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Constructing personalized transportation networks in multi-state supernetworks: a heuristic approach

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An integrated view encompassing the networks for public and private transport modes as well as the activity programs of travelers is essential for accessibility analysis. In earlier research, the multi-state 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 involving multi-modal and multi-activity is the personalized transportation network, which is an under-researched topic in the academic community. This article 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: public transport network and private vehicle network. Three examples are presented to illustrate that the public transport network and private vehicle network can represent an individual's attributes and be applied in large-scale applications for analyzing the synchronization of land-use and transportation systems.

Keywords: supernetwork; multi-modal and multi-activity; accessibility analysis; heuristic approach; personalized networks

1. Introduction

The concept of accessibility has a long history in urban planning, transportation research, and geographic information science. Accessibility of locations is commonly conceptualized as a characteristic of a transportation system and location-based facilities, which determines the ease with which users can implement their activity programs. In the past 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 (Wachs and Kumagai 1973, 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, that is, 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 behavior. Examples are the utility-based accessibility measures (Ben-Akiva and Lerman 1977, Pirie 1979) and the time-space measures suggested in time geography (Ashiru *et al.* 2003, Neutens *et al.* 2008), which

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capture the available opportunities in time–space prisms or the number of alternative ways that any given activity–travel pattern can be realized, given a set of time–space constraints. Especially, the latter measures cause challenges to geographic information science in deciding an optimal representation.

Irrespective of the specific approach, these existing measures are largely insensitive to the degree by which transport networks for different modes and location-based facilities are mutually adjusted or synchronized with respect to activity programs. In addition, none of the existing measures appear to sufficiently consider the multi-modal trips and the related effort involved in transfers and waiting. An integral representation of multi-modal networks and the inclusion of more details related to activity participation, transfer, and waiting time requires new ways of representing the complex synchronized networks. 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 allowing such representation (Arentze and Timmermans 2004a, Liao *et al.* 2010, Ramadurai and Ukkusuri 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. Thus, the multi-state supernetwork supports the analysis of synchronization of different networks.

However, the network becomes very large and complex when multiple transport networks and activity locations are integrated into a single representation. It is therefore important to construct personalized networks. This idea is based on the observation that from the perspective of an individual's activity program only a small number of destinations and also a relatively small proportion of the complete transport system will be relevant. As indicated (Arentze and Timmermans 2004a, Liao *et al.* 2010), personalized supernetworks are essential because they reduce the computation time in large-scale applications for analyzing land-use and transport systems without loss of representational possibilities. Nevertheless, 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 article therefore is to develop an efficient heuristic approach to construct personalized networks for a given individual activity program. In this approach, the personalized network consists of two types of network extractions from the original transportation system, namely public transport network (PTN) and private vehicle network (PVN). PTN is composed of selected public transport connections by an individual's preferences on walking distance, transfer times, fare and time cost, and so on, whereas the PVN is constructed with optimal routes of the considered private vehicles in a hierarchical road network based on multi-attribute link cost functions. We develop the new approach and test it using the administrative Eindhoven region (the Netherlands) and a large sample of activity programs obtained from an activity diary data collection in the Netherlands as a case. The remainder of this article 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 article is completed with a discussion of major conclusions and avenues for future research.

2. 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. Such augmented networks allow researchers to model multi-modal trips as paths through the supernetwork (Carlier *et al.* 2003). Nagurney and coworkers (2002, Nagurney and Smith 2003) proposed further extensions of supernetworks that also include links representing particular transactions between actors and telecommunications to model communications and transactions involved in supply chains and other economic activities.

