

# Supernetwork approach for modeling traveler response to park-and-ride

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2 **A supernetwork approach for modeling traveler response to park-and-ride**  
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**1 ABSTRACT**

2

3 Park-and-ride has been identified by transport planners as a key element of any sustainability package  
4 that can help promote multi-modal trips, improve air quality and alleviate congestion in urban areas.

5 This paper presents a supernetwork approach that can assess traveler response to park-and-ride in an  
6 integrated fashion. The supernetwork is constructed to include all the choice facets of each traveler's  
7 activity program in terms of individual preferences and thus, capable to represent the traveler's action

8 space. The choices of park-and-ride facilities are fitly embedded in the full activity and trip chains.

9 Under this frame, not only the trade-off between the use of private vehicles and public transport but  
10 also the trade-off between car-and-ride and bike-and-ride can be captured. In addition, sensitivity  
11 analysis of the design of services or facilities is allowed. A series of scenario studies are presented to  
12 demonstrate that the proposed supernetwork approach can be applied as a systemic analytical tool to  
13 examine traveler response to park-and-ride at a higher level of detail.

14

15 **Keywords:** supernetwork, park-and-ride, multi-modal, activity program

16

## 1. INTRODUCTION

One of the key transport issues facing the world is that urban areas, especially the city centers, suffer from surges of cars and consequently constant or even increasing traffic congestion [1]. Congestion is recognized as the major cause of inefficient mobility and insufficient accessibility in urban areas. Further undesirable effects are the production of noise and emissions, and a reduction of quality in public places [2]. Transport planners are constantly searching for solutions, which can be easily implemented and do not involve too much investment, to decrease car use and increase the patronage of energy-efficient, high-capacity public transport (PT) in urban areas. A set of strategies concerning new spatial planning or stricter road and parking pricing comes into planners' perspective, which are categorized as either "push" or "pull" strategies. Among them, engaging in or developing a system of park-and-ride (P+R) is of great importance and interests as P+R can be easily implemented in existing urban systems and the perceived results perfectly fit planners' intentions.

P+R facilities, which were used originally by local authorities to add capacity to their urban parking stock [3], are mostly situated in urban fringe areas and enable people coming from suburban and rural areas to park their car and switch to PT to access destinations located in urban areas. Accordingly, the traffic share of car use from urban edges to urban areas, which is otherwise infused into critically congested urban areas, is diluted by PT. Hence, it is argued that P+R has positive environmental and congestion benefits through reducing overall car usage and energy consumption, replacing long car-only trips (particularly in peak-periods, the most congested and environmentally damaging bad effects) with multi-modal trips [4]. Holding the same purpose and belief, a number of major cities in Europe have introduced or are in the middle of introducing P+R facilities [1, 5]. Moreover, to benefit from the higher speed railway service, derivatives of P+R facilities for short car trip together with other services are set up in many intercity train stations to meet the hierarchy needs, which in turn encourage new modes of P+R, namely bike-and-ride and park-and-bike at train stations and other transport hubs [6].

Despite its popularity in practice, P+R has not attracted equal scientific interest [7]. A small body of literature has analyzed the planning and the design of P+R facilities with minimizing total travel time as the main objective. Other related studies tend to focus on either the factors influencing the choices of P+R or the effects of P+R schemes on the host urban system. Bos *et al.* [2, 8, 9] carried out several comprehensive stated choice experiments in the Netherlands to examine what characteristics of P+R facilities and policy measures can increase the usage of P+R. Results show that the quality of connected PT, i.e. frequency, number of transfers and punctuality, is of the highest importance to travelers and that carrot strategies are generally more effective than stick ones. Syed *et al.* [10] investigated traveler response to parking user fee introduction in the San Francisco Bay Area. They found no significant change in travel and park behavior. Similarly, a stated preference experiment by van der Waerden *et al.* [11] showed that less travel time from P+R to city center stimulated travelers to use P+R but parking-related characteristics are less important. However, as far as benefits of P+R to the urban system are concerned, there is an inconformity in the literature. While P+R seems to perform satisfactory in many large European cities [1, 8], research undertaken in the UK suggests that the impact on congestion is limited. On the one hand, it is mentioned that P+R in Amsterdam brings a reduction of millions VTM [11]; on the other hand, survey from Melbourne [12] found that a P+R facility's opening had drawn users from those who were not targeted and formerly used PT for their entire journey.

