes at existing mobility hubs, types of vehicle sharing systems available, and the impacts which are caused due to shared modes. The review of the shared modes and vehicle sharing system acts as the basis for Section 3.4, while the impacts caused are used as the base for Chapter 7.

Shared Modes in Existing Mobility Hubs

From different case studies presented in the literature (Aono, 2019; CoMoUK, 2019; RI.SE 2020), some commonly found shared transportation modes across Europe are standard cars, electric cars, standard bikes, electric bikes, and scooters. The shared modes available at the mobility hub vary based on the typology of the hub and based on the modes used and preferred by the people in the region.

In the Netherlands, there are around 150 small scale mobility hubs operated by different service providers, of which 60 are private, i.e., the hubs and shared modes are accessible only for a specific group of residents/employees, and 90 are accessible publicly (van Gerrevink, 2021). In these hubs, the shared modes available are electric cars, electric bikes, electric cargo bikes, or standard shared cars and bikes based on the city's service provider. The type of vehicle sharing system to use the shared modes also depends on the service provider. Car sharing and bike-sharing are common in most mobility hubs.

Car Sharing System and Modal Shift due to it

The principle of carsharing systems is to allow individuals to benefit from private cars without the responsibilities and costs of car ownership (Shaheen et al., 2020). There are different types of carsharing systems which are present currently (Blomme, 2016; Lagadic et al., 2019; Nansubuga & Kowalkowski, 2021):

- **Peer-to-Peer Model (P2P):** private cars are shared directly with other private users.
- **Business-to-Business Model (B2B):** cars are shared with a given firm.
- **Business-to-Consumer Model (B2C):** service providers share cars with the general public.

An overview scheme of car-sharing systems is shown in Figure 8 based on (Blomme, 2016; Machado et al., 2018; Lagadic et al., 2019; Shaheen et al., 2020; Roukouni & Correia, 2020).

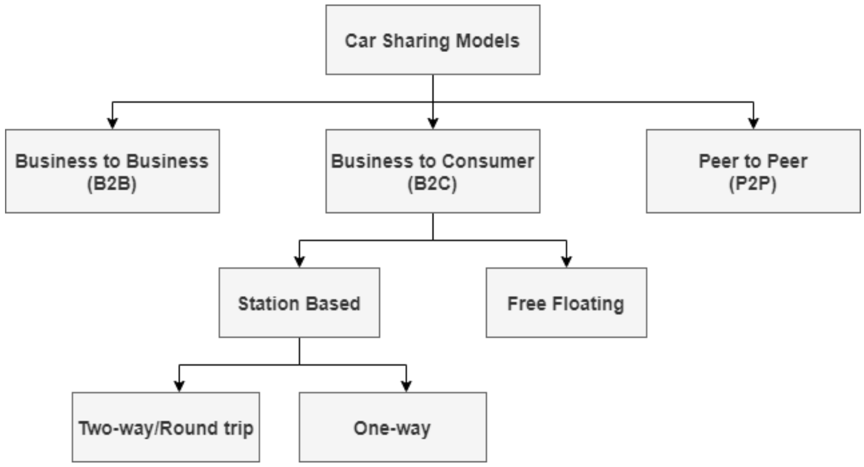

Figure 8: Overview of car-sharing systems (Based on Blomme, 2016; Machado et al., 2018; Lagadic et al., 2019; Shaheen et al., 2020; Roukouni & Correia, 2020)

For mobility hubs in residential areas, only business to consumer (B2C) models are looked into further. In such models, the ownership of the fleet of cars is by a service provider (Nansubuga & Kowalkowski, 2021). The B2C models are divided into two categories: Station Based and Free-Floating, based on their type, function, and target audience (Machado et al., 2018).

- **Station Based Car Sharing System**

  In station based sharing systems, the cars can be picked up or dropped off at stations pre-defined by service providers or local administration (Ferrero et al., 2017). The station-based systems are further divided into two categories: Two-way/Round trip vehicle sharing and One-way vehicle sharing (Roukouni & Correia, 2020).

  In two-way/round trip car sharing, the user picks up the shared car from the designated station and returns it back to the same station after using, while the payment for it is on an hourly basis (Shaheen et al., 2020). This kind of vehicle sharing is usually used for short journeys where the vehicle is parked for a short period of time like leisure, shopping trips (Machado et al.,2018). Representation of two-way station based trips is shown in Figure 9.

  In one-way car sharing, the users can pick up the car from a designated station and drop it off at another designated station after use, which increases flexibility in usage (Shaheen et al., 2020). The operational management of such systems is complex for service providers (Machado et al., 2018). Representation of one-way station-based trip is shown in Figure 9.

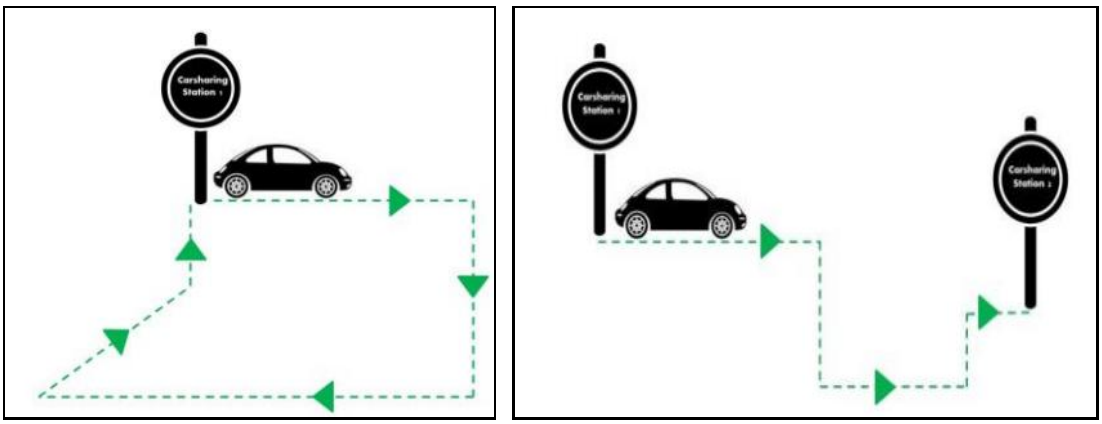

Figure 9: Representation of two-way station based sharing (left), one-way station-based sharing (right) (Lage et al., 2018)

- **Free Floating Car Sharing System**

  In a free-floating car share system, the vehicles are parked freely in public spaces within an operating area designated by the service provider of shared cars and the shared cars can be picked up and dropped off at any point in this operating area (Lage et al., 2008). The users can drive outside the operating area, but the drop off should be within this area. (Machado et al., 2018). Representation of this system is shown in Figure 10.

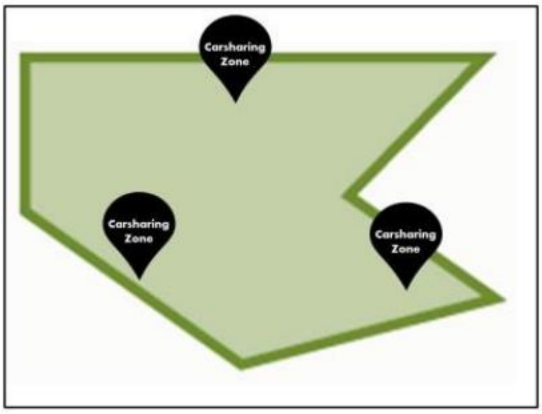

Figure 10: Representation of free-floating car-sharing systems (Lage et al., 2018)

In a study by Martin & Shaheen (2011), when using car-sharing systems, the shift in public transit usage is observed to be mixed while the shift towards walking, bicycling and carpooling is found to increase.

Bike Sharing System and Modal Shift due to it

Bike-sharing systems have emerged as one of the fastest developing transport innovations (Shaheen et al., 2020). Such systems are similar to carsharing models and consist of station and free-floating based bike-sharing models (Machado et al., 2018). Apart from these two models, other models in bike-sharing systems are P2P sharing models, closed campus sharing models and hybrid models (van Waes et al., 2018; Shaheen et al., 2020; Roukouni & Correia, 2020). An overview of these systems is shown in Figure 11.

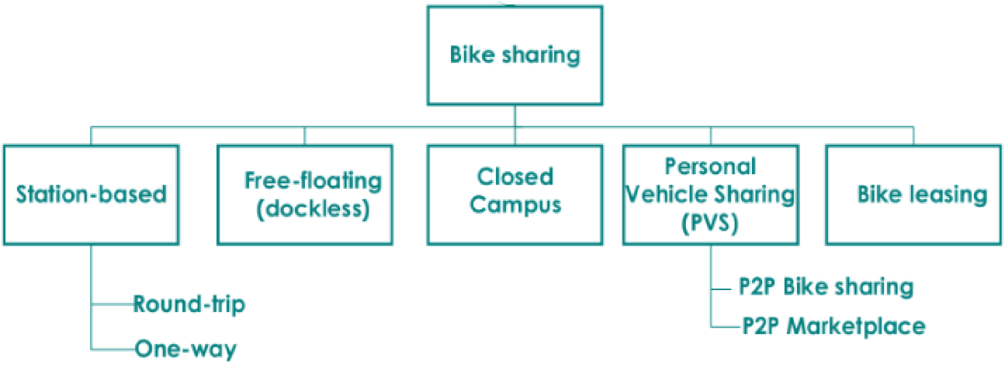

Figure 11: Overview of bike-share models (Roukouni & Correia, 2020).

Closed Campus bike-sharing models are used at universities and office complexes, and they are accessible to the community they serve like students and employees (Shaheen et al., 2020). While in peer to peer bike sharing models, residents rent their private bikes to other users directly, where the user has to return the bike from where it was picked up (van Waes et al., 2018). In leasing models, the users can lease the bikes from a service provider for a fixed subscription fee like Swapfiets.

Station-based bike-sharing models, also called docked models, are similar to station-based carsharing models. For a two-way sharing model, also known as roundtrip models, the bikes have to be returned to the same station from where it was picked up, and for one-way sharing models, the bikes can be returned after use to any station where the service provider operates (Machado et al., 2018).

Free-floating bike-sharing models are also called dockless models, and in such models, the users can drop off the bike at any location within the operating area of the service provider of shared bikes (van Gerrevink, 2021). In such models, the users can drop off bikes at places with or without bike racks. (Ma et al., 2020).

Bike-sharing systems have a modal shift impact on private cars, public transportation and active modes like bicycling and walking (Daniel et al., 2013; Martin & Shaheen, 2014). Existing literature has focused on modal split impact due to station-based and free-floating bike-sharing systems (Ma et al., 2020). Trips shift from private cars to shared bikes when the system acts as a first or last-mile connection with public transit (Fan et al., 2019). Socio-demographic factors such as gender, age, income, ownership & household type and travel behaviour factors like commute type and length influenced bike share usage and modal substitution decisions (Barbour et al., 2019). Weather conditions, temperature and pollution also affect bike sharing when deciding modes (Li & Kamargianni, 2018).

Bike-sharing acted as a substitute for public transportation in large and dense cities. In contrast, it served as a complement to public transportation, serving as first or last mile integration at less dense and small to medium-sized cities (Martin & Shaheen, 2014). Ma & Knaap (2019) found similar results where rail ridership decreased at core transit stations and increased at transit stations in outer neighbourhoods with bike-sharing systems.

Bike share trips replaced walking trips as walking time is more than cycling time, resulting in an overall decrease in active travel time (Fishman et al., 2015). Users reporting inconvenience carrying private bikes on trains shifted to bike-sharing if it is flexible and accessible (Ma et al., 2020).

According to Ma et al. (2020), in the Netherlands, usage of private cars, private bikes, bus/tram and walking reduces for bike-sharing users while usage of trains increases. Compared to other modes, the quality of bikes and cost are considered significant factors for using shared bikes.

Impacts of Shared Mobility

Roukouni & Correia (2020) combine the key areas of impacts of shared mobility into six categories: travel behaviour, built environment, society, traffic conditions, economy and environment. The relevant category is selected based on the research being conducted, and the key areas of impact under the category are further examined. The impacts under each category are illustrated in Figure 12, where VKT/VMT is Vehicle Kilometres Travelled/Vehicle Miles Travelled.

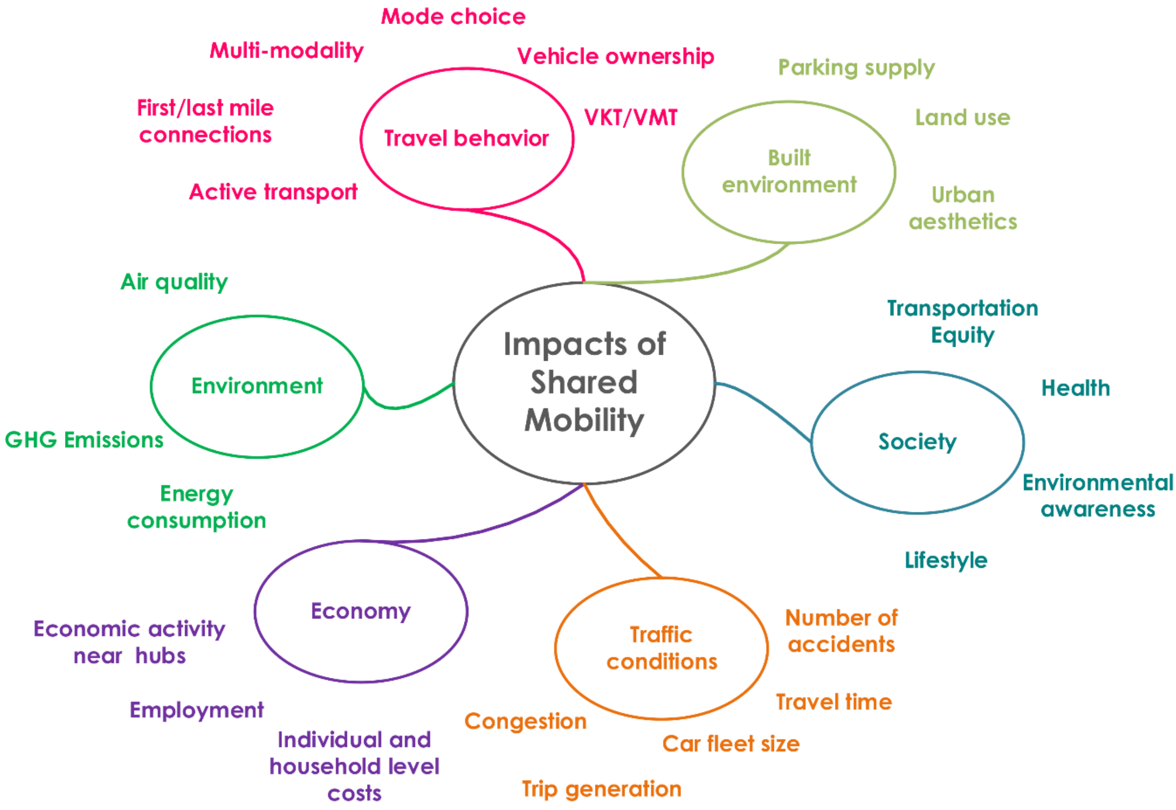

Figure 12: Categories and key areas of impacts of shared mobility (Roukouni & Correia, 2020).

Among the six main categories shown in Figure 12, the majority of the reports and studies published so far belong to the category of environment and travel behaviour (Roukouni & Correia, 2020).

Based on a survey study conducted by Share North (2018) at Bremen, Germany, every car-sharing vehicle replaces 16 private cars. Alternatively, it prevents their purchase while the vehicle kilometres travelled by car in a household using car-sharing was 50% lower than in an average household in the city.

In the Netherlands, PBL (2015) conducted a survey study where a 30% decrease in car ownership and 15-20% decrease in vehicle kilometres travelled was noticed among car sharers compared to before they used car sharing.

This categorisation of impacts will be used for understanding the effects of shared modes in the transport network.

2.3. Transport Modelling

This section focuses on the literature on the concept of aggregate and disaggregate transport modelling followed by the trip, tour and activity-based models. Finally, the traditional four-step transport model is examined. This section helps understand the modelling methods that can be used in Chapter 4.

Aggregate and Disaggregate Transport Modelling

Aggregate models focus on zones and groups within the zones, i.e., macroscopic level. It considers the group's transportation decisions based on the group's socio-economic characteristics (van Steijn, 2016). Household surveys and counts are used to provide data to such models. In aggregate modelling, the variety in travel behaviour & inhomogeneity within zones are not captured. Thus forecasts from such models are not expected to succeed when zones are heterogeneous. (McFadden & Reid, 1975).

Disaggregate models focus on individual types/household level, i.e., microscopic level. It considers the transportation decisions among different available alternatives that individuals or households varying in socio-economic characteristics make in different scenarios (van Steijn, 2016). Observed choice behaviour and ideally chosen options & their alternatives are used to provide data to disaggregate models. It is based on discrete choice modelling. Such models should have the properties of implying the aggregate models under homogenous conditions and properties of forecasting correctly under heterogeneous conditions (McFadden & Reid, 1975).

The disaggregate models provide a theoretical foundation for the aggregate models and provide conditions under which the aggregate models will give valid forecasts. The aggregate models may provide the most convenient way of forecasting when homogeneous zonal conditions are met (McFadden & Reid, 1975).

Trip, Tour and Activity-Based Models

A trip is a one-way movement from a point of origin to a point of destination, while a tour is a sequence of trips from one location to another where the endpoint is the start location (Ortúzar & Willumsen, 2011). The activity schedule is a program that indicates all activities and travels made during a day, along with the time duration spent during each phase (Rot, 2015). A representation of trips and tours is shown below in Figure 13.

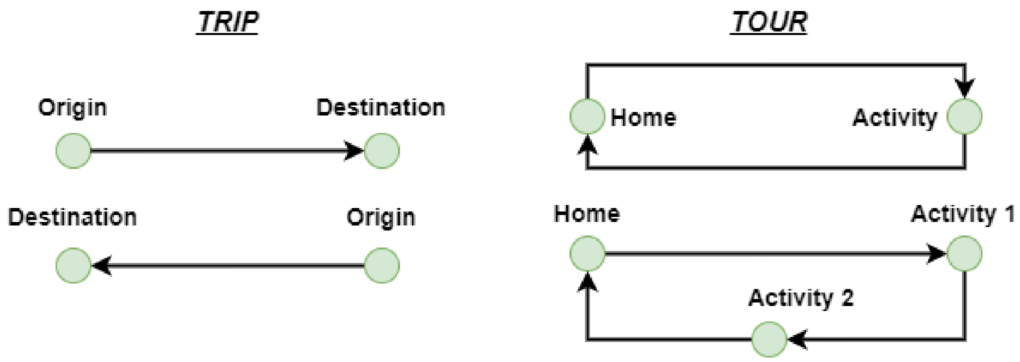

Figure 13: Representation of trip and tour

A trip-based model considers travel from one location to another and is usually from zone to zone, i.e., usually associated with aggregate models. A tour-based model considers travel from one location to another. The endpoint of travel is the start location and is usually from segment per zone to zone, i.e., usually considered among disaggregate models. An activity-based model considers the travel along with the activity schedule for an individual and thus is considered among disaggregate models.

Traditional Four-Step Transport Model

The traditional transport model consists of four steps: Trip Generation, Trip Distribution, Modal Split and Trip Assignment. (Fiorenzo-Catalano, 2007; Ortúzar & Willumsen, 2011; MOTOS, 2016). A representation of the four-step model is shown in Figure 14.

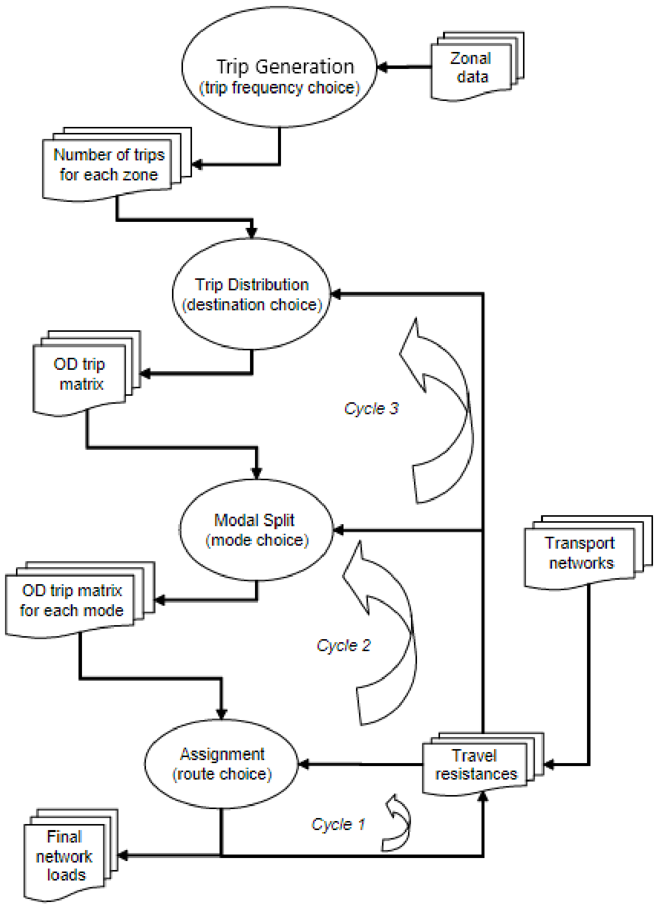

Figure 14: Traditional transport model (Fiorenzo-Catalano, 2007)

In Figure 14, the four main steps are shown in the centre. The exogenous input data for each of the four steps are shown on the figure's right-hand side, and the endogenous data predicted by each step in the model is shown on the left-hand side.