In view of the different characteristics of links, Arentze and Timmermans (2004a) suggested an extension of the basic supernetwork concept that integrates activity programs of individuals and multi-modal transport networks. Their supernetwork model is based on the notion that the costs on any kinds of links are mode and activity state dependent and personalized. The mode state defines whether and which particular mode is used, and activity state defines which activities have already been conducted. In addition, to capture the choice facets of parking a private vehicle and picking up a private vehicle, vehicle state is used to define where the private vehicle is (in use or parked somewhere). In each vehicle state, a link can be further mode-identified by its feature. Thus, the multi-state supernetworks are constructed for each individual and made up of physical networks of different activity–vehicle states (combinations of activity and vehicle states). In their representation, nodes represent real locations in space; links connecting different nodes of the same activity state are travel links; those interconnecting the same nodes of the same activity states are transition links referring to parking/picking up a private vehicle or boarding/alighting public transport; and those interconnecting the same nodes of different activity states are transaction links representing the implementation of activities. This so-called multi-state supernetwork provides a powerful framework for analyzing accessibility. The cost of a least-cost path through a multi-state supernetwork represents the effort of implementing an activity program. Such a measure takes into account multi-modal and multi-activity patterns as well as the synchronization of transport networks and the land-use system. However, a drawback of the approach is that the supernetwork may become very large and possibly intractable because it needs to incorporate as many copies of a physical network as there are possible activity–vehicle states associated with an activity program.

Founded on this multi-state supernetwork, Liao *et al.* (2010) proposed an improved representation, which is easier to construct and considerably reduces the size needed to include all choice combinations. In this approach, the integrated transport network is decomposed into a PTN and PVNs. PTN contains the modes of walking and public transport. As 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. Although the walking network can be separated from the PTN, in our model it is appropriately combined with the PTN by adding boarding and alighting links. This does not affect the definition of vehicle state. In contrast, only one mode is involved in each PVN so there is no need to extend it. PTN and PVNs share joint nodes of parking locations interconnected by transition links where the individual can transfer between a private mode and a public one. To represent all possible choice facets for conducting an activity program, PTN and PVNs are assigned to all possible activity–vehicle states and then connected by state-labeled transition and transaction links.

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3. Personalized transportation network

To keep consistency with our supernetwork model, the personalized transportation network refers to an interconnected PTN and PVNs. 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 possible 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 2004b). 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 home location). Note that the most satisfactory route may be dependent on the state the individual is in when traversing the route. The remainder of this section will first consider the cost functions of the links in the supernetwork. 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 2004a) for all the links. In general, the costs of a link represent a perceived disutility of the 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. Travel link cost functions

Travel links include the links that can be traveled by walking, bike, car, or public transport. Given the objective of an illustration 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-cost paths correspond to maximum utility paths.

- Walking: $\text{dis}U_{isWl} = \beta_{isWt} \times \text{time}_{Wl} + \epsilon_{isWl} \quad (1)$

- Bike: $\text{dis}U_{isBl} = \beta_{isBt} \times \text{time}_{Bl} + \epsilon_{isBl} \quad (2)$

- Car: $\text{dis}U_{isCl} = \beta_{isCt} \times \text{time}_{Cl} + \beta_{isCc} \times \text{cost}_{Cl} + \epsilon_{isCl} \quad (3)$

- Public transport: $\text{dis}U_{isPTl} = \beta_{isPTt} \times \text{time}_{PTl} + \beta_{isPTc} \times \text{cost}_{PTl} + \epsilon_{isPTl} \quad (4)$

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

3.1.2. Transition link cost functions

Transition links represent the changes of modes. Costs functions on these levels are defined as follows:

- Parking: $\text{dis}U_{isPKvp} = \beta_{isPKv} \times X_{isPKvp} + \epsilon_{isPKvp}$ (5)

where $\text{dis}U_{isPKvp}$ denotes the disutility of parking private vehicle v ($v \in \{B, C\}$) at location p ; X_{isPKvp} is a vector of factors of parking v at p including cost, access time, parking type, and safety; β_{isPKv} is a weight vector of these factors; and ϵ_{isPKvp} relates to unobserved components.

- Picking up: $\text{dis}U_{isPUvp} = \beta_{isPUve} \times e\text{Time}_{isPUvp}$ (6)

where $\text{dis}U_{isPUvp}$ denotes the disutility of picking up private vehicle v at location p , $e\text{Time}_{isPUvp}$ 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.

