PREDICTING MULTI-MODAL TRAVEL FOR INTEGRATED LAND-USE TRANSPORT SCENARIOS

Feixiong Liao
Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands
F.Liao@tue.nl

Theo Arentze
Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands

Eric Molin
Delft University of Technology, Delft, 2600 GA, The Netherlands

Wendy Bothe
Delft University of Technology, Delft, 2600 GA, The Netherlands

Harry Timmermans
Eindhoven University of Technology, Eindhoven, 5600 MB, The Netherlands

ABSTRACT

Integrated land-use transport modelling is essential to address policy questions arising from spatial and transport planning sectors. This paper applies the multi-state supernetwork approach to investigate the effects of integrated land-use transport scenarios on individuals' travel patterns. A multi-state supernetwork is capable to represent individual activity-travel patterns as path choice at a high level of detail, including the choice of mode, route, parking and activity location. Multi-faceted travel preferences can be assigned in the supernetworks. Therefore, individuals' travel choices are policy-sensitive when they seek the most desirable activity-travel patterns. The adaptation of individuals' travel patterns policies related to land-use and transport can also be readily captured. The application is illustrated for Rotterdam city (The Netherlands), in which a set of possible integrated land-use transport scenarios of a broader area are evaluated. Results manifest the accessibility change, modal substitution and shift in the use of facilities under different scenarios.

Keywords: multi-state supernetwork; integrated land-use transport; travel pattern; policy-sensitive

INTRODUCTION

Cities throughout the world are struggling with the challenge of improving the mobility efficiency of their transport systems, which have developed to be heavily dependent on private motor vehicles. Considerable efforts of today's spatial and transport planning have been devoting to designing future scenarios that can stimulate mobility while reducing car dependency and increasing the share of energy-efficient transport modes. However, to predict the impacts of those policies is not an easy task due to the overwhelming data dependency and multitude of concurrent changes (Wegener, 2004). Spatial development determines the need for spatial interaction, and thus transport, which in turn has impacts on land use patterns. They together shape individuals' activity-travel behavior. In that sense, land use and transport systems are closely interweaved, and the models used to support travel demand management need to integrate them to capture the underlying effects (Waddell, 2011). This notion has been widely accepted in contemporary activity-based travel demand models.

Activity-based models acknowledge the fact that the travel needs of a population are determined by their need to participate in activities spread out in time and space (Sivakumar, 2008). The explicit modeling of activities and the consequent trip chaining allows an exquisite analysis of individuals' response to land-use and transport policies. The responses can be viewed as a serial of travel choices concerning how to implement the activity programs. Thus, effects of the policies become part of the activity-travel scheduling process, which should, as a rule, take into account the travel preferences from the demand side and locations of facilities/services and transport from the supply side (Shiftan and Ben-Akiva, 2011). A variety of policy-sensitive systems have been developed along this line of logic, which include platforms principally based on (1) computational process models, i.e. AMOS (Kitamura et al., 1998), TASHA (Miller and Roorda, 2003) and ALBATROSS (Arentze and Timmermans, 2004a) etc.; (2) utility-maximization, i.e. SMASH (Ettema et al, 1996) and DAS (Bowman and Ben-Akiva, 2001) etc.; (3) and micro-simulation, i.e. CEMDAP (Bhat et al., 2004) and MATSIM (Balmer et al., 2006) etc. Many of these systems still exhibit great vitality to date in that refinements and new applications of them are continuing at different levels.

To the best of our knowledge, however, few of these systems can capture multi-modal trip chaining in full activity-travel patterns. The use of private vehicles (PV) such as car and bike is often separated from the use of public transport (PT) in single trips since parking choices are not explicitly modeled. This model limitation causes insensitivity to parking and transit-related policies, and thus incapability to evaluate modal substitution effects. In addition, most of these models adopt a hierarchical structure, downgraded from activity pattern via home-based tours to trips, to derive the activity-travel patterns. The hierarchy overlooks the impacts of the lower layer choice facets on the higher layer ones. It would result in inaccuracy in predicting the effects of land use policies on activity location choice, which usually lies on the higher layer. Overall, a mechanism that can systematically model the choice of mode, route, parking and activity location is lacking.

The multi-state supernetwork approach (Arentze and Timmermans, 2004b) is a promising way to model high dimensions of choice. This approach was extended and further developed by Liao et al. (2010, 2011, 2012, 2013). Networks of passenger transport (both PV and PT) and locations of facilities/services with activity programs of individuals are integrated into structured multi-state supernetworks. Different choice facets mentioned above are converted to a unified "path choice" (Nagurney, 2002) through the supernetworks, and the optimal paths predict how individuals would make choices to implement their activity programs. Thus, this approach can be applied to predict changes in travel choice made due to adaptations of the land-use and transport systems. Since the choice facets can be represented at a high level of detail, the approach is also highly policy-sensitive.

The purpose of this paper is to apply the multi-state supernetwork approach to simulate the effects of a set of integrated land-use transport scenarios on individuals' travel patterns. The approach is applied for Rotterdam city (The Netherlands), where several policy scenarios are in perspective concerning transit improvement, increase of parking cost, and several land use redevelopment patterns. In the simulation, the population is extracted from travel diaries collected in a broader area i.e. Den Haag-Rotterdam-Dordrecht corridor; individuals' travel preferences on multi-modal trips and activity participation are estimated from stated and revealed data; and key mobility indicators such as accessibility, mode distribution, shift in facility usage etc. are compared under different scenarios.

To that effect, the following part of this paper is organized as follows. In section 2, we discuss the essences of the multi-state supernetwork approach and how it is tailored to evaluate the effects of different integrated land-use transport scenarios on individuals' travel patterns. Next, we describe the data and scenarios gathered from different actors in the study area. Then, results and interpretations are presented in section 4. Finally, the paper is completed with conclusions and future research.

2. MULTI-STATE SUPERNETWORK

2.1 Basics for supernetwork representation

Network extension techniques have long been applied to solve transport-related problems. Dafermos (1972) first demonstrated an abstract traffic network to model multi-class users through the expansion of a road network. Later on, road network and transit network have been integrated into a hyper-network (Sheffi and Daganzo, 1978) or supernetwork (Sheffi, 1985) to model mode and route choice simultaneously. Several studies (Nguyen and Pallottino, 1989; Carlier *et al*., 2002; Lozzano and Storchi, 2002) also modelled multi-modal trip scheduling and equilibrium based on a higher network extension, in which transfer links are added at any locations where an individual can switch any transport modes. Meanwhile, Nagurney *et al.* (2003) introduced transaction links to model one-activity implementation, i.e. *commuting* versus *telecommuting*. The logic behind these supernetwork models is that a higher choice dimension can be additionally modeled by another higher dimension of network extension.

Nevertheless, all the above supernetwork models treated travel only at the trip-level. Arentze and Timmermans (2004b) extended the supernetworks to an activity-based level and proposed a multi-state supernetwork framework for multi-modal and multi-activity travel planning. Liao *et al.* have further developed this approach for activity-travel scheduling. The essence of this approach is the supernetwork representation for the choice space of an activity program. Several concepts for the representation are given as follows:

(1) Daily activity program: including a list of out-of-home activities during the day, (in)-complete sequencing between activities, and available private vehicles.

(2) Mode state: which particular mode is in use, i.e. foot, bike, car, or a PT mode.

(3) Activity state: which activities have already been conducted.

(4) Vehicle state: where the private vehicles are (in use or parked at particular locations).

(5) Activity-vehicle state: the combination of activity and vehicle state. When an individual is conducting an activity, the private vehicles must be parked.

Meanwhile, a node denotes a real location in space, for example, home, an activity location or a parking location. Links are defined in terms of three categories:

(6) Travel links: connecting different nodes of the same activity state, representing the movement of the individual; there is one and only one transport mode in one travel link.
(7) Transition links: connecting the same nodes of the same activity states but different vehicle states (i.e., parking/picking-up a private vehicle for changes of vehicle states or boarding/alighting PT for changes of mode states);
(8) Transaction links: connecting the same nodes of different activity states, representing the implementation of activities or change of activity states.