Although these studies provide insightful suggestions for transport planners, none of them can capture traveler response to P+R facilities at a higher level of detail that takes into account travelers' full daily activity program, trip chains, the real schedule of PT, and the trade-off between private vehicles (car or bike) and PT. If not integrating these elements, traveler response cannot be accurately represented and consequently the findings of effects of P+R may be misleading. Therefore, the purpose of this paper is to propose a supernetwork approach [13-17] that can assess traveler response to P+R in a consistent and integrative way. With this approach, sensitivity analysis of the design of services and facilities is also supported.

To achieve these objectives, the remainder of this paper is structured as follows. In section 2, we will briefly introduce the basic concepts and properties of a multi-state supernetwork. Next, we will discuss how this multi-state supernetwork can be tailored to assess travelers' responses to P+R

1 facilities while conducting their daily activity programs. In section 3, a series of numerical  
2 experiments are carried out to indicate that the proposed supernetwork approach can be a systemic  
3 tool for transport planners better implementing P+R. Finally, a discussion of conclusions and future  
4 work concludes the paper.

## 5 6 **2. SUPERNETWORK APPROACH**

### 7 8 **2.1 Multi-state supernetwork**

9  
10 The concept of *supernetwork* was first introduced in 1985 by Sheffi [18], who defined a supernetwork  
11 as a network of transport networks. Later, some related studies were focused on traffic assignment of  
12 multi-modal trips or trip chains. During the last decade, the supernetwork approach has been also  
13 applied to other fields such as biology, supply chain management, and telecommunication. This sub-  
14 section reviews the line of supernetwork applications in transportation and urban studies.

15 Initially, a supernetwork was just equal to an augmented network by interconnecting different  
16 physical transport sub-networks. One sub-network may represent the car network, while another may  
17 represent the network for PT. In this supernetwork, links are added to interconnect these networks at  
18 the same locations for different transport modes to represent transfers where individuals can switch  
19 between modes. Examples of applications of this concept to multimodal trips can be found in [19-20].  
20 Later, the concept was extended to include virtual travel by means of ICT use [21-23].

21 Critical to the understanding of the contribution of the present study to the literature on  
22 supernetworks and P+R is the extension suggested by Arentze and Timmermans [13], who attempted  
23 to integrate activity programs of individuals and multi-modal transport networks into a single formal  
24 representation. The quintessence of their approach is that a supernetwork is constructed for each  
25 individual and that each supernetwork consists of physical networks of different activity-vehicle  
26 states (combinations of activity and vehicle states). Activity state defines which activities at a  
27 certain stage have already been conducted, and vehicle state defines where the private vehicle is (in  
28 use or where it is parked). In this representation, nodes represent real locations in space. In addition,  
29 the following links are distinguished:

30 • *Travel links*: connecting different nodes of the same activity state, representing the movement  
31 of the individual from one location to another; the modes can be walking, bike, car, or any PT modes  
32 such as bus, train, metro etc.;

33 • *Transition links*: connecting the same nodes of the same activity states but different vehicle  
34 states (i.e., parking/picking-up a private vehicle or boarding/alighting PT);

35 • *Transaction links*: connecting the same nodes of different activity states, representing the  
36 implementation of activities.

37 Disutility values can be attached to each of these links as the meaning of each link is explicitly  
38 represented. Note that we use the term disutility to emphasize that a broader set of choice criteria is  
39 taken into account. Consequently, a least disutility path through this multi-state supernetwork can be  
40 identified to find the optimal activity-travel pattern for a given activity program. In other words, this  
41 representation of a supernetwork potentially has a lot to offer in terms of applications such as activity  
42 planning and scheduling, activity-travel implementation and the analysis of land use in a spatial and  
43 transportation setting.

