CONSTRUCTING PERSONALIZED TRANSPORTATION NETWORKS IN MULTI-STATE SUPERNETWORKS: A HEURISTIC APPROACH

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ABSTRACT

For accessibility analysis, an integrated view encompassing the networks for public and private transport modes as well as the activity programs of travellers is essential. In earlier research, the supernetwork has been put forward by the authors as a suitable technique to model the system in such an integrated fashion. An essential part of a supernetwork model for multi-modal and multi-activity travel planning is the personalized transportation network. This is an under researched topic in the academic community. This paper attempts to develop a heuristic approach to construct personalized transportation networks for an individual's activity program. In this approach, the personalized network consists of two types of network extractions from the original transportation system, namely the public transport network (PTN) and the private vehicle network (PVN). PTN is composed of selected public transport connections based on an individual's preferences related to walking distance, transfer times, fare and time cost, etc.; whereas the PVN is constructed on the basis of optimal routes of the considered private vehicles in a hierarchical road network based on multi-attribute link costs functions. Two cases are presented to illustrate that the PTN and PVN can represent an individual's attributes and perceptions appropriately and be applied in large-scale applications for analyzing land-use and transport systems.

Keywords: supernetwork, multi-modal and multi-activity trips, accessibility analysis, heuristic approach, personalized networks.

1. INTRODUCTION

Accessibility of locations is commonly conceptualized as a characteristic of a transportation system and location-based services that determines the ease with which users can implement their activity programs. This concept of accessibility has a long history in urban planning and transportation research. In the last century various measurements and related operationalizations have been suggested. Originally, accessibility was measured in terms of the number of opportunities that could be reached within a user defined radius for a certain motive (Vickerman,1974). Later, distance decay functions were used rather than deterministic radii (Handy and Niemeier,1997). These measures thus focus on the spatial configuration of opportunities, i.e. on the supply side. Based on the criticism that these measures did not take individuals' preferences and constraints into account, these supply measures were complemented with measures focusing on spatial choice behaviour. Examples are the utility-based accessibility measures (Ben-Akiva and Lerman, 1977; Pirie,1979) and the time-space measures (Ashiru et al. 2003), suggested in time geography, which captures the available opportunities in time-space prisms or the number of alternative ways any given activity-travel pattern can be realized, given a set of time-space constraints.

Irrespective of the specific approach, these existing measures are largely insensitive to the degree transport networks for different modes and location-based services are mutually adjusted or synchronized with respect to activity programs. More recently, Multi-state supernetworks have been identified as a promising way to analyze the accessibility of land-use and transportation systems for implementing full activity programs of individuals (Arentze and Timmermans, 2004; Liao et al., 2010). A supernetwork is a network connecting different networks for different transport modes (private and public ones) as well as the locations where individuals can conduct activities. A path through such a supernetwork describes a particular way of implementing a given activity program in time and space. This approach allows the simultaneous choice of all relevant facets of an activity program including the sequence of activities, transport modes, routes, parking and transfers, locations, and a multi-criteria, state-dependent evaluation of paths through the network.

The fact that multiple transport networks and activity locations are integrated into a single representation implies that the network becomes very large and complex. It is therefore important to construct personalized networks. This idea is based on the assumption that from the perspective of an individual and activity program only a small number of destinations and also a relatively small section of the complete transport system will be relevant. As indicated (Arentze and Timmermans, 2004; Liao et al., 2010), personalized supernetwork are essential because they reduce the computation time in large-scale applications for analyzing land-use and transport systems with loss of representational possibilities. However, as an important part of such a supernetwork model, the personalized network is an under researched topic in the academic community.

The objective of this paper therefore is to report the development of a heuristic approach to construct personalized networks for a given individual and activity program. In this approach, the personalized network consists of two types of network extractions from the original transportation system, namely PTN and PVN. The PTN is composed of selected public transport connections based on the individual's preferences related to walking distance, transfer times, fare and time cost, etc., whereas the PVN consists of the optimal routes of the chosen private vehicles in a hierarchical road network based on multi-attribute link-costs functions as well. To make the PTN and PVN fit into the multi-state supernetwork, the assumption is made that the activity state may affect the total disutility of a public transport or private vehicle connection between two locations but does not change the connection composition itself. Based on this, the PTN and PVN are valid until the activity program is changed.

We develop the new approach and test it on the multi-state supernetworks of the administrative Eindhoven region (the Netherlands) using a large sample of activity programs obtained from an activity diary data collection in the Netherlands. The paper is organized as follows. First, based on Liao et al. (2010), we will summarize the quintessence of multi-state supernetworks. Next, we will discuss the principles of the heuristic approach. This is followed by a discussion of the results of the empirical application. The paper is completed with a discussion of major conclusions and avenues for future research.

2. THE MULTI-STATE SUPERNETWORK MODEL

Supernetworks were originally introduced in transportation research as a means of integrating transport networks of different modes (Sheffi, 1985). To connect these networks, links interconnecting the physical networks are identified and represent transfer locations where individuals can switch between modes. Arentze and Timmermans (2004) suggested an extension of the basic supernetwork concept to integrate activity locations and multi-modal transport networks, which realized the transition from trip-based supernetworks to activity-based supernetworks. For this, nodes representing activity locations are added to represent the characteristics of activities at these nodes. These nodes are interconnected by links that represent the implementation of activities and where a traveller changes state by moving to a next stage of implementing his/her activity program. A potential drawback of their approach is that the networks may become very large and possibly intractable since the networks need to incorporate as many copies of a physical network as there are possible states associated with the different stages of an activity program.

Based on the work of Arentze and Timmermans (2004), Liao et al. (2010) proposed an improved supernetwork representation, which is easier to construct and reduces the size needed to embody all combinations of choice facets considerably. In this approach, the integrated transport network is split into PTN and PVNs, which are interconnected by links where the traveller can transfer from a private to a public mode. PTN contains the modes of walking and public transport. Since it can be a multi-modal network, if any node induces a mode change, extra bi-directed links are added to denote boarding/alighting transition links. In contrast, only one mode is involved in each PVN so there is no need to extend it. As many copies of PTN and PVNs are included as there are activity-vehicle states. An activity-vehicle state refers to the combination of activity and vehicle state where an activity state defines the subset of activities that has been conducted and a vehicle state defines which private vehicles, if any, are used during executing the activity program. To capture all possible state transitions, the PTNs and PVNs positioned at different states are connected into a supernetwork through transition links representing activities at a location (activity state transition) or picking-up or parking a vehicle (vehicle state transition).