- Boarding: $\text{dis}U_{isBDt} = \beta_{isBD} \times X_{isBDt} + \epsilon_{isBDt}$ (7)

where $\text{dis}U_{isBDt}$ denotes the disutility of boarding at public transport stop t ; X_{isBDt} is a vector of factors of boarding at t , including waiting time and location attractiveness; β_{isBD} is a weight vector; and ϵ_{isBDt} is an error term.

- Alighting: $\text{dis}U_{isATt} = \beta_{isATe} \times e\text{Time}_{isATt}$ (8)

where $\text{dis}U_{isATt}$ denotes the disutility of alighting at public transport stop t , $e\text{Time}_{isATt}$ is the egress time which refers to the time taken from t to the road network, and β_{isATe} is the weight.

- Departing home: $\text{dis}U_{idm} = C_{idm}$ (9)

where m denotes the departing mode, $m \in \{W, B, C\}$; $\text{dis}U_{idm}$ denotes the disutility of departing home with mode m ; and C_{idm} is the constant component for preference. Note that as 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.

- Returning home: $\text{dis}U_{itm} = C_{itm}$ (10)

where $\text{dis}U_{itm}$ denotes the disutility of returning home with mode m and C_{itm} , as before, relates to a base preference for the mode.

3.1.3. Transaction link cost function

Despite the fact that conducting an activity as a rule produces utility, to keep consistency with the supernetwork model, this article 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 (Zhang et al. 2004). In other words, disutility refers to a loss compared to a hypothetical ideal location.

- Conducting an activity: $\text{dis}U_{isCAjk} = \beta_{isCAj} \times X_{isCAjk} + \epsilon_{isCAjk}$ (11)

where $\text{dis}U_{isCAjk}$ denotes the disutility of conducting activity j at alternative location k ; X_{isCAjk} is a vector of factors of conducting j at k including price, quality, service, and activity duration; β_{isCAj} is a weight vector; and ϵ_{isCAjk} is an error term.

In the functions above, the disutility on each link is state dependent. However, as a preprocessing step for the supernetwork model, the construction of PTN and PVN 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 next for selecting the locations and connections are not referring to any activity state occurring in later stages of the activity program.

3.2. 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, it can be classified as a fixed location or a flexible location. Consider, for example, the activity *work*. If the individual is required to be present at a specified working location, *work* is an activity with a fixed location. Similarly, *home* is regarded as a fixed location where the individual leaves and returns. 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 (dis-)utility of conducting the activity at an alternative and a trip association with other activities. 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 can be applied to narrow down the choice set for an activity with flexible locations:

$$\text{dis}U_{icCAjk} = \text{dis}U_{iCAjk} + \text{travel}_{iCAjk} \quad (12)$$

where $\text{dis}U_{icCAjk}$ is the disutility of individual i choosing alternative k for activity j ; $\text{dis}U_{iCAjk}$ is the disutility of conducting j at alternative k ; and travel_{iCAjk} is the average travel disutility from or to associable locations.

As the modes in the trips from or to associable activity locations are not known in this extraction process, average travel disutility by different modes is adopted here. If average travel disutility is consistent with the real travel disutility, we can argue in situations when any flexible activity only has at most two associable locations that the location with the least $\text{dis}U_{icCAjk}$ is the optimal location. In other cases, a subset selection is necessary

to ensure that the optimal location will be selected. In theory, there are two ways of narrowing down the choice set: (1) selecting a specified number N_j of alternatives with the least disutility or (2) selecting a specified proportion P_j of the total with the least disutility. The larger N_j or P_j , the higher probability the optimal location is in the subset. At the same time, however, the size of the supernetwork and computation times increase. Sensitive analysis on N_j (Section 4.3) indicates that a very small value compared to the original size already gives a high probability that the optimal alternative location is picked out.