In the trip generation step, the total number of trips departing/produced and arriving/attracted by each zone of the study area is generated. In trip distribution, the trips generated in the trip generation step are allocated to particular destinations, i.e., the trip matrix from each zone to all other zones is produced, i.e., origin to destination (O-D). In the modal split step, the trip matrices are allocated to different transport modes in the network. Finally, trips by different modes are allocated to corresponding routes in the trip assignment step. The model follows an iterative procedure to obtain consistent results. This iterative procedure is because the network usage level is obtained after the assignment step and the input module travel resistances varies based on the network usage level. The travel resistances include travel influence choices such as travel costs, distance and time.

The main steps need not be simulated individually always. Sometimes two steps like trip distribution and modal split can be simulated simultaneously. Furthermore, each step consists of several other techniques within it (Rot, 2015). The period of the day can also be added as an additional step between the trip distribution and modal split; alternatively, it can be simulated simultaneously with the trip distribution and modal split step.

2.4. MULTIMODAL TRIPS

This section focuses on the literature on the concept of multi-modal trips, followed by the different techniques to model multi-modal trips in transport models.

Multi-Modal Trips

Multi-modal trips are trips in which two or more different transportation modes/networks apart from walking are used for a single trip from origin to destination and between which at least one transfer between modes is necessary (van Nes, 2002). Such trips always consist of two or more legs with different modes(van Nes & Bovy, 2004). A representation of a multi-modal trip is shown in Figure 15.

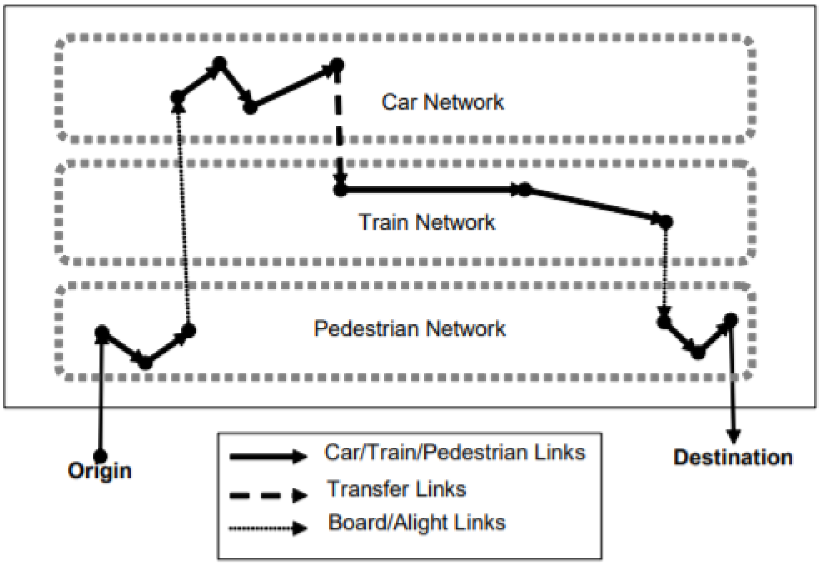

Figure 15: Representation of a multi-modal trip (Fiorenzo-Catalano, 2007)

The main factors which determine multi-modal trip making are trip purpose, trip distance and destination area type (van Nes, 2002), where more than 50% of such trips are for work or education purposes. In Europe, of all multi-modal trips largest share for main transport mode in such trips are for public transportation modes.

Multi-Modal Modelling Techniques

There are several techniques in literature for modelling multi-modal trips. Two of the most commonly stated techniques are *pre-specified mode chain technique* (Fernandez et al., 1994; Fiorenzo-Catalano, 2007; van Eck et al., 2014), which is an extension of the classic transport model and *super-network technique* (Kristof et al., 2002; Fiorenzo-Catalano, 2007; van Eck et al., 2014), which integrates several uni-modal networks into a single multi-modal network through transfer links.

In the pre-specified mode chain technique, the possible mode combinations by the travellers in a multi-modal trip are pre-specified in the model along with the unimodal options. In this technique, the mode (chain) choice and route choice are sequential, similar to the classic four-step model. The nodes representing stops and stations for vehicle parking also need to be pre-specified. In this technique, individual trip legs of the mode-chain combination can also be obtained after the route choice assignment.

The primary advantage of this technique is that it can be modelled with minimal computational complexity for common-mode combinations. However, some realistic mode-combinations might be missed in modelling, leading to fixed and limited mode chains. The correlation or overlap between alternatives can be captured using a nested choice model in the technique. An illustration of the pre-specified mode chain technique is shown in Figure 16.

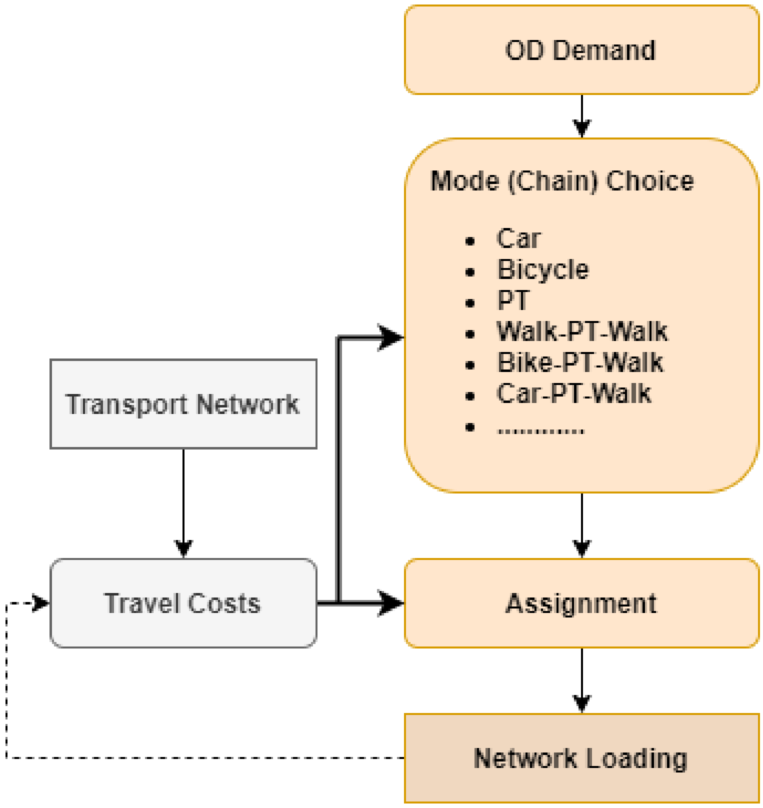

Figure 16: Illustration of pre-specified mode chain technique

In the super-network technique, mode choice and route choice steps are simulated simultaneously. Thus, the multi-modal trips are directly applied to the super-network, and there is no need for separate origin-destination trip leg matrices.

The main advantage of this technique is that it considers the network-specific characteristics and additional attributes related to nodes & links with no constraints on mode-combinations. In theoretical terms, the super-network technique is attractive to include in the model, but its computational complexity is a significant disadvantage, especially in large networks. An illustration of a multi-modal super-network is shown in Figure 17.

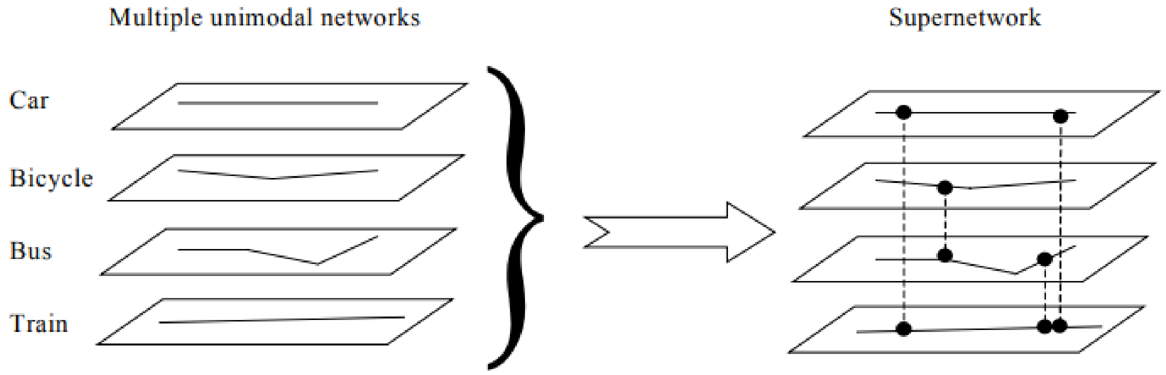

Figure 17: Illustration of multi-modal super-network (Kristof et al., 2002)

Another technique that exists for modelling multi-modal trips is the *access-main-egress mode choice technique* (Fiorenzo-Catalano, 2007). In this technique, the mode choice sets and route choice sets are generated for the access trip leg, main trip leg, and egress trip leg. Mode choice and route choice occur sequentially. The major drawback of this technique is that many different choice sets need to be generated not only for the origin-destination level but also for trip legs. The nested choice model can also capture overlap between alternatives only within each trip leg.

As a result, only the pre-specified mode chain technique and super-network technique will be used as the base for discussion in Section 4.1.

2.5. Research Gap

Based on the literature study done for this research, it is observed that the majority of the studies related to mobility hubs is based on grey literature. The attention of these studies are also usually on city centres or in regions with high people movement, and limited focus has been given to residential areas. Among the studies related to mobility hubs in residential areas, the findings have been based on stated preference surveys and interviews. These studies help understand the behavioural characteristics of people using the mobility hub. However, they do not give much insight into how the complete transport network in the region changes with the mobility hub. As it is observed that users' travel behaviour with mobility hubs can change, it becomes necessary to understand the overall impacts that the hub can cause. For this, it is essential to study a complete transport network with mobility hubs present in it.

Existing literature on mobility hubs concerning transport networks proposes methods to identify potential locations for mobility hubs. However, there is still missing research in terms of integrating such mobility hubs with shared modes in transport models. A methodology to integrate these elements into transport models makes it easier to study the potential effects of mobility hubs in existing transport models and hence is identified as a key area of research to be conducted.

3. Mobility Hub in Residential Areas

This chapter defines the general characteristics of mobility hubs and shared modes that can be incorporated into residential areas. As the research is focused on residential areas, first, the various definitions of residential areas that exist will be looked into, followed by the travel behaviour typical in such areas. Then the typology & components of mobility hubs suitable for residential areas will be elaborated. Finally, the usual transport modes that are present and vehicle sharing systems that can be adopted are explained.

3.1. Definition of Residential Area

Some of the definitions for residential areas found from literature are as follows:

According to Földi (2006), residential environment provides a place for daily life and does not exclude other functions like business, transportation, retailing or even small scale production, while the key criterion is that residential function prevails in it.

According to Detroit City Council (2021), residential areas range from low-density to high-density areas based on the number of houses per residential acre. These areas can consist of commercial development that serves the daily day to day needs of residents but not developments that attract high vehicular traffic.

Several other definitions exist, but it is noticed that there is no fixed definition to describe a residential area, so based on the existing definitions and literature, for this research, the definition adopted is:

"A residential area focuses predominantly on housing function while being supported for daily needs by the presence of small scale functions like transportation, retail and business."

3.2. Travel Behaviour in Residential Areas with Mobility Hubs

The usual preference for the residents in any area is to travel at any time to any location of their choice using their preferred mode of commute (van Rooij, 2020). This preference applies to situations both with and without hubs. The behaviour of people varies based on their socio-demographic characteristics such as gender, age, income, education level, number of people in a household, & vehicle ownership and trip characteristics such as travel purpose, travel length, departure time, and travel time (De Witte et al. 2013; Mathijs, 2021).

As little research exists on the actual travel behaviour of people in the presence of mobility hubs, studies in the form of pilot studies and surveys were analysed for gaining insights into how mobility hubs affect travel behaviour.

In a pilot study conducted among Amsterdam residents where the residents handed in their private cars in exchange for travel credit to be used in carsharing, public transport and taxis, it was observed that 30% of the participants decided to discard their cars permanently (NWEurope, 2019).

Knippenberg (2019), in his thesis, focussed on the usage of two hubs by the service provider "Hely", one in Amsterdam and one in Delft, using a mix of study techniques that included: user survey, investigating Hely database and non-user survey. It was observed from the research that among active participants actually using the hub, the majority of the trips were covered by shared cars and that users access the hub either by biking or walking. Among non-users of the hub, the main reason for not using hubs was the costs of using the shared modes. It was also observed that the users see transport modes offered in the hub as a replacement for their second private vehicle. Furthermore, according to Knippenberg (2019), the presence of mobility hubs currently increases the overall number of car trips, i.e., car trips including both private and shared cars.

Another research by van Rooij (2020) focuses on potential users of mobility hubs in residential areas and the travel behavioural effects which can take place. This report is based on interviews with specialists in the field of shared mobility and on surveys conducted among potential hub users as seen by the specialists, thus a combination of theoretical and stated preference findings. His research found that along with socio-demographic characteristics like age and income, parking pressure faced by individuals and the sustainable mindset of individuals play a vital role in the usage of mobility hubs by users. Based on surveys and interviews with residents and students in the city of Delft, it was noticed that people's travel behaviour in the presence of hubs potentially leads to more car trips. The increase is because users consider shared cars as a flexible alternative to public transport and consider the hub to only replace their second or third car and not the first car, which is similar to findings of Knippenberg (2019).

van Gerrevink (2021) carried out qualitative research on residential mobility hubs through interviews of stakeholders & experts, practice and literature research. Through a causal loop diagram analysis, it was found that parking policy, the proximity of hub and its attributes along with user characteristics and their perspectives can influence the travel behaviour of people and the manner in which they use the hubs.

Based on these different studies, attributes such as distance to hubs, vehicle costs, vehicle availability, and diversity of vehicles and services at hubs are perceived by residents as important factors that could impact travel behaviour. Additionally, it can be inferred that mobility hubs could potentially decrease car ownership based on area characteristics such as high parking demand but not in the total number of car trips occurring in the area.

The travel behavioural findings elaborated in this section are used in the discussion chapter of this report as the basis for making comparisons of the results of this research.

3.3. Typology and Components of Mobility Hub in Residential Areas

From the literature study mentioned in Section 2.1, based on the typologies of hubs, it can be inferred that the classification type "Neighbourhood Mobility Hubs" are the ideal hubs for residential areas when the area is of urban context (Goudappel & APPM, 2020; Urban Design Studio, 2020; van Gerrevink, 2021). The reach and size of such hubs vary based on the region they are placed but are usually small. They provide shared mobility transportation options in alternative to private car possession to the residents in the direct surroundings of the mobility hub (Blad, 2021).

According to van Rooij (2020), a neighbourhood mobility hub's universal aspect is to be at a central location in the neighbourhood and to offer shared transportation options. It was also highlighted that while focussing on neighbourhood hubs, the main actors are: residents of the neighbourhood, municipalities where the hub belongs, hub owners, shared mobility service providers, and housing developers of the region. Based on the goals of different actors, the attributes of the hub are modified. A representation of a neighbourhood mobility hub is shown in Figure 18.

Figure 18: Representation of neighbourhood mobility hub (ShareNorth, n.d)

Each mobility hub is unique, and a tailor-made one should be applied for each location while deciding its components (SEStran, 2020). For a neighbourhood mobility hub used by residents, the vital components at the hub are bike share, bike parking, and wayfinding. Apart from this, the recommended components are car share, electric vehicle charging station, bus shelter, real-time travel information, Wi-Fi, waiting area, and access to pedestrians. (Figure 19) (Urban Design Studio, 2016; Blad, 2021). van Gerrevink (2021) states that a variety of shared mobility services can be offered at the neighbourhood hub but at least shared cars and shared bikes are present. Such neighbourhood hubs are the start and endpoint of most working days (Koedood, 2020).

Mobility Hub Amenities	Bicycle Connections			Vehicle Connections			Bus Infrastructure		Information-Signange			Support Services				Active Uses		Pedestrian Connections	
	2.1. Bike Share	2.2. Bike Parking	2.3. Bicycling Facilities	3.1. Ride Share/Pick up-Drop off	3.2. Car Share	3.3. EV Charging Stations	4.1. Bus Layover Zone	4.2. Bus Shelters	5.1. Wayfinding	5.2. Real-time Information	5.3. Wi-Fi / Smartphone Connectivity	6.1. Ambassadors	6.2. Waiting Area	6.3. Safety and Security	6.4. Sustainable Approach	7.1. Retail	7.2. Public Space	8.1. To the Mobility Hub	8.2. At the Mobility Hub
(N) Neighborhood	●	●	■	■	○	○	■	○	●	○	○	■	○	○	○	■	■	○	○
(C) Central	●	●	○	●	●	●	○	●	●	●	●	○	○	●	●	○	●	●	●
(R) Regional	●	●	●	●	●	●	●	●	●	●	●	●	○	●	●	●	●	●	●

Legend: Vital: ● Recommended: ○ Optional: ■

Figure 19: Typology of mobility hub with amenities suggestion (Urban Design Studio, 2016)

Several studies give different descriptions of the components available at neighbourhood mobility hubs. Based on these descriptions, a neighbourhood mobility hub is defined as

"A central location in the residential area that provides at least one shared transportation option such as shared cars or shared bikes to its residents as an alternative to private vehicles with retail services, public transportation and other facilities being optional elements".

3.4. Shared Modes & Vehicle Sharing Systems at Mobility Hubs in Residential Areas

Based on existing case studies (Aono, 2019; CoMoUK, 2019; RI.SE 2020; van Gerrevink, 2021) of shared transportation modes at mobility hubs, common modes that are available to the hub users are shared cars and shared bikes.

From the literature study stated in Section 2.2, it is observed that both cars and bikes have a similar sharing system where station-based and free-floating are common. Station and free-float systems have a similar user structure, but different factors influence the frequency of use. The main factors influencing the frequency of use of station-based systems are travel purpose, travel distance, car ownership, and educational background. (Chen et al., 2020).

There are certain drawbacks to station-based and free-floating vehicle sharing systems. Operational management of a one-way station-based system is complex for service providers (Machado et al., 2018). While, service providers and municipalities have faced negative experiences while providing free-floating systems such as poor maintenance of vehicles by users and improper parking after use (van Rooij, 2020). Thus, from a service provider's point of view, a two-way station-based system is appealing to develop at the mobility hub.

From a user's point of view, free-floating and one-way station-based systems are more attractive than two-way systems. This desirability for free-floating and one-way systems is because they offer more flexibility in usage (Shaheen et al., 2020) and prevent users from paying unnecessary costs while not using the shared modes.

As defined earlier, neighbourhood mobility hubs offer the residents shared modes at their location. Thus, a station-based sharing system is ideal to understand the impacts on travel behaviour and network usage due to mobility hubs with shared modes where the hubs will act as the station. According to the service provider's preference or the municipality, the station-based system can either be one-way or two-way.

These findings are used in Section 4.3 while developing the methodology for incorporating mobility hubs and are also used while introducing mobility hubs in the Delft case study.

4. Methodology for Incorporating Mobility Hubs with Shared Modes in Aggregate Transport Models

In this chapter, a generalized adjustment to the four-step transport model framework will be created and elaborated in detail for incorporating mobility hubs and shared modes in aggregate transport models. First, the method to introduce the hubs and shared modes in the appropriate transport model will be explained, followed by highlighting the critical areas of focus in the four-step model while making these new introductions. Finally, the generalized adjusted framework of the four-step model to introduce these new elements will be discussed.

4.1. Introduction of Mobility Hubs and Shared Modes in Transport Models

In Section 2.3, the different transport modelling approaches were discussed. This research focuses on aggregate models, and as mentioned earlier, activity-based models are considered among disaggregate models and thus is not chosen. Tour-based models, even though counted usually among disaggregate models, can be modelled using aggregated data as well. Tours consist of a sequence of trips that requires more modelling. Trip-based models are structured in the four-step model form and can be modelled relatively easily when compared to tour-based models. More data is also required for tour-based models when compared to trip-based models. As a result, the trip-based model structured in the four-step transport modelling approach is selected for this research.

A mobility hub should provide access to at least one shared transportation option to its users as an alternative to private vehicle possession (Urban Design Studio, 2016; Aono, 2019; van Rooij, 2020; Blad, 2021; van Gerrevink, 2021). While using these shared modes at the hubs, users perform a multi-modal trip. For example, consider that a user wants to use a shared car, then the user could either cycle or take a mode of preference to the hub and then proceed to his/her final destination in the shared car from the hub. This user trip becomes multi-modal as a combination of modes is being used.