Furthermore, in reality, only a small set of locations are relevant to an individual's daily activity program. The multi-modal transport network representation (Carlier *et al*., 2002) is divided and reduced into personalized PVNs and PTN, which are generated by location selection models. Only parking and activity locations are explicitly labelled in PVNs and PTN:

(9) PVNs: denoting private vehicle networks, each of which can only be accessed by one particular private vehicle. There are only parking locations (home is regarded as a parking location) in a PVN. Between each pair of parking locations, there is a PVN connection, corresponding to a set of travel links looking into the road network.
(10) PTN: denoting PT network, where an individual can walk and access PT modes. In the PTN, there are parking (if any private vehicle is involved) and activity locations connected by PTN connections, corresponding to links such as walking, waiting, boarding/alighting, and in-vehicle looking into PT time-expanded graph (Pyrga *et al*., 2008).

Based on these definitions, a multi-state supernetwork can be constructed for an individual's daily activity program in two steps. Firstly, the PVNs and PTN are distributed to all the possible activity-vehicle states with a PVN or a PTN at one activity-vehicle state; secondly, all the discrete networks are interconnected by transition links (between PVNs and PTNs) and transaction links (between PTNs and PTNs). Fig. 1 is an example of a multi-state supernetwork representation for an individual's activity program including two fixed activities (A_1&A_2), two private vehicles (car and bike). P_1&P_2 and P_3&P_4 are parking locations for car and bike respectively. Each of them in the first row denotes the specific private vehicle parked at that location. P_0 and P_5 denote car and bike in use respectively. s_1s_2 represents the activity states for A_1&A_2 (0-unconducted and 1-conducted). Let H and H' denote home at the start and end of the activity states respectively; the path denoted by the bold links indicates an activity-travel pattern that the individual leaves home by car to conduct A_1 with parking at P_2, returns home and switches to bike to conduct A_2 with parking at P_4, and finally returns home. (Undirected links are bi-directed.).

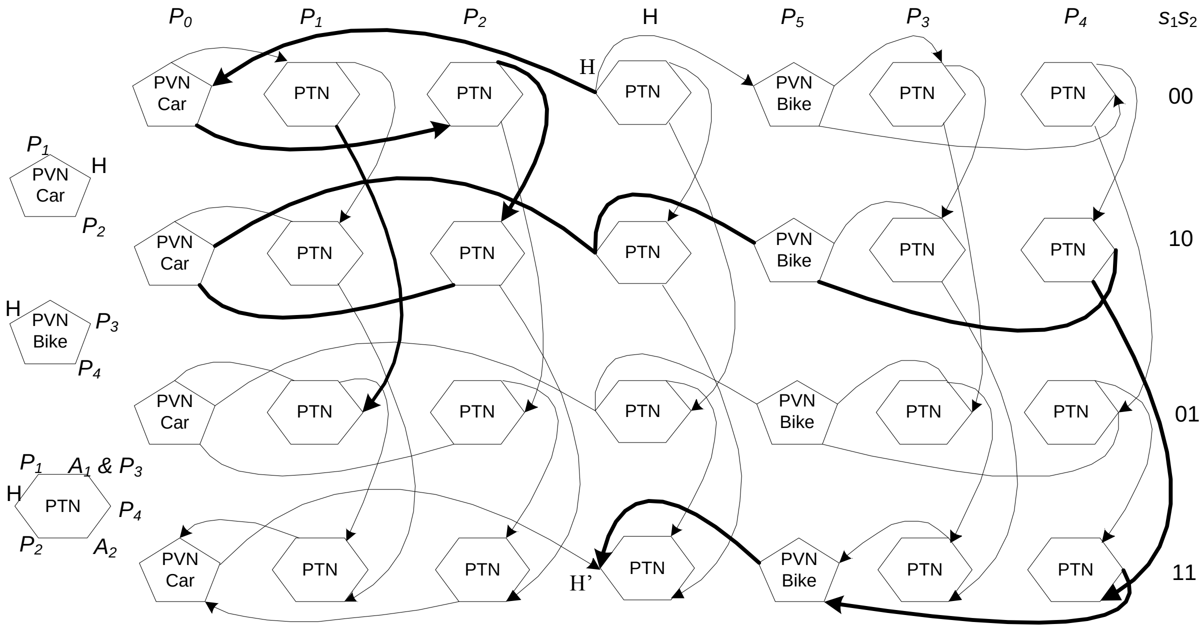


Fig. 1 Multi-state supernetwork representation

As shown in Fig. 1, locations of facilities and transport have been organically integrated via a multi-state supernetwork. In general, a personalized multi-state supernetwork represents the reduced choice space of an individual's activity program. Moreover, it can be proved that any path from H to H' is a possible activity-travel pattern, on which every link is explicitly expressed as a choice of mode, route, parking location or activity location. The next sub-section discusses how the multi-state supernetworks are applied to assess policy scenarios.

2.2 Application for assessing scenarios

As every link is explicitly represented in a personalized multi-state supernetwork, each link can be defined in a state-dependent and personalized way as follows:

$$disU_{isml} = \boldsymbol{\beta}_{ism} \times \boldsymbol{X}_{isml} + \epsilon_{isml} \quad (1)$$

where $disu_{isml}$ denotes the disutility on link *l* for individual i in activity state *s* with mode state *m*, $\boldsymbol{X}_{isml}$ denotes a vector of factors, $\boldsymbol{\beta}_{ism}$ is a weight vector, and ϵ_{isml} is an error term. Some factors may be time-dependent, for instance, travel time/disutility on the same PTN or PVN connection may vary with the arrival time of a node while the weight vector $\boldsymbol{\beta}_{ism}$ is more stable over the time; therefore, Eq. 1 should be extended to the time-dependent case as:

$$disU_{isml}(t) = \boldsymbol{\beta}_{ism} \times \boldsymbol{X}_{isml}(t) + \epsilon_{isml} \quad (2)$$

where *t* is the arrival time at *l*.

Since the personalized parameters $\boldsymbol{\beta}_{ism}$ are assigned in the supernetwork, a path from H to H' with the least disutility is the optimal or the most desirable activity-travel pattern. Consequently, *i* is likely to follow the optimal pattern to travel and conduct activities. If the daily activity program is typical to *i*, the least disutility can be considered as an accessibility index to *i*, equaling to the ease with which *i* can conduct daily activities (Kwan *et al*., 2003). Then, the personal accessibility index is expressed as:

$$\min \{ disU_i(p_{\mathrm{H}\rightarrow\mathrm{H}'}) \}, \qquad p_{\mathrm{H}\rightarrow\mathrm{H}'} \in P \quad (3)$$

where $p_{\mathrm{H}\to\mathrm{H}'}$ and P denote a path from H to H' and the path space respectively. This value can be obtained by standard or time-dependent shortest path algorithms varying with link cost structure.
If enlarging an individual to a population level of an area and $\boldsymbol{\beta}_{ism}$ to $\forall i$ is estimated at the same scale, the accessibility index, $disA_j$, for an area under an integrated land-use transport scenario *j* can be derived as:

$$disA_j = \sum_i \min\{disU_i(p_{\mathrm{H}\to\mathrm{H}'})\}, \quad p_{\mathrm{H}\to\mathrm{H}'} \in P, i \in POP \tag{4}$$

where POP denotes population in the area. When *j* equals to 0, the scenario is called base scenario, representing the current situation. Other future scenarios ($j \neq 0$) are comparable to $disA_0$. If a new scenario cause $disA_j$ larger than $disA_0$, we content this scenario reduces accessibility; vice-versa. It should be noteworthy that Eq. 4 does not take into account the dynamic equilibrium when the individuals travelling to conduct the activities. Instead, Eq. 4 supposes that individuals follow a certain priori equilibrium condition on the integrated land-use transport scenarios. For example, the individuals perceive less driving speed in the rush hours.