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 activity locations; the five 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 the five locations have the same disutility. If the individual has a strong dislike of travel, 4 and 5 will be eliminated.

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 neighboring public transport stops, transit paths, boarding and alighting at 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 PTN 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:

$$\text{disU}_{\text{PTC}c} = (\text{disU}_{iW} + \text{disU}_{iPT} + \text{disU}_{iBD} + \text{disU}_{iAT})|_c \quad (13)$$

where $\text{disU}_{\text{PTC}c}$ denotes the disutility of taking public transport connection c , and the right-hand side of the function represents four parts of the disutility distributed on c , which are defined by Equations (1), (4), (7), and (8).

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

Figure 2. Example of narrowing down the choice set.

Figure 3. Example of public connections.

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 $(n \times (n - 1))/2$ 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 PTNw. 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 away. 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 $v \in \{B, C\}$: 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 of d_{ivl} , it is not considered a potential parking location. If there exists one activity location outside the circle of d_{iva} , potential parking locations include the transport hubs that reside inside this and occur in PTNw. If such a transport hub does not exist, the public transport stop that is in PTNw and closest to home is considered. Otherwise, activity locations are all considered as potential parking locations. Figure 4 shows an example that activity location A and transport hub TH are potential parking locations.

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:

Figure 4. Example of potential parking location.

$$\text{dis}U_{icPKvp} = \text{dis}U_{iPKvp} + \text{travel}_{PKp} \quad (14)$$

where $\text{dis}U_{icPKvp}$ is the disutility of i choosing parking for v at p ; $\text{dis}U_{iPKvp}$ is the disutility of parking v at p ; and travel_{PKp} is the travel disutility to its corresponding potential parking location.

At most two parking locations are selected for each potential parking location: at most one with parking cost and at most one without parking cost. As there is always a short walking path between the parking location and the destination, such walking paths are added to the PTNw. After executing all the steps mentioned above, the PTN is constructed. It contains the home location, activity locations, parking locations, a few public transport stops/stations, and walking paths and transit paths that connect the locations.

3.3. Construction of PVN

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 it. 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 locations.

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, that is, bike and car (see Figure 1). For each departing mode, the individual can assign mode-dependent and personalized costs to 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, PVNs are mode-specified networks which, respectively, contain home, parking locations, and optimal paths that connect these locations.

Following the steps above, we can obtain the personalized transportation networks for an individual's activity program. However, they are only the network extractions at the beginning activity state, that is, before implementing the activity program. To make them fit into the supernetwork model, we make an assumption that the subsequent 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 state. The assumption is based on the notion that people in most cases take the same route given a transport mode irrespective of the activity state. Note that this solution still allows that travelers 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.

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 locations of activities with fixed location.

- Step 3: Select the location choice set for activities 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.

4. Case study

In this section, we present three 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 in a PC with Intel® Core™2 Duo CPU E8400@ 3.00 GHz 3.21G RAM. The study area is the administrative Eindhoven region, which includes 20 cities/towns. The case study focuses on the population living in Eindhoven city and assumes that people 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 study area. In Figure 5, pink, green, orange, and blue dots denote the locations for Nos. 1–4 in Table 1, respectively, and gray lines denote the road network. Given the purpose of accessibility analysis, the operational capacities of activities facilities and public transport are not considered.

As 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

Table 1. Data sets collected for the case study.

No.	Data set	Data source	Description
1	Locations for residence	NRM 2004	Residence information of Eindhoven city
2	Locations for employee	Selected by TransCAD	Employee information of the administrative Eindhoven region, including 15,851 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 28,734 nodes and 40,680 undirected links

Figure 5. Delineation of the study area (scale: 1:500,000). (a) Locations of residents and public transport. (b) Locations of services.

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_{iCAI} and β_{iCAs} . As there is no complete information about the factors mentioned in the parking location choice model, the average parking cost is used as the only factor of parking at a location. Its corresponding weight is denoted by β_{iPKC} . Twenty-five 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 $[0, 200 \text{ m}]$. Any locations can be considered for bike parking, and it is free.