Figure 1 is an example of the supernetwork representation, which unifies three optional modes, i.e. car, bike and walking, with which the traveller can depart from home to implement an activity program. A horizontal transition link represents parking/picking-up a private vehicle while a vertical one denotes conducting an activity. This example represents an activity program of 2 activities, 2 private vehicles and 4 parking locations resulting in 4 activity states and 7 vehicle states. As an example, the bold route represents the tour characterized by the individual leaving home by bike, parking the bike at P_4, and taking public transport connection to conduct A_2. Then, the individual goes back to P_4 and picks up the bike, rides the bike again, parks at P_3, conducts A_1, and finally picks up the bike at P_3, and returns home with all activities conducted and the vehicle returned. As shown, multi-modal trips involving private and public transport modes are supported in this supernetwork representation.

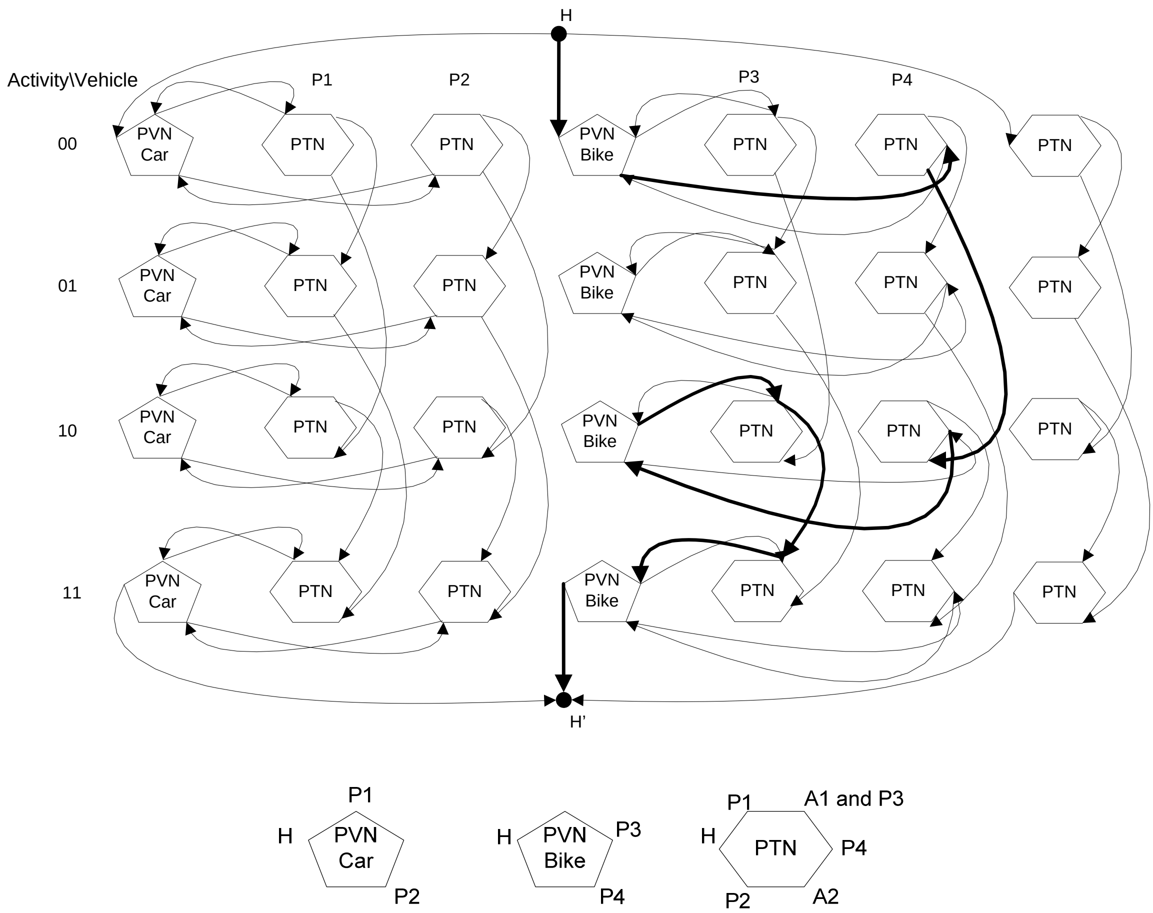


Figure 1 – supernetwork representation of an activity program

In the supernetwork, the nodes denote real locations in space and every link represents an individual's action such as walking, cycling, driving, parking or picking-up a car, boarding or alighting a bus or train, conducting a specific activity, etc. Therefore, every link cost can be defined in a state-dependent and personalized way. Proofs were also provided that the supernetwork represents a reduced action space and that the least-cost path is the most desirable activity tour of a rational individual. The size of the costs of the least-cost path is considered a measure of accessibility of locations for the activity program considered that takes into account interconnectivity of transport networks and locations.

Although the split between PTN and PVN is beneficial to the supernetwork model, the approach still leaves open the question how personalized networks can be constructed to reduce the representation and thus allow full-scale applications of the model. The following part of this paper therefore discusses a heuristic approach to construct the personalized transportation networks for any given individual and activity program.

3. PERSONALIZED TRANSPORTATION NETWORK

To keep consistency with our supernetwork model, the personalized transportation network refers to an interconnected PTN and PVN. We also adopt the same definition of *activity program*, which includes three aspects: (1) the individual leaves home with at most one private vehicle to conduct at least one activity, and returns home with all activities conducted and all private vehicles at home; (2) there may be some sequential relationship between the activities, due to the nature of the activity or due to individual preferences; (3) the individual has at most three departing modes: walking, bike, and car.

It is widely recognized that location-based facilities and transportation system together form the urban space that influences people’s life by providing both opportunities and constraints when people conduct their activities (Arentze and Timmermans, 2000). However, as far as an individual’s daily activity program is concerned, only a rather small set of locations for activities will be of interest to the individual. Once the locations of activity facilities are determined, the individual will always consider the most satisfactory routes with the least generalized costs to get there. Therefore, a natural way to obtain the personalized transportation networks is to select and unify all most satisfactory routes that interconnect all locations concerned including the home location. The remainder of this section will first consider the cost functions of the links in the supernetwork model. Next, we will focus on the construction of personalized networks based on this concept.

3.1 Link cost functions

We adopt a generalized link cost framework (Arentze and Timmermans, 2004) for both transport and transition links. In general, the costs of a link represent a perceived disutility of the link. A Link that always causes a change of location is a transport link; whereas, a link that never causes a change of location but a change of mode or activity state is a transition link. Let s be the state of an individual i at a given point in time. Then the link costs functions are defined as follows.