For modelling multi-modal trips in transport models, *pre-specified mode chain technique* (Fernandez et al., 1994; Fiorenzo-Catalano, 2007; van Eck et al., 2014), and *super-network technique* (Kristof et al., 2002; Fiorenzo-Catalano, 2007; van Eck et al., 2014) was discussed in Section 2.4. On comparing the two techniques to incorporate mobility hubs, the super-network technique is deemed very complex, especially while modelling hubs in large networks. In the Netherlands, this technique is currently used only in research models and not in actual modelling software.

On the contrary, an existing software –'OmniTRANS' in the Netherlands allows to model using the pre-specified mode chain technique and is used in Chapter 5. While knowing the transport modes offered at the mobility hub and the other modes in the region, mode chain combinations can be created, and the pre-specified mode chain technique can be applied.

As stated earlier in section 2.1, the shared modes available at the mobility hub vary based on the hub's location. Thus, the possible mode chain combinations will vary based on the modelled hub while applying the pre-specified mode chain technique. A general and simplified approach is to introduce the mobility hub in the transport model as a new transport mode. The new mode representing the mobility hub is called "Hub-Travels" in this research.

The new mode - “Hub-Travels”, will further consist of different transport mode options that the users can use through the mobility hub. These mode options will vary based on the mobility hub being modelled. A further explanation is given in the upcoming sections in this regard.

4.2. Area of Focus in Four-Step Transport Model

In the previous section (4.1), the mobility hubs were introduced as a new transport mode in the model. While making this introduction, certain parts of the transport model must be adjusted. For this purpose, it is essential to know the key areas in the transport model that must be looked into while modelling mobility hubs. The traditional four-step transport model (Fiorenzo-Catalano, 2007; Ortúzar & Willumsen, 2011) discussed in section 2.3 will be used to highlight the areas of focus.

In the four-step transport model framework, zonal data, transport network characteristics, and travel resistances are exogenous input data (data determined outside the model) for each of the four steps. The introduction of mobility hubs in the model will lead to changes in the network characteristics and the travel choice of people. As a result, the travel resistances such as travel time, costs and distances also change. Thus, the initial travel resistances used as a model input becomes an area of focus.

The new mode– “Hub-Travels”, is introduced in the modal split-step of the model, which is directly linked to trip distribution and trip assignment steps. Also, the travel resistances act as inputs for trip distribution, modal split, and trip assignment steps. Thus, these three steps become a crucial area of focus as the outputs produced by these steps in the presence of mobility hubs can change.

The trip generation step is not considered an area of focus as irrespective of the presence of hubs, the total number of trips generated by the travellers to different zones will remain the same. The points of focus mentioned above are highlighted in red in the traditional four-step framework below in Figure 20.

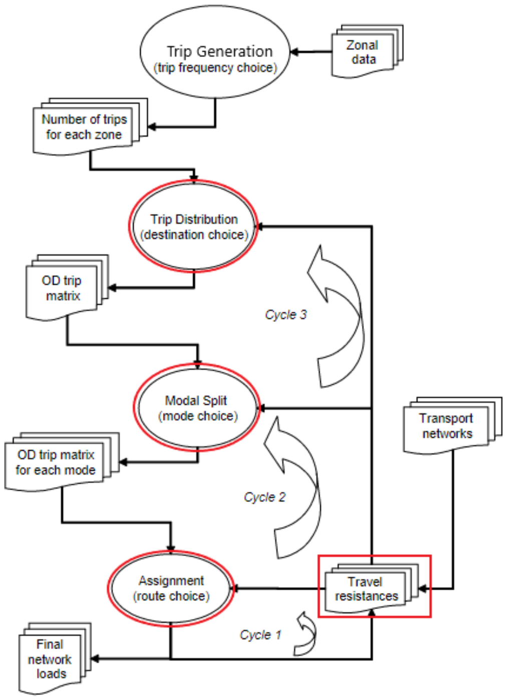

Figure 20: Area of focus in the four-step transport model

4.3. Generalized Adjustments to Four-step Transport Model while Incorporating Hubs for Areas of Focus

In Section 4.2, the key areas of focus in the four-step transport model when introducing a mobility hub was elaborated. This section explains the adjustments that have to be made in the transport model for the focus areas. A generalized framework for these adjustments is provided at the end of this section in Figure 21.

Based on the focus areas, while introducing a mobility hub in the model, the primary attention must be given to the "travel resistance" as it acts as the initial input for the model. Travel resistances are termed Level of Service (LOS) in this chapter. The level of service includes the generalized travel cost, travel distance and travel time by each mode to its origin-destination (O-D) pair. Thus, for the new mode- "Hub-Travels", the LOS concerning each O-D pair needs to be known for modelling.

As stated in section 4.1, a mobility hub provides access to at least one shared transportation option for its users; thus, using the hub to access these alternative travel options leads to multi-modal trips. Similarly, in the transport model, the newly introduced transport mode - "Hub-Travels", will comprise different shared transportation modes based on the available modes in the research region or based on the modes of study interest. All mode-chain combinations that can be implemented on the transport network from the available transport options need to be enlisted.

A hub can be accessible from origin or destination even if it is very far away. However, in reality, people's travel behaviour is different, and they might not prefer such hubs while making a travel decision. Thus, it is essential to consider distance or time-based boundary conditions. For example, a maximum of 2km via a private bike to find and use a hub can be defined. This boundary condition can vary based on the transport modes, the purpose of study, or the focus region. In the Netherlands, the maximum acceptable time for finding a mobility hub by walking is 5 minutes (Mathijs, 2021).

The level of service by each mode-chain combination for making a multi-modal trip through the hub needs to be generated for all origin-destination pairs considering the boundary conditions. For example, suppose the mode-chain combination to go from origin to destination via the hub is 'Private Bike-Shared Car'. Then, the level of service for the trip mode combination is 'LOS of Private Bike from Origin to Hub + LOS of Shared Car from Hub to Destination'. The level of service primarily used as input in transport models is generalized travel costs, which considers travel distance and travel time, but it can vary based on the study.

Based on case studies (Aono, 2019; CoMoUK, 2019; van Gerrevink, 2021), it can be inferred that some transport networks have multiple mobility hubs. As mentioned in section 3.4, the shared modes can adopt a station based vehicle sharing system with the mobility hubs acting as the station. Thus, in the presence of multiple hubs in the network, both one-way and two-way station based vehicle sharing systems can be modelled based on the research. The primary condition while modelling one-way systems is that the mode-chain combinations should consider the availability of hubs near origin and destination within the set boundary.

A two-way station-based system can be modelled if only a single mobility hub is available in the network. In the two-way system, it is assumed in the thesis that if a user of the shared vehicle uses a particular mode-combination to travel from origin to destination, then the same mode combination can be used by other users in the reverse order to travel from destination to origin in the same period of time. For example, if the mode-chain combination from origin to destination is ‘Bike-Shared Car’, then the mode-chain combination from destination to origin is ‘Shared Car-Bike’.

In the scenarios with multiple hubs, it should be ensured that the initial LOS generated for all O-D pairs by each mode-chain combination considers all the accessible hubs in the network. The shared modes available at each mobility hub usually vary; thus, the hub nearest to the origin might not always lead to the best mode-combination selection. The LOS generated for the mode-chain combinations helps identify the best hub choice for all origin-destination pairs.

It is considered that the trip distribution and modal split-step occur simultaneously for this research. The new mode- “Hub-Travels”, is introduced in this step of the model, where the enlisted mode chain-combinations are modelled using the pre-specified mode-chain technique with inputs of LOS. A single value of level service will be used, either travel costs or time or distance. For situations where a hub cannot be used for an O-D pair or situations where travelling via hub is ineffective, unimodal trips are selected instead.

The simultaneous trip distribution and modal split step will generate the origin-destination matrices per mode (for uni-modal trips) and generate origin-destination matrices per mode-chain (for multi-modal trips). The mode-chain trip matrices after segregation to trip matrices per mode will be used as an input for the transport assignment step where the route choice modelling takes place. The outputs of trip assignment update the level of service about the network usage, and the iterative behaviour of the four-step model helps obtain consistent results.

The time of day modelling step can be added along to the simultaneous trip distribution and modal split step for incorporating time dimension in the model. If the time of day is also included in the modelling, then the output out of the ‘Simultaneous distribution, modal split and time of day’ step will be O-D matrices per mode-chain per time period. For using this data as the input for trip assignment, it has to be segregated per mode for each time period. Then, it will be the same process from the trip assignment step.

The adjustments mentioned above without including the time of day step are displayed in the form of a diagram below in Figure 21. Simulation of the proposed model helps obtain the modal split among the different modes and mode combinations. Thus, the variation in travel behaviour with the introduction of mobility hubs is captured. The route choice obtained on simulation for the different modes in the presence of mobility hubs further indicates the changes in traffic conditions.

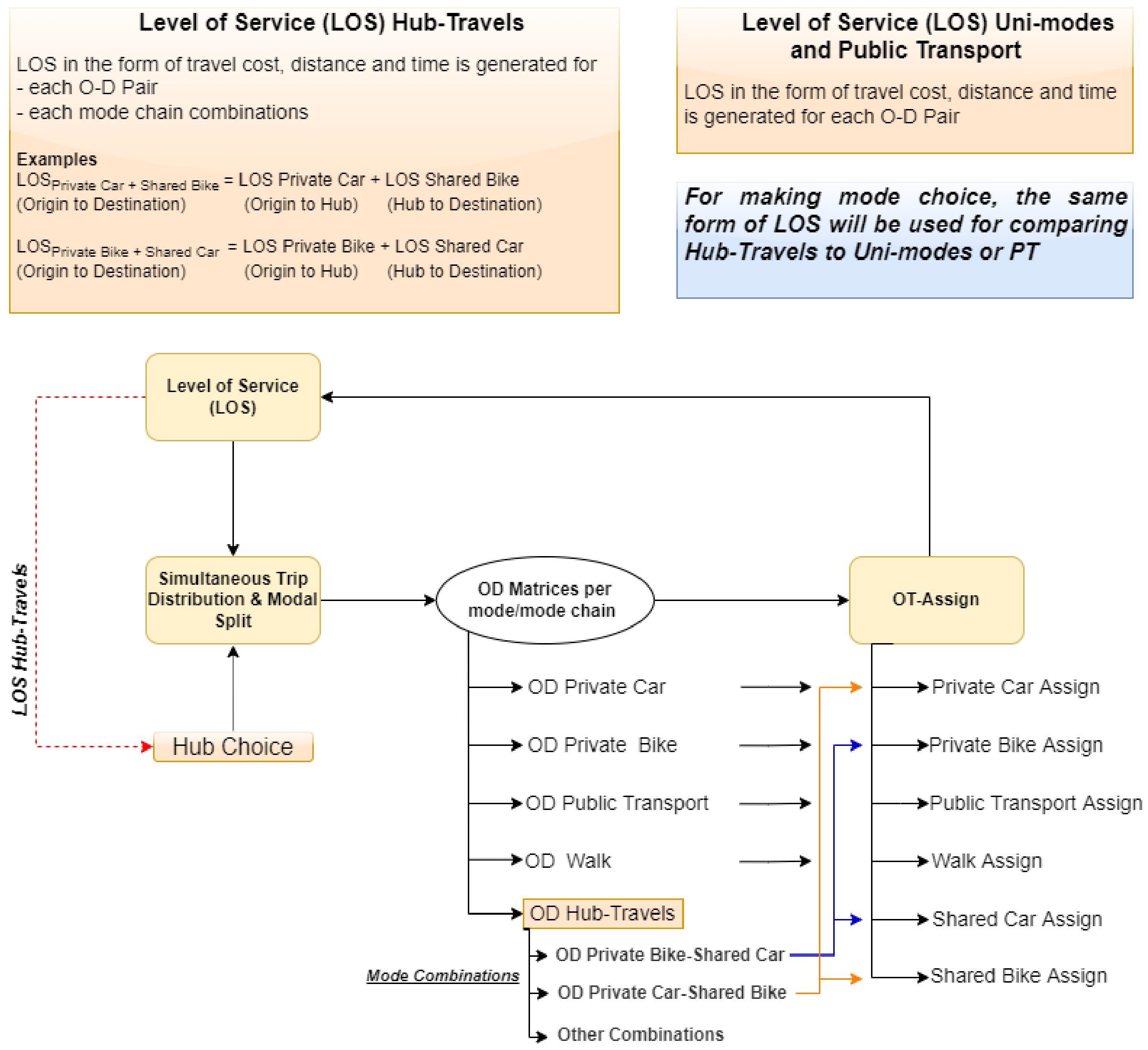

Figure 21: Adjustments to the four-step framework for incorporating mobility hubs with shared modes based on the area of focus

5. Model Application – A Case Study of Delft

The typology and the vital components required for a mobility hub in a residential area were discussed in the previous chapters, along with the method to incorporate such hubs in aggregate transport models. The focus of this chapter is to combine the previous topics and apply them to an existing transport network.

This chapter presents a case study that will be performed by introducing mobility hubs with shared modes to the Delft transport network in residential areas. The case study is used to understand the impact on the network due to the mobility hubs. The transport modes available at the mobility hubs are defined later in this chapter in section 5.4. The two scenarios selected are the Delft network without mobility hubs and the Delft network with mobility hubs in residential areas.

First, the initial structure of the Delft transport network will be explained, along with the reason for selecting this model. Then, the four-step model on the software will be described. Following this, the adjustments to be made in the initial network of Delft and the four-step model of the software for introducing the two scenarios in the Delft network will be explained. The results obtained from the simulation of the scenarios will be provided in the next chapter.

5.1. Delft Transport Network and its Initial Structure

As stated in section 4.1 for this research, the pre-specified mode chain technique is ideal for modelling mobility hubs in aggregate transport models and is possible using the OmniTRANS software. For this research, the Delft transport network is selected due to the following reasons:

- Compared to other networks, its relatively smaller region size reduces simulation run-time and allows to understand and analyse obtained results efficiently. The simulation time is around 5 to 10 minutes for the Delft transport network, while it will be in hours for networks such as Amsterdam or Rotterdam.
- Its availability on the OmniTRANS software.
- Familiarity with working on the Delft transport network in the past.

The Delft network focuses on the city of Delft along with a small region surrounding it. The network consists of 25 centroids, 692 links & 473 nodes which represent different zones, roads and junctions, respectively. Zones 1 to 7 are external zones in the network which represent the trips coming from and going to the areas outside the city of Delft. Zones 8 to 25 are internal zones that represent trips inside the city of Delft. The roads in the network have different properties defined like the transport modes allowed on it, capacity, free speed and the speed at capacity. They are also classified into 18 types, ranging from motorways to bus lanes to cycle tracks. The nodes representing junctions indicate the presence of traffic signals and roundabouts. The available Delft transport network consists of morning peak data for one hour. The representation of the Delft network on OmniTRANS is shown below in Figure 22, where the icons represent the centroids and the lines with different colours represent the links.

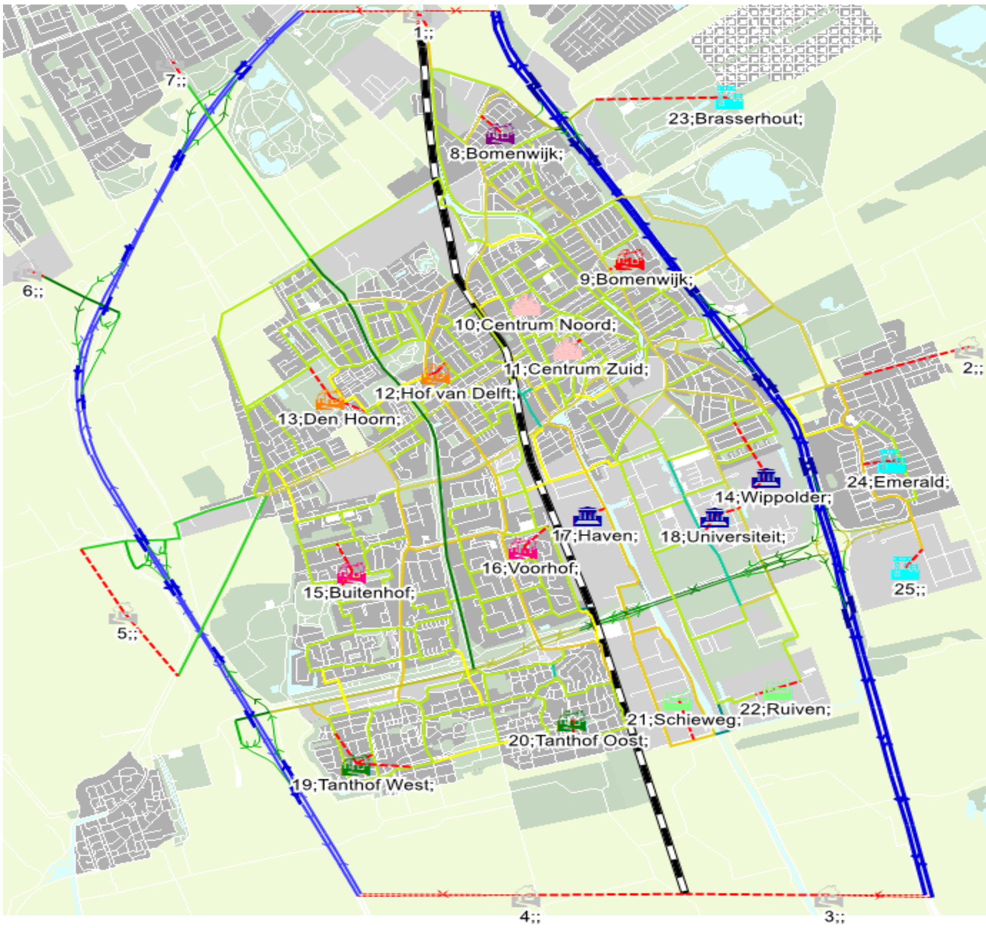

Figure 22: Delft network on OmniTRANS

The trips are modelled in the network for six different purposes: home to work, work to home, home to education, education to home, home to other, and other to home, where 'education' includes schools and universities and 'other' includes all alternate travel purposes such as shopping, leisure, and business trips.

The network consists of the three main transport modes: Private Cars, Private Bikes and Public Transport. Public transport mode has different sub-modes like bus, train, LRT and tram. Walking is also set as a mode, but it is only used as access and egress for public transport. The public transportation mode has 19 different transit lines that share 43 stops.

In the OmniTRANS software, zonal data representing socio-economic characteristics are available for the internal zones of Delft, i.e., zones 8 to zone 25, but is limited to only the number of residents, jobs, research places, and education places per zone.

5.2. Four-Step Model for Delft Network on OmniTRANS

The modelling steps on OmniTRANS for the Delft network is similar to the traditional four-step transport model. An illustration of the approach on OmniTRANS is shown in Figure 23, where the trip distribution and modal split steps occur simultaneously.

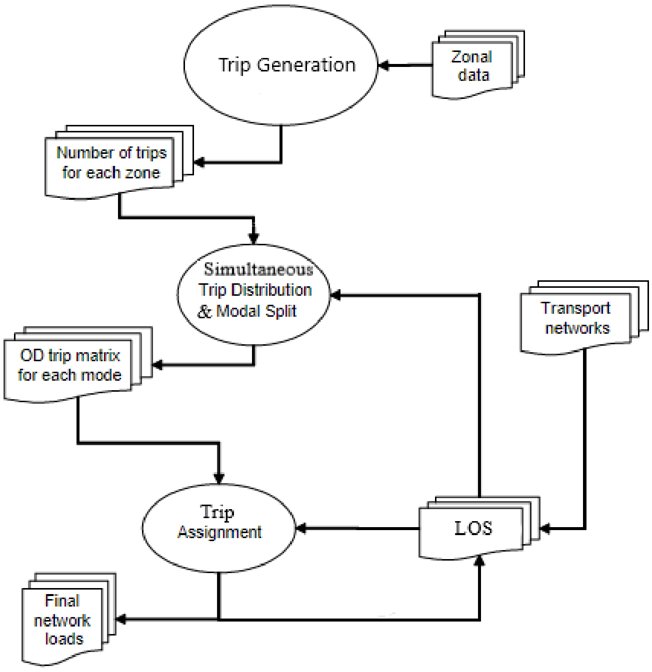

Figure 23: Four-step transport model on OmniTRANS

The steps/process for running the transport model on OmniTRANS are trip generation step, skim generation process, simultaneous trip distribution & modal split step, and trip assignment step. The steps are simulated on OmniTRANS as different job scripts using the programming language "Ruby". This section further contains the basic knowledge of transport modelling that is used with respect to OmniTRANS.

Trip Generation

In the trip generation step, the trip productions and attractions for all internal zones, i.e., zones 8 to 25 for the different trip purposes, are calculated using trip end functions. The trip end functions on OmniTRANS for the different purposes are obtained from regression models and use socio-economic characteristics data available in the network as inputs. These functions were inbuilt as default in the job script. The functions used in the Delft network for the different purposes is shown in Appendix A

The trip productions and attractions for the external zones are available as external data and provided along with the Delft model. The external data was obtained from traffic counts and surveys. This data set is also imported to the network along with internal zone trips in the trip generation step.

Skim Generation

The skim generation process is where the travel resistances/impedances are calculated. In the model, the generalized cost (a weighted combination of time & distance), distance (km) and travel times (minutes) for the different modes are computed and generated in the form of skim matrices for all zones. The skim matrices are generated using the shortest path between zones.