44 However, a potential weakness of their approach is that the supernetwork could become very  
45 large and possibly intractable because it incorporates as many copies of a physical network as there  
46 are possible activity-vehicle states associated with an activity program. Liao et al. [14] therefore  
47 proposed an improved representation, which is easier to construct and reduces the size needed to  
48 include all the possible choice facets. In their approach, the multimodal transport network is split into  
49 a PT network (PTN) and private vehicle networks (PVNs). The PTN includes the home location,  
50 activity locations, parking locations, auxiliary transit locations and mode-specified links (PTN  
51 connections) that connect all the locations. It contains the modes of walking and PT. Since it can be a  
52 multi-modal network, if any node induces a mode change, extra bi-directed links are added to denote  
53 boarding/alighting transition links. Although the walking network can be separated from the PTN, it is  
54 appropriately incorporated by adding boarding and alighting links. On the contrary, a PVN contains

1 just home and parking locations, and links (PVN connections) that connect all these locations. As only  
 2 one mode is involved in each PVN, there is no need to extend it. PTN and PVNs share joint nodes of  
 3 parking locations interconnected by transition links where the individual can transfer between a  
 4 private mode and a public one. Next, all PVNs and PTNs in different states are connected through  
 5 feasible transition and transaction links. A straightforward way to define *feasible* in the whole  
 6 activity-vehicle state space is to create links between parking locations from PVN and PTNs of the  
 7 same activity state (Figure 1.1) and between activity locations from PTNs of the same vehicle state  
 8 but different reachable activity states (Figure 1.2).

### 10 **FIGURE 1 Example of Parking/Picking-up and Transaction Links.**

11  
 12 Figure 2 shows the supernetwork representation for an activity program, which includes two  
 13 activities and one private vehicle (car). H and H' denote home at the start and end of the activity state  
 14 respectively; A<sub>1</sub> and A<sub>2</sub> denote the locations for activity 1 and 2, while P<sub>1</sub> and P<sub>2</sub> represent the parking  
 15 locations for the car and P<sub>0</sub> denotes the car is in use; and the column of  $s_1s_2$  represents the activity  
 16 states for A<sub>1</sub> and A<sub>2</sub> (0-unconducted and 1-conducted). The bold directed links represent a tour that  
 17 the individual leaves home by car, parks car at P<sub>1</sub>, and travels in PTN to conduct A<sub>1</sub>; then picks up car  
 18 at P<sub>1</sub>, drives car again, parks at P<sub>2</sub>, and travels in PTN to conduct A<sub>2</sub>; lastly picks up car at P<sub>2</sub>, and  
 19 returns home with all activities conducted. Similarly, if the individual has the options of leaving home  
 20 by bike or by foot, there is a corresponding supernetwork related to the leaving home mode. The  
 21 union of all the leaving-home mode based supernetworks is the final individual supernetwork.

22 The individual supernetwork represents the action space for the activity program. The type,  
 23 mode and activity state of each link can be derived and therefore, its associated disutility can be  
 24 defined. Any a path, a set of links, from H to H' through the supernetwork corresponds to a feasible  
 25 activity-travel pattern to conduct the activity program. Any a feasible pattern corresponds to a  
 26 particular set of sequential choices on mode, route, parking and activity locations. Thus, the path with  
 27 least disutility includes the aforementioned choices together making the most desirable activity-travel  
 28 pattern to the individual.

### 30 **FIGURE 2 Example of Multi-state Supernetwork.**

31  
 32 To make PTN and PVN more specified and applicable to large-scale simulation, Liao *et al.* [16]  
 33 further proposed a heuristic approach to construct personalized PTN and PVN components for a given  
 34 activity program. It is based on the empirical finding that only a rather small set of possible locations  
 35 for activities are of interest to the individual. For example, in the case of grocery shopping activity,  
 36 individuals typically consider one or two of the closest local shopping centers, and perhaps some  
 37 peripheral retail developments, while the total number of choice options is perhaps a hundred times as  
 38 high. The approach involves first estimating the disutility of activity locations as a trade-off between  
 39 attractiveness and travel time to associated locations. Next, the individual choice set is narrowed  
 40 down by selecting either a specified number of alternatives or a specified proportion with the least  
 41 disutility. Likewise, this procedure applies to the selection of parking locations. [16] adopts the same  
 42 generalized link cost function structure as [13, 14], which is

$$43 \quad disu_{ismTl} = \beta_{ismT} \times X_{ismTl} + \epsilon_{ismTl} \quad (1)$$