3.1.1 Transport link cost functions

Transport links include the links that can be travelled by walking, bike, car or public transport. Given the objective on accessibility analysis, only *two* most important components *time* and *cost* are presently included in the functions. We define disutility rather than utility to make sure that least costs paths correspond to maximum utility paths.

1. Walking: $disU_{isWl} = \beta_{isWt} \times time_{Wl} + \epsilon_{isWl}$ (1)

2. Bike: $disU_{isBl} = \beta_{isBt} \times time_{Bl} + \epsilon_{isBl}$ (2)

3. Car: $disU_{isCl} = \beta_{isCt} \times time_{Cl} + \beta_{isCc} \times cost_{Cl} + \epsilon_{isCl}$ (3)

4. Public transport: $disU_{isPTl} = \beta_{isPTt} \times time_{PTl} + \beta_{isPTc} \times cost_{PTl} + \epsilon_{isPTl}$ (4)

where $disU_{is*l}$ denote the disutility of using link l by a particular mode ($* = \{W, B, C\}$), β_{is*t} and β_{is*c} represent the weights of time and cost components by different modes respectively, and ϵ_{is*l} are unobserved components of the individual's preferences. Note that transport links for public transport represent only the in-vehicle parts of trips, since access, egress, alighting and boarding components of these trips are represented as separated links. For example, disutility of waiting at stops/stations is modelled as costs of transition links.

3.1.2 Transition link cost functions

Transition links include parking and picking-up a private vehicle, boarding and alighting a public transport vehicle, and conducting an activity. Costs functions on these levels are defined as follows.

1. Parking: $disU_{isPKvp} = \boldsymbol{\beta}_{isPKv} \times \boldsymbol{X}_{isPKv\boldsymbol{p}} + \epsilon_{isPKvp}$ (5)

where $disU_{isPKvp}$ denotes the disutility of parking private vehicle v ($v \in \{\mathrm{Bike}, \mathrm{Car}\}$)at location p, $\boldsymbol{X}_{PKvp}$ is a vector of factors of parking v at p including cost, access time, parking type and safety, $\boldsymbol{\beta}_{isPKv}$ is a weight vector of these factors, and ϵ_{isPKvp} relates to unobserved components.

2. Picking-up: $disU_{isPUvp} = \beta_{isPUve} \times eTime_{isPUvp}$ (6)

where $disU_{isPUvp}$ denotes the disutility of picking-up private vehicle v at location p, $eTime_{PUvp}$ is the egress time which refers to the time taken by v from p to the road network, and β_{isPUve} is the weight on egress time.

3. Boarding: $disU_{isBDt} = \boldsymbol{\beta}_{isBD} \times \boldsymbol{X}_{isBDt} + \epsilon_{isBDt}$ (7)

where $disU_{isBDt}$ denotes the disutility of boarding at public transport stop t, $\boldsymbol{X}_{BDt}$ is a vector of factors of boarding at t, including waiting time and location attractiveness, $\boldsymbol{\beta}_{isBD}$ is a weight vector, and ϵ_{isBDt} is an error term.

4. Alighting: $disU_{isATt} = \beta_{isATe} \times eTime_{isATt}$ (8)

where $disU_{isATt}$ denotes the disutility of alighting at public transport stop t, $eTime_{ATt}$ is the egress time which refers to the time taken from t to the road network, and β_{isATe} is the weight.

5. Conducting an activity: $disU_{isCAjk} = \boldsymbol{\beta}_{isCAj} \times \boldsymbol{X}_{isCAjk} + \epsilon_{isCAjk}$ (9)

where $disU_{isCAjk}$ denotes the disutility of conducting activity j at alternative location k, $\boldsymbol{X}_{isCAjk}$ is a vector of factors of conducting j at k including price, quality, service, and activity duration, $\boldsymbol{\beta}_{isCAj}$ is a weight vector, and ϵ_{isCAjk} is an error term. Despite the fact that conducting an activity as a rule produces utility, to keep consistency with the supernetwork model, this paper adopts the concept of disutility in the sense that the location where an activity is conducted is at most as good as an ideal location. In other words, disutility refers to a loss compared to a hypothetical ideal location.

6. Departing home: $disU_{idm} = C_{idm}$ (10)

where m denotes the departing mode, $m \in \{\text{Walking}, \text{Bike}, \text{Car}\}$, $disU_{idm}$ denotes the disutility of departing home with mode m, and C_{idm} is the constant component for preference. Note that since travel costs are accounted for on the level of transport links, the disutility on this level represents a base preference for the mode or, more precisely, a loss relative to the most preferred mode evaluated at a distance of zero.

7. Returning home: $disU_{irm} = C_{irm}$ (11)

where $disU_{irm}$ denote the disutility of returning home with mode m and C_{irm}, as before, relates to a base preference for the mode.

As shown in the functions above, the disutility on each link is state-dependent. However, as a preprocessing step for the supernetwork model, the construction of PTNs and PVNs is contingent on no activity state or only on the beginning situation when the individual has not departed home. This means that the heuristic rules discussed below for selecting the locations and connections are not referring to any activity state occurring in later stages of the activity program.

3.1 Construction of PTN

Due to the fact that public transport provides an affordable choice for personal mobility and freedom for people from every walk of life, public transport is always an alternative means for mobility. Thus, public transport is always taken into account in judging what an individual can do within the existing urban environment, even if the individual has higher preference for a private vehicle.

To get the public transport connections, the first step is to decide on the relevant activity locations. Given an activity program, an individual would in the first place think about where to locate the activities. According to whether an activity has more than one alternative location or not, it can be classified as *with fixed location* or *with flexible locations*. Consider for example the activity *work*. If the individual is required to be present at a specified working location, *work* is an activity with fixed location. Similarly, home is regarded as a fixed location where the individual leaves from and returns to. By contrast, *shopping* often allows a location choice and, therefore, generally is an activity with flexible locations. It is trivial to locate activities with fixed locations. For those with flexible locations, the individual may need to narrow down the choice set into a smaller consideration set. In this decision-making process, two key factors are the disutility of conducting the activity at a location alternative and a trip association with other activities (Joh et al., 2005). The former is defined by Equation (9) when we assume the activity state the individual is in before leaving home. The latter can be defined in terms of average travel efforts from or to so-called associable activity locations. Depending on the sequential relationship, two activities are associable only if the two activities can be conducted in succession. Similarly, two *locations* are associable only if there are activities at these two locations that are associable. Based on these two components, a location choice model (Sivakumar and Bhat, 2007)can be applied to narrow down the choice set for an activity with flexible locations:

$$disU_{iCAjk} = disU_{iCAjk} + travel_{iCAjk} \quad (12)$$

where

$disU_{iCAjk}$: disutility of individual i choosing alternative k for activity j

$disU_{iCAjk}$: disutility of conducting j at alternative k

$travel_{iAjk}$: average travel disutility from or to associable activity locations