Additional values such as waiting time, transfer penalty, and fare are also computed for public transport. Its generalized cost is a weighted combination of one or more attributes. The intrazonal impedances are also computed for the internal zones in this process. However, for the external zones, the intrazonal impedances are set to 99999.

Simultaneous Trip Distribution and Modal Split

In the simultaneous trip distribution and modal split step, the origin-destination (O-D) matrices for all modes for all purposes are generated. The travel impedances obtained from the skim generation step along with the productions and attractions of each zone obtained from the trip generation step are used as input for it. The destination and mode choice are calculated simultaneously for each purpose. The trips are modelled only for the morning peak. The number of trips is calculated using the doubly constrained gravity model. The formula for it is shown in Equation 1 (Ortúzar & Willumsen, 2011).

Equation 1: Doubly Constrained Gravity Model (Ortúzar & Willumsen, 2011).

$$T_{ijm} = a_i * b_j * P_i * A_j * f(c_{ijm})$$

Where, T_{ijm} = number of trips from zone i to zone j in mode m,
a_i, b_j = scaling factors,
P_i = trip productions of zone i,
A_j = trip attraction of zone j,
f(.) = deterrence function describing the incentive of travelling to zone j from zone i,
c_{ijm} = travel impedance (travel time, generalized costs) from zone i to zone j using mode m

The top-lognormal deterrence function is used in the doubly constrained gravity model. It describes the incentive to travel from zone 'i' to zone 'j' using the mode 'm'. The formula for it is shown in Equation 2 (van Kuijk, 2018).

Equation 2: Top-Lognormal Deterrence Function (van Kuijk, 2018)

$$\textbf{Top} - \textbf{Lognormal Function } [f(c_{ijm})] = \alpha \cdot e^{-\beta \cdot \ln^2(c_{ij}/\gamma)}$$

The parameter α represents attractiveness, β represents availability, and γ represents sensitivity.

Trip Assignment

In the trip assignment step, the routes are assigned to the various trips for the different modes. Thus, it generates the loads on the network for all modes. A classification scheme for trip assignment type from Ortúzar & Willumsen (2011) is shown in Figure 24.

Model		Congestion Effect Modelled?	
	Condition	No	Yes
Multiple Routes Modelled?	No	All or Nothing Assignment	Deterministic User-Equilibrium Assignment
	Yes	Stochastic Assignment	Stochastic User-Equilibrium Assignment

Figure 24: A classification scheme for trip assignment (Ortúzar & Willumsen, 2011)

In the model, the trip assignment method varies for different modes. All or Nothing (AON) assignment or Deterministic Equilibrium Assignment (DUE) is used for cars. In AON, congestion is neglected, and only link travel times are taken into account (Equation 3), while in DUE, both congestion and travel times on the routes are considered (Equation 4). Congestion on the network due to cars can be obtained as the capacity on car links is defined.

Equation 3: All or Nothing Assignment

$$\mathbf{t_a} = \frac{\mathbf{L_a}}{\mathbf{v_a^{max}}}$$

Where,
t_a = travel time on link a (h)
L_a = length of link a (km)
v_a^{max} = maximum speed on link a (km/h)

Equation 4: Deterministic User Equilibrium Assignment

$$\mathbf{t_a(q_a)} = \frac{\mathbf{L_a}}{\mathbf{V_a^{max}}}\left[\mathbf{1} + \boldsymbol{\alpha}_\mathbf{a}\left(\frac{\mathbf{q_a}}{\mathbf{C_a}}\right)^{\beta_a}\right]$$

Where,
t_a = travel time on link a (h)
q_a = flow(load) on link a (veh/h)
L_a = length of link a (km)
v_a^{max} = maximum speed on link a (km/h)
C_a = capacity on link a (veh/h)
α_a, β_a = parameters of link a

Bikes are assigned the loads using Stochastic Assignment (Equation 5), in which congestion is not taken into account. The random component added in the stochastic assignment is to take into account the uncertainty in travel time while making route choices. For public transport, the loads are assigned using OtTransit assignment on OmniTRANS, where travel time, waiting time, transfer penalty, and fares are considered during route allocation. Capacities on bikes and public transport links are not defined in the model; thus, congestion levels for these modes cannot be obtained, and only loads can be obtained.

Equation 5: Stochastic Assignment

$$\mathbf{t_a} = \frac{\mathbf{L_a}}{\mathbf{v_a^{max}}} + \boldsymbol{\epsilon}_\mathbf{a}, \quad \boldsymbol{\epsilon}_\mathbf{a} \sim \mathbf{N}(\mathbf{0}, \boldsymbol{\sigma}_\mathbf{a}^\mathbf{2})$$

Where,
t_a = travel time on link a (h)
L_a = length of link a (km)
v_a^{max} = maximum speed on link a (km/h)
σ_a = standard deviation of the travel time of link a (h)

5.3. Scenario 1: Delft Network without Mobility Hubs

In this section, the changes made to the initial Delft network stated in section 5.1 for implementing scenario one will first be described. Following this, the adjustments to the job scripts of modelling steps as stated in section 5.2 to simulate the scenario will be explained.

Changes to Initial Delft Network

In this scenario, the Delft transport network only consists of the standard modes that already exist in the model, i.e., private cars, private bikes and public transport. Walking, which was considered only for access and egress of public transportation in the initial network, is considered one of the main modes for this scenario.

Due to limited data availability, trips were modelled only for morning peak hour in this scenario. As the model network is uncalibrated and does not consider actual costs of usage for different modes, adjustments were made in the network by referring to reliable studies and reports that stated some additional network characteristics of the city of Delft.

The city of Delft consists of seven different parking zones with street parking machines and five additional parking garages around the city centre region (ParkerenDelft, 2021; Gementee Delft, 2021). The parking is free for the cars in other zones. Based on this parking layout, the network of Delft on OmniTRANS was split into four zones.

Among the seven different zones stated in ParkerenDelft (2021), only the city centre zone had a different pricing structure compared to the other six zones. As a result, the seven parking zones reduced two zones in this model. Additional to the two zones, free parking areas and external zones were added as an additional classification.

In the OmniTRANS network, the parking cost in zone 1 (city centre) was set as 4.5€/h, zone 2 (other paid parking zones of Delft) was set as 1€/h, and for the remaining two zones, parking rates were set as zero. The costs adopted for the model correspond with the reality in Delft. The representation of the four parking zones adopted for this model is shown in Figure 25.

Parking for bikes was set as zero as it's free parking for bikes in majority of the places in Delft.

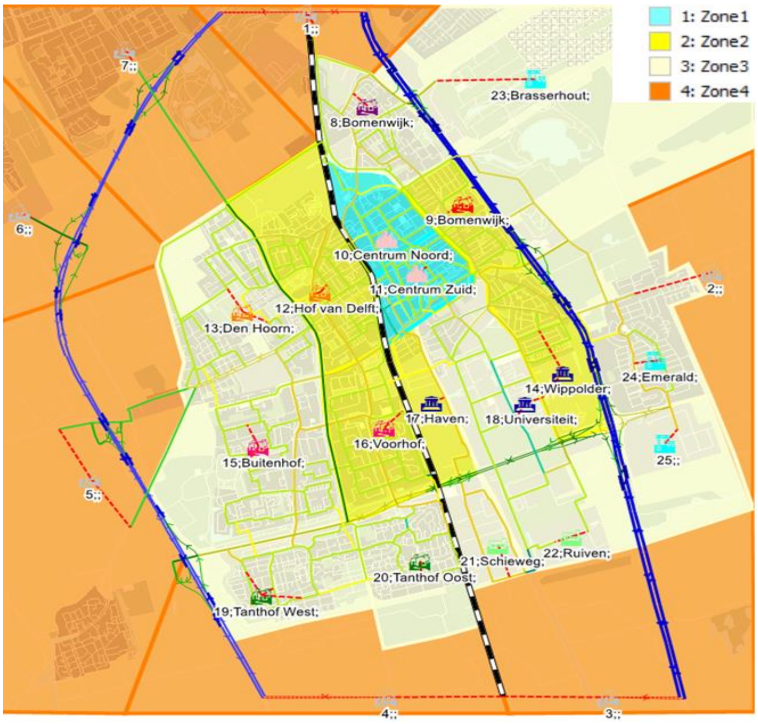

Figure 25: Car parking zones for Delft network.

Adjustments to Modelling Scripts

The ***Trip Generation*** step is left unchanged for implementing the scenario. The trip end functions for the different purposes already inbuilt for the Delft model were used. The trip end functions used for the traffic study in Delft by AnteaGroup (2019) was referred to for incorporation in the case study. However, the inbuilt functions on OmniTRANS were only used due to constraints on the Delft network's available socio-economic data for the different zones.

In the ***Skim Generation*** process, a few adjustments were made for the generalized costs generated for each transport mode. The generalized costs were calculated by assigning weights to distance and time skim matrices along with other travel-related costs based on the transport mode. All parameters were converted to the same units Euros (€) using operational costs or Value of Time (VoT). The generalized cost functions used for the different modes in scenario one are shown in Table 1.

Table 1: Generalized cost functions for different modes in scenario one.

Transport Mode	Generalized Cost Function
Private Car	VoT*Time Skim + Operational Cost*Distance Skim + Parking Cost
Private Bike	VoT*Time Skim
Public Transport	VoT*Time Skim + Fares
Walk	VoT*Time Skim

The time skim matrix for public transportation includes waiting and transfer penalties. The fares for public transportation is also already defined in the model. Based on Significance (2019), the Value of Time assumed for private cars, private bikes, and walking is 9€/h and for public transport is 6.75€/h. Operational costs for cars includes the costs related to fuel consumption, tire wear, maintenance and depreciation. Using consumer prices data from CBS (2021), the operational costs for cars are assumed to be 0.3€/Vehicle km. Using these values, the parameters of generalized costs are converted to the same units, i.e., Euros.

In the ***Simultaneous Trip Distribution and Modal Split*** step, adjustments were made to the top-lognormal deterrence function parameters as the Delft transport network was uncalibrated. Two steps were followed to overcome this limitation and model realistic trends for trip distribution and modal split. First, the data on the average distance and average time travelled by different modes for all types of trip motives in the Netherlands were obtained from Statistics Netherlands (CBS), which is the official statistical database of the Netherlands. Along with this data, the actual modal split of Delft was obtained from the traffic study conducted by AnteaGroup (2019). In the second step, the average travel characteristics obtained from CBS were generalized, taking into account the cost parameters for the different modes. Then the deterrence function parameters are adjusted to represent the different travel characteristics per mode while generating a similar modal split to that reported by AnteaGroup (2019). This adjustment does not lead to calibration of the model but helps obtain results similar to trends in the Netherlands while using the different transport modes.

In the ***Trip Assignment*** step, only adjustments to model the route choice for transport mode – 'Walk' was added using the All or Nothing (AON) assignment. The assignments for the other modes remained the same. These four steps/processes are simulated in the described order on OmniTRANS. The obtained results are presented in the next chapter.

5.4. Scenario 2: Delft Network with Mobility Hubs in Residential Areas

This section will first discuss the changes to the initial Delft network and the assumptions for incorporating the mobility hubs. Then adjustments to the modelling scripts based on the proposed adjustment framework for introducing mobility hubs in transport models from section 4.3 will be explained.

Changes to Initial Delft Network

The adjusted network from scenario one is used as the base network. It was done to ensure that the changes in this network due to the addition of mobility hubs can be directly compared with scenario one without mobility hubs.

In this scenario, the mobility hubs are introduced in the network in residential areas. For identifying residential areas, the definition stated in section 3.1, "A residential area focuses predominantly on housing function while being supported for daily needs by the presence of small scale functions like transportation, retail and business", is used. Along with the definition, the zonal data on OmniTRANS indicating the number of residents per zone and Delft area characteristics were used to identify residential areas on the transport network. Based on these, seven zones in the network were identified as residential zones.

As stated in the definition for neighbourhood mobility hub in section 3.3, public transport is optional at the hub for a residential area. The transport network of Delft is small, and all the selected residential areas had at least one public transportation transit stop near them. As a result, public transport was considered one of the modes at the mobility hub. The hubs were modelled on the network in the selected residential areas close to the nearest public transportation transit stop from the residential zones centroid.

On OmniTRANS, the hubs were modelled using the centroids option and connected to the network using road connector links. The Delft transport network representing the different internal zones and the network displaying the position of the seven modelled mobility hubs in residential areas is shown in Figure 26. The nine colours on the network in Figure 26 represent the different area sectors of Delft like centre, north, south, east, west, TU Delft, Tanthof, Ruiven, and Emerald.

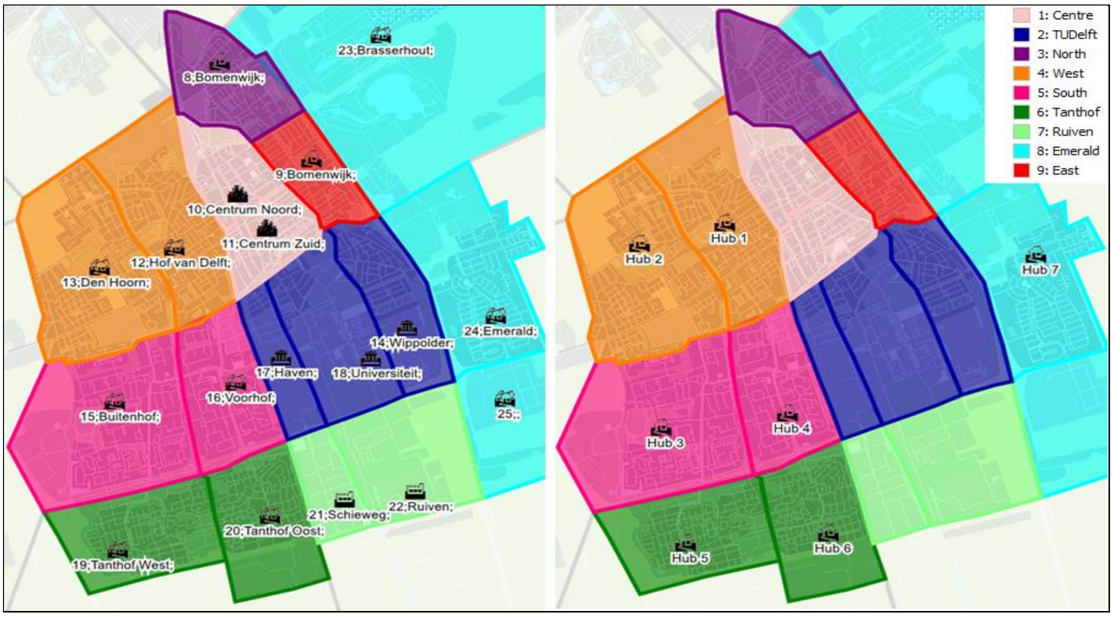

Figure 26: Delft network displaying internal zones(left), displaying modelled mobility hubs(right)

The shared modes considered available at the mobility hubs are shared cars and shared bikes, as these were common in most case studies. Shared scooters and shared mopeds were left out. Thus, the Delft transport network consists of private cars, private bikes, public transportation, walking, shared cars, and shared bikes in this scenario.

On OmniTRANS, the shared cars and shared bikes were modelled on the Delft network by creating new transport mode dimensions in the Project Setup tab. Following this, characteristics such as speed, capacity, free-flow speed, saturation flow and speed at capacity for the shared modes for all different road types in the network were defined. For shared bikes, the same network characteristics as that of private bikes were used, and for shared cars, the same characteristics of private vehicles were used in the model. Costs for using the shared modes were incorporated in the job scripts.

As mentioned earlier in section 3.4, most service providers and municipalities prefer to introduce a two-way station based vehicle sharing system than one-way station-based systems and free-floating systems. Similarly, in this model, it is considered that the shared bikes and cars follow a two-way station based sharing system, where the mobility hubs act as the station.

To implement a well-structured one-way station-based vehicle sharing system in a transport network, there is a necessity to place mobility hubs in locations like the city centre and university, which fall outside the category of residential areas. The research aims to study the impact on the network caused by mobility hubs in residential areas. Hence, a two-way station based sharing system was considered.

The data available in the Delft transport network model consists of only morning peak data. The available data makes it possible to only model trips made by the different modes from origin to destination and vice-versa for one-time frame. Limited data acts as a constraint for introducing a vehicle-sharing system because it is essential to know the duration of possession of shared vehicles. Most service providers use the duration of vehicle possession to calculate tariffs. The available Delft network being static cannot incorporate this time element.

On observing the tariff calculation in the Netherlands for shared vehicles by services providers Hely, Greenwheels, and Mywheels, it was noticed that users were charged a base fee for at least one hour. In general, the users of work or education-based trips might be in possession of the vehicle for a long duration of time, but with limited data, there is a need to assume the duration of possession while modelling. For the success of the two-way system, the minimal duration of one hour is considered for vehicle possession while using the shared modes in this model. As a result, for the incorporated two-way sharing system, it is assumed that the users are charged the base tariff along with an additional tariff based on the distance covered by shared cars in the trip. The additional tariff element compensates for operational costs that were considered for standard cars. The values incorporated for the model will be explained in the modelling adjustment of this scenario.

In the model, it is also assumed that shared bikes and shared cars are always available at the mobility hubs to be used by the users, i.e., the number of shared vehicles present at the hub is not considered. Furthermore, the mobility hubs were directly placed on the network in residential areas near transport stops without considering empty spaces and exact suitable locations from maps of Delft. These two assumptions were mainly made as the fleet size of shared modes at a mobility hub and optimal location of hubs in a Delft are topics that require extensive research more than the scope of this study.

As shared vehicles are always available, it is assumed that the transfer that occurs while switching to shared modes is fast. As a result, transfer penalties are not modelled for the shared modes, while a time transfer penalty is applied for switching to public transportation at the hub.

It is also assumed that only shared bikes and shared cars along with public transport are available at the mobility hub. In the model discussed, other elements like retail facilities, car parking, service points are not considered at the mobility hub. As the mobility hubs are in residential areas, it is considered that all the residents will either walk or bike to the hub. In the Netherlands, bike parking is usually available everywhere; hence it is considered that residents can park their private bikes in the mobility hub.

With the introduction of mobility hubs in the residential area, the residents will have new alternative travel options compared to before introducing the hubs. Thus, a trip can have a combination of transport modes if the user decides to travel via the mobility hub, i.e., one mode to travel from origin to hub and another mode to travel from hub to destination. As stated in section 4.1, the pre-specified mode chain modelling technique is applied in this research to model the mode combinations. Before modelling the technique, all the mode-chain combinations considered possible using a private bike and walk to use the mobility hubs were enlisted. The list of the initial mode-chain that were considered possible is shown in Table 2.

Table 2: Possible mode chain combinations using private bikes and walking to use the mobility hub

Possible Walking Combinations	Possible Private Bike Combinations
Walk – Private Car	Private Bike – Private Car
Walk – Private Bike	Private Bike – Private Bike
Walk – Public Transport	Private Bike – Public Transport
Walk – Walk	Private Bike – Walk
Walk – Shared Car	Private Bike – Shared Car
Walk – Shared Bike	Private Bike – Shared Bike

The mode-chain combinations were then filtered to identify the ideal mode combinations to model in the Delft transport network. First, the combinations with private cars were removed as the modelled mobility hub does not have space for car parking. Usage of the same transport mode from origin to hub and hub to destination is possible in cases where the mobility hub has other services and facilities. However, as the mobility hub developed in the model consists of only transport modes, the same mode combinations for both legs of the trip, such as ‘walk-walk’ and ‘private bike-private bike’, were filtered out of the list. The OmniTRANS model already considers access and egress to public transport is via walking, so the option of ‘walk-public transport’ was removed from the list.

The combination of first taking a private bike to a mobility hub and then continuing to the destination via a shared bike is possible. However, in reality, it is not very practical. A few people might travel in such a manner, but those are sporadic cases, and such combinations are not considered.

For the selected mode combinations, the inverse combinations were also considered for trips that originate from the destination and proceed towards the origin. The selected list of mode combinations modelled in the network is shown in Table 3.

Table 3: Mode combinations modelled in the delft network for scenario two

	Possible Walking Combinations	Possible Private Bike Combinations
Origin to Hub – Hub to Destination	Walk – Shared Car	Private Bike – Shared Car
	Walk – Shared Bike	Private Bike – Public Transport
Destination to Hub – Hub to Origin	Shared Car – Walk	Shared Car – Private Bike
	Shared Bike – Walk	Public Transport – Private Bike

The different mode combinations were added on OmniTRANS in the project setup tab by creating new transport mode dimensions.

Adjustments to Modelling Scripts

After introducing the different elements on the transport network, the next action was to adjust the simulation job scripts related to the four-step model on OmniTRANS defined in section 5.2. The adjustments to these steps were based on the methodology proposed in Chapter 4.

Based on the proposed methodology, two additional modelling processes were introduced on OmniTRANS as job script files in addition to the existing steps/process. These two new processes were added to help simulate trips via the hubs and to differentiate between trips in mode combinations for different trip legs.

The steps/processes for simulation in order are – 1) Trip Generation, 2) Skim Generation, 3) Hub Routes and Skim Generation for mode combinations, 4) Simultaneous Trip Distribution and Modal Split, 5) O-D Matrices Generation per trip leg, and 6) Trip Assignment.