44 where  $disu_{ismTl}$  denotes the disutility on link  $l$  of type  $T$  for individual  $i$  at activity state  $s$  with  
 45 transport mode  $m$ ,  $X_{ismTl}$  denote a vector of factors on link  $l$ ,  $\beta_{ismT}$  is a weight vector, and  $\epsilon_{ismTl}$  is  
 46 an error term. As an illustration [16], time and monetary cost are the two main factors for travel and  
 47 transition links, while time and attractiveness (combination of monetary cost and quality) are the most  
 48 important criteria for transaction links. If some links do not cause monetary cost, for example travel  
 49 links of walking, this component is omitted automatically. Despite without theoretic proof, sensitivity  
 50 analysis showed that the optimal locations can be selected out by setting a small selection parameter ( $N_s$ ).  
 51 With the heuristic approach, large-scale accessibility analysis is feasible and carried out for a  
 52 population of 42991 in Eindhoven city (the Netherlands).

53 Meanwhile, the multi-state supernetwork has its tentacle stretched to ICT use, and joint travel  
 54 and activity. Like the concepts of tele-working and tele-shopping, ICT substitution can be easily  
 55 represented in the multi-state supernetwork. If an activity can be conducted due to ICT use at a

1 location rather than at the actual activity location(s), a virtual transaction link can be added to connect  
 2 the locations just as the physical transaction links [15]. Following the same logic, if considering  
 3 several sub-activities as the fragments of an activity, the effects of temporal or spatial activity  
 4 fragmentation and multi-tasking while traveling or at a fixed location can also be captured in the  
 5 supernetwork. Based on [16], one episode of joint travel and/or activity has been embedded into  
 6 individuals' supernetwork by tracing the activity-vehicle states when the individuals involved meet or  
 7 depart each other [17]. Again, costs of every link can be defined in a personalized and stated-  
 8 dependent way.

9 In the next sub-section, we will describe how the multi-state supernetwork approach can be  
 10 tailored to assess travellers' responses to P+R facilities. The approach is based on the work of [16],  
 11 which uses the concepts of PVN and PTN, and does not consider ICT use and joint travel and activity.  
 12

## 13 2.2 Supernetwork for P+R

14  
 15 In practice, P+R facilities are dedicated for commuters and other people traveling into city centers to  
 16 avoid the stress of congestion, and scarce and expensive parking. From the perspective of activity-  
 17 based modeling that travel is a derived result of conducting activities at the destinations, it is therefore  
 18 essential to take into account the full activity program and the full trip chains when examining a  
 19 traveler's travel behavior ( an activity program is defined as the activities the traveler concerned is  
 20 going to conduct during the day) To be more specific, not only the supply side, service levels of PT,  
 21 activity and parking locations etc., but also the demand side, a traveler's attributes and preferences for  
 22 example power to use private vehicles and trade-off between time and money cost etc., should be  
 23 taken into account. In this sense, a systemic approach that can represent a traveler's action space is  
 24 necessary.

25 As discussed in section 2.1, the multi-state supernetwork representation in [16] possesses this  
 26 ability. However, at its core, the personalized supernetwork is constructed in a static way as its main  
 27 purpose is to provide a tool for accessibility analysis. Although the link costs of PVN and PTN  
 28 connections may vary with activity states, the link components between selected locations are fixed.  
 29 In the following part, we discuss three refinements of constructing the personalized supernetwork that  
 30 support the assessment of traveler response to P+R at a higher level of detail.