There are two ways of narrowing down the choice set: (1) selecting a specified number N_j of alternatives with the least disutilities; or (2) selecting a specified proportion P_j of the total with the least disutilities. Note that the target of the selection is not to find the best location, which is done in the supernetwork model, but to eliminate candidates that are highly unlikely to be chosen. Thus, travel disutility can be calculated by means of estimated distance. For example, suppose an activity program (see Figure 2), in which A and B are fixed locations, 5 black dots are the alternative locations for activity C given that they are associable to both A and B. Suppose further that direct distance is taken as a measure of travel effort and 5 locations have the same disutility. If the individual has a strong dislike of travel, 4 and 5 will be eliminated.

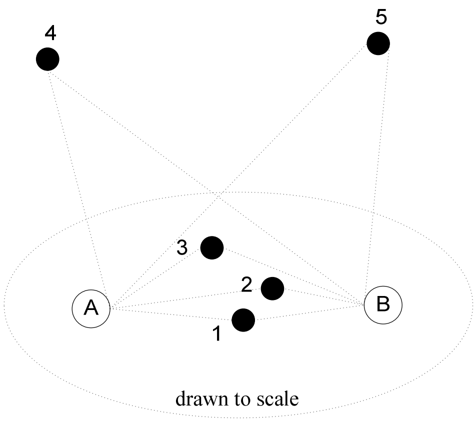


Figure 2 – Example of narrowing down the choice set

The second step is to select the most satisfactory public transport connections between any two associable locations. Public transport connections include walking paths to the neighbouring public transport stops, boarding, transit paths and alighting between the stops. Allowing for the case that walking could be better than taking any public transport, the walking path between the two locations is also regarded as a public transport connection. Figure 3 is an example of a public transport connection set between two locations A and B. Note that these components refer to different types of links in a supernetwork that are combined sequentially in a path (Wardman, 2003). For each pair of associable locations, a public transport connection choice model can be applied for the selection:

$$disU_{PTCc} = (disU_{iW} + disU_{iPT} + disU_{iBD} + disU_{iAT})|_c \tag{13}$$

where $disU_{PTCc}$ denotes the disutility of taking public transport connection c, and the right-hand side of the function represents 4 parts of the disutility distributed on c, which are defined by Equations (1), (4), (5) and (6) assuming, again, the activity state before the trip.

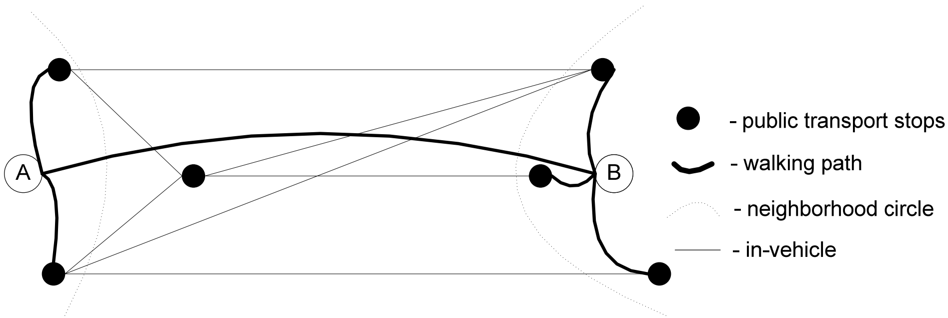


Figure 3 – example of public connections

Unlike the location choice model, the public transport connection choice model only chooses one alternative with the least disutility because the individual always selects the most satisfactory one when the two locations are known. We assume that the selected connection is symmetrically bi-directed. Hence, if there are n locations appearing in the activity program after the first step, at most $\frac{n\times(n-1)}{2}$ public transport connections will be selected.

After the first two steps, all the selected public transport connections together form the PTN of departing home by the mode of walking, denoted as PTN_w. If the individual has the freedom to use a private vehicle, the next step is to add parking locations and related walking paths to complete the PTN.

The purpose of using a private vehicle is either to access an activity location directly or access transport hubs and switch to public transport if the destination is a bit far from home. Thus, reasonable choices of parking locations can be in the vicinity of transport hubs and activity locations, which are called *potential parking locations*. Without loss of generality, we set two types of distance circles with both centers at home for a private vehicle v ($v \in \{\text{Bike}, \text{Car}\}$): acceptance distance circle (d_{iva}) and limitation distance circle (d_{ivl}), which satisfy $d_{iva} < d_{ivl}$. If an activity location lies outside the circle with radius d_{ivl}, it is not considered a potential location for parking. If there exists one activity location outside the circle with radius d_{iva}, potential locations include the transport hubs that reside inside this and occur in PTN_w. If such a transport hub does not exist, the public transport stop that is in PTN_w and closest to home is considered. Otherwise, activity locations are all considered as potential locations for parking. Figure 4 shows an example that activity location A and transport hub TH are potential parking locations.

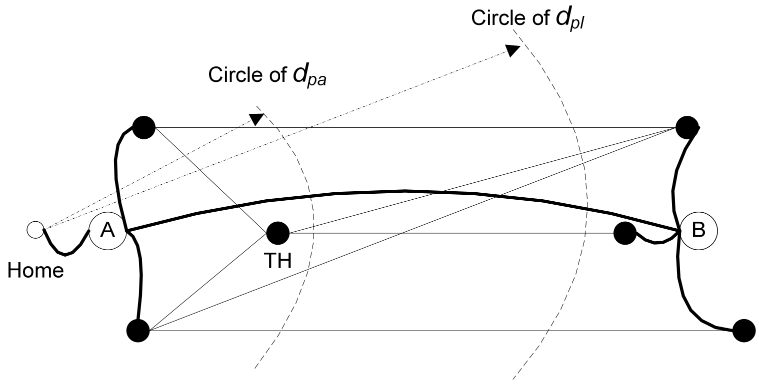


Figure 4 – example of potential parking location

To further evaluate the parking locations, we adopt a traditional parking choice model (Benenson et al., 2008) to select specific parking locations for each potential parking location:

$$disU_{iPKvp} = disU_{iPKvp} + travel_{PKp} \tag{14}$$

where

$disU_{iPKvp}$: disutility of i choosing parking for v at p

$disU_{iPKvp}$: disutility of parking v at p

$travel_{PKp}$: travel disutility to its corresponding potential parking location

At most 2 parking locations are selected for each potential parking location: at most one with parking cost and at most one without parking cost. Since there is always a short walking path between the parking location and the destination, such walking paths are added to the PTN_w.