In the ***Trip Generation*** step, no changes are made to the job script compared to the previous scenario. Hence, the overall number of trips produced and attracted in this scenario will be the same as the scenario without mobility hubs.

In the ***Skim Generation*** process, only additions were made to the job script from scenario one to generate travel impedances (generalized travel cost, travel distance and travel time) for shared cars and shared bikes. The generalized cost functions used for the different modes in scenario two is shown in Table 4.

Table 4: Generalized cost functions for different modes in scenario two.

Transport Mode	Generalized Cost Function
Private Car	VoT*Time Skim + Operational Cost*Distance Skim + Parking Cost
Private Bike	VoT*Time Skim
Public Transport	VoT*Time Skim + Fares
Walk	VoT*Time Skim
Shared Car	VoT*Time Skim + Distance charge*Distance Skim + Base Tariff
Shared Bike	VoT*Time Skim + Base Tariff

The value of Time for shared cars and shared bikes are defined as 9€/h. The base tariff for shared bikes and cars was set as 1.5€/h and 6€/h respectively, based on tariffs charged by actual service providers Hely, Greenwheels and Mywheels in the Netherlands. The distance charge for shared cars is the fee charged by service providers to account for fuel and parking costs. The distance charge was set as 0.34€/Vehicle km. The parameter values for the other modes remained the same from scenario one. Using these values, the parameters of generalized costs are converted to the same units, i.e., Euros.

The ***Hub Routes and Skim Generation for Mode Combinations*** process is a new addition to the model. As stated in section 4.3, in this process, the boundary conditions for using private bikes and walking to find and travel via the hubs are first defined. The maximum time to find and use a hub using bikes and walking is restricted to 5 minutes, based on SANDAG (2017) and Mathijs (2021). All the selected mode combinations are introduced into the simulation process in the present *Hub Routes* process.

The skim matrices generated in the *Skim Generation* process for the different transport modes are used as inputs in the *Hub Routes* process. The boundary conditions are checked for the different mode combinations using the travel time skim matrices to identify the possible trips combinations. It is also checked if the trip from hub to destination is possible via the selected mode as some destinations in the network might not be accessible by certain modes. If the conditions are met, the generalized travel costs for the trip from origin to destination via the hub are saved as the utility. This process checks for the possibility of travel from origin to destination via all the hubs within specified boundary limits and stores the generalized travel cost via the hub that results in the lowest utility among available options. The data is generated as a new skim matrix for all mode combinations in the model. If a trip is not possible via a hub, the value 99999 is saved in the matrix for the specific origin-destination pairs. The travel costs generated per mode combination are used as the Level of Service (LOS) to find the best suitable hubs. A separate skim generated indicates the best hub used to travel per mode combination between origin and destination. The best hub skim matrix based on the lowest utility among mode options is used in the *O-D Matrices Generation per trip leg* process.

In the ***Simultaneous Trip Distribution and Modal Split Step***, only additions are made to the script that was adjusted in scenario one. Using data from STARS (2018) on the average distance and average time travelled by shared cars, similar adjustments as scenario one are made to the top-lognormal deterrence function parameters to show similar trends of shared cars. The access legs by walking and private bikes are constrained to 5 minutes due to the boundary conditions from the literature. As a result, in the mode combinations, the transport modes shared cars, shared bikes, and public transport is considered the main mode of the trip. The parameters are adjusted accordingly for mode-combinations. This step also indicates the modal split for the different modes and mode combinations in the model.

In the *simultaneous trip distribution and modal split* step, the Origin-Destination trip matrices generated for the mode combinations are for the mode chain and not per mode, i.e., the trip matrices are for the whole trip and not for the different trip legs. As the mode combinations involve different types of modes per trip leg, the total O-D trip matrices have to be separated per trip leg. A trip-leg is a part of a trip that is carried out by the same mode. The representation of trip-legs for mode combination "Private Bike-Shared Car" is shown in Figure 27.

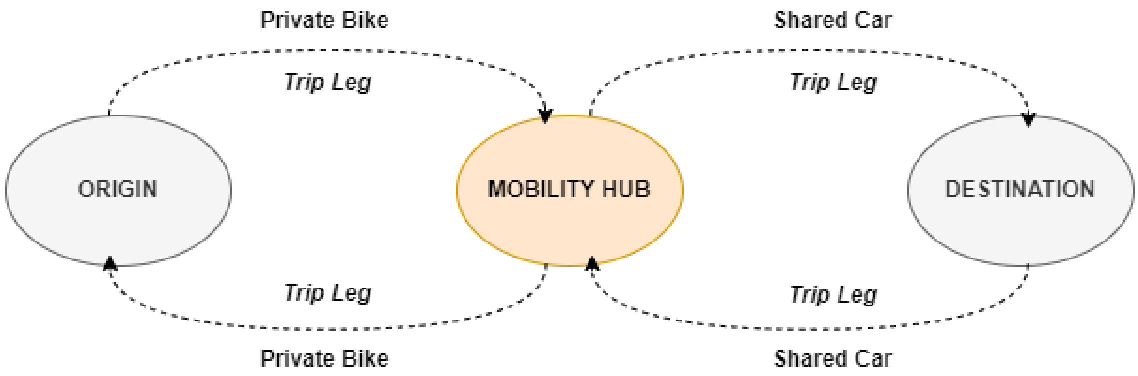

Figure 27: Representation of trip-legs for mode combination "private bike-shared car"

For splitting the matrices per mode per trip leg, the ***O-D Matrices Generation per trip leg*** process is used. The inputs for this step are the best hub indicator skim matrix and O-D trip matrices for different mode combinations. The trip legs are split into two parts and saved as different users in the model based on the mode. For example, if the mode combination is "Private Bike-Shared Car", the trip matrix for the private bike leg is stored along with other private bike trips in the form of a different user representing the mode combination. Similarly, the trip matrix for the shared car leg is stored along with other shared car trips. As stated in section 4.3, the separation of matrices per leg is crucial for the trip assignment step.

In the ***Trip Assignment Step,*** new adjustments to model route choice of shared cars and shared bikes were made. The trip assignment for shared bikes is considered to be similar to that of private bicycles. At the same time, the trip assignment for shared cars is considered to be similar to that of private cars.

These different steps/processes are simulated in the described order on OmniTRANS to observe the changes in the Delft transport network with mobility hubs and shared modes. The obtained results are presented in the next chapter.

The OmniTRANS job scripts for the ***Hub Routes and Skim Generation for Mode Combinations*** process and the ***O-D Matrices Generation per trip leg*** process is shown in Appendix B and C, respectively.

6. RESULTS

This section presents the results obtained from simulating the two scenarios explained in Chapter 5. The results presented are based on the overall modal split, modal split per trip purpose, vehicle kilometres and total travel time travelled by the different modes for the two scenarios. As the trips generated are in the morning peak, only the trips produced from home for the different purposes are shown in this chapter. In addition, the usage of mobility hubs by the different modes for arrivals and departures is shown. Finally, the congestion level variation on the network for cars in the two scenarios is presented. These results will help understand the impact of mobility hubs on the transport network. Discussion into the obtained results will be provided in the next chapter.

6.1. OVERALL MODAL SPLIT

On simulating the two scenarios on OmniTRANS, the total number of trips produced and attracted per zone remained the same. A representation of the trips produced for all purposes from each internal zone by different modes in the Delft network in both scenarios is shown in Figure 28. It is observed that in the scenario with mobility hubs, there is a good shift towards mode-combinations from uni-modal options and public transport in areas where the mobility hub has been modelled and also a minor shift in other areas that are within accessible distance to the hubs.

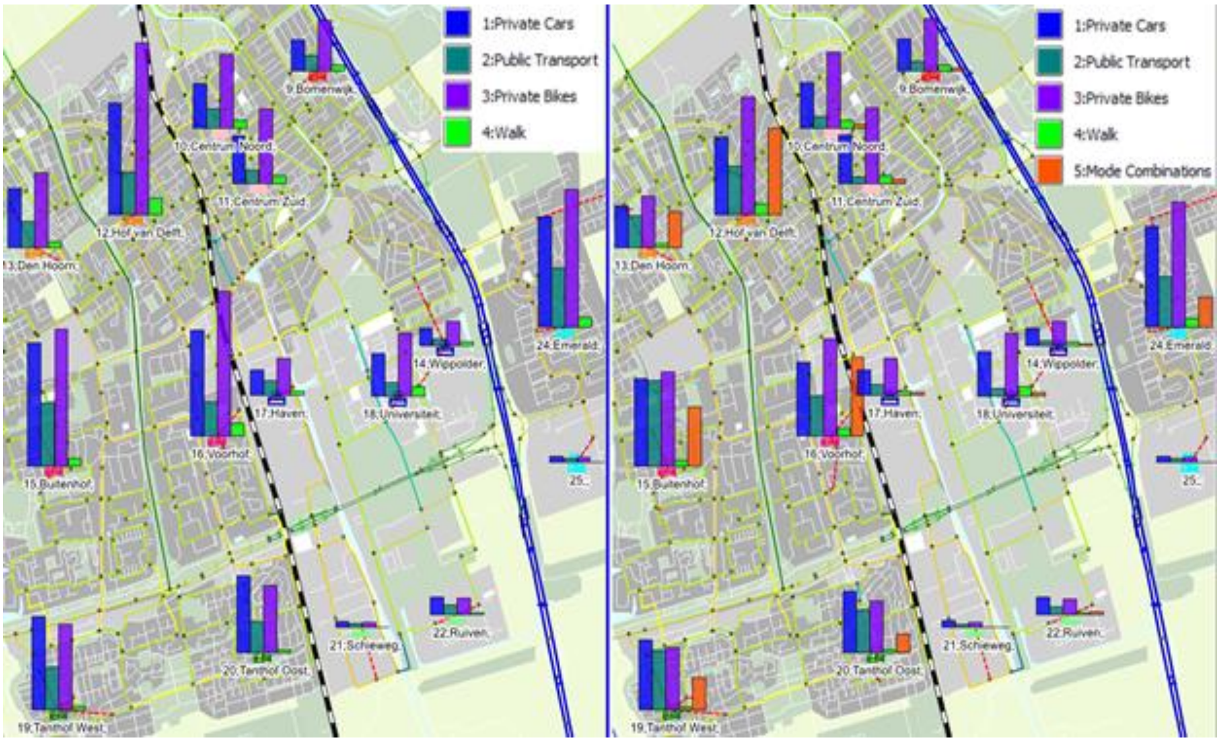

Figure 28: Representation of total trips departing from internal zones by different modes: without hubs (left), with hubs (right) on OmniTRANS.

The modal split represents the percentage of travellers using a particular transport mode in comparison to the ratio of trips made (Ungvarai, 2019). The variation in the modal split for the overall total trips (for all trip purposes and all zones) generated in the two scenarios is shown in Table 5.

Table 5: Overall total trips modal split

Overall Total Trips		Scenario 1	Scenario 2	Comparison
	Uni-Mode, PT and Mode Combinations	**Overall Modal Split (%)**	**Overall Modal Split (%)**	**Overall Change (%)**
Uni-Mode	Private Car	50.9	49.1	-3.5
	Private Bike	31.8	27.8	-12.3
	Walk	2.4	2.1	-11.6
Public Transport	Public Transport (PT)	14.9	10.2	-31.8
	Private Bike – PT		1.9	
	PT – Private Bike		0.6	
Mode Combinations	Private Bike – Shared Car		1.8	
	Shared Car – Private Bike		0.8	
	Walk – Shared Bike		2.5	
	Shared Bike – Walk		1.3	
	Walk – Shared Car		1.2	
	Shared Car – Walk		0.6	
	Overall Total Number of Trips	***77734***	***77734***	***0***
	Total Number of Uni-Modal Trips	***66124***	***61477***	***-7.0***
	Total Number of Public Transport Trips	***11610***	***9906***	***-14.7***
	Total Number of Mode-Combination Trips	***0***	***6351***	

It is observed from Table 5 that in both scenarios, with and without mobility hubs, there is a high representation of trips by private cars (50.9% and 49.1%) and private bikes (31.8% and 27.8%). The total number of uni-modal trips in the network in the presence of mobility hubs reduces by 7% compared to the scenario without hubs. The total number of public transport trips reduces by 14.7% when mobility hubs are modelled in the transport network.

The reduction in the total number of uni-modal and public transport trips is compensated by the mode-combinations trips, and the overall total number of trips in both the scenarios remains the same. The total number of trips in the network is noted to be 77734. Among the 77734 trips, the total modal share percentage for uni-modal, public transport and mode-combination trips in the presence of mobility hubs is 79% (61477 trips), 13% (9906 trips) and 8% (6351 trips), respectively.

6.2. Home to Work Modal Split

Home to Work is among the three different trip purposes modelled in the Delft network. It represents the trips that are made from home to go to work. A representation of the home to work bound trips by different modes from each internal zone in the Delft network in both scenarios is shown in Figure 29. It is observed that trips in the seven zones with the mobility hubs have a shift from uni-modal options and public transport to mode combinations. While the other areas within accessible distance to mobility hubs still continue to travel nearly all their trips by the previously used transport modes when mobility hubs were not introduced.

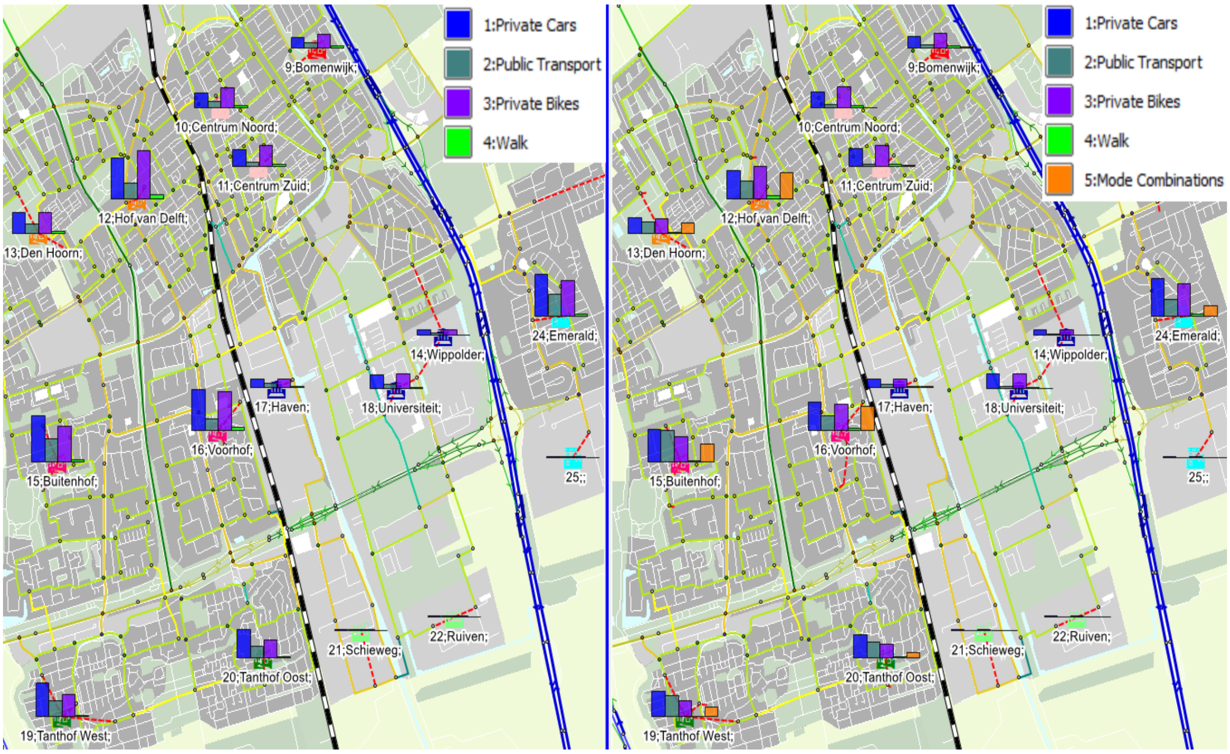

Figure 29: Representation of home to work trips departing from internal zones by different modes: without hubs (left), with hubs (right) on OmniTRANS

The variation in the modal split for the home to work total trips (all zones) generated in the two scenarios are shown in Table 6.

Table 6: Home to work total trips modal split

Home to Work Total Trips		**Scenario 1**	**Scenario 2**	**Comparison**
	Uni-Mode, PT and Mode Combinations	**Overall Modal Split (%)**	**Overall Modal Split (%)**	**Overall Change (%)**
Uni-Mode	Private Car	60.0	59.9	-0.2
	Private Bike	22.9	20.7	-9.7
	Walk	1.6	1.4	-9.5
Public Transport	Public Transport (PT)	15.5	10.0	-35.4
	Private Bike – PT		1.7	
	PT – Private Bike		0.4	
Mode Combinations	Private Bike – Shared Car		1.6	
	Shared Car – Private Bike		0.6	
	Walk – Shared Bike		1.6	
	Shared Bike – Walk		0.8	
	Walk – Shared Car		1.0	
	Shared Car – Walk		0.4	
Overall Total Number of Trips		***31028***	***31028***	***0***
Total Number of Uni-Modal Trips		***26220***	***25455***	***-2.9***
Total Number of Public Transport Trips		***4808***	***3754***	***-21.9***
Total Number of Mode-Combination Trips		***0***	***1819***	

It is observed from Table 6 that private cars (60% and 59.9%) are the most dominant mode used to make trips for this purpose among the available transport options in both scenarios. The total number of uni-modal and public transport trips in the network in the presence of mobility hubs reduces by 2.9% and 21.9%, respectively, compared to the scenario without hubs.

The total number of home to work-related trips is noted to be 31028. Among the 31028 trips, the total modal share percentage for uni-modal, public transport and mode-combination trips in the presence of mobility hubs in the Delft network is 82% (25455 trips), 12% (3745 trips) and 6% (1819 trips), respectively.

It is also noticed that "Private Bike – Public Transport" and "Private Bike – Shared Car", which have a private bike as the first mode in mode combinations, has a higher representation of trips compared to the other mode combinations.

6.3. Home to Education Modal Split

Home to Education is one of the three different trip purposes modelled in the Delft network. It represents the trips that are made from home to go to schools and universities. A representation of the home to education bound trips by different modes from each internal zone in the Delft network in both scenarios is shown in Figure 30. It is observed in scenario two with mobility hubs that only the seven areas with mobility hubs have a shift from uni-modal options and public transportation to mode combinations. There is no shift in the other zones towards mode-combination trips.

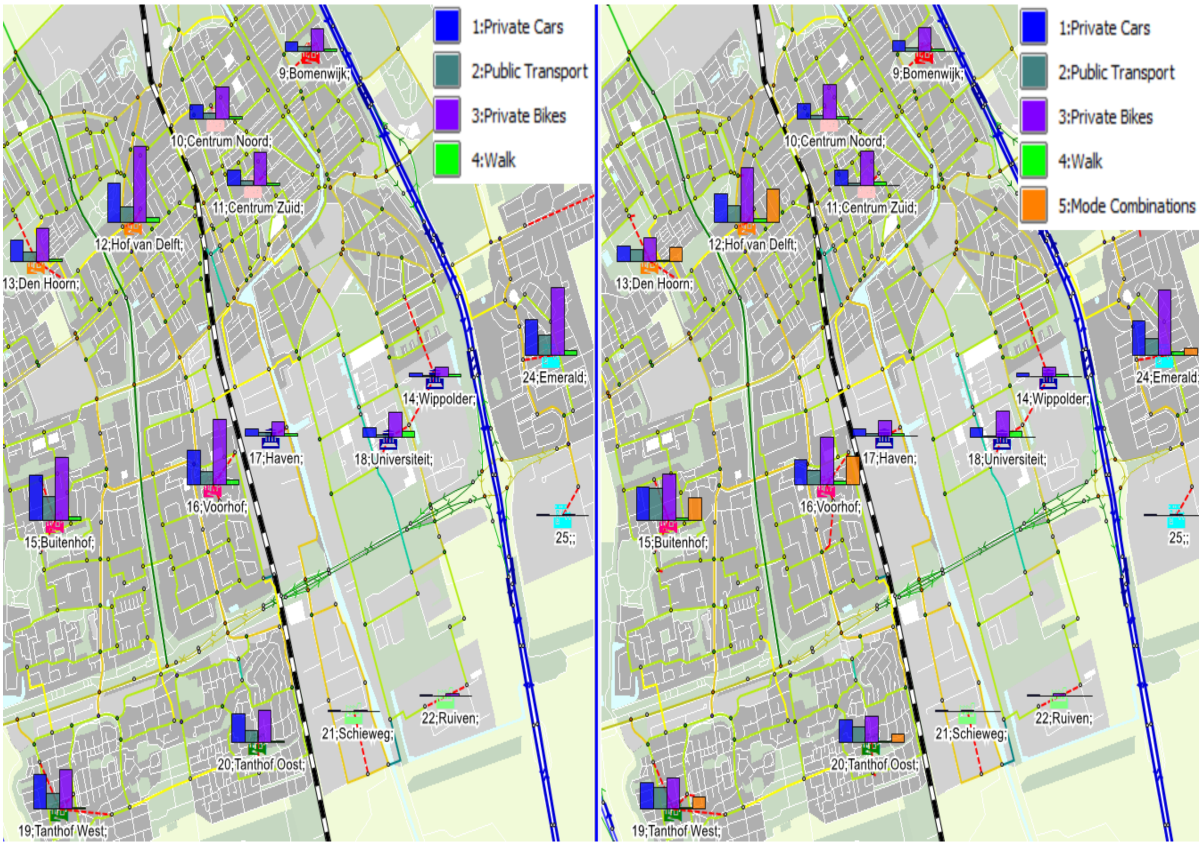

Figure 30: Representation of home to education trips departing from internal zones by different modes: without hubs (left), with hubs (right) on OmniTRANS

The variation in the modal split for the home to education total trips (all zones) generated in the two scenarios is shown in Table 7.