31 First of all, the P+R location choice model is complemented. In [16], parking locations are  
 32 selected based on heuristic rules. After activity location(s) are selected for an activity program,  
 33 parking locations are selected in terms of the available private vehicles. For each private vehicle  $p$ ,  
 34  $p = c$  (*car*) or  $p = b$  (*bike*), two types of distance circles with both centers at home are set for the  
 35 traveler  $i$ , acceptance distance  $d_{ip}^a$  and limit distance  $d_{ip}^l$ , which satisfy  $d_{ip}^a < d_{ip}^l$  and  $d_{ic}^l = +\infty$ . The  
 36 heuristic rule is: (1) with  $p$ ,  $i$  will not drive a distance over  $d_{ip}^l$  away from home but may drive over a  
 37 distance of  $d_{ip}^a$ ; and (2) if there is an activity location that lies out of circle  $d_{ip}^l$ ,  $i$  must find a parking  
 38 location near a PT stop for  $p$  inside circle  $d_{ip}^l$ , if it lies between  $d_{ip}^a$  and  $d_{ip}^l$ ,  $i$  may find a parking  
 39 location near a PT stop inside circle  $d_{ip}^a$ , otherwise,  $i$  will drive directly to the activity location. To  
 40 narrow down the choice of PT stops, they are only chosen from PT hubs because generally PT hubs  
 41 provide space for parking. In a word, the method in [16] selects only parking locations near activity  
 42 locations or at PT hubs, by which bike-and-ride is supported by default. However, this method does  
 43 not consider dedicated P+R facilities for car use, even though some PT hubs are used in effect as P+R.  
 44 Thus, the method should be extended so that P+R facilities are considered as well.

45 The procedure for selecting P+R facilities runs as follows. Assume  $i$  drives to a city center to  
 46 conduct one or more activities, in which  $i$ 's home is not located. If there is no P+R facility, the  
 47 procedure terminates for this city center. Else, it involves selecting a certain number of P+R facilities  
 48 with the least disutility based on the following formula:

$$49 \quad \text{dis}U_{iCr} = \text{dis}U_{iPRr} + \text{travel}_{iPRr} \quad (2)$$

50 where  $\text{dis}U_{iCr}$  denotes the disutility of  $i$  choosing a P+R facility  $r$ ,  $\text{dis}U_{iPRr}$  is the disutility of  
 51 parking car at  $r$ , and  $\text{travel}_{iPRr}$  is the average travel disutility from or to associable activity locations.  
 52 Note that the purpose of this procedure is not finding the best P+R facility, which is actually done in  
 53 the supernetwork model, but to eliminate candidates that are highly unlikely to be chosen. Figure 3 is

1 an example, which shows that except activity location, TH/1, TH/2, P+R/1 and P+R/2 can be options  
 2 for parking the car, and TH/1 for the bike. If P+R/2 and the activity location are selected for parking  
 3 car and TH/1 for bike, the resulting supernetwork representation is displayed in Figure 4. If more than  
 4 one activity is included in the activity program, the supernetwork is expanded as shown in Figure 2.

5  
 6 **FIGURE 3 Example of Location Considered for Parking.**

7  
 8 **FIGURE 4 Example of Action Space of a Traveller.**

9  
 10 Secondly, the real PT timetable is applied for PTN connections in the supernetwork. In the  
 11 literature, none of the P+R studies take into account the real timetable of PT. Instead, estimated  
 12 average waiting time and travel time are uniformly used. To more precisely study the synchronization  
 13 between inter-modal trips and between trips and activity locations, using the timetable schedule is  
 14 important, especially for low-frequency intercity train connections and the urban bus system.  
 15 Traveler's activity scheduling is very sensitive to timetable schedules since little adjustments in the  
 16 time schedule of certain routes may cause travelers to switch from one mode to another. Thus, we  
 17 adopt the realistic time-expanded model [24] for PTN connections between selected locations. In this  
 18 model, the PT timetable has expanded into a directed graph, in which any a link is tagged with a 5-  
 19 tuple  $\langle stop_{dep}, stop_{arr}, time_{dep}, time_{arr}, mode \rangle$  describing the start and end stop, start and end  
 20 time and mode. If mode does not belong to any PT mode, this link is a waiting link. This model is  
 21 consistent with the supernetwork approach as every link is explicitly represented. In this way, a link in  
 22 the PTNs represents a PTN connection. The disutility and components of PTN connections are  
 23 calculated on-the-fly, which are also dependent on the arriving time at locations.