After executing all the steps mentioned above, the PTN is constructed. It contains the home location, parking locations, a few public transport stops/stations, and walking paths and transit paths that connect the locations.

3.2 Construction of PVN

In our supernetwork model, PVN is constructed when the individual has the possibility to use private vehicles. It is used to realize the transitions between different vehicle states. If the individual has no private vehicle, PVN is not relevant and there is no need to construct the PVN. Otherwise, the PVN is a set of private vehicle connections between different locations where private vehicles can be parked. Just as the individual always selects the most satisfactory public transport connection, she/he would also choose the most satisfactory private vehicle connection once two locations and the mode are given. Thus, the PVN is reduced to a set of the most satisfactory private vehicle connections except between those parking locations which correspond to and only to the same potential parking location or same activity.

To capture the transition between vehicle states and consequences for link costs and link availability, the PVN is constructed specifically for each possible departing mode, i.e. bike and car (see Figure 1). For each departing mode, the individual can assign mode-dependent and personalized costs to the roads of the road network, which are functions of mode, travel time and travel costs (see Section 3.1).

Therefore, the most satisfactory private vehicle connection between two locations is the least-cost path, which can be solved by standard shortest path algorithms. In sum, PVN are mode-specified networks which respectively contain home, parking locations and optimal paths that connect these locations.

In summary, based on the rules mentioned above, the proposed heuristic algorithm to construct *personalized transportation networks* can be described as follows:

Step 1: observe an individual's activity program, and set all personalized parameters;

Step 2: select the location of each activity with fixed location;

Step 3: select the location choice set for each activity with flexible locations using Equation (12);

Step 4: select the most satisfactory public transport connection for any two associable locations using Equation (13);

Step 5: if the individual does not have the possibility to use a private vehicle, define the union of selections as the output PTN, and exit; else, go to Step 6

Step 6: for each possible departing mode, first select the potential parking locations and then select the specific parking locations using Equation (14); then define the union of the selections as the output PTN;

Step 7: for each possible departing mode, and for any two locations selected in PVN, if there needs to be a private vehicle connection, select the most satisfactory one;

Step 8: unify the selections and output the mode-specific PVN.

Using this algorithm, we obtain the personalized transportation networks for an individual's activity program. However, they are only the network extractions before implementing the activity program. To make them fit into the supernetwork model, we make an assumption that the activity state may affect the total disutility on a public transport or private vehicle connection but does not change the choice of connection within a mode. The assumption is based on the notion that people in most cases take the same route given a transport mode irrespective the activity state (although they may choose a different mode depending on the activity state). With this assumption, we can argue that the personalized transportation networks contain the routes and locations that are most likely to be chosen by the individual. Therefore, the supernetwork representation is the action space of implementing the whole activity program.

4. **Case study**

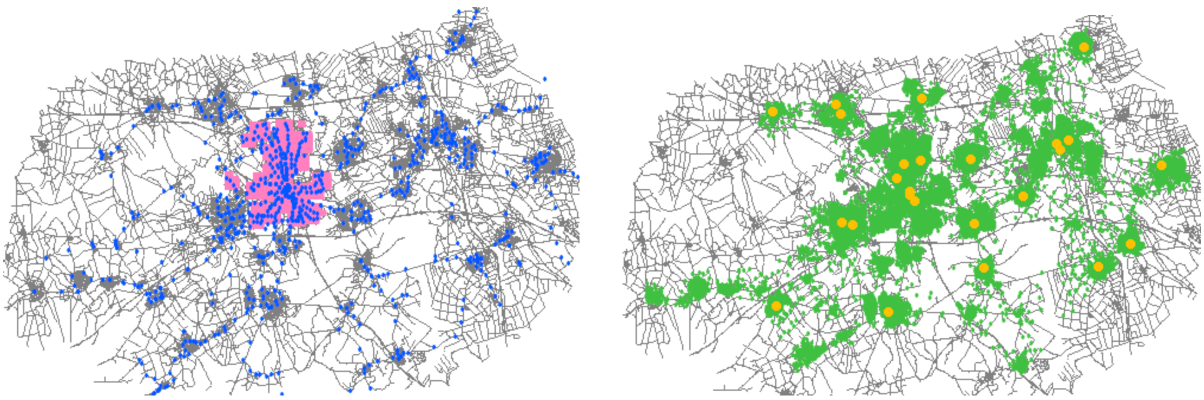
In this section, we present two examples to illustrate how the personalized transportation networks are constructed for a given activity program and how they can be applied in the supernetwork model for a large-scale accessibility analysis. The heuristic algorithm and the supernetwork model is executed in Matlab in Windows environment running at a PC with Intel® Core™2 Duo CPU E8400@ 3.00GHz 3.21G RAM. The study area is the administrative Eindhoven region, which includes 20 places (towns). The case study assumes that people living in Eindhoven city have their activities conducted within the administrative Eindhoven region.

4.1 Data

Five data sets (Table 1) are collected for delineating the location-based facilities and transport system of the administrative Eindhoven region. In Figure 4, pink, green, orange and blue dots denote the locations for 1-4 items in Table 1, and gray lines denote the road network.

Table I – Data sets collected for the case study

NO.	Data Set	Data source	Description
1	Locations for residence	NRM 2004	*Residence information of the Eindhoven city.*
2	Locations for employee	(*selected by TransCAD*)	*Employee information of the administrative Eindhoven region, including 15851 different locations for 32 types of occupation.*
3	Locations for paid parking	(*selected manually)*	*Paid parking at city centers, shopping centers and train stations.*
4	Public transport (bus and train)	www.hermes.nl www.ns.nl	*Timetable of all the buses and trains in the administrative Eindhoven region.*
5	Road network	NWB 2003 (*selected by TransCAD*)	*Road information of the administrative Eindhoven region, including 28734 nodes and 40680 undirected links.*



(a) (b)

Figure 4 – delineation of the study area (scale: 1:500,000)

Since there is no complete information about the factors mentioned in the link cost function of conducting an activity, activity duration (time component)and the difference between the number of employees at a activity location and the maximum number of the same activity type (service component) are used as the two factors. The corresponding weights are denoted by β_{iCAt} and β_{iCAs}. As there is no complete information about the factors mentioned in the parking location utility model, the average parking cost is used as the only factor of parking at a location. Its corresponding weight is denoted by β_{iPKc}. 25 paid parking areas are selected for car; elsewhere, there is no monetary parking cost. Assume the distance from a car parking location to its potential parking location is uniformly distributed in the range [0, 200 m]. Any locations can be considered for bike parking, and it is free.