There are 877 stops/stations in 63 public transport lines in the study area. We assume that the average waiting time at a stop is 7.5 minutes and the average cost is 0.2 €/km in the bus or train. There are three road classifications: G (local), P (provincial), and R (national) roads. We suppose that the average car speed is 36, 50, and 80 km/h, respectively, on G, P, and R, whereas assumed fuel cost is 0.13, 0.11, and 0.09 €/km, respectively, on G, P, and R roads. Average bike speed is 12 and 15 km/h, respectively, on G and P roads, and average walking speed is 5 km/h on G and P roads.

4.2. Example 1: PTN and PVN

This example considers an individual (male), who lives in the northern part of Eindhoven city, having an activity program on a typical day, which includes (1) three activities, that is, working at the office, picking up 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; and (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 implies the following:

- (1) There are fixed activity locations for working and picking-up, and flexible activity locations for shopping.
- (2) There will be six 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, as bike is the only private vehicle and it is free to park a bike anywhere. Consequently, there is only one mode-specific PVN.

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}
2.84	2.13	1.77	6.0	3.55	2.66	1.77	6.0
β_{iBD}	β_{iATe}	β_{iCAt}	β_{iCAs}	C_{dB}	C_{dw}	C_{rB}	C_{TW}
(2.5, 0)	1	1	0.008	-5.0	-10.0	0	0

The relevant personalized parameters of the link costs are set as shown in Table 2. In applications of the model, all personalized parameters are supposed to be obtained by empirical estimation, for example, by using stated preference experiments. Because empirical estimation is not the focus of this study, they are set here by rule of thumb. Acceptance and limitation distances for bike are set as $d_{iBa} = 5$ km and $d_{iBt} = 15$ km, respectively. As an illustration, three 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 as zero.

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 6 a, in which the green dots denote the alternative locations for shopping. Second, the three alternatives are selected for shopping, S1–S3, in terms of Equation (12) (Figure 6b). Then, the public transport connections are selected in terms of Equation (13) (Figure 6c). Next, the parking locations, (P1–P5), are selected at the activity location as they are all inside the circle of d_{iBa} (Figure 6d). Finally, the bike connections are selected (Figure 6e). Figure 6f and g 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.

After incorporating PTN and PVN in the multi-state supernetwork model, two least-disutility activity tours are generated for two different departing modes, with disutility of 609.31 and 783.23 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 rides the bike to the activity location, parks it there and conducts the activity, then pick ups the bike and rides 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 as the scale of the following steps are all based on this. Table 3 shows the results of 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 the average disutility and running time are shown. It indicates when setting $N_j > 10$, no further significant improvements are obtained, but running time increases considerably (running time is expected to be less, as the model is implemented in an interpreter 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 link costs of the supernetworks may vary with different individuals’ attributes, which renders 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. It will

Figure 6. Example of extracting PVN and PTN. (a) Locating activities (scale 1:100,000); (b) locating activities (scale 1:50,000); (c) public transport connections; (d) selecting parking locations; (e) bike connections; (f) bike mode-specified PVN; (g) extension of PTN with boarding and alighting links.

Table 3. Comparison with different values of N_j . Bold values indicate that Aver_disU does not decrease significantly when N_j is larger than 10.

N_j	Number of nodes in			Aver_disU (Bike)	Aver_time (seconds)
	PVN	PTN	Supernetwork		
1	4	17	126	615.89	0.07
3	6	25	486	612.47	0.10
5	8	32	1008	603.62	0.14
10	13	43	2658	593.52	0.19
30	23	98	17,778	593.39	0.52
50	103	125	38,118	593.34	0.87
100	203	208	1,26,018	593.47	1.8
500	503	807	24,24,018	593.21	29.0

take much longer or even be intractable if either increasing the number of activity states or putting the activity program in a larger area.