In addition to the effect on accessibility, many other effects can be also assessed under different scenarios. Since the optimal paths contain every detail of the choice of route, mode and location, the multi-state supernetworks are highly policy sensitive. This paper especially focuses on travel patterns, although activity patterns are also somehow reflected in the following application. Other effects on travel patterns can also be evaluated by aggregating the population, including (1) average trip distance/travel time; (2) VMT or total distance travelled by car; (3) average waiting time for PT; (4) mode distribution per trip; (5) choice of a particular location, for example, a P+R location, a train station or a large shopping area; etc. All these effects are counted on a trip unit, which are obtained through backtracking the optimal activity-travel pattern. In this paper, a trip is defined as the travel stage either between an activity location and another activity location or home and an activity location.
For a real case application, considerable effort goes into the preparation for the valid input data. The application needs input of integrated land-use transport scenarios from the supply side and synthesized population and daily activity programs with travel preferences from the demand side. Once receiving the input, the multi-state supernetwork approach generates the PVNs and PTN for each individual. We adopt a different model specification from Liao *et al*. (2011) for the activity location choice model, while the model for parking location choice remains the same. The new model is tested with better goodness-of-fit when using the revealed data in the study area, which will be discussed in section 3. PTN and PVN connections are derived by on-the-fly queries (Liao *et al.* 2012). Then, the personalized multi-stated supernetworks are constructed in the way as mentioned above. Meanwhile, this application can also incorporate car travel speed profiles and PT time table. By assuming that individuals take the shortest time route when travelling with private vehicles, label-setting shortest path algorithm can find the optimal activity-travel pattern. After executing the multi-state supernetwork module for each *i* of *POP* of a scenario *j*, the aggregate effects are compared with the results of other scenarios.

Overall, the flowchart of applying the multi-state supernetwork approach for assessing individuals' travel patterns can be depicted as Fig. 2.

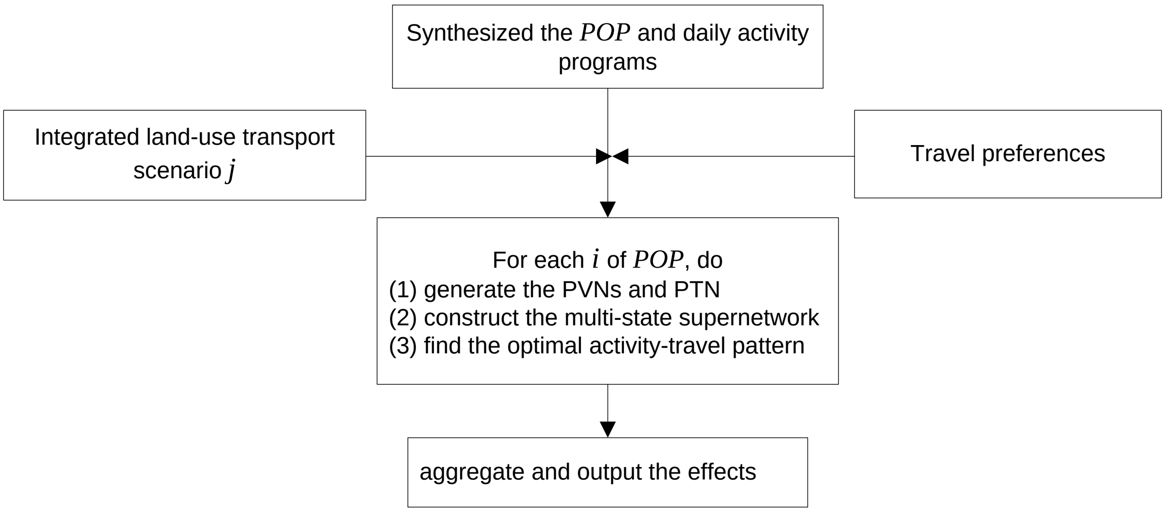


Fig. 2 Flowchart of the application

3. DATA

The multi-state supernetwork approach is applied for Rotterdam city (The Netherlands), where several policy scenarios are in perspective concerning transit improvement, increase of parking cost, and several land use redevelopment patterns. The purpose of these changes is to improve the overall accessibility of the region, and at the same time reduce car use and keep cars from outside going to Rotterdam city center. The following part will describe the input data about the study area and policy scenarios.

3.1 Study area

We select the long corridor i.e. Den Haag- Rotterdam-Dordrecht (Fig. 1) as the study area, which takes up the majority share of population and facilities in South-Holland province. Although Rotterdam city is the targeted area, it is reasonable to look into a broader area when evaluate the effects of policies since people living in the targeted area may go outside to conduct activities, and people living outside may also go inside.

According to MON (Dutch mobility travel dairy survey) from year 2004 to 2008, 89.4% of all the fixed activities including work/business, education and chauffeur etc. are conducted inside the corridor. In addition, around half of the people living in Rotterdam city have work activity outside and 16.4% living outside have the work activity inside Rotterdam. In Fig. 1, gray, green and blue lines denote local, regional and national road respectively, the dashed lines differentiate three parts with Rotterdam region in the middle, and the red line determines the border of Rotterdam city. The study area is divided into four areas, which will be used to track where individuals come from. Area 2 excludes area 2. Other related data are described below.

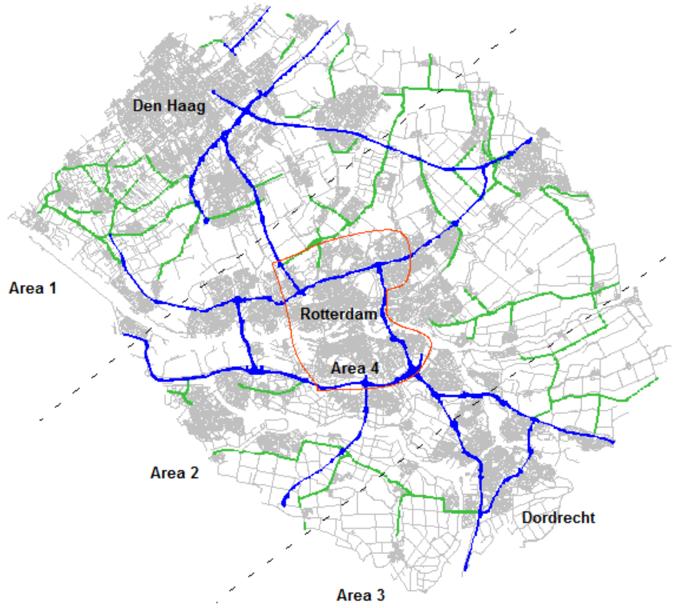


Figure 1 Den Haag-Rotterdam-Dordrecht corridor

The population are extracted from MON (from 2004 to 2008). Individuals, no younger than 12 years old, living in the corridor and having travel records, are selected. In total, there are 21,117 and 4,000 individuals in the corridor and Rotterdam respectively, which take up around 1% of the real population respectively. This low percentage is compensated by the person and trip weight information provided by MON. The individuals are differentiated into 4 classes in terms of their origin of areas in Fig. 1.

The activities are taken out from MON with removing some outliers. The sequencing of activities of an activity program is taken AS IS given the fact that the focus of this paper is to assess individuals' travel patterns, although the approach can also model the sequences of activities. Due to fixed sequencing, the time window constraints are self-evidently satisfied for most of activities. Thus, we do not consider time window constraints in this application. Activities are classified into two types: either fixed or flexible in terms of whether the activity can be conducted only at one fixed location or not. Table 1 shows the ratio and classification of activities with 1 for fixed and 0 for flexible. For flexible activities, an activity location choice model will be applied to select several alternative locations. Table 2 shows the distribution of number of trip per person. On average, each person has 2.46 activities, 1.57 home-based tours and 4.11 trips in the daily activity programs.

Table 1 Ratio and type of activities

activity	work	business	education	pick& send	city service	shopping	Leisure			
							going-out	culture	sports	recreation trip
ratio	20.7%	3.3%	4.9%	6.6%	5.1%	24.5%	17.1%	4.7%	4.9%	8.2%
type	1	1	1	1	1	0	0	0	0	0

Table 2 Distribution of number of trips

# of trips	2	3	4	5	6	7	>7
ratio	47.46%	7.34%	25.71%	4.91%	9.12%	2.49%	2.98%

Table 3 displays the ratio of possession of private vehicles per person. In this application, we consider only two types of private vehicles, i.e. car and bike, and assume that everyone has a bike and car owners remain unchanged.

Table 3 Possession of private vehicles in MON

vehicle	Car	bike	other	none
ratio	54.9%	86.8%	3.29%	4.65%

Locations/facilities of activities are made based on BAG (2011) (Dutch building geo-data), which provides the floor space and functions of buildings. The functions are mapped into the activities in Tabe 1. Since floor space is the only attribute of the activity locations, it is used as an indication for attractiveness. In BAG, one building represents a small area in geography. In MON, however, the activity locations at the destinations are indicated in terms of 4-digit postcode, which represent a larger area. To keep consistency, we use 4-digit postcode as an indication for activity location to flexible activities. For one thing, the revealed choices of flexible activity locations in MON can be used for the activity location choice model. For another, it can heavily reduce the choice space in the activity location choice model. The resolution for accuracy is still valid. For fix activities, 5-digit postcode is used as an indication for activity locations. 4-digit fixed locations in MON are assigned with a 5-digit postcode by Monte-Carlo method in terms of floor space. (In total, there are 389 4-digit postcodes in the corridor.)