There are 877 stops/stations in 63 public transport lines. We assume that the average waiting time at a stop is 5 minutes and the average cost is 0.2 €/km in the bus or train. There are 3 road classifications: G (local), P (provincial) and R (national) roads. We assume that the average car speed is 36 km/h, 60 km/h and 90 km/h respectively on G, P and R, whereas assumed fuel cost is 0.18 €/km, 0.15 €/km and 0.12 €/km respectively on G, P and R roads. Average bike speed is 12 km/h and 18 km/h respectively on G and P roads, and average waking speed is 6 km/h on G and P roads.

4.2 Case 1: PTN and PVN

This case considers an individual who lives in the northern part of Eindhoven city has an activity program on a typical day, which includes (1) three activities, i.e. working at the office, picking-up her/his child from the day-care, and shopping, with durations 540, 2 and 10 minutes respectively; (2) sequential relationship satisfying working prior to picking-up, picking-up prior to shopping and free to choose dropping off the child at home before or after shopping; (3) ownership of a bike. In addition, we assume that the disutility will increase only when walking or cycling with the child. The activity program further implies:

1. There are fixed activity locations for working and picking-up, and flexible activity locations for shopping.

2. There will be 6 activity states in the supernetwork representation according to the sequential relationships.

3. The parking locations could be the activity locations and some transport hubs, if any, since bike is the only private vehicle and it is free to park a bike anywhere. Consequently, there is only one mode-specific PVN.

The relevant personalized parameters of the link costs are set as follows (Table 2). Acceptance and limitation distance for bike are set as d_{iBa} = 5 km and d_{iBl} =15 km respectively. As an illustration, 3 locations are selected for shopping when applying the location choice model (N_j=3), and the egress time for picking-up the bike and alighting is set zero. (Error components of link costs functions are randomly drawn from a normal distribution.)

Table 2- Personalized parameters

For transport links							
The activity state without child				The activity state with child			
β_{iWt}	β_{iBt}	β_{iPTt}	β_{iPTc}	β_{iWt}	β_{iBt}	β_{iPTt}	β_{iPTc}
1.95	1.87	1.71	5.16	2.43	2.06	1.71	5.36
For transition links							
$\boldsymbol{\beta}_{iBD}$	β_{iATe}	β_{iCAt}	β_{iCAs}	C_{dB}	C_{dw}	C_{rB}	C_{rw}
(1.56, 0)	1	1	0.008	-9.75	-5.76	0	0

According to the steps of the heuristic algorithm, the construction of PTN and PVN can be described as follows. First the activities with fixed locations are located in Figure 5, in which the green dots denote the alternative locations for shopping. Second, the three alternatives are selected for shopping in terms of Eq. (10) (Figure 6). Then, the public transport connections are selected in terms of Eq. (11) (Figure 7). Next, the parking locations are selected at the activity location since they are all inside the circle of d_{ipa} (Figure 8). Finally, the bike connections are selected (Figure 9). Figure 10 and 11 are the PVN and PTN of the individual's activity program, in which the public transport and private vehicles are considered bi-directed. Thus, there are 6 nodes and 24 edges, and 25 nodes and 60 edges in PVN and PTN respectively, which are considerably reduced compared to the raw integrated network.

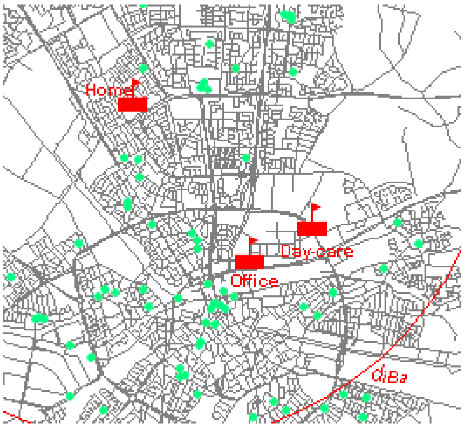


Figure 5 – Locating activities (scale: 1:100,000)

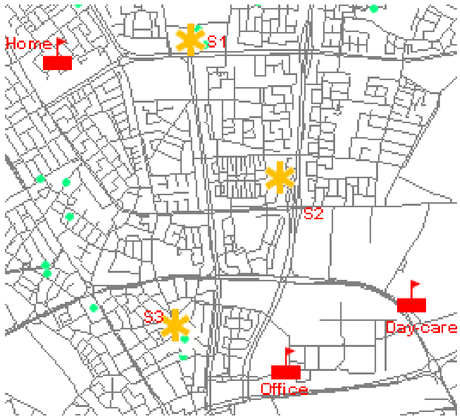


Figure 6 – Locating activities (scale: 1:50,000)