Table 7: Home to education total trips modal split

Home to Education Total Trips		Scenario 1	Scenario 2	Comparison
	Uni-Mode, PT and Mode Combinations	**Overall Modal Split (%)**	**Overall Modal Split (%)**	**Overall Change (%)**
Uni-Mode	Private Car	38.7	36.7	-5.3
	Private Bike	44.5	40.2	-9.6
	Walk	3.1	2.9	-7.1
Public Transport	Public Transport (PT)	13.6	9.6	-29.4
	Private Bike – PT		2.5	
	PT – Private Bike		0.0	
Mode Combinations	Private Bike – Shared Car		2.3	
	Shared Car – Private Bike		0.0	
	Walk – Shared Bike		4.2	
	Shared Bike – Walk		0.0	
	Walk – Shared Car		1.6	
	Shared Car – Walk		0.0	
Overall Total Number of Trips		***18153***	***18153***	***0***
Total Number of Uni-Modal Trips		***15684***	***14490***	***-7.6***
Total Number of Public Transport Trips		***2470***	***2202***	***-10.8***
Total Number of Mode-Combination Trips		***0***	***1461***	

It is observed from Table 7 that in both scenarios, private bikes (44.5% and 40.2%) are the most used transport mode, followed by private cars (38.7% and 36.7%) for the trip purpose 'home to education'. The total number of uni-modal and public transport trips in the network in the presence of mobility hubs reduces by 7.6% and 10.8%, respectively, compared to the scenario without mobility hubs.

The total number of home to education-related trips is observed to be 18153. Among the 18153 trips, the total modal share percentage for uni-modal trips is 80% (14490 trips), public transport trips is 12% (2202 trips), and mode-combination trips is 8% (1461 trips) in the presence of mobility hubs in the Delft network.

It is also noticed that for the newly introduced mode-combinations, only the combinations that have a private bike or walk as the first transport mode have a representation of trips while the other mode-combinations have no trips.

6.4. Home to Other Modal Split

As mentioned in section 5.1, the Home to Other trips includes purposes apart from work and education such as shopping, business and leisure. These trips are produced from home to the different zones. A representation of the trips bound by different modes from home for all other purposes from each internal zone in the Delft network in both scenarios is shown in Figure 31. It is observed in the scenario with mobility hubs that there is a major shift towards mode-combinations from uni-modal options and public transport in areas where the mobility hub has been modelled and also a minor shift in other areas that are within accessible distance to the hubs.

Figure 31: Representation of home to other trips departing from internal zones by different modes: without hubs (left), with hubs (right) on OmniTRANS.

The variation in the modal split for home to other total trips (all zones) generated in the two scenarios is shown in Table 8.

Table 8: Home to other total trips modal split

Home to Other Total Trips		**Scenario 1**	**Scenario 2**	**Comparison**
	Uni-Mode, PT and Mode Combinations	**Overall Modal Split (%)**	**Overall Modal Split (%)**	**Overall Change (%)**
Uni-Mode	Private Car	46.2	42.2	-8.6
	Private Bike	35.4	29.2	-17.4
	Walk	3.2	2.7	-16.6
Public Transport	Public Transport (PT)	15.3	11.0	-27.9
	Private Bike – PT		2.2	
	PT – Private Bike		1.1	
Mode Combinations	Private Bike – Shared Car		2.1	
	Shared Car – Private Bike		1.5	
	Walk – Shared Bike		2.8	
	Shared Bike – Walk		2.7	
	Walk – Shared Car		1.4	
	Shared Car – Walk		1.1	
Overall Total Number of Trips		***22503***	***22503***	***0***
Total Number of Uni-Modal Trips		***19068***	***16670***	***-12.6***
Total Number of Public Transport Trips		***3435***	***3223***	***-6.2***
Total Number of Mode-Combination Trips		***0***	***2610***	

From Table 8, it is observed that for the 'home to other' trip purpose in both scenarios, private cars (46.2% and 42.2%) are the most used transport mode, followed by private bikes (35.4% and 29.2%). The total number of uni-modal and public transport trips in the network in the presence of mobility hubs reduces by 12.6% and 6.2%, respectively, compared to the scenario without mobility hubs.

The total number of trips for the trip purpose 'home to other' is observed to be 22503. Among the 22503 trips, the total modal share percentage for uni-modal, public transport and mode-combination trips in the presence of mobility hubs in the Delft network is 74% (16670 trips), 14% (3223 trips) and 12% (2610 trips), respectively.

It is also observed that all the introduced mode combinations have a nearly equal distribution of trips (between 1.1% and 2.8%) among them to compensate for the uni-modal and public transport trip reductions.

6.5. Vehicle Kilometres Travelled (VKT) by Different Modes

Vehicle Kilometres Travelled, also known as VKT, refers to the total kilometres travelled by vehicles on roadways (Weerasekera & Amarasingha, 2017). This section presents the changes in VKT for the two scenarios in three different ways. First, the complete Delft network variation will be presented, followed by the variation within internal zones and, finally, the variations linked to external zones.

The variation in vehicle kilometres travelled for all zones in the network by the different modes is shown in Table 9. It is observed that the majority of the kilometres covered in both scenarios is by private cars (59.2% and 58.4%). A significant decrease is noticed in the kilometres covered by private cars, private bikes and public transport, while that covered by walking is seen to increase by 26.4%.

The total vehicle kilometres travelled over the different modes in scenario two with mobility hubs is observed to decrease by 1.8% compared to scenario one. The total kilometres travelled in scenario two across private and shared cars combined is found to increase by 3.4% and that across private and shared bikes combined by 2.3% compared to only private cars and bikes respectively in scenario one.

Table 9: Total vehicle kilometres travelled by different modes

Total Vehicle Kilometres			
	Scenario 1	**Scenario 2**	**Comparison**
Transport Mode	**Total Vehicle Kilometres (%)**	**Total Vehicle Kilometres (%)**	**Overall Change (%)**
Private Car	59.2	58.4	-3.3
Shared Car		4.0	
Private Bike	20.8	19.2	-9.2
Shared Bike		2.4	
Public Transport	18.9	14.6	-24.4
Walk	1.1	1.4	+26.4
Total Vehicle Kms	***523316***	***513652***	***-1.8***
Total Car (Pvt+Shared) Kms	***309887***	***320426***	***+3.4***
Total Bike (Pvt+Shared) Kms	***108844***	***111376***	***+2.3***
Total PT Kms	***99084***	***74894***	***-24.4***
Total Walk Kms	***5502***	***6955***	***+26.4***

The variation in vehicle kilometres travelled within all internal zones of the Delft network by the different modes is shown in Table 10. It is noticed that in both scenarios, the major share of the kilometres travelled within internal zones is covered by private bikes (51.4% and 42.3%). However, compared to scenario one, the total distance covered by private bikes reduces (13.9%), as is the case with private cars (24.9%). On the contrary, the distance covered by both public transport and walking increases by 2.9% and 63% respectively.

The internal vehicle kilometres travelled over the different modes in scenario two with mobility hubs is observed to increase by 4.5% compared to scenario one. The internal kilometres travelled in scenario two across private and shared cars combined is found to increase very slightly by 0.1% and that across private and shared bikes combined by 2.9% compared to only private cars and bikes respectively in scenario one.

Table 10: Internal zones vehicle kilometres travelled by different modes

Internal Vehicle Kilometres			
	Scenario 1	**Scenario 2**	**Comparison**
Transport Mode	**Internal Vehicle Kilometres (%)**	**Internal Vehicle Kilometres (%)**	**Overall Change (%)**
Private Car	24.3	17.4	-24.9
Shared Car		5.8	
Private Bike	51.4	42.3	-13.9
Shared Bike		8.3	
Public Transport	20.7	20.4	+2.9
Walk	3.7	5.7	+63.0
Internal Vehicle Kms	***71230***	***74404***	***+4.5***
Total Car (Pvt+Shared) Kms	***17281***	***17295***	***+0.1***
Total Bike(Pvt+Shared) Kms	***36585***	***37663***	***+2.9***
Total PT Kms	***14748***	***15183***	***+2.9***
Total Walk Kms	***2616***	***4263***	***+63.0***

The variation linked to external zones refers to the kilometres covered by vehicles that start from external zones 1 to 7 in the model to proceed to internal zones and the kilometres covered by vehicles to travel to external zones from the internal zones of Delft. The variation linked to external vehicle kilometres by the different modes is shown in Table 11. It is observed that private cars (64.7% and 65.3%) account for the majority of the kilometres travelled. Compared to scenario one, the kilometres travelled by public transport in scenario two drastically reduces by 29.2%, while that of the private cars, private bikes and walk reduce by 2%, 6.8%, and 6.7% respectively.

The external vehicle kilometres travelled over the different modes in scenario two with mobility hubs is observed to decrease by 2.8% compared to scenario one. The external kilometres travelled in scenario two across private and shared cars combined is found to increase by 3.6% and that across private and shared bikes combined by 2% compared to only private cars and bikes respectively in scenario one.

Table 11: External zones vehicle kilometres travelled by different modes

External Vehicle Kilometres			
	Scenario 1	**Scenario 2**	**Comparison**
Transport Mode	**External Vehicle Kilometres (%)**	**External Vehicle Kilometres (%)**	**Overall Change (%)**
Private Car	64.7	65.3	-2.0
Shared Car		3.7	
Private Bike	16.0	15.3	-6.8
Shared Bike		1.5	
Public Transport	18.7	13.6	-29.2
Walk	0.6	0.6	-6.7
External Vehicle Kms	***452087***	***439248***	***-2.8***
Total Car(Pvt+Shared)Kms	***292606***	***303131***	***+3.6***
Total Bike(Pvt+Shared)Kms	***72259***	***73713***	***+2.0***
Total PT Kms	***84336***	***59711***	***-29.2***
Total Walk Kms	***2886***	***2692***	***-6.7***

6.6. Total Travel Time by Different Modes

This section presents the total time travelled by all the different vehicles for the trips made. The changes in travel time for the two scenarios are presented in three different ways. First, the total travel time variations for all the zones in the Delft transport network is presented, followed by the variation within internal zones and finally, the variations linked to the external zones.

The variation in travel time for all zones in the network by the different modes is shown in Table 12. It is observed that the time travelled by public transport (36.8% and 32.9%) is highest in both scenarios. The time travelled by private cars, private bikes, and public transport reduces by 1.7%, 9.4%, and 11.3% respectively in scenario two while that by walk increases by 25.4%.

The total time travelled over the different modes in scenario two with mobility hubs is observed to be nearly the same as that of scenario one. The total time travelled in scenario two over private and shared cars combined is found to increase by 6.2% and that over private and shared bikes combined by 2.2% compared to only private cars and bikes respectively in scenario one.

Table 12: Total time travelled by different modes

Total Travel Time			
	Scenario 1	**Scenario 2**	**Comparison**
Transport Mode	**Total Travel Time (%)**	**Total Travel Time (%)**	**Overall Change (%)**
Private Car	25.9	25.5	-1.7
Shared Car		2.0	
Private Bike	29.6	26.8	-9.4
Shared Bike		3.4	
Public Transport	36.8	32.6	-11.3
Walk	7.7	9.6	+25.4
Total Time (mins)	***1444469***	***1444929***	***+0.03***
Total Car(Pvt+Shared) Time (mins)	***374297***	***397464***	***+6.2***
Total Bike(Pvt+Shared) Time (mins)	***427508***	***436752***	***+2.2***
Total PT Time (mins)	***531722***	***471590***	***-11.3***
Total Walk Time (mins)	***110943***	***139123***	***+25.4***

The variation in time travelled within all internal zones of the Delft network by the different modes is shown in Table 13. It is observed that the time travelled within internal zones is highest for private bikes followed by public transport and then walking in both scenarios. It is noted that the time travelled by private cars and private reduces by 19.8% and 14.3% respectively while the time travelled by public transport and walking increased by 15.8% and 60.2% respectively in scenario two compared to scenario one.

The total internal time travelled over the different modes in scenario two with mobility hubs is observed to increase by 16.6%. The internal time travelled in scenario two across private and shared cars combined is found to increase by 7.5% and that across private and shared bikes combined by 2.6% compared to only private cars and bikes respectively in scenario one.

Table 13: Internal zones travel time by different modes

Internal Travel Time			
	Scenario 1	**Scenario 2**	**Comparison**
Transport Mode	**Internal Travel Time (%)**	**Internal Travel Time (%)**	**Overall Change (%)**
Private Car	7.7	5.3	-19.8
Shared Car		1.8	
Private Bike	45.0	33.1	-14.3
Shared Bike		6.5	
Public Transport	30.8	30.6	+15.8
Walk	16.5	22.7	+60.2
Total Internal Time (mins)	***322770***	***376188***	***+16.6***
Total Car (Pvt+Shared) Time (mins)	***24842***	***26707***	***+7.5***
Total Bike(Pvt+Shared) Time (mins)	***145399***	***149169***	***+2.6***
Total PT Time (mins)	***99298***	***115035***	***+15.8***
Total Walk Time (mins)	***53230***	***85276***	***+60.2***

The variation linked to external zones refers to the time travelled by vehicles that start from external zones 1 to 7 in the model to proceed to internal zones and the time travelled by vehicles to travel to external zones from the internal zones of Delft. The variation linked to external time travelled by the different modes is shown in Table 14. It is observed that the time travelled by public transport (38.6% and 33.4%) is the highest in both scenarios, followed by private cars (31.2% and 32.6%).

The total external time travelled over the different modes in scenario two with mobility hubs is observed to decrease by 4.7%. The external time travelled in scenario two across private and shared cars combined is found to increase by 6.1% and that across private and shared bikes combined by 1.9% compared to only private cars and bikes respectively in scenario one. While the time travelled by public transport and walk is found to increase by 15.8% and 60.2% respectively in scenario two compared to scenario one.

Table 14: External zones travel time by different modes

External Travel Time			
	Scenario 1	**Scenario 2**	**Comparison**
Transport Mode	**External Travel Time (%)**	**External Travel Time (%)**	**Overall Change (%)**
Private Car	31.2	32.6	-0.4
Shared Car		2.1	
Private Bike	25.2	24.6	-6.9
Shared Bike		2.3	
Public Transport	38.6	33.4	-17.5
Walk	5.1	5.0	-6.7
Total External Time (mins)	***1121699***	***1068741***	***-4.7***
Total Car(Pvt+Shared) Time (mins)	***349454***	***370756***	***+6.1***
Total Bike(Pvt+Shared) Time (mins)	***282108***	***287583***	***+1.9***
Total PT Time (mins)	***432424***	***356555***	***-17.5***
Total Walk Time (mins)	***57712***	***53846***	***-6.7***

6.7. Arrivals and Departures from Mobility Hubs

The Delft network in scenario two consists of seven mobility hubs modelled in identified residential areas. Each hub attracts and produces trips by different modes based on the modelled mode combinations. A representation of the arrivals at and departures from the mobility hubs by different modes is shown in Figure 32. It can be observed that the proportion of arrivals at the mobility hub is more by private bikes and walking while for the departures from hubs the proportion is more varied over the different modes.

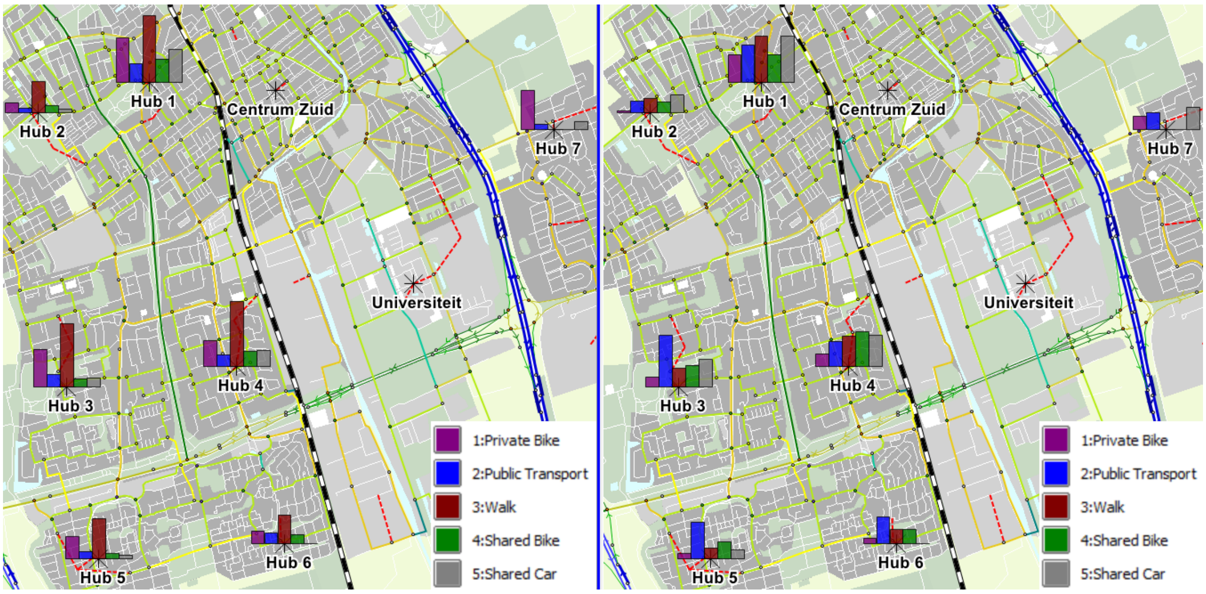

Figure 32: Representation of arrivals at mobility hubs by different modes (left), departures from mobility hubs by different modes (right) on OmniTRANS

The arrivals at the seven mobility hubs by the different modes are shown in Table 15. Similar to Figure 32, it can be observed from the table that the leading share of arrivals at the mobility hubs is either by private bike or walk. It is also noticed that for hubs 7, the arrivals by private bike is very high while that by walking is 0.

Table 15: Arrivals to mobility hubs by different modes

Arrivals to Mobility Hubs by Different Modes						
Hub Number	**Private Bike (%)**	**Public Transport (%)**	**Walk (%)**	**Shared Bike (%)**	**Shared Cars (%)**	***Total Arrivals***
1	24.2	9.8	35.9	12.2	17.9	2798
2	16.9	8.7	54.5	13.3	6.6	874
3	29.1	9.2	48.8	5.8	7.0	1949
4	19.3	8.6	48.5	11.5	12.1	2041
5	28.3	9.3	52.0	6.4	4.0	1155
6	20.3	18.0	47.4	14.2	0.0	900
7	74.6	10.1	0.0	0.0	15.3	803

The departures from the seven mobility hubs by the different modes are shown in Table 16. It is noticed that the variation in the trips departing from mobility hubs is more spread out over the different modes. It is noticed that the departures share is most balanced in hub one and ranges from 14.7% to 25.2% among the five modes at the mobility hub. It is also observed that public transport has a good representation of trips departing in all the mobility hubs. In hub 6, it is noticed that there are no shared cars, while in hub seven, there are no shared bikes being used. The reason for this will be discussed in the next chapter.

Table 16: Departures from mobility hubs by different modes

Departures from Mobility Hubs by Different Modes						
Hub Number	**Private Bike (%)**	**Public Transport (%)**	**Walk (%)**	**Shared Bike (%)**	**Shared Cars (%)**	***Total Departures***
1	14.7	20.2	25.2	14.9	25.0	2798
2	3.5	20.6	25.1	19.7	31.1	874
3	7.8	40.2	14.3	16.6	21.1	1949
4	9.7	18.5	22.6	26.0	23.3	2041
5	6.4	47.5	13.2	21.7	11.1	1155
6	8.3	44.2	24.0	23.4	0.0	900
7	25.4	32.4	0.0	0.0	42.2	803

From Table 15 and Table 16, it can be observed that the total arrivals and total departures are equal at the mobility hubs. It is also noticed that among the seven modelled hubs, the highest usage is by Hub 1 (2798 trips), followed by Hub 4 (2041 trips) and Hub 3 (1949 trips). The variation among the different mobility hubs is discussed in Chapter 7.

6.8. Congestion of Car Network

In the Delft network on OmniTRANS, capacity on the different road types was initially defined only for private cars. While modelling shared cars in the network, similar road characteristics to private cars were incorporated; thus, the capacity for shared cars was also defined. As a result, it was possible to observe the congestion levels of the car network that included both private and shared cars. A representation of the car congestion levels in both the scenarios modelled on OmniTRANS is shown in Figure 33. The network with mobility hubs includes both private cars and shared cars, while the network without hubs includes only private cars.