PT timetable in the study area is taken into account, including modes of bus, tram, stop train and intercity train. The data are provided by 9292OV for the year of 2010. Realistic time-expanded model is adopted for PT queries with at least one minute margin for transfer in the same PT stop and at most four minutes walking distance allowed for transfer between different PT stops. In the base scenario, the PT system includes 1576 stops/stations and 177,147 basic connections. In the expanded graph, there are 533,241 nodes and 1,026,371 links. The fares for PT bus/tram, stop train and intercity train are assumed as 0.12 €/min, 0.14 €/min and 0.15 €/min respectively.

Road network is updated from NWB (2003) by appending the major road changes. In total, there are 72,513 nodes and 205,072 links. Road type is differentiated in four types, namely, <urban, local, regional and national>, in which urban road are selected from local road in the city centers of Den Haag, Rotterdam and Dordrecht. Car speeds are defined by profiles in terms of the time of the day, which are shown in Fig. 3. Average speeds for bike and walking are assumed as <14, 16, 17, 0> and <5, 6, 0, 0> respectively in km/h. The car fuel consumption is assumed as <0.17, 0.15, 0.125 and 0.105> in €/km in the four corresponding types of roads.

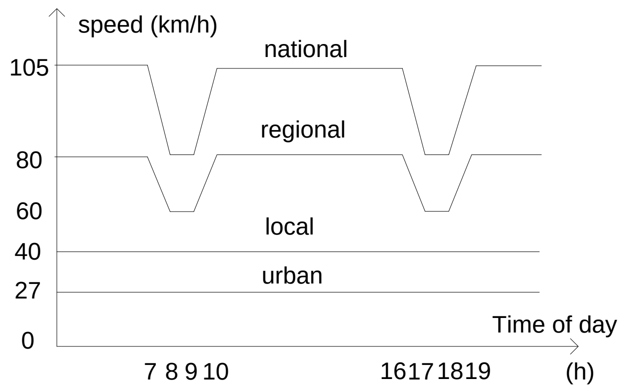


Fig. 3 Car travel speed profiles

Parking locations are differentiated by parking facility type and parking cost. Potential parking locations are activity locations, P+Rs (park and ride facilities) and THs (transport hubs, like train stations). Parking cost is dependent on the parking location and the parking duration, which is assumed in the structure of the following:

$$y_{P_k} = a_{P_k} + b_{P_k} \times t \tag{5}$$

where t and y_{P_k} denote the parking duration and the parking fee respectively. <a_{P_k}, b_{P_k}> are two parameters for every potential parking location, which are in unit of <€, €/h> respectively. For bike parking, we assume that it is possible everywhere and free of charge. Thus, $a_{P_k} = b_{P_k} = 0$ for any P_k. Since there is always a distance limitation for bike riding on a daily basis, bike and ride is also considered in the application. All the train stations are possible for bike and ride, which are blue dots in Fig. 4.1.

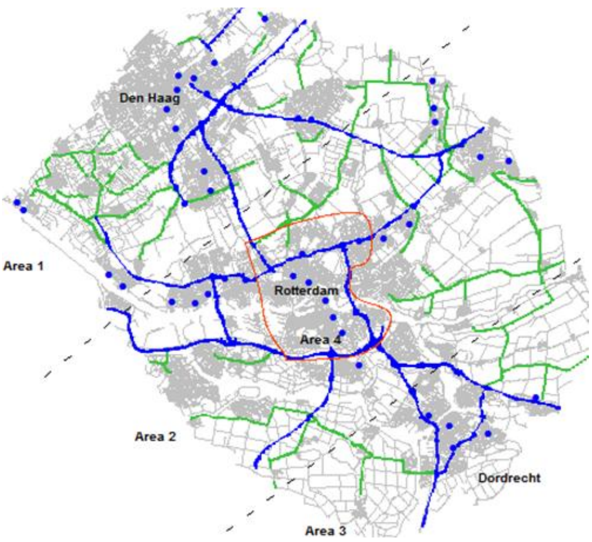


Fig. 4.1 Bike and ride

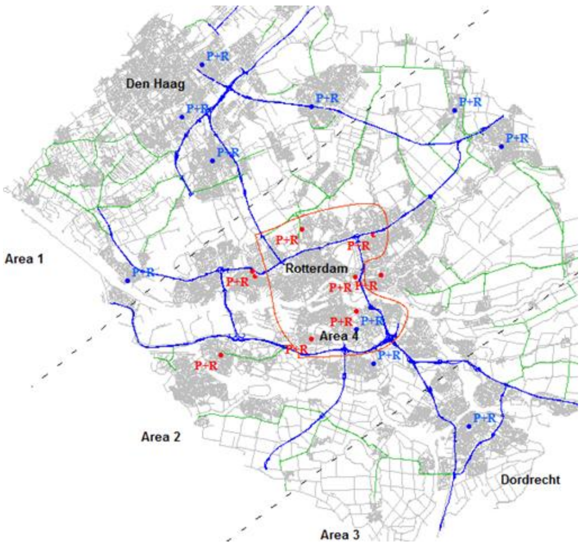


Fig. 4.2 Park and ride

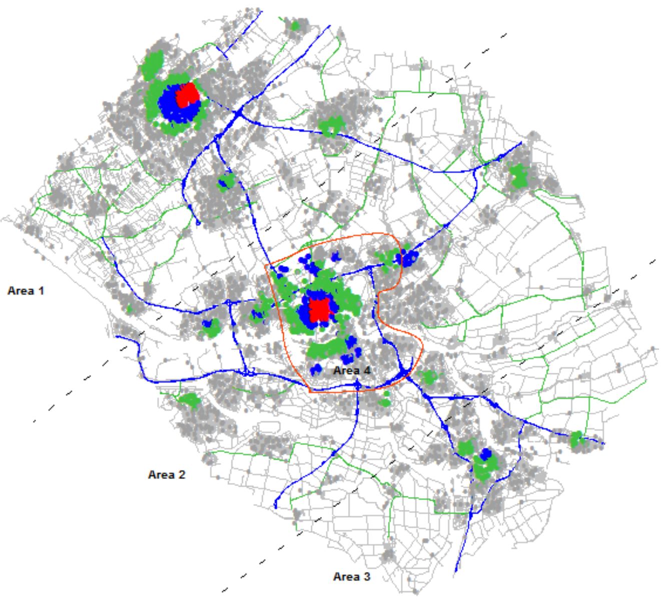


Fig. 4.3 Parking at activity locations

For car parking, park and ride is also taken into account in the application. Nine P+R facilities (in red) are especially designed to alleviate the car traffic in Rotterdam city center, which are located around the border. In addition, ten train stations are selected as alternatives for P+R (marked in blue in Fig. 4.2). Only two P+R facilities in Schiedam charge parking cost, and others do not charge as long as the drivers take PT.

Parking cost at the activity location is classified into four levels: L1, with the high parking cost in Rotterdam and Den Haag center (marked in red in Fig. 4.3); L2, with medium parking cost (marked in blue); L3, with low parking cost (marked in green); and L4 , no parking cost otherwise. <a_{P_k}, b_{P_k}> are set as <0.6, 2.4>, <0.5, 1.2> and <0.4, 0.6> for L1, L2 and L3 respectively. For example, Eq. 5 is written as $y_{P_k} = 0.6 + 2.4 \times \text{hour}$ for L1.

We use the parameters estimated from a series of choice experiments that have been developed for a comprehensive multi-modal and multi-state travel choice model (Arentze and Molin, 2013). A large nation-wide sample of individuals participated in the experiments (N=2,746) and efficient designs were used to develop the choice tasks. Preferences related to time, cost and service-quality attributes are estimated with relatively high detail. Tab. 4.1 and 4.2 show the parameter setting for individuals' preferences to travel components. Average level of preference is used for the current application. (More accurate parameters incorporating socio-demographics should be set in future applications.)