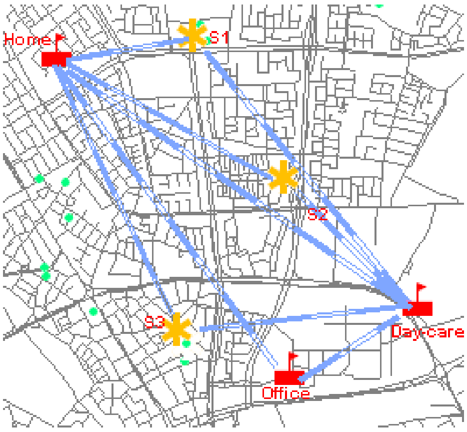


Figure 7 – Public transport connection

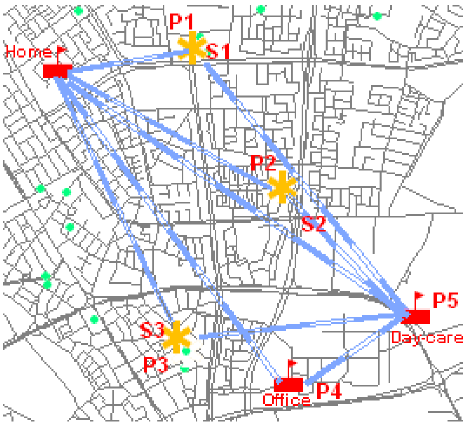


Figure 8 – Selecting Parking Locations

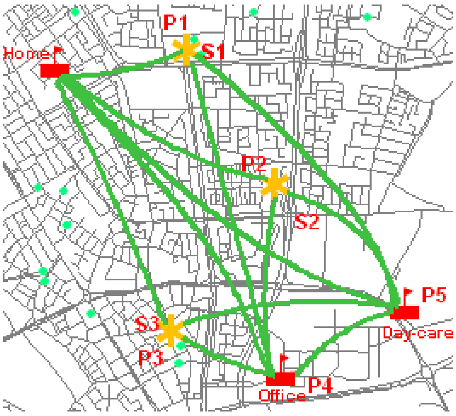


Figure 9 – Bike connections

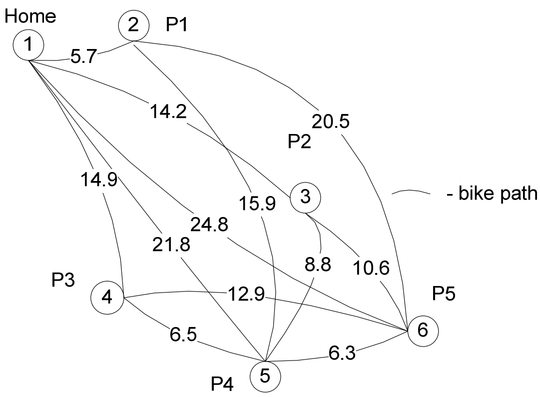


Figure 10 – Bike mode-specified PVN

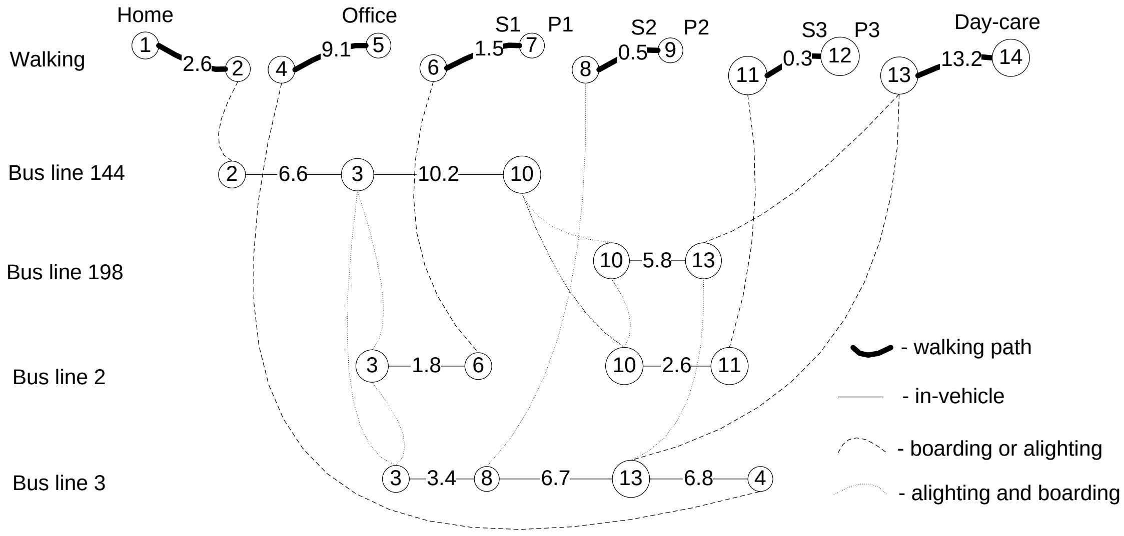


Figure 11 – Extension of PTN with boarding and alighting links

After incorporating PTN and PVN units in the multi-state supernetwork model (see Section 2), two least-disutility activity tours are generated for two different departing modes, with disutilities of 589.31 and 637.24 units respectively for bike and walking. Thus, the individual would take the bike as the departing mode, and its activity tour suggests that the individual always ride the bike to the activity location, park it there, and conduct the activity, then pick-up the bike and ride to the next activity location, and so forth.

In constructing the PTN and PVN, the key parameter is how many alternatives are selected for shopping since scale of the following steps are all based on this. Table 3 is the comparisons with different values of N_j in the supernetwork of departing mode as bike. As there are unobserved components, the model including the constructions of personalized transportation networks and supernetwork runs 10 times for each N_j and averages are shown in the table. It shows when N_j=10 a good balance is reached between optimality and running time (which is expected to be less since the model is implemented in an explanatory language).

However, if using the same supernetwork representation with the original integrated network and without any selection, there will be more than 3×10^8 nodes in the supernetwork given that there are 2031 alternatives for shopping. Moreover, the supernetwork is no longer a road network and the link costs are dynamic with different individuals' attributes, which render the optimization speeding-up techniques such as goal-directed search and highway hierarchy invalid. It takes several minutes to find the optimal activity tour in a personal computer. However, it will take much longer or even be intractable if either increasing the number of activity states or putting the activity program in a larger area.

Table 3- Comparison with different value of N_j

N_j	Number of nodes in			*Aver_disU* *(Bike)*	*Aver*_time(s)
	PVN	PTN	Supernetwork		
1	4	17	126	599.33	0.07
3	6	25	486	598.14	0.10
5	8	32	1008	588.08	0.14
10	13	43	2658	579.91	0.20
30	23	98	17778	579.69	0.52
50	103	125	38118	579.92	0.87
100	203	208	126018	579.83	1.8
500	503	807	2424018	580.06	29.2

4.3 Case 2: accessibility analysis

This case study concerns a set of activity programs which are converted based on the definition of *activity program* from the Dutch national travel survey collected in 2004 (MON). A population of 44090 individuals (over 11 and under 80) from 23800 households with total 83750 activities are examined. Table 4 and 5 display the classifications of trip purposes (activities in this paper) in the MON and ratios of different activity types respectively. We classify an activity as whether with fixed or flexible locations in the *fixed* column. 1 denotes *with fixed activity locations*; 0 otherwise. The activities with fixed locations are located by roulette wheel selection in terms of numbers of employees at the locations corresponding to same Lisa occupation classification. Table 6 and 7 display the ratios of different number of activities and possession of different private vehicles respectively. As mentioned above, only car and bike are considered as private vehicles in this illustration.