It can be observed from Figure 33 that there is no significant change in the car congestion levels in the transport network of Delft with the introduction of mobility hubs. There are minor reductions in congestions only on a few links.

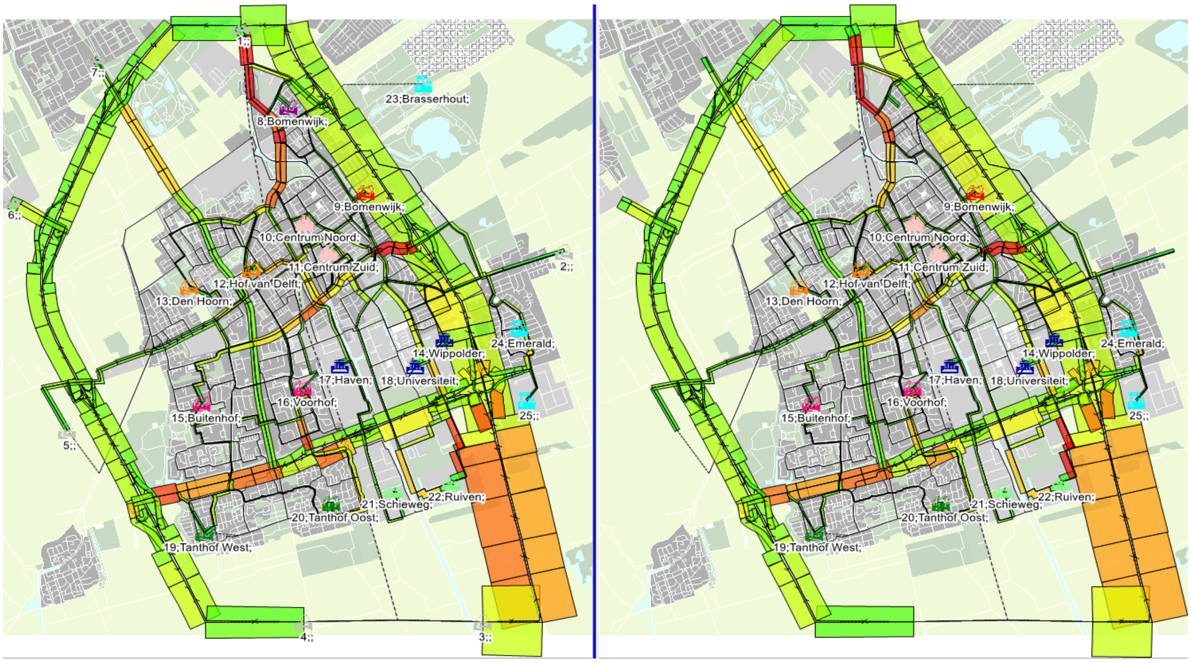

Figure 33: Representation of car congestion levels: without hubs (left), with hubs (right) on OmniTRANS

6.9. Summary of Results

The total number of trips produced in the Delft network over all the trip purposes in the morning peak hour is 77734. Amongst these trips, 71684 trips are produced from home for different trip purposes. In the model, it is observed that the majority of the trips (31028 trips) produced are for the purpose of home to work, followed by the trip purpose 'home to other' (22503 trips) and then home to education (18153 trips).

The introduction of the seven mobility hubs in the Delft network leads to an overall decrease in uni-modal trips by 7% and public transport trips by 14.7%. It is also observed that across all the trip purposes in the scenario with mobility hubs in the Delft network, the total number of uni-modal and public transport trips reduced compared to the scenario without mobility hubs. The newly introduced mode-combination options compensated for the reduction in uni-modal and public transport trips in the presence of mobility hubs in the network.

The total vehicle kilometres and total time travelled is observed to increase across private cars and shared cars combined in the network for all trip purposes in the scenario with mobility hubs. With the introduction of seven hubs, there is an overall increase in kilometres and time travelled for cars (private and shared combined) in the network by 3.4% and 6.2%, respectively.

With regard to the total kilometres and total time travelled across private bikes and shared bikes combined, similar findings to that of the car network stated above were observed. The kilometres and time travelled increased by 2.3% and 2.2% respectively for private and shared bikes.

The proportion of arrivals at the mobility hubs by different transport modes was found to be more by private bikes and walk while for the departures from hubs the proportion was more varied over the different modes.

There is no significant change in the car congestion levels in the transport network of Delft with the introduction of mobility hubs that considers both private and shared cars. There are minor reductions in congestions only on a few links.

7. DISCUSSION

This chapter discusses the different results obtained from the simulation of the two Delft network scenarios presented in Chapter 6. This research aims to assess the impacts on the transport network due to shared mobility hubs in residential areas. Hence, to better discuss the obtained results, a few categories suggested by Roukouni & Correia (2020) are used to assess the impacts. The selected categories are Travel behaviour, which includes the mode choice and vehicle kilometres travelled; Traffic conditions, which include the congestion and travel time of vehicles; and finally, Environment, which is referred to as sustainability in this chapter.

7.1. IMPLICATIONS ON TRAVEL BEHAVIOUR

With the introduction of mobility hubs with shared modes, it is necessary to discuss the travel behavioural changes that occur in the network. The necessity to discuss is mainly due to the changes in behaviour that were observed in section 3.2. The change in behaviour can be interpreted from the mode choice of travellers and the vehicle kilometres travelled by the different modes (Roukouni & Correia, 2020). The results of modal split and vehicle kilometres travelled obtained in Chapter 6 are used as a base for the discussion.

On analysing the modal split results obtained on simulation of the two scenarios in the Delft network, the decrease in the number of uni-modal and public transport trips is linked to the introduction of new mode-combination options in the model. The mode-combinations act as alternative travel options that can be selected for making trips apart from the uni-mode options and public transport. This result is similar to the findings stated in literature by van Rooij (2020), where people consider shared modes as flexible alternatives to available transport modes.

The mode-combination 'Private Bike – Public Transport' acts as an alternative to access public transportation, which was only accessible by walking in the scenario without hubs. Private bikes being a faster and inexpensive commute mode makes it more attractive than walking to access public transport.

On further analysis, it is also observed that among the different mode combinations introduced in the network in the presence of mobility hubs, the combinations with private or shared bikes have a higher share of trips made than combinations with walk and shared cars. This finding further suggests that bikes are more attractive than walking. This result is similar to the findings stated by Fisherman et al., 2015 where bike trips were found to be attractive and replace walk trips.

On observing the trips departing from internal zones of Delft by different mode options, it is noticed that the major shift in trips from uni-modal options and public transportation to mode-combinations occurs in residential areas where the mobility hub has been placed. The boundary conditions that are set in the Delft model based on literature (SANDAG, 2017; Mathijs 2021) to access the hubs from different zones acts as a reason for the trip shift concentration to be more within the selected residential areas.

On analysing the arrivals and departures from the seven modelled hubs in the Delft network, it was observed that in hub 7, the arrivals and departures by modes walk and shared bikes was 0%. In this research, the hubs are modelled on the network in the selected residential area close to the nearest public transport transit stop from the residential zones centroid. The modelled hub 7 is 15 to 20 minutes away by walking from the residential zone for which it was introduced. As the boundary condition to accessing the hub by walking is set to five minutes, walking trips to hub seven are not possible and are thus represented as 0%. Among the introduced mode-combinations, the shared bikes are available only in combination with walking. As the walking trips are 0% for hub 7, the shared bike trips are also 0%.

For hub 6, the arrivals and departures of shared cars are 0%. The modelled hub number 6 on the Delft network is very close to the public transportation transit stop and the residential zone centroid. Quicker connectivity to the transit stop makes public transport more attractive and leads to more trips. As a result, the shared car trips are 0% at this hub. The share of trips among the other hubs is balanced.

The reduction in the number of uni-modal trips for the purpose of home to work with mobility hubs in the network is only 2.9%, and the reduction in private car trips for this purpose is also very small (0.2%). While the reduction in uni-modal trips for the purposes ‘home to education’ and ‘home to other’ is 7.6% and 12.6%, respectively. The reduction in private car trips for these purposes is also 5.3% and 8.6%. The difference in reduction percentage for the home to work trip purpose compared to the other trip purposes can be linked to the distance of destinations carried out in the work trip. The work-related trips are often to external zones and hence compared to other alternative options, private cars are still attractive.

The share of mode-combination trips is highest for the trip purpose ‘home to other’ at 12% while the share for education and work trips is 8% and 6% respectively. The high share for the home to other purposes could be because the ‘other’ category includes all alternate travel purposes such as shopping, leisure, and business trips which could be shorter trips compared to work and education-based trips.

Even though the model does not produce results on car ownership, based on the trips produced by private cars in both scenarios, it is observed that even in the presence of mobility hubs, the decrease of private car trips is very minimal in the network. The introduction of mobility hubs is to reduce the usage of private cars, and it is achieved to some extent in the model.

On the other hand, the total number of car trips (including private and shared cars) produced in the network is more than the total car trips produced without mobility hubs as the users consider shared cars as a flexible alternative to public transport and use it. A similar pattern was also observed in the works of Knippenberg (2019) and van Rooij (2020).

With the introduction of mobility hubs in the network, the distance travelled by walking increases drastically within the internal zones. The increase can be directly related to the mode-combinations trips, which involve walking as one of the modes.

The total car (private and shared) vehicle kilometres in the Delft network increased by 3.4% even though the vehicle kilometres of private cars reduced because the newly introduced shared cars act as an alternative to public transport and cover a portion of distance which was earlier covered by public transportation. Similarly, the total bike vehicle kilometres also increased by 2.3% as shared bikes are an inexpensive and faster mode of commute for certain distances.

7.2. IMPLICATIONS ON TRAFFIC CONDITIONS

In addition to the existing transport modes, shared bikes and cars are introduced in the Delft network with mobility hubs. As a result, it becomes essential to discuss the changes that occur in the traffic conditions of the network. The results of travel time by the different modes and congestion levels of cars obtained in Chapter 6 are used for this discussion.

The total travel time within the internal zones in the presence of shared modes is seen to increase by 16.6%. The main reason for the increase can be linked to walking to the hubs to access shared modes and public transport as it is observed that the travel time of the modes available at the hub also increases.

The internal travel time in the car network (private and shared combined) of Delft is found to increase by 7.5%. This increase can be linked to the travel time of the new shared cars which were introduced or to the congestion in the network that could increase travel times.

As capacity is defined only for cars in the model, congestion effects due it only can be observed directly. Based on the observations, the car network's congestion levels do not reduce with the introduction of mobility hubs. Two main factors can be linked to the lack of reduction in the network's congestion. First, the number of private car trips that reduce in the network with the introduction of mobility hubs is very low, and another reason is that shared cars are also present in the car network.

7.3. IMPLICATIONS ON SUSTAINABILITY

With the introduction of new transport modes and mobility hubs in the network in the current day, it becomes key to discuss sustainability. In this work, sustainability is discussed with regard to the environmental impacts that the new transport modes can cause.

Even though the number of private car trips reduces in the scenario with mobility hubs, it cannot be directly inferred that the introduction of mobility hubs lead to a sustainable transport network. As the number of trips by public transport also reduces, it is necessary to examine the newly introduced transport modes at the mobility hubs.

Suppose the hubs had only shared bikes and reduced the total number of private car trips. In that case, it could have been directly interpreted that the mobility hubs lead towards a sustainable transport network as the shared bikes do not affect the environment. However, with shared cars being available at the mobility hubs, more study has to be done. The shift towards a sustainable transport network with shared cars depends on the energy source upon which the car operates. If it is assumed that the shared cars are electricity-powered, they can be classified as sustainable. It can then be inferred that the introduction of shared modes does lead to some extent of sustainability.

8. Conclusions & Recommendations

In this chapter, the conclusions of the research will be presented along with the limitations of this research and recommendations for future research. First, the sub-research questions and the main research are answered, followed by limitations and recommendations.

8.1. Conclusions

This study aimed to understand the impact that a shared mobility hub has on the transport network in a residential area. To focus on the aim, the main research question and corresponding sub-questions were framed.

As the sub-research questions help guide towards the main research question, first they are discussed and answered, followed by the main question.

Sub-question 1: What typology of mobility hub is needed for a residential area? And what are the components that are required in the hub?

Based on literature studies, the typology classification 'Neighbourhood Hubs' is deemed ideal for a mobility hub in a residential area. The reach and size of such hubs vary based on the region in which they are placed but are usually small. As the components in the neighbourhood hub varied, a general definition for it was framed.

"A neighbourhood mobility hub is a central location in the residential area that provides at least one shared transportation option such as shared cars or shared bikes to its residents as an alternative to private vehicles with retail services, public transportation and other facilities being optional elements".

A station-based vehicle sharing system is identified to be suitable for a mobility hub in a residential area where the hubs will act as stations.

Sub-question 2: What is the methodology for introducing mobility hubs with shared modes in aggregate transport models?

A trip-based model with the traditional four-step approach is identified as a suitable model among the different transport models. Trips through a mobility hub are identified to be of multi-modal nature. For modelling, such multi-modal trips in transport models pre-specified mode combination technique is identified as the suitable approach.

The methodology introduces mobility hubs as a new transport mode in the four-step model and applies the pre-specified mode combination technique to the transport modes that are available at the mobility hub.

For making this introduction into the four-step model, the key areas to focus on in the traditional four-step model were identified as the travel resistances input, trip distribution step, modal split step, and trip assignment step. Based on the key areas of focus in the four-step model, the adjustments that have to be made for these steps were created into a generalized methodology.

Sub-question 3: How to model mobility hubs in an existing transport model?

To answer this sub-question, the existing transport network of Delft was selected, and a case study was performed. The case study involved applying the proposed adjustments methodology into the existing Delft network step by step on OmniTRANS.

Main Research Question

"What is the impact on the transport network usage caused by a mobility hub in a residential area?"

The results indicate that the modal shift from uni-modal options and public transport to mode-combinations is significant in the residential areas where the mobility hub has been placed, but the shift in other regions is minimal.

The total vehicle kilometres travelled (VKT) and total time travelled by private and shared modes combined, such as private cars and shared cars or private bikes and shared bikes, increases in the transport network with mobility hubs.

The number of private car trips in the transport network decreases marginally with the presence of mobility hubs. On the other hand, the total number of car trips, i.e., including private cars and shared cars in the network, increases. As a result, congestion on the network does not decrease.

8.2. LIMITATIONS OF RESEARCH

In the case study performed, the data set available is unverified and does not provide enough insight into socio-economic characteristics. As a consequence of which obtained results could not be validated.

Another limitation in the case study performed is that the model considers a two-way station based sharing system, and data available in the model is only on the number of trips produced and attracted for the morning peak. As a result, trips where people might be in possession of shared vehicles for a long duration cannot be determined and is still modelled.

For integrating mobility hubs with shared modes into transport models, the pre-specified mode chain technique was used. While using this technique, it is necessary to always pre-determine and state the mode-combinations into the model. So, this limits the model to only consider the combinations which are defined and do not account for other possible options.

During the simulation, the model assumed that there is a shared car and shared bike always available for users while using the mobility hubs. But, in reality, the fleet size of shared vehicles is limited.

In this research, the modal shift occurred from single-mode options to mode combinations, but the actual drift in numbers from one specific mode to another cannot be determined.

8.3. RECOMMENDATIONS

Recommendations for future analysis

The current case study of Delft focuses only on the morning peak. This could be analysed more in the upcoming studies by taking into account evening peak and other seasonal variations to see the overall effect of mobility hub with change in time.

Tour-based or Activity-based models can be incorporated into the study with mobility hubs to observe more realistic trends of people while making a trip and to also account for the time of possession of shared vehicles while modelling.

Mobility hubs have several components apart from shared modes of transport such as retail services, cafes and parcel pick-up points. The future analysis can consider these elements to also be present at the hub and analyse how the travel behaviour changes.

The 'home to other' trip purpose, which consists of all alternate travel purposes such as shopping, leisure, and business trips apart from work and education trips, can be modelled separately per purpose. The Delft case study indicated the highest share of mode-combination trips is for this purpose, so segregating it would lead to better insights.

The boundary conditions set for accessing the shared modes at the mobility hubs can be varied over different simulations to understand the impact of the defined conditions on the model.

Recommendations for future research

More research can be conducted on integrating the concept of mobility hubs with transport networks using the super-network technique. This technique overcomes the drawbacks of the pre-specified mode chain technique, but as it is complex, more research is needed.

The behaviour of people varies from region to region. Pilot studies can be conducted in residential areas with mobility hubs to reflect on the actual behaviour, and using this as the base, modelling of hubs on the particular study area can be conducted for better accurate results.

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APPENDIX A

The trip end functions for the production and attraction of trips for the different trip purposes are shown in Table 17.

Table 17: Trip end function for production and attraction of different purposes

Trip Purpose	Trip End Function
Home to Work Production	0.09* Residents
Home to Work Attraction	0.20 * (jobs + research + education)
Work to Home Production	0.02 * (jobs + research + education)
Work to Home Attraction	0.01 * residents
Home to Education Production	0.10 * residents
Home to Education Attraction	0.76 * education + 0.09 * research
Education to Home Production	0.04 * education
Education to Home Attraction	0.005 * residents
Home to Other Production	0.10 * residents
Home to Other Attraction	0.30 * jobs + 0.2 * residents
Other to Home Production	0.04*jobs
Other to Home Attraction	0.005*residents