Tab. 4.1 Parameter setting for travel preference

Time (minute)												Cost (€)	
travel						transition							
walk	bike	bus& tram	stop train	IC train	car	Board &wait	alight	car park	car pick	bike park	bike pick	fuel	ticket
β_{it}^{W}	β_{it}^{b}	β_{it}^{bus}	β_{it}^{st}	β_{it}^{ic}	β_{it}^{c}	β_{it}^{W}	β_{it}^{AT}	β_{it}^{PKc}	β_{it}^{PCc}	β_{it}^{PKb}	β_{it}^{PCb}	β_{ic}^{f}	β_{ic}^{T}
0.0115	0.08	0.065	0.06	0.055	0.044	0.10	0.0	0.075	0.04	0.03	0.02	0.098	0.21

Tab 4.2 Parameter setting for travel preference

Constant for travel links										
walk	car main	bike access	Bike main	bike egress	PT access	bus/tram main	train main	PT egress	P+R	transfer per time
β_{iCT}^{W}	β_{iCT}^{cm}	β_{iCT}^{ba}	β_{iCT}^{bm}	β_{iCT}^{be}	β_{iCT}^{PTa}	β_{iCT}^{BUSm}	β_{iCT}^{TRAINm}	β_{iCT}^{PTe}	β_{iCT}^{PR}	β_{iCT}^{T}
0.0	0.0	0.44	0.6	-0.055	0.85	0.80	1.0	0.165	0.05	0.12

In the location choice model, every flexible activity is associated with a pair of fixed activities. If considering home-departing and home-returning as two fixed activities, a flexible activity may be conducted in-between at least one pair of fixed activities. For each pair of fixed activities, the activity location choice model is specified as:

$$disU_{f_n} = \alpha_{f_n} + \beta_{iAD}^{*} \times \ln\left(1 + aDist_{f_n}\right) - \beta_{is}^{*} \times size_{f_n} \qquad (6)$$

where $disU_{f_n}$ is the choosing disutility for flexible activity f at location n, α_{f_n} is the base disutility, $aDist_{f_n}$ denotes the access distance from the former fixed activity location to n, $size_{f_n}$ is the size for f_n, and β_{iAD}^{*} and β_{is}^{*} are the parameters for the factors of access distance to f_n and size of f_n respectively. Each 4-digit postcode area is assigned with a constant of α_{f_n}. $disU_{f_n}$ is taken into account of the path choice process. The parameters (Table 5) for location choice model are estimated from MON.

Table 5 Parameter setting for location choice model

attractiveness of flexible activity locations									
coefficient of ln(1+ access distance in km)					coefficient of every 10^3 m^2				
shopping	going-out	Culture	sports	recreational tour	shopping	going-out	culture	sports	recreational tour
β^S_{iAD}	β^G_{iAD}	β^C_{iAD}	β^P_{iAD}	β^R_{iAD}	β^S_{is}	β^G_{is}	β^C_{is}	β^P_{is}	β^R_{is}
1.78	1.35	1.4	1.65	1.67	0.023	0.0232	0.0157	0.0314	0.0101

In the application, five alternatives are selected for each flexible activity. The parking location selection process follows the model in Liao et al. (2012). For each activity program, at most 20 parking locations are selected for car and 10 for bike. Other parameters are set as: bike acceptance distance d^A_{ib}=5 km, bike limit distance d^L_{ib}=15 km, car acceptance distance d^A_{ic}=15 km and car limit distance d^A_{ic}=+∞.

3.2 Scenarios

The data described above on land-use and transport is considered as the base scenario. Seven policy scenario elements are collected from different departments of the Rotterdam region, which are described in the following:

(1) increase train frequency (PHS program). This program plans to increase the frequency of train connection in the corridor, which is a part of a larger program aiming at concentrating spatial developments around the railway stations and improving transfer options in the south-wing of the Randstad. In this scenario, the frequencies of inter-city (fast) and stop (slow) train connections are increased from 6 to 8 and 4 to 6 per hour respectively. After increasing the frequencies, the basic PT connections increase from 177,147 to 179,076. In addition, β^{TRAINm}_{iCT}, the constant for using train as the main mode, is reduced to 0.75.

(2) upgrade Rotterdam Stadion station. Rotterdam Stadion station is now a stop train station only used for special events taking place on weekends in the stadion. This scenario upgrades this station to an inter-city station to stimulate the mobility in the south part of Rotterdam. Meanwhile, a P+R facility is open near the station. Conversely, Rotterdam Blaak station, about 2.5 km in the north of Stadion station, is downgraded.

(3) introduce a tram line. To further coordinate with the upgrade of Rotterdam Station station, a new tram line is introduced connecting the east and the west of Rotterdam city, which goes through the station. This tram runs in every 8 minutes on average.

(4) increase parking cost at activity locations. To reduce the car traffic in the city centers of Den Haag, Rotterdam and Dordrecht, parking cost is doubled compared to the base scenario. The increase on parking cost is supposed to promote the use of P+R facilities and bike and ride. Thus, <a_{P_k}, b_{P_k}> are set as <1.2, 4.8>, <1.0, 2.4> and <0.8, 1.2> for red, blue and green areas respectively in Fig. 4.3.

(5) land-use development pattern 1: scattered (Fig. 5.1). Many scattered 4-digit postcode areas in Rotterdam have moderate increase (5% -10% more) on the floor space for four types of flexible activities. Thus, the attractiveness of these areas to the individuals is increased moderately. In Fig. 5.1, the pink areas are marked for new development, which also applies to Fig. 5.2 and 5.3.

(6) land-use development pattern 2: city center (Fig. 5.2). This scenario focuses on the land-use development in Rotterdam city center, where major increases (35% more) occur on the floor space for flexible activities. This city center area is not necessarily the same as L1 area in Fig. 4.3.

(7) land-use redevelopment pattern 3: transport node-oriented (Fig. 5.3). In this scenario, there are large increases (25% more) on floor space for all the flexible activities in three big transport hubs. Note that the city center is also a big transport node.

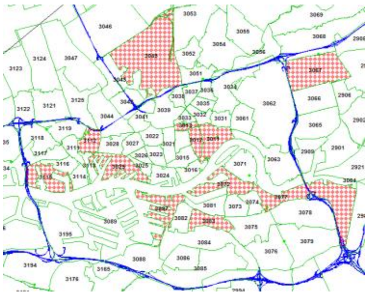


Fig. 5.1 Pattern 1

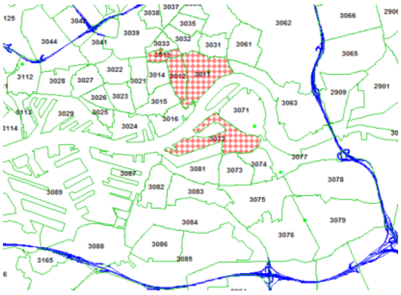


Fig. 5.2 Pattern 2

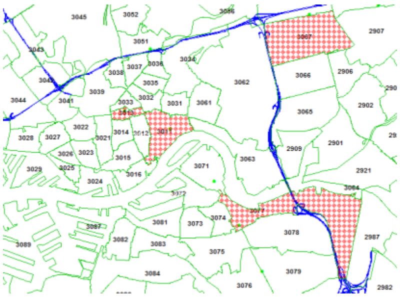


Fig. 5.3 Pattern 3

The integrated land-use transport scenarios in the application are formed on the above scenario elements. The scenario combination is dependent on the planning timeline and purpose so that assessing the exhaustive combinations is not necessary. According to the planning timeline, the three transport scenario elements are supposed to be implemented sequentially and prior to land use policies (the latter four). Therefore, we run the scenarios in a cumulative way from scenario element (1) to (4). For example, the first scenario only includes the first scenario element, and the second includes the first two elements, and so on. Since the three land use development patterns are mutually exclusive, they are accumulatively added on the fourth scenario respectively. Note that all these seven scenarios are based on the base scenario. Hence, there are eight running scenarios in total.

4. APPLICATION

In this section, we present the results of the application, which follows the steps discussed in subsection 2.2 (Fig. 2). Key indicators on accessibility index and VMT, and individual travel patterns on trip time, mode distribution, facility usage, etc. are compared under the eight scenarios. The application is executed with C++ in Windows® environment at four PCs with Intel® Core™2 Duo CPU E8400@ 3.00GHz 3.00G RAM. The computation time is around 4.5 hours per PC.

4.1 Results

As aforementioned, in addition to the policy-targeted area, a broader corridor is selected as the study area to sufficiently assess the travel patterns. Thus, for some of the effects, the comparison under eight different scenarios is applied to two areas separately, i.e. Corridor and Rotterdam.