24 Thirdly, disutility of parking also depends on the real duration of parking. The disutility related  
 25 to parking a private vehicle includes first parking and then pick-up. In [16], they are both set as  
 26 estimated average values in terms of the attributes of the parking locations. In reality, this rule holds  
 27 only for parking a bike. For car parking, the monetary cost often depends on duration. While the  
 28 pricing profiles may differ from location to location, most apply piecewise linear non-decreasing  
 29 pricing schemes: the longer the parking time the cheaper per unit time. P+R facilities encourage long  
 30 time parking, for example 6 to 10 hours during the day, whereas city centers repel especially long  
 31 time parking. Figure 5 is an example of a scatter diagram which shows the sampling price of parking  
 32 in two different types of parking pricing profiles. Hence, the produced disutility for car parking should  
 33 also be duration dependent.

34  
 35 **FIGURE 5 Example of Parking Price Profile.**

36  
 37 It is apparent that the first refinement keeps the properties of the supernetwork the same since  
 38 P+R facilities can be generically regarded as parking locations. For the second, although the PTN  
 39 connections are calculated on-the-fly, the PT time-expanded graph holds the same property as the  
 40 supernetwork. For the third, however, the link costs of parking/pick-up cannot be uniquely defined  
 41 beforehand because from a given time that a car is parked to the time the traveler picks-up the car,  
 42 there are many possibilities of duration through the PTNs. Therefore, we use the pricing profiles after  
 43 linearizing, which is as follow:

$$44 \quad y = a + b \times t \quad (3)$$

45 where  $y$  (€) and  $t$  (hour) denote monetary cost and parking duration respectively. The sampling for  
 46 linearization is based on the purpose of the parking locations. If it is a PT hub, a P+R facility, or for  
 47 long duration activity such as work and education etc., prices are sampled with duration increasing  
 48 every 15 minutes till 8 hours; and if for short duration activities like shopping, prices are sampled  
 49 with duration increasing every 15 minutes till 4 hours Then,  $y$  is decomposed. Constant  $a$  is dealt in  
 50 parking links, unit  $b$  in terms of time is assigned to every link in that parking-location related PTNs  
 51 and transaction links, and no change is made in the picking-up links. In such a way, the standard  
 52 label-setting shortest path algorithm is still valid to find the best activity-travel path. Another  
 53 advantage of the linearization is that it makes sensitivity analysis of parking price easier.



1 All in all, the supernetwork itself can model multi-modal and multi-activity traveling [13, 14]  
 2 and the above three refinements have taken into account the conditions that travelers may face in  
 3 choosing P+R facilities. The steps of the supernetwork approach for P+R are:

4 Step1: set up transport and land use system and personalized parameters based on the traveler's  
 5 attributes and preferences;

6 Step2: generate PVNs and PTN [16] for the activity program including the first refinement;

7 Step3: construct the supernetwork and find the optimal activity-travel path including the second  
 8 and third refinements;

9 Step4: trace the choices of P+R facilities in the path.

### 11 3. APPLICATION

12  
 13 In this section, we present several examples to indicate the advantages of the supernetwork approach  
 14 for assessing traveler response to P+R. The study area concerns the Eindhoven-Helmond corridor of  
 15 the Netherlands (Figure 6), which is about 14 km long and takes up a large share of mobility in the  
 16 Eindhoven region. As the major consumers of P+R facilities are commuters, the following examples  
 17 consider travelers as commuters in this corridor. Based on the Dutch national travel survey  
 18 collected in 2004 (MON), commuters typically have one activity (*work*) or two activities  
 19 (*work* combined with another activity like *shopping*) to conduct during the day. Thus, we  
 20 assume that only activity *work* and *shopping* could be in the commuters' activity programs.  
 21 The supernetwork approach is executed with C++ in Windows environment running at a PC using one  
 22 core of Intel® CPU Q9400@ 2.67 GHz, 8 G RAM. Figure 6 and other related data are described as  
 23 follows:

24 (1) Two red dots denote bus and intercity train stations. In between, there is an intercity train  
 25 connection which takes 11 minutes and runs every 30 minutes, and two bus line connections, which  
 26 take 44 minutes and each runs on average every 20 minutes. The timetable is provided by a PT  
 27 routing company, 9292OV [25], for the purpose of scientific research.