4.3. Example 2: accessibility analysis

The example in this section 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 (Mobiliteit Onderzoek Netherlands (MON)). A population of 42,991 individuals (over 11 and under 80 years old) from 24,183 households with a total of 85,332 activities are examined. Tables 4 and 5 display the classifications of trip purposes (activities in this article) in the MON and ratios of different activity types, respectively. We classify an activity as whether its location is fixed or flexible (see the *Fixed* column); 1 denotes 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 occupational sector classification. Tables 6 and 7 display the ratios of different numbers 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 that the parameters in the heuristic algorithm are dependent on three major factors of an individual, that is, gender, age, and income. The parameters of the link costs are set as in Table 8 and the weights of personal attributes (in the bold box of Table 8) are set as 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: $d_{Ba} = 5$ km, $d_{Bl} = 15$ km, $d_{Ca} = 15$ km, and $d_{Cl} = 200$ km; (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: $N_{as} = \min(10, 0.9 \times N_{JT})$, where N_{JT} is the total number of alternative locations for activity j .

Based on the parameter settings, we run the supernetwork model embedding with the heuristic algorithm for all the activity programs. The running time is 3815.5 seconds in total and 0.089 seconds on average per person. The aggregate disutility for conducting all the activity programs is 2.011×10^7 or 467.78 on average per person. Hence, the accessibility of Eindhoven city is equal to 2.011×10^7 units of disutility for the population. Figure 7 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 segment.

Table 4. Classification of trip purposes (activities).

Activity type	Classification	Fixed	Activity type	Classification	Fixed
1. Working	10 office or factory	1	7. Pick/put	65 freight of goods, truck	1
	11 farmer, agriculture	1		66 postman, newspaper	1
	12 at temporal address	1		67 profession outside	1
	13 sideline, recall force	1		68 other	1
	14 volunteer (all forms)	1		71 to drop off	1
2. Business	20 office or factory	1	8. Leisure	72 to pick up	1
	21 one-day trip	1		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	9. Use service	87 sports	1
	41 at city center	1		88 neighbor meeting	1
	42 at shopping center	0		89 recreational movement	1
5. Returning	51 other home	1		90 medical care	1
6. Transport-profession	61 taxi	1		91 bank or post, etc.	0
	62 public transport	1		92 public town hall, tax	1
	63 other	1		93 personal care	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. Attributes and components.

Vehicles	Car	Bike	Car and bike	None
Ratio	57.29%	92.64%	96.35%	3.65%

4.4. Example 3: accessibility comparison

This example investigates the accessibility effect of an operation change of public transport services. The public transport system in Eindhoven city has the characteristic of a one-hub transfer structure. The ‘Eindhoven Station’ stop is the transport hub, from which all the bus routes originate. With this structure, any two stops in Eindhoven city can be reached

Table 8. Link cost functions.

For transport link		For transition link	
At the beginning activity state		β_{iBD}	$(\beta_{iCt}, 0)$
β_{iCt}	$1 + G_{Ct}(\text{gender}_i) + A_{Ct}(\text{age}_i) + I_{Ct}(\text{income}_i) + \epsilon_{it}$	β_{iATe}	1
β_{iCc}	$3 + G_{Cc}(\text{gender}_i) + A_{Cc}(\text{age}_i) + I_{Cc}(\text{income}_i) + \epsilon_{ic}$	β_{iCAt}	1
β_{iPTt}	$1.25 \times \beta_{iCt}$	β_{iCAc}	$0.0016 \times \beta_{iCc}$
β_{iPTc}	β_{iCc}	β_{iPKc}	β_{iCc}
β_{iBt}	$1.5 \times \beta_{iCt}$	β_{iPUve}	1
β_{iWt}	$1.5 \times \beta_{iCt}$	C_{idC}	0
States with child or heavy products (shopping longer than 45 minutes)		C_{irC}	0
β_{iBt}	$1.8 \times \beta_{iBt}$	C_{idb}	$-3 \times \beta_{iBt}$
β_{iWt}	$2.4 \times \beta_{iWt}$	C_{irB}	0
At the state with child and heavy products		C_{idW}	$-5 \times \beta_{iWt}$
β_{iBt}	$2.1 \times \beta_{iBt}$	C_{irW}	0
β_{iWt}	$2.8 \times \beta_{iWt}$		

Table 9. Attributes and components.