Fig. 6 illustrates the effect on the accessibility index, which indicates that the accessibility changes follow the same trend in the two areas. As expected, increasing train connection frequency leads to accessibility increase. Upgrading Rotterdam Stadion station hardly influences the accessibility, which is compensated and enhanced by coupling with a tram line going through this station. Doubling parking cost obviously hampers accessibility since people need to pay more or switch less efficient transport modes or locations; this effect is stronger for people living outside Rotterdam. Moreover, all the land use development patterns have brought substantial increase in accessibility with the city center pattern excelling others.

Fig. 7 shows the effect on VMT. Like the effect on accessibility index, transport changes do not bring substantial impacts on VMT. On the contrary, higher parking cost immediately decreases VMT and the effect is stronger for people living in Rotterdam. Surprisingly, scattered land use development pattern does not reduce VMT as others. It is probably because those 4-digit postcode areas are scattered away with lower parking cost and increased attractiveness so that people drive longer to the locations. Likewise, city center pattern excels others as city center bears highest parking cost, big transport hub and the most attractive flexible activity locations.

Fig. 8 and 9 display the average PT travel time (including waiting time) and PT waiting time respectively. On average, people living in Rotterdam spend less time on PT travel and waiting. It should be noted in scenario 4 that higher parking cost not only suppresses car cars, but also reduces long-distance PT usage since people are likely to switch to closer activity locations. On the other side, land use development stimulates individuals to travel further by PT given that car use is suppressed due to higher parking cost.

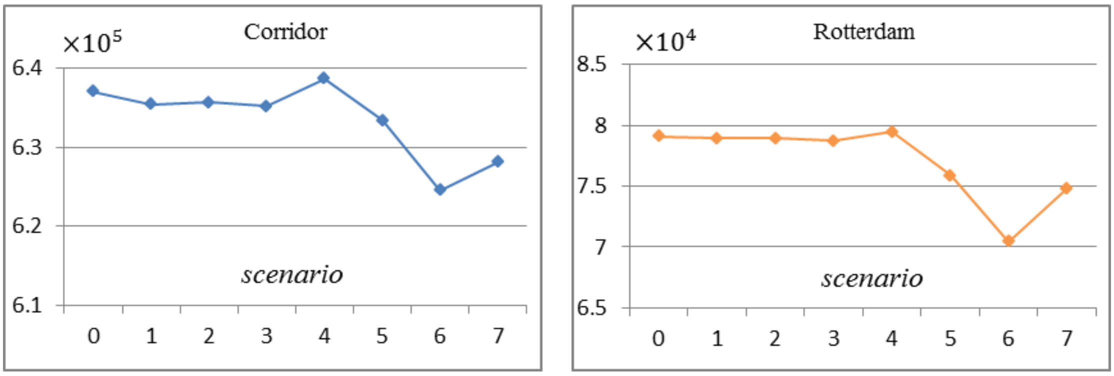


Fig. 6 Accessibility index

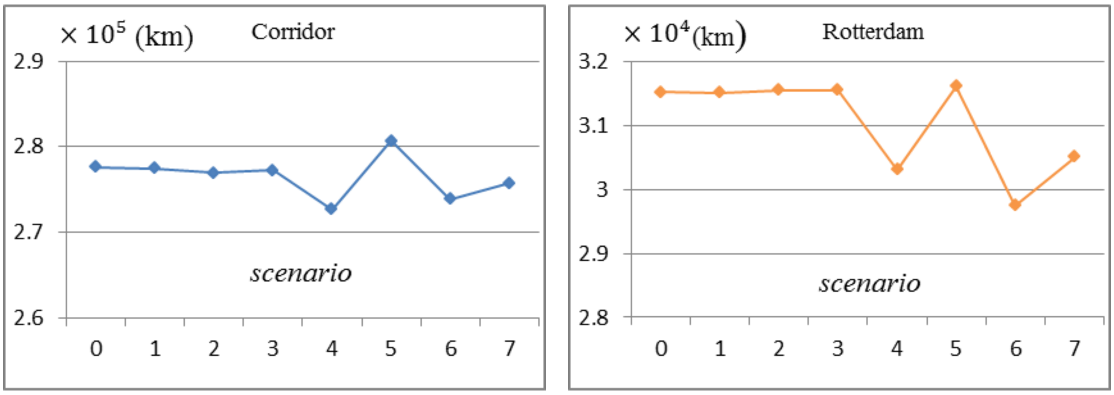
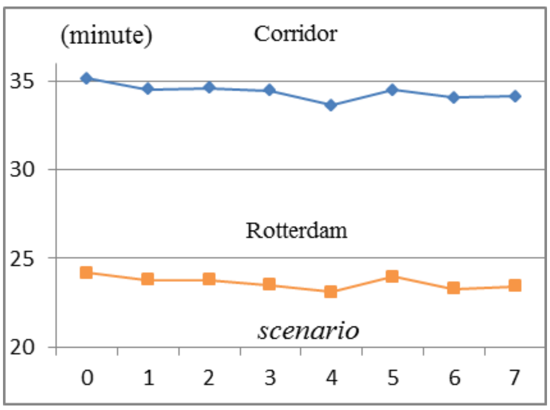


Fig. 7 VMT by car



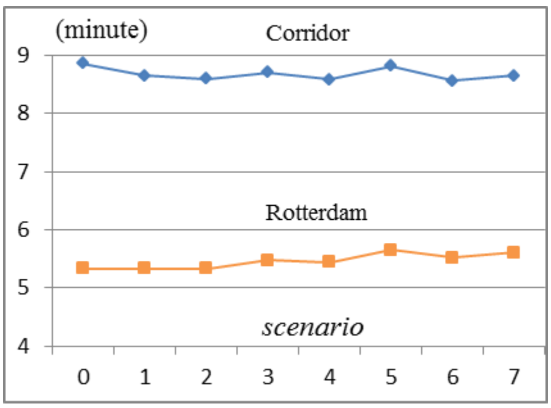


Fig. 9 PT time per trip including waiting/transfer   Fig. 10 PT waiting time per trip

Fig. 10.1 and 10.2 show the mode distribution, in which B+R and c-ride represent bike + ride and car passenger respectively. Since there is no parking and fuel cost involved in c-ride, the share is little changed over the scenarios. As observed, the mode shares are quite stable with the transport changes, and dramatically changed at and after scenario 4. Overall, higher parking cost in urban and highly developed area reduces car use, which are unexpectedly not primarily substituted by PT but by bike. A noticeable part of walk mode share is replaced by PT use in scenario 5 to 7, in which several areas become more attractive. In addition, high parking cost promotes substantial P+R use, while B+R share only increases marginally.