28 (2) The red circle defines the border of Eindhoven city center, inside which the roads are called  
 29 urban roads. Gray, blue and green links denote local, regional and national roads respectively. For the  
 30 four types of roads,  $\langle \text{urban}, \text{local}, \text{regional}, \text{national} \rangle$ , the average speeds for car, bike and walking  
 31 are assumed as  $\langle 25, 35, 50, 80 \rangle$ ,  $\langle 10, 12, 15, 0 \rangle$  and  $\langle 5, 6, 0, 0 \rangle$  respectively in km/h, and the fuel  
 32 cost for car is set as  $\langle 0.16, 0.12, 0.1, 0.08 \rangle$  in €/km, the fares for PT bus and train are 0.3 €/km and  
 33 0.2 €/km respectively.

34 (3) Six travelers ( $T_{0-5}$ ), whose homes are located around the black eclipse in Helmond, are the  
 35 targeted individuals of the following examples. Assume they all work at the same location  $\underline{Q}$ , which is  
 36 the city center point of Eindhoven.

37 (4) Activity locations are generated based on employee data that cover the Eindhoven region.  
 38 Quality of the locations is set to be positively correlated with the number of employees  
 39 accommodated. Activity locations provide facilities for parking. The car parking costs depend on a  
 40 con-centric zoning system: the closer to the city center point the more expensive the parking cost per  
 41 unit time is. Bike parking is always free. The two stations are PT hubs, where cars and bikes can be  
 42 parked. In addition, a P+R facility for car parking is located at the southern edge of Eindhoven city  
 43 center. Linearization parameters  $\langle a, b \rangle$  for TH/1, TH/2, the P+R facility and point  $\underline{Q}$  are set as  $\langle 1,$   
 44  $0.3 \rangle$ ,  $\langle 0.5, 0.25 \rangle$ ,  $\langle 0.3, 0.2 \rangle$  and  $\langle 2, 0.5 \rangle$  respectively in Euro.

45 (5) The components and structure of link costs are set as in Equation 1, and capacity is not  
 46 considered in the following examples.

### 48 FIGURE 6 Eindhoven-Helmond Corridor (Scale: 1:100000).

#### 50 3.1 Example 1: one traveler

51  
 52 This example considers the traveler  $T_0$  having an activity program on a typical day, which includes (1)  
 53 two activities, i.e. working at the office,  $\underline{Q}$ , and shopping with flexible locations, with durations of  
 54 510 and 15 minutes respectively; (2) sequential relationship placing working prior to shopping; (3)

1 availability of both a car and a bike; (4)  $T_0$  leaves home at 8:00 am in the morning and returns home  
 2 when all the activities have been conducted. For the sake of simplicity, we assume that change of  
 3 activity states does not affect parameters of link costs. The assumed personalized parameters are  
 4 shown in Table 1. Other parameters are set as follows:  $N_s = 4$  (selection number for shopping),  $d_{ia}^b=5$   
 5 km,  $d_{il}^b=10$  km,  $d_{ia}^c=20$  km and  $d_{il}^c = +\infty$ .

6  
 7 **TABLE 1 Personalized Parameters**  
 8

9 The execution time for this activity program is 0.065 seconds including point-to-point queries  
 10 for 44 PTN and 108 PVN connections. The optimal path of the whole supernetwork indicates that  $T_0$   
 11 would rather leave home with car to the location  $\underline{O}$  directly; after working,  $T_0$  would pick-up the car  
 12 and drive to a shopping location near home. The total disutility on this path is 670.32 units, which are  
 13 1.67 and 12.23 units less than leaving home by bike and foot respectively; and the total out-of-home  
 14 duration is 608 minutes, which is 8 minutes less than leaving home by bike or foot. If leaving home  
 15 with bike,  $T_0$  still has to wait for the same train to come as when leaving home by foot (by adapting  
 16 the departure time from home). Based on these outputs, therefore, we can argue the P+R facility fails  
 17 to attract  $T_0$ .