Attributes (ratio)/components		Time	Cost	
Male (49.2%)	$G_{Ct}(\text{gender}_i)$	0.05	$G_{Cc}(\text{gender}_i)$	0
Female (50.8%)		0		0.5
12–<20 (9.28%)	$A_{Ct}(\text{age}_i)$	0.05	$A_{Cc}(\text{age}_i)$	0
20–<60 (67.4%)		0.12		1.0
60–<80 (23.8%)		0.1		1.2
<15K€ (50.0%)	$I_{Ct}(\text{income}_i)$ (yearly)	0.15	$I_{Cc}(\text{income}_i)$	3
15K€–<30K€ (33.5%)		0.25		2
≥30K€ (16.5%)		0.35		1

Figure 7. Percentage of disutility.

by bus via at most one transfer. However, an inherent drawback of this so-called spoke-hub paradigm is that most pairs of stops can only be reached by a transfer at the *Eindhoven Station* stop. For example, it takes around 45 minutes from the north (a business area) to the south (high-tech campus) by bus including one transfer at *Eindhoven Station*. To improve the accessibility of the residents who live in the north but have their activities in the south or the other way around, the transport planners of Eindhoven city try to add a new faster

Figure 8. Increase of disutility in different classifications.

route (30 minutes) that connects the south and the north passing through several residential areas and *Eindhoven Station* in between. Due to budget limitations, one or two other routes have to be canceled. Short-distance routes 182 and 184 are in the planners' perspective because their stops can be completely covered by other routers. Therefore, the question to the planners is what effects will arise if this option would be adopted?

The approach applied in the second example above can provide sufficient answers to this question. As the choice-sets of locations for (flexible) activities are based on physical distances and attributes of the facilities (see Section 3.2), the substitution of public transport routes does not lead to changes in the pre-selected set of activity locations in Example 2. The aggregate disutility for this scenario is obtained by keeping the parameter settings the same and running the algorithm again. Figure 8 depicts the increase in disutility of different classifications, which together bring the aggregate 0.05% down. This is an aggregate amount, but the benefits may differ locally and includes effects of possible adaptations. For example, we observe that 0.02% of the sample population shifts its departing mode from walking (then taking public transport) to cycling as a result of the cancellation of routes 182 and 184. Nevertheless, the results show that overall the measure improves the accessibility of Eindhoven city taking into account the activity programs of a large sample of the population, activity locations, and transport services.

5. Conclusions

Multi-state supernetworks have been suggested in geographic information science as a potentially powerful representation for integrating different transportation networks and the implementation of activity-travel programs. It may serve in the context of simulating multi-modal travel behavior and advanced accessibility analysis. A potential disadvantage of the supernetwork approach is that computation times may become high as many copies of the networks are created. Personalized networks can offer a solution in this regard. The current article has proposed an approach for constructing such personalized networks and illustrated their applications. Results indicate that the suggested approach offers a feasible solution and represents another step forward in constructing operational multi-state supernetworks.

The proposed approach is based on the critical assumption that the activity state may affect the costs or disutility of a public transport or private vehicle connection but does not change the connection composition on itself. Although this assumption is consistent with the empirical observations, it is not a general assumption. Thus, in future work, this assumption may be relaxed and an even more general approach may be suggested. In addition, the current approach is based on individual activity-travel programs. However, recent

developments in accessibility analysis have emphasized the importance of the household in that task allocation may have an impact on the ease with which a household agenda can be realized in time and space and hence on accessibility. Moreover, in the household case, different members of the household may need to synchronize their activities and travel, for example, in the context of joint activities, implying additional constraints on the representation of the supernetworks.

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