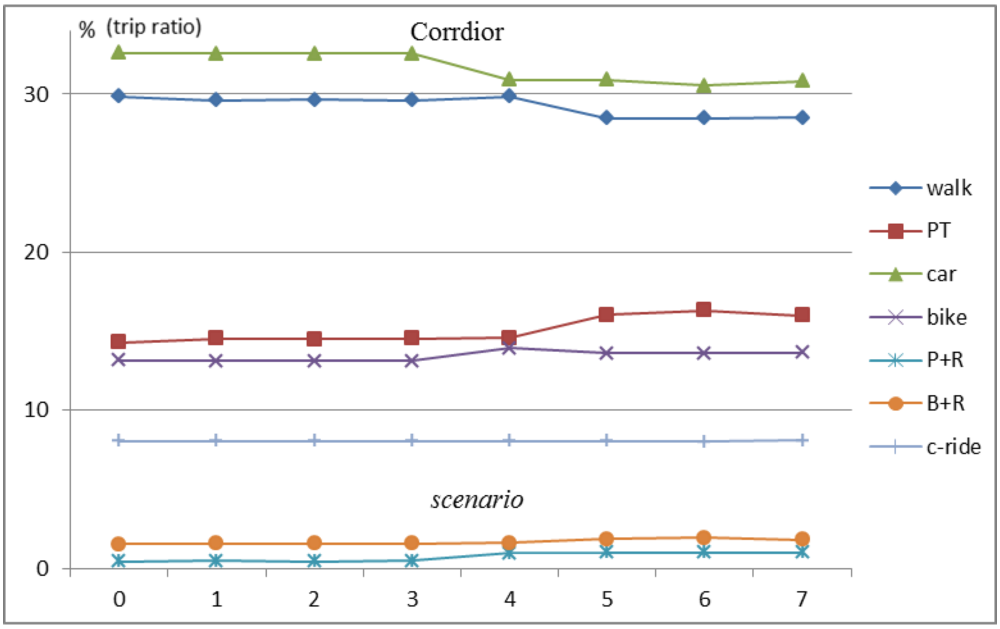


Fig. 10.1 Mode distribution in the corridor

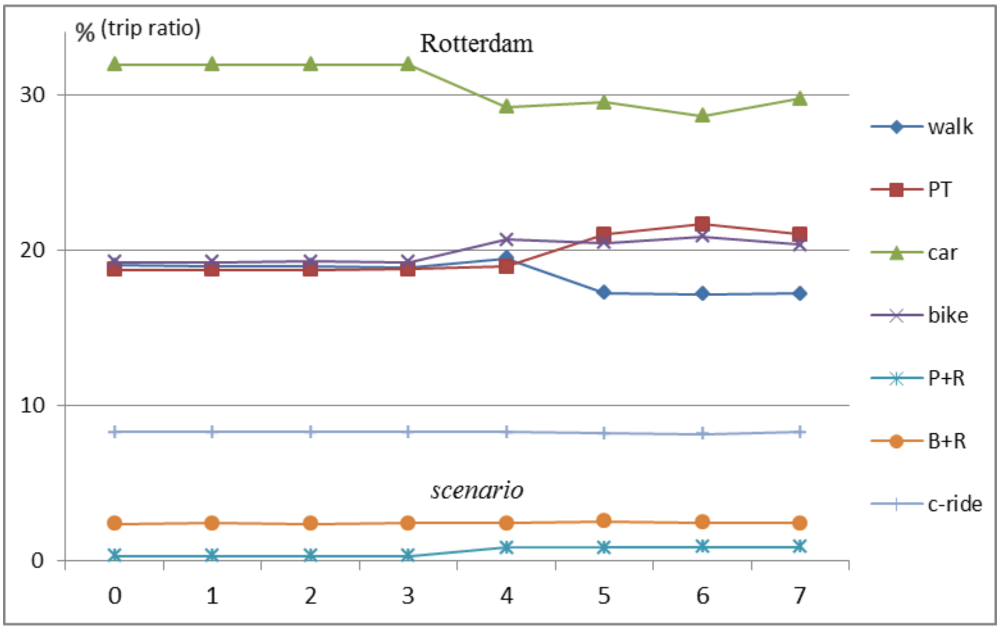


Fig. 10.2 Mode distribution in Rotterdam

The multi-state supernetwork approach also allows tracing facility use and who use them. Fig. 11 shows the number of P+R users in terms of individuals' origin. As shown, the number of P+R users increases along the scenarios except that a few individuals in area 3 switch to full PT use under scenario 1. As the majority of the synthesized population comes from area 1 and 2, more people choose P+R from these two areas. It is observed that scenario 7 attracts the most P+R users compared to scenario 5 and 6, which is logic because it is easier to combine PT ride with activity implementation at big transport nodes. However, higher parking cost also renders people living in Rotterdam to use P+R inside Rotterdam, which are in principle designed for people living outside.

In Fig. 12, the y-axis represents the number of trips with P+R use in terms of the trip purposes. Only the four common activities occupying the highest shares are shown in this figure with work and shopping activity in the top. Note that when a car is parked at a P+R facility, the multi-state supernetwork approach allows an individual to conduct multiple activities, which is in line with the reality. Land use development patterns do not cause the effect as strong as higher parking cost. Conversely, people may not choose P+R for work activity after the land use development, which is contradictory at the first glance. By tracing the activity-travel pattern of such an instance, it is found that the individual uses P+R for work and shopping activity in scenario 4, and he/she drives directly to the working location and later switches both P+R location and shopping location in scenario 5.

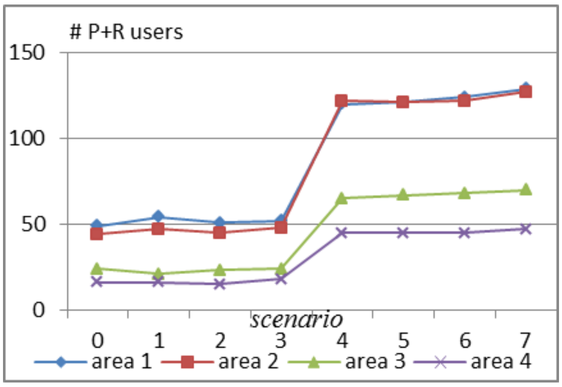


Fig. 11 P+R user's origin

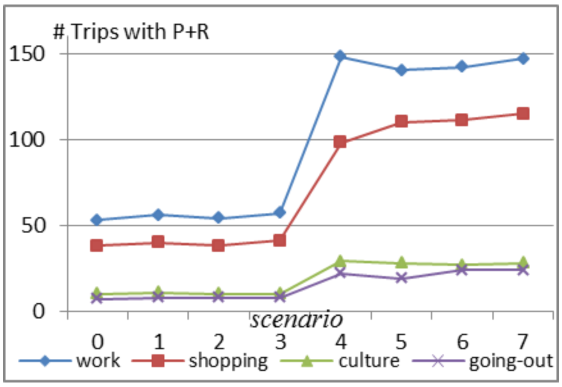


Fig. 12 Trip purpose with P+R

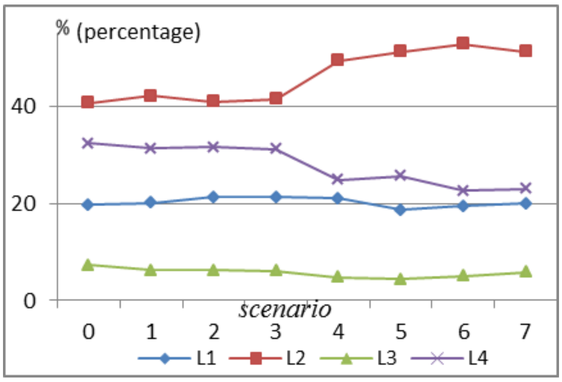


Fig. 13 Trip destination's parking level with P+R

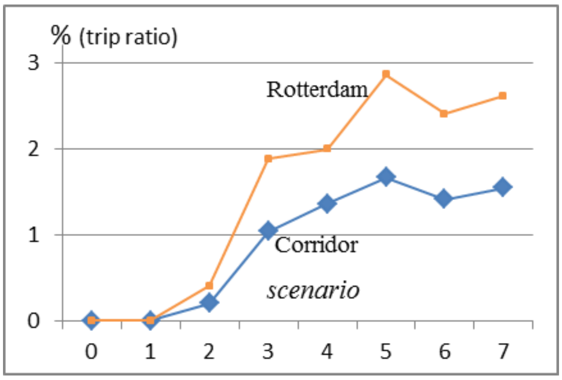


Fig. 14 Use of Rotterdam Stadion station

In Fig. 13, the y-axis represents the parking level distribution of trip destinations of trips with P+R. Fig. 13 should be looked into Fig. 10.1 for absolute numbers. Basically, it shows that most P+R trips have destinations in quasi-city center (L2 area) and this effect is intensified by land use policies (scenario 4 to 7). Fig. 14 demonstrates the effect of use of Rotterdam Stadion station for accessing or egressing, in which the y-axis represents trip ratio. Apparently, it has stronger effect for people living in Rotterdam. The scattered land use development pattern causes the most frequent use compared to scenario 6 and 7. Since more attractive locations are scattered far away, people living or working in the south part of Rotterdam need PT travel with train.

4.2 Interpretation

Several indicators predicted in this application under the base scenario are also compared with MON in the year of 2004, and the results show the validity of this application. For example, the average trip length and travel time in the model are 9.2 km and 25.2 minutes while in MON are 9.4 km and 22.1 minutes respectively, which means that the flexible activity locations are predicted quite accurately. Moreover, the model predicts 36 and 142 individuals choose P+R and B+R, while in MON the numbers are 41 and 127 respectively. One point should be mentioned here that in Fig. 10.1, there are some biases from MON in the mode share of walk and bike, though staying in the same magnitude. In MON, the percentages are 22.3 % and 19.7% for walk and bike respectively. It is due to the space resolution that the flexible activity locations are indicated by the centroids of the 4-digit postcode areas and they are much larger in rural area than in the urban area. Therefore, more individuals prefer walking to cycling in the model based on the travel preferences, whereas they would prefer bike in reality. The fact is well-reflected in Fig. 10.2, where mode distribution is consistent with MON. Since such biases only occur in the same 4-digit postcode areas, the overall validity of the model is not affected.