To get the personalized transportation network for each individual, we assume the parameters in the heuristic algorithm are dependent on three major factors of an individual, i.e. gender, age and income. The parameters of the link costs are set in Table 8 and the weights of personal attributes (in the bold box of Table 8) are set in Table 9. Other parameters are set the same for each individual without referring to any activity state, including (1) acceptance distance and limitation distance for bike and car: d_{Ba} =5km, d_{Bl}=15km, d_{Ca}=15km and d_{Cl}=200km; (2) egress time of picking-up a private vehicle and alighting at a stop: $eTime_{PU} = 0$ and $eTime_{AT}$=0; and (3) selection number in the activity location choice model: N_{as}=min(10, 0.9× N_{jT}), in which N_{jT} is the total number of alternative locations for activity *j.*

Table 4 – Classification of trip purposes(activities)

activity type	classification	*fixed*	activity type	classification	*fixed*
1. working	10 office or factory	1		65 freight of goods, truck	1
	11 farmer, agriculture	1		66 postman, newspaper	1
	12 at temporal address	1		67 profession outside (GP)	1
	13 sideline, recall force	1		68 other	1
	14 volunteer(all forms)	1	7. pick/put	71 to drop-off	1
2. business	20 office or factory	1		72 to pick-up	1
	21 one-day trip	1	8. leisure	80 common	0
	22 overnight business	1		81 private meeting	1
3. education	30 formal	1		82 cafe or restaurant	0
	31 temporal	1		83 cinema or museum	0
	32 stage	1		84 social center	0
	33 day-care	1		85 church	1
	34 school excursion	1		86 hobby	0
4. shopping	40 general	0		87 sports	1
	41 at city center	1		88 neighbour meeting	1
	42 at shopping center	0		89 recreational movement	1
5. returning	51 other home	1	9. use service	90 medical care	1
6. transport-profession	61 taxi	1		91 bank or post ect.	0
	62 public transport	1		92 public town hall, tax	1
	63 other	1		93 personal care, haircut	0
	64 supply goods	1		94 physical care	1

Table 5 - Ratio of activity types

type	work	business	education	shopping	transport	pick/put	leisure	service	other
ratio	20.1%	5.22%	4.94%	24.19%	0.85%	6.63%	32.66%	5.39%	0.03%

Table 6 - Ratio of number of activities per person

number	1	2	3	4	5	6	>6
ratio	43.38%	34.54%	14.63%	5.19%	1.45%	0.49%	0.32%

Table 7 - Ratio of number of activities per person

vehicles	car	Bike	None
ratio	57.29%	92.64%	3.65%

Table 8 – Link cost functions

For transport link		**For transition link**	
At the beginning activity state		$\boldsymbol{\beta}_{iBD}$	$(\beta_{iCt}, 0)$
β_{iCt}	$1 + G_{Ct}(gender_i) + A_{Ct}(age_i) + I_{Ct}(income_i) + \epsilon_{it}$	β_{iATe}	1
β_{iCc}	$3 + G_{Cc}(gender_i) + A_{Cc}(age_i) + I_{Cc}(income_i) + \epsilon_{ic}$	β_{iCAt}	1
β_{iPTt}	$1.1 \times \beta_{iCt}$	β_{iCAs}	$0.0016 \times \beta_{iCc}$
β_{iPTc}	β_{iCc}	β_{iPKc}	β_{iCc}
β_{iBt}	$1.2 \times \beta_{iCt}$	β_{iPUve}	1
β_{iWt}	$1.25 \times \beta_{iCt}$	C_{idC}	0
At the state with child or heavy products(shopping longer than 45 minutes)		C_{irC}	0
β_{iBt}	$1.2 \times \beta_{iBt}$	C_{irc}	$-3\times \beta_{iBt}$

β_{iWt}	$1.25 \times \beta_{iWt}$	C_{irB}	0
At the state with child and heavy products		C_{idW}	-5× β_{iWt}
β_{iBt}	$1.5 \times \beta_{iBt}$	C_{irW}	0
β_{iWt}	$1.5 \times \beta_{iWt}$		

Table 9 – Attributes and components

Attributes(ratio)\components	$time$		$cost$	
Male (49.2%) Female (50.8%)	$G_{Ct}(gender_i)$	0.05 0	$G_{Cc}(gender_i)$	0 0.5
12-<18 (8.8%) 18-<60 (67.4%) 60-<80 (23.8%)	$A_{Ct}(age_i)$	0.05 0.12 0.1	$A_{Cc}(age_i)$	0 1.0 1.2
<15 k€ (50.0%) 15 K€-<30 K€ (33.5%) >=30 K€ (16.5%)	$I_{Ct}(income_i)$ (yearly)	0.15 0.25 0.35	$I_{Cc}(income_i)$	3 2 1

Based on the parameter settings, we run the heuristic and supernetwork model for all the activity programs. The running time is 3902.5 seconds in total and 0.088s on average. The aggregate disutility for conducting all the activity programs is 1.694× 10^7. Figure 12 shows the percentages of the total disutility distributed in different classifications of the population. Applying this model, we can readily test whether a change of the urban design or a new governmental policy is beneficial to the whole or a specific population.

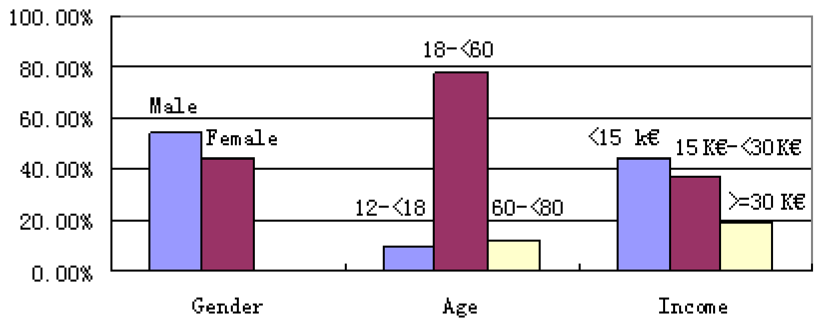


Figure 12 – percentage of disutility

5. CONCLUSIONS

Multi-state supernetworks have been suggested as a potentially powerful representation for integrating different physical transportation networks and the implementation of activity-travel programs. It may serve in the context of simulating multi-modal travel behaviour, advanced accessibility analysis and in transportation planning. A potential disadvantage of the supernetwork approach may be computation times as many copies of the networks are created. Personalized networks may offer a solution in this regard and are also required for personalised transportation planning. The current paper has proposed an approach for constructing such personalised networks and illustrated their application. Results suggest that the suggested approach offers a feasible solution and represents another step forward in building operational multi-state supernetworks.

The suggested approach is based on the critical assumption that the activity state may affect the total disutility on a public transport or private vehicle connection but does not change the connection composition itself. While this assumption is consistent with the empirical observation, it is not a general assumption. Thus, in future work, we intend to relax this assumption. Another line of future development will be the household case. This is important in the sense that different members of the household may need to synchronize their activities and travel, for example in the context of joint activities. Finally, we plan to illustrate the approach with more accurate parameters, obtained for empirical data.

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