APPENDIX B

Hub Routes and Skim Generation for Mode Combinations OmniTRANS Job Script

```
###HUB ROUTES AND SKIMS###
#THE SCRIPT CURRENTLY HAS 8 MODE-CHAINS:
# PRIVATE BIKE-PT
# PT-PRIVATE BIKE
# PRIVATE BIKE-SHARED CAR
# SHARED CAR- PRIVATE BIKE
# WALK-SHARED BIKE
# SHARED BIKE-WALK
# WALK-SHARED CAR
# SHARED CAR-WALK

#write start time
p Time.now
starttijd = Time.now

### INPUT: ###
BikeRadius = 5 #maximum time range in which hubs should be found by mode bike
WalkRadius = 5 #maximum time range in which hubs should be found by mode walking
PtRadius = 1 #minimum time duration range for which PT should be used
SbRadius = 1 #minimum time duration range for which shared bike should be used
ScRadius = 1 #minimum time duration range for which shared car should be used
omrijFactor = 1 #how much of a detour is allowed by car (from/to hub compared to org-dest)
maxZone = 32 #32 #total number of zones including hubs
grootgetal = 99999 #large number to used as 'default' skim value if no suitable hub is present for an OD-pair

T = 10 #time period

writeln "Creating hub routes and skims for time period: ", T

### HUBS: ###
hubs=[26,27,28,29,30,31,32] #list of hubs modelled
writeln 'hubs: ', hubs.join(",  ")
writeln Time.now, ' hubs list created'

### OPEN SKIM CUBES AND MATRICES ###
skimCube = OtSkimCube.open('Hubs')
#cost skims
BikeCost = skimCube[1,20,10,1,11,1] #bike cost between all orgs and dests
PtCost = skimCube[1,30,10,1,11,1] #PT cost between all orgs and dests
WalkCost = skimCube[1,40,10,1,11,1] #walk cost between all orgs and dests
SbCost = skimCube[1,50,10,1,11,1] #shared bike cost between all orgs and dests
ScCost = skimCube[1,60,10,1,11,1] #shared car cost between all orgs and dests
#distance skims
BikeDistance = skimCube[1,20,10,1,12,1] #bike distance between all orgs and dests
PtDistance = skimCube[1,30,10,1,12,1] #PT distance between all orgs and dests
WalkDistance = skimCube[1,40,10,1,12,1] #walk distance between all orgs and dests
SbDistance = skimCube[1,50,10,1,12,1] #shared bike distance between all orgs and dests
ScDistance = skimCube[1,60,10,1,12,1] #shared car distance between all orgs and dests
#traveltime skims
BikeTime = skimCube[1,20,10,1,13,1] #bike travel time between all orgs and dests
PtTime = skimCube[1,30,10,1,13,1] #PT travel time between all orgs and dests
WalkTime = skimCube[1,40,10,1,13,1] #walk travel time between all orgs and dests
SbTime = skimCube[1,50,10,1,13,1] #shared bike travel time between all orgs and dests
ScTime = skimCube[1,60,10,1,13,1] #shared car travel time between all orgs and dests

writeln Time.now, ' skims opened'

#Note: checking for qualified hubs (within requested distance) happens based on distance
# the most attractive hub is decided upon based on travel time

### GENERATING MATRICES FOR SAVING SKIMS, BEST HUB PER OD-PAIR AND AN INDICATOR WHETHER OR NOT AN OD-PAIR HAS A SUITABLE HUB (0/1): ###

# Bike-Pt
skimBikePt = OtMatrix.new(maxZone) # skim for the saving of travel cost utility for the best trail bike -pt
skimBikePt[] = grootgetal
hubBikePt = OtMatrix.new(maxZone) #keep track via which Hub the best route is by OD for bike -pt
BikePtHubIndicator = OtMatrix.new(maxZone) # 1 when there is a hub reached is on route of org to dest , 0 if not

# Pt-Bike
skimPtBike = OtMatrix.new(maxZone)
skimPtBike[] = grootgetal
hubPtBike = OtMatrix.new(maxZone)
PtBikeHubIndicator = OtMatrix.new(maxZone)

# Bike-Sc
skimBikeSc = OtMatrix.new(maxZone)
skimBikeSc[] = grootgetal
hubBikeSc = OtMatrix.new(maxZone)
BikeScHubIndicator = OtMatrix.new(maxZone)
# Sc-Bike
skimScBike = OtMatrix.new(maxZone)
skimScBike[] = grootgetal
hubScBike = OtMatrix.new(maxZone)
ScBikeHubIndicator = OtMatrix.new(maxZone)

# Walk-Sb
skimWalkSb = OtMatrix.new(maxZone)
skimWalkSb[] = grootgetal
hubWalkSb = OtMatrix.new(maxZone)
WalkSbHubIndicator = OtMatrix.new(maxZone)

# Sb-Walk
skimSbWalk = OtMatrix.new(maxZone)
skimSbWalk[] = grootgetal
hubSbWalk = OtMatrix.new(maxZone)
SbWalkHubIndicator = OtMatrix.new(maxZone)

# Walk-Sc
skimWalkSc = OtMatrix.new(maxZone)
skimWalkSc[] = grootgetal
hubWalkSc = OtMatrix.new(maxZone)
WalkScHubIndicator = OtMatrix.new(maxZone)

# Sc-Walk
skimScWalk = OtMatrix.new(maxZone)
skimScWalk[] = grootgetal
hubScWalk = OtMatrix.new(maxZone)
ScWalkHubIndicator = OtMatrix.new(maxZone)
```

```

writeln Time.now, ' matrices for skims, best hub and indicators are generated'

### COMPUTING HUB ROUTES AND SKIMS: ###

#Bike-Pt
for org in 1..maxZone
  for h in 1..hubs.length
    hub = hubs[h-1]
    writeln hub

    if BikeTime[org,hub] < BikeRadius #if biking time is within accepted range
      for dest in 1..maxZone
        if PtTime[hub,dest] > PtRadius #if PT time is larger than minimum range
          # ---------- adjust to right utility-computation: -------------
          skimValueBikePt = BikeCost[org,hub] + PtCost[hub,dest] #compute utility (travel cost) of route via hub
          if skimValueBikePt < skimBikePt[org,dest] #if the currently considered hub is the best one (so far)
            skimBikePt[org,dest] = skimValueBikePt #replace value in skim value by current computed skim value
            hubBikePt[org,dest] = hub #replace best hub by current hub
            BikePtHubIndicator[org,dest] = 1 #indicate that this OD-pair has a route via a hub
          end
        end
      end
    end

  end
end

writeln Time.now, ' skims Bike-Pt computed'

#Pt-Bike
for dest in 1..maxZone
  for h in 1..hubs.length
    hub = hubs[h-1]
    writeln hub

    if BikeTime[hub,dest] < BikeRadius
      for org in 1..maxZone
        if PtTime[org,hub] > PtRadius
          # ---------- adjust to right utility-computation: -------------
          skimValuePtBike = PtCost[org,hub] + BikeCost[hub,dest]
          if skimValuePtBike < skimPtBike[org,dest]
            skimPtBike[org,dest] = skimValuePtBike
            hubPtBike[org,dest] = hub
            PtBikeHubIndicator[org,dest] = 1
          end
        end
      end
    end


  end
end

writeln Time.now, ' skims Pt-Bike computed'


 #Bike-Sc
 for org in 1..maxZone
  for h in 1..hubs.length
  hub = hubs[h-1]
  writeln hub

   if BikeTime[org,hub] < BikeRadius
      for dest in 1..maxZone
        if ScTime[hub,dest] > ScRadius
          if omrijFactor * ScDistance[org,dest] < ScDistance[hub,dest]
# ---------- adjust to right utility-computation: -------------
            skimValueBikeSc = BikeCost[org,hub] + ScCost[hub,dest]
            if skimValueBikeSc < skimBikeSc[org,dest]
              skimBikeSc[org,dest] = skimValueBikeSc
              hubBikeSc[org,dest] = hub
              BikeScHubIndicator[org,dest] = 1
            end
          end
        end
      end
    end

  end
end

writeln Time.now, ' skims Bike-Sc computed'

#Sc-Bike
for dest in 1..maxZone
  for h in 1..hubs.length
    hub = hubs[h-1]
    writeln hub

    if BikeTime[hub,dest] < BikeRadius
      for org in 1..maxZone
        if ScTime[org,hub] > ScRadius
         if omrijFactor * ScDistance[org,dest] < ScDistance[org,hub]
# ---------- adjust to right utility-computation: -------------
            skimValueScBike= ScCost[org,hub] + BikeCost[hub,dest]
            if skimValueScBike < skimScBike[org,dest]
              skimScBike[org,dest] = skimValueScBike
              hubScBike[org,dest] = hub
              ScBikeHubIndicator[org,dest] = 1
            end
          end
        end
      end
    end

   end
```

```
end

writeln Time.now, ' skims Sc-Bike computed'


#Walk-Sb
for org in 1..maxZone
  for h in 1..hubs.length
    hub = hubs[h-1]
    writeln hub

    if WalkTime[org,hub] < WalkRadius
      for dest in 1..maxZone
        if SbTime[hub,dest] > SbRadius
          # ---------- adjust to right utility-computation: -------------
          skimValueWalkSb = WalkCost[org,hub] + SbCost[hub,dest]
          if skimValueWalkSb < skimWalkSb[org,dest]
            skimWalkSb[org,dest] = skimValueWalkSb
            hubWalkSb[org,dest] = hub
            WalkSbHubIndicator[org,dest] = 1
          end
        end
      end
    end

  end
end

writeln Time.now, ' skims Walk-Sb computed'

#Sb-Walk
for dest in 1..maxZone
  for h in 1..hubs.length
    hub = hubs[h-1]
    writeln hub

    if WalkTime[hub,dest] < WalkRadius
      for org in 1..maxZone
        if SbTime[org,hub] > SbRadius
          # ---------- adjust to right utility-computation: -------------
          skimValueSbWalk = SbCost[org,hub] + WalkCost[hub,dest]
          if skimValueSbWalk < skimSbWalk[org,dest]
            skimSbWalk[org,dest] = skimValueSbWalk
            hubSbWalk[org,dest] = hub
            SbWalkHubIndicator[org,dest] = 1
          end
        end
      end
    end


  end
end

writeln Time.now, ' skims Sb-Walk computed'

 #Walk-Sc
 for org in 1..maxZone
  for h in 1..hubs.length
  hub = hubs[h-1]
  writeln hub

   if WalkTime[org,hub] < WalkRadius
      for dest in 1..maxZone
        if ScTime[hub,dest] > ScRadius
          if omrijFactor * ScDistance[org,dest] < ScDistance[hub,dest]
# ---------- adjust to right utility-computation: -------------
           skimValueWalkSc = WalkCost[org,hub] + ScCost[hub,dest]
           if skimValueWalkSc < skimWalkSc[org,dest]
             skimWalkSc[org,dest] = skimValueWalkSc
             hubWalkSc[org,dest] = hub
             WalkScHubIndicator[org,dest] = 1
           end
          end
        end
      end
    end

  end
end

writeln Time.now, ' skims Walk-Sc computed'

#Sc-Walk
for dest in 1..maxZone
  for h in 1..hubs.length
    hub = hubs[h-1]
    writeln hub

    if WalkTime[hub,dest] < WalkRadius
      for org in 1..maxZone
        if ScTime[org,hub] > ScRadius
         if omrijFactor * ScDistance[org,dest] < ScDistance[org,hub]
# ---------- adjust to right utility-computation: -------------
           skimValueScWalk= ScCost[org,hub] + WalkCost[hub,dest]
           if skimValueScWalk < skimScWalk[org,dest]
             skimScWalk[org,dest] = skimValueScWalk
             hubScWalk[org,dest] = hub
             ScWalkHubIndicator[org,dest] = 1
           end
          end
        end
      end
    end

   end
end
```

```
writeln Time.now, ' skims Sc-Walk computed'


### SAVING SKIMS, BEST HUB PER OD-PAIR AND INDICATOR: ###
#Bike-Pt
skimCube[1,70,10,1,11,1] = skimBikePt #saving skim matrix
skimCube[1,70,10,1,18,1] = hubBikePt #saving best hub per OD-pair
skimCube[1,70,10,1,19,1] = BikePtHubIndicator #saving indicator whether or not a suitable hub is present for OD-pair (0/1)

#Pt-Bike
skimCube[1,80,10,1,11,1] = skimPtBike
skimCube[1,80,10,1,18,1] = hubPtBike
skimCube[1,80,10,1,19,1] = PtBikeHubIndicator

#Bike-Sc
skimCube[1,90,10,1,11,1] = skimBikeSc
skimCube[1,90,10,1,18,1] = hubBikeSc
skimCube[1,90,10,1,19,1] = BikeScHubIndicator

#Sc-Bike
skimCube[1,100,10,1,11,1] = skimScBike
skimCube[1,100,10,1,18,1] = hubScBike
skimCube[1,100,10,1,19,1] = ScBikeHubIndicator

#Walk-Sb
skimCube[1,110,10,1,11,1] = skimWalkSb
skimCube[1,110,10,1,18,1] = hubWalkSb
skimCube[1,110,10,1,19,1] = WalkSbHubIndicator

#Sb-Walk
skimCube[1,120,10,1,11,1] = skimSbWalk
skimCube[1,120,10,1,18,1] = hubSbWalk
skimCube[1,120,10,1,19,1] = SbWalkHubIndicator

#Walk-Sc
skimCube[1,130,10,1,11,1] = skimWalkSc
skimCube[1,130,10,1,18,1] = hubWalkSc
skimCube[1,130,10,1,19,1] = WalkScHubIndicator

#Sc-Walk
skimCube[1,140,10,1,11,1] = skimScWalk
skimCube[1,140,10,1,18,1] = hubScWalk
skimCube[1,140,10,1,19,1] = ScWalkHubIndicator


writeln Time.now, ' skims, hubs and indicators saved'

#write end time
p Time.now
tijd=Time.now - starttijd
uren    = (tijd/3600.0).floor
minuten = ((tijd/60.0)-(uren*60)).floor
seconden=(tijd-uren*3600-minuten*60).round
writelnt "  END OF SCRIPT"
writeln "Running time was #{uren} hours : #{minuten} min : #{seconden} sec = (#{tijd.round} seconds)"
```

APPENDIX C

O-D Matrices Generation per trip leg OmniTRANS Job Script

```
# O-D Matrices Generation per Trip-Leg
#write  start time
p Time.now
starttijd = Time.now

### INPUT: ###
maxZone = 32 #32 #total number of zones including hubs
grootgetal = 0 # number to used as 'default' skim value if no suitable hub is present for an OD-pair
T = 10 #time period

writeln "Creating new matrices for time period T ", T

### OPEN SKIM CUBES AND MATRICES ###

skimCube = OtSkimCube.open('Hubs')
BikePthub = skimCube[1,70,10,1,18,1] #skim indicating best hub for each OD pair for bike-PT mode chain
PtBikehub = skimCube[1,80,10,1,18,1]
BikeSchub = skimCube[1,90,10,1,18,1]
ScBikehub = skimCube[1,100,10,1,18,1]
WalkSbhub = skimCube[1,110,10,1,18,1]
SbWalkhub = skimCube[1,120,10,1,18,1]
WalkSchub = skimCube[1,130,10,1,18,1]
ScWalkhub = skimCube[1,140,10,1,18,1]
writeln Time.now, 'Skims Opened'
writeln 'Imported skim. Total: ', BikePthub.sum

matrixCube = OtMatrixCube.open('2025Shared')
BikePtMat = matrixCube[1,70,10,1]
PtBikeMat = matrixCube[1,80,10,1]
BikeScMat = matrixCube[1,90,10,1]
ScBikeMat = matrixCube[1,100,10,1]
WalkSbMat = matrixCube[1,110,10,1]
SbWalkMat = matrixCube[1,120,10,1]
WalkScMat = matrixCube[1,130,10,1]
ScWalkMat = matrixCube[1,140,10,1]
writeln Time.now, 'Matrices Opened'
writeln 'Imported matrix. Total: ', BikePtMat.sum

### GENERATING MATRICES FOR DIFFERENT LEGS OF MODE CHAINS: ###
#Bike-Pt
matrixBikePt1 = OtMatrix.new(maxZone)
matrixBikePt1[] = grootgetal
matrixBikePt2 = OtMatrix.new(maxZone)
matrixBikePt2[] = grootgetal

#Pt-Bike
matrixPtBike1 = OtMatrix.new(maxZone)
matrixPtBike1[] = grootgetal
matrixPtBike2 = OtMatrix.new(maxZone)
matrixPtBike2[] = grootgetal

#Bike-Sc
matrixBikeSc1 = OtMatrix.new(maxZone)
matrixBikeSc1[] = grootgetal
matrixBikeSc2 = OtMatrix.new(maxZone)
matrixBikeSc2[] = grootgetal

#Sc-Bike
matrixScBike1 = OtMatrix.new(maxZone)
matrixScBike1[] = grootgetal
matrixScBike2 = OtMatrix.new(maxZone)
matrixScBike2[] = grootgetal

#Walk-Sb
matrixWalkSb1 = OtMatrix.new(maxZone)
matrixWalkSb1[] = grootgetal
matrixWalkSb2 = OtMatrix.new(maxZone)
matrixWalkSb2[] = grootgetal

#Sb-Walk
matrixSbWalk1 = OtMatrix.new(maxZone)
matrixSbWalk1[] = grootgetal
matrixSbWalk2 = OtMatrix.new(maxZone)
matrixSbWalk2[] = grootgetal

#Walk-Sc
matrixWalkSc1 = OtMatrix.new(maxZone)
matrixWalkSc1[] = grootgetal
matrixWalkSc2 = OtMatrix.new(maxZone)
matrixWalkSc2[] = grootgetal

#Sc-Walk
matrixScWalk1 = OtMatrix.new(maxZone)
matrixScWalk1[] = grootgetal
matrixScWalk2 = OtMatrix.new(maxZone)
matrixScWalk2[] = grootgetal


writeln Time.now, ' new matrices are generated'


### ASSIGNING VALUES FOR THE NEW MATRICES###

#Bike-Pt

 for org in 1..maxZone
    for dest in 1..maxZone

      hub = BikePthub[org,dest]
      hub = hub.to_int
      trips = BikePtMat[org,dest]

      if hub > 0
      #writeln "origin zone:#{org}, destination zone: #{dest}"
      #writeln "hubs: #{hub}, trips: #{trips}"
      matrixBikePt1[org,hub] = matrixBikePt1[org,hub] + trips
      #writeln 'Imported matrix. Total: ', matrixBikePt1.sum
      matrixBikePt2[hub,dest] = matrixBikePt2[hub,dest] + trips
```

```
        #writeln 'Imported matrix. Total: ', matrixBikePt2.sum
      end
      end
    end

    #Pt-Bike

     for org in 1..maxZone
       for dest in 1..maxZone

        hub = PtBikehub[org,dest]
        hub = hub.to_int
        trips = PtBikeMat[org,dest]

        if hub > 0
        #writeln "origin zone:#{org}, destination zone: #{dest}"
        #writeln "hubs: #{hub}, trips: #{trips}"
        matrixPtBike1[org,hub] = matrixPtBike1[org,hub] + trips
        #writeln 'Imported matrix. Total: ', matrixPtBike1.sum
        matrixPtBike2[hub,dest] = matrixPtBike2[hub,dest] + trips
        #writeln 'Imported matrix. Total: ', matrixPtBike2.sum
      end
      end
    end

    #Bike-Sc

     for org in 1..maxZone
       for dest in 1..maxZone

        hub = BikeSchub[org,dest]
        hub = hub.to_int
        trips = BikeScMat[org,dest]

        if hub > 0
        #writeln "origin zone:#{org}, destination zone: #{dest}"
        #writeln "hubs: #{hub}, trips: #{trips}"
        matrixBikeSc1[org,hub] = matrixBikeSc1[org,hub] + trips
        #writeln 'Imported matrix. Total: ', matrixBikeSc1.sum
        matrixBikeSc2[hub,dest] = matrixBikeSc2[hub,dest] + trips
        #writeln 'Imported matrix. Total: ', matrixBikeSc2.sum
      end
      end
    end

    #Sc-Bike

     for org in 1..maxZone
       for dest in 1..maxZone

        hub = ScBikehub[org,dest]
        hub = hub.to_int
        trips = ScBikeMat[org,dest]

        if hub > 0
        #writeln "origin zone:#{org}, destination zone: #{dest}"
        #writeln "hubs: #{hub}, trips: #{trips}"
        matrixScBike1[org,hub] = matrixScBike1[org,hub] + trips
        #writeln 'Imported matrix. Total: ', matrixScBike1.sum
        matrixScBike2[hub,dest] = matrixScBike2[hub,dest] + trips
        #writeln 'Imported matrix. Total: ', matrixScBike2.sum
      end
      end
    end

    #Walk-Sb

     for org in 1..maxZone
       for dest in 1..maxZone

        hub = WalkSbhub[org,dest]
        hub = hub.to_int
        trips = WalkSbMat[org,dest]

        if hub > 0
        #writeln "origin zone:#{org}, destination zone: #{dest}"
        #writeln "hubs: #{hub}, trips: #{trips}"
        matrixWalkSb1[org,hub] = matrixWalkSb1[org,hub] + trips
        #writeln 'Imported matrix. Total: ', matrixWalkSb1.sum
        matrixWalkSb2[hub,dest] = matrixWalkSb2[hub,dest] + trips
        #writeln 'Imported matrix. Total: ', matrixWalkSb2.sum
      end
      end
    end

    #Sb-Walk

      for org in 1..maxZone
       for dest in 1..maxZone

        hub = SbWalkhub[org,dest]
        hub = hub.to_int
        trips = SbWalkMat[org,dest]

        if hub > 0
        #writeln "origin zone:#{org}, destination zone: #{dest}"
        #writeln "hubs: #{hub}, trips: #{trips}"
        matrixSbWalk1[org,hub] = matrixSbWalk1[org,hub] + trips
        #writeln 'Imported matrix. Total: ', matrixSbWalk1.sum
        matrixSbWalk2[hub,dest] = matrixSbWalk2[hub,dest] + trips
        #writeln 'Imported matrix. Total: ', matrixSbWalk2.sum
      end
      end
    end

    #Walk-Sc

    for org in 1..maxZone
```

```
      for dest in 1..maxZone

       hub = WalkSchub[org,dest]
       hub = hub.to_int
       trips = WalkScMat[org,dest]

       if hub > 0
       #writeln "origin zone:#{org}, destination zone: #{dest}"
       #writeln "hubs: #{hub}, trips: #{trips}"
       matrixWalkSc1[org,hub] = matrixWalkSc1[org,hub] + trips
       #writeln 'Imported matrix. Total: ', matrixWalkSc1.sum
       matrixWalkSc2[hub,dest] = matrixWalkSc2[hub,dest] + trips
       #writeln 'Imported matrix. Total: ', matrixWalkSc2.sum
     end
     end
   end

   #Sc-Walk

   for org in 1..maxZone
      for dest in 1..maxZone

       hub = ScWalkhub[org,dest]
       hub = hub.to_int
       trips = ScWalkMat[org,dest]

       if hub > 0
       #writeln "origin zone:#{org}, destination zone: #{dest}"
       #writeln "hubs: #{hub}, trips: #{trips}"
       matrixScWalk1[org,hub] = matrixScWalk1[org,hub] + trips
       #writeln 'Imported matrix. Total: ', matrixScWalk1.sum
       matrixScWalk2[hub,dest] = matrixScWalk2[hub,dest] + trips
       #writeln 'Imported matrix. Total: ', matrixScWalk2.sum
     end
     end
   end

writeln Time.now, 'Values for new matrices generated'

### SAVING SKIMS, BEST HUB PER OD-PAIR AND INDICATOR: ###
#Bike-Pt
matrixCube[1,20,10,70] = matrixBikePt1
matrixCube[1,30,10,70] = matrixBikePt2

#Pt-Bike
matrixCube[1,30,10,80] = matrixPtBike1
matrixCube[1,20,10,80] = matrixPtBike2

#Bike-Sc
matrixCube[1,20,10,90] = matrixBikeSc1
matrixCube[1,60,10,90] = matrixBikeSc2

#Sc-Bike
matrixCube[1,60,10,100] = matrixScBike1
matrixCube[1,20,10,100] = matrixScBike2

#walk-sb
matrixCube[1,40,10,110] = matrixWalkSb1
matrixCube[1,50,10,110] = matrixWalkSb2

#sb-walk
matrixCube[1,50,10,120] = matrixSbWalk1
matrixCube[1,40,10,120] = matrixSbWalk2

#walk-sc
matrixCube[1,40,10,130] = matrixWalkSc1
matrixCube[1,60,10,130] = matrixWalkSc2

#sc-walk
matrixCube[1,60,10,140] = matrixScWalk1
matrixCube[1,40,10,140] = matrixScWalk2
writeln Time.now, 'New Matrices Saved'
```