The results above provide multi-faceted effects on travel patterns under integrated land-use transport scenarios. According to the results, transport improvements alone have not caused strong effects on those indicators as these changes take place on a small-scale. Nevertheless, they indeed increase accessibility and reduce VMT especially when the upgraded station is facilitated with the new tram line. In collaboration with transport changes, land use policies bought clear-cut changes on the travel patterns. Scenario 6 excels other two peer scenarios because city center is also a big transport node. However, it is unwise to focus on a single effect since there are many factors act on each other. For instance, while scenario 5 attracts more usage of Rotterdam Stadion station, it also results in higher VMT; and while scenario 7 leads to the highest P+R use, scenario 6 brings the highest share of PT use. In addition, some factors behind the scenarios should be considered, for example, scenario 6 brings the best effects on accessibility and VMT; on the other hand, it needs the largest investment in land use development. All in all, the multi-state supernetwork application provides rich information for urban and transport planners

5. CONCLUSIONS AND FUTURE RESEARCH

Integrated land-use transport modelling is one of the major research fields in the transportation engineering section. Current state-of-the-art models evolve to apply multi-modal activity-based modeling paradigm to improve the time-space resolution and policy-sensitivity. As a representative, multi-state supernetwork approach is in nature capable to integrate locations of facilities and multi-modal transport with individuals' activity programs and therefore to model high choice dimension problems. This paper applied this approach to assess the effects of policy scenarios on individuals travel patterns. A set of cumulative integrated land-use transport scenarios have been evaluated. The output provides the basis for analyzing multi-faceted effects. Results exhibit the interplay between transport and land-use policies. Results manifest the accessibility change, modal substitution and shift in the use of facilities under different scenarios. However, several issues should be recalled. Firstly, the travel preferences were estimated on an average level; whereas, socio-demographic variables should be incorporated to obtain more accurate predictions. Secondly, the scenarios were set according to planning timeline in the study area, which stressed the added value of land-use policies based on transport changes. However, it overlooks the impacts in the opposite way. Thus, extra scenarios should be appended in the new applications. Lastly, the multi-state supernetworks were constructed separately for each individual. Although the mode of car-passenger was included in the application, it was considered as a constant component, which might result in bias on mode distribution. For this matter, joint travel problem should be modeled explicitly like other choices. These issues will be addressed in the future applications.

ACKNOWLEDGEMENT

This study is supported by Dutch Science foundation (NWO).

REFERENCES

Arentze, T., Molin, E.J., 2013. Travelers' preferences in multimodal networks: design and results of a comprehensive series of choice experiments. Proceedings of the 92st Annual Meeting of the Transportation Research Board, Washington, D.C.

Arentze, T.A., Timmermans, H.J.P., 2004a. A learning-based transportation oriented simulation system. Transportation Research Part B: Methodological 38(7), 613-633.

Arentze, T.A., Timmermans, H.J.P., 2004b. A multi-state supernetwork approach to modelling multi-activity multi-modal trip chains. International Journal of Geographical Information Science 18, 631-651.

Balmer, M., Nagel, K., Raney, B., 2006. Agent-based demand modelling framework for large scale micro-simulations Transportation Research Record 1985, 125-134

Bhat, C. R., Guo, J. Y., Srinivasan, S., Sivakumar, A., 2004. A Comprehensive Econometric Micro-simulator for Daily Activity-travel Patterns (CEMDAP).Transportation Research Record 1894(1), 57-66

Bhat, C.R., Guo, J.Y., Srinivasan, S. and Sivakumar, A., 2004. A Comprehensive Econometric Microsimulator for Daily Activity-Travel Patterns. Transportation Research Record, Vol. 1894, 57-66.

Bowman, J.L. and Ben-Akiva, M., 2001. Activity-based disaggregate travel demand model system with activity schedules Transportation Research A 35 (1), 1-28

Carlier, K., Fiorenzo-Catalano, S., Lindvel, C., Bovy, P., 2002. A supernetwork approach towards multimodal travel modelling. Proceedings of the 82nd Annual Meeting of the Transportation Research Board, Washington, D.C.

Dafermos, S., 1972. The traffic assignment problem for multimodal networks. Transportation Science 6, 73-87.

Ettema, D., Borgers, A., Timmermans, H.J.P., 1996. SMASH (simulation model of activity scheduling heuristics): Some simulations. Transportation research record 1551, 88-94.

Fujii S., Kitamura R., Monma T., 1998. A utility-based micro-simulation model system of individuals' activity-travel patterns. Proceedings of the 77th Annual Meeting of the Transportation Research Board, Washington, D.C.

Gärling, T., Brännäs, K., Garvill, J., Golledge, R., Gopal, S., Holm E., Lindberg, E., 1989. Household activity scheduling, In Transport Policy, Management and Technology Towards 2001, 9, Contemporary Developments in Transport Modeling, WCTR, Yokohama, 235-248.

Kwan, M.-P., Murray, A.T., OKelly, M.E., Tiefelsdorf, M., 2003. Recent advances in accessibility research: representation, methodology and applications. Journal of Geographical Systems 5 (1), 129–138.

Liao, F., Arentze, T.A., Timmermans, H.J.P., 2010. Supernetwork approach for multi-modal and multi-activity travel planning. Transportation Research Record: Journal of the Transportation Research Board 2175, 38-46.

Liao, F., Arentze, T.A., Timmermans, H.J.P., 2011. Constructing personalized transportation network in multi-state supernetworks: a heuristic approach. International Journal of Geographic Information Science 25(11), 1885-1903.

Liao, F., Arentze, T.A., Timmermans, H.J.P., 2012. A supernetwork approach for modeling traveler response to park-and-ride. Proceedings of the 91st Annual Meeting of the Transportation Research Board, Washington, D.C.

Liao, F., Arentze, T.A., Timmermans, H.J.P., 2013. Multi-state supernetwork framework for two-person joint travel problem. Proceedings of the 92st Annual Meeting of the Transportation Research Board, Washington, D.C.

Lozano, A., Storchi, G., 2002. Shortest viable hyperpath in multimodal networks. Transportation Research Part B: Methodological 36: 853-874.

Miller, E., Roorda, M., 2003. A prototype model of household activity-travel scheduling. Transportation Research Records, Vol. 1831, 98-105.

Nagurney A., Dong J., 2002. Urban location and transportation in the Information Age: A multiclass, multicriteria network equilibrium perspective. Environment and Planning B 29, 53-74.

Nagurney A., Dong J., Mokhtarian P.L., 2003. A space-time network for telecommuting versus commuting decision-making. Regional Science 82, 451-473.

Nguyen, S., Pallottino, S., 1989. Hyperpaths and shortest hyperpaths, in: Combinatorial Optimization (B.Simeone, ed.), Lecture Notes in Mathematics, 1403, Springer-Verlag, Berlin, 258-271

Pyrga, E., Schulz, F., Wagner, D., Zaroliagis, C., 2008. Efficient models for timetable information in public transportation systems. ACM Journal of Experimental Algorithmics 12, 1-39.

Sheffi, Y., 1985. Urban transportation networks equilibrium analysis with mathematical programming methods. Prentice-Hall, Englewood Cliffs, New Jersey.

Sheffi, Y., Daganzo, C. F., 1978. Hypernetworks and supply-demand equilibrium obtained with disaggregate Demand models. Transportation Research Record 673, 113-121.

Shiftan, Y. and Ben-Akiva, M., 2011. A practical policy-sensitive, activity-based, travel-demand model. The Annals of Regional Science 47, 517-541.

Sivakumar, A., 2008. Modelling Transport: a Synthesis of Transport Modelling Methodologies. Technical report, Imperial College London.

Waddell, P., 2011. Integrated land use and transportation planning and modelling: addressing challenges in research and practice. Transport Reviews 31(2), 209–229.

Wegener, M., 2004. Overview of land-use transport models. Transport Geography and SpatialSystems. Handbook 5 of the Handbook in Transport. Pergamon/Elsevier Science, Kidlington, UK, 127-146.