### 18 19 **3.2 Example 2: multiple travelers**

20  
 21 This example considers a series of scenarios, in which six travelers' ( $T_{0-6}$ ) responses to the P+R  
 22 facility are examined simultaneously. Unless otherwise stated in the following scenarios, for better  
 23 comparison, the transport and land use system, all personalized parameters are set the same as in  
 24 example 1. The following scenarios regard example 1 as a base scenario:

- 25 • S1: same activity program as  $T_0$  in example 1;
- 26 • S2: only working activity in the activity program in example 1;
- 27 • S3: a new shopping location is opened near P+R with very high attractiveness;
- 28 • S4: increase the frequency of the intercity train connection to 4 times an hour;
- 29 • S5: add a direct PT bus line from the P+R to  $\underline{O}$  with frequency 10 times an hour.
- 30 • S6 to S9: set  $b$  as 0.55, 0.65, 0.75 and 0.85 respectively with  $a$  fixed at 2 for  $\underline{O}$ ;
- 31 • S10 to S12: set  $\langle 2, 0.85 \rangle$  and  $\langle 1, 0.6 \rangle$  for the  $\langle a, b \rangle$  of  $\underline{O}$  and TH/1 respectively; and set  $b$   
 32 0.05, 0.15, 0.25 and 0.25 respectively with  $a$  fixed at 0.3 for the P+R facility;

33  
 34 The six travelers' respective choices of private vehicle and parking locations are displayed in  
 35 Table 2. B, -, and TH/1 denote using bike, parking at TH/2 and then taking PT (bike-and-park), using  
 36 car and only parking at the activity locations, and using car, parking at TH/1 and then taking PT  
 37 respectively. The results show that a particular policy is difficult to change travelers' behaviors (S1 to  
 38 S5), which implies that combinations of them could be more effective. They (S6 to12) also disclose  
 39 one of the reasons that why P+R cannot attract travelers by increasing parking cost at city centers,  
 40 which is travelers always seek to other alternatives, for using bike instead of car or parking car at  
 41 alternative locations with the trade-off between travel and monetary cost.

42  
 43 **TABLE 2 Choices of Private Vehicles and Parking Locations under Different Scenarios**  
 44

45 The above two examples demonstrate that the supernetwork can represent the action space of a  
 46 traveler and all the choice facets of conducting an activity program can be subtly weighted. Therefore,  
 47 it can be systemic tool for transport planners to manage and design P+R facilities.

## 48 49 **4. CONCLUSION AND FUTURE WORK**

50  
 51 P+R schemes are often promoted by researchers and transport planners as a way to avoid congestion  
 52 and the difficulties and cost of parking within the city centers. It has been suggested that special  
 53 attention should be paid to the design of P+R facilities as there is a lack of evidence that P+R has  
 54 attracted the targeted users. This paper proposes a supernetwork approach for assessing traveler

1 response to P+R facilities. This approach not only takes into account the activity and trip chain but  
2 also applies the real PT schedule timetable and parking price profiles. Meanwhile, travelers'  
3 preferences for transport modes and locations can also be embedded in the supernetwork. Thus,  
4 traveler response to P+R as well as the trade-off between PT modes and private modes can be more  
5 precisely captured. Illustrative examples are discussed to demonstrate the properties of the proposed  
6 supernetwork representation. Applications to transportation planning practice require accurate  
7 estimates of the personalized parameters. Incorporating the capacity of the P+R facilities and  
8 integrating P+R into the supernetwork extension of ICT use and joint travel (Section 2.1) is a  
9 potentially relevant avenue of future research.

## 11 ACKNOWLEDGEMENTS

12  
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- 25
- 26

1	<b>FIGURE 1 Example of Parking/Picking-up and Transaction Links.</b>
2	
3	<b>FIGURE 2 Example of Multi-state Supernetwork.</b>
4	
5	<b>FIGURE 3 Example of Location Considered for Parking.</b>
6	
7	<b>FIGURE 4 Example of Action Space of a Traveller.</b>
8	
9	<b>FIGURE 5 Example of Parking Price Profile.</b>
10	
11	<b>FIGURE 6 Eindhoven-Helmond Corridor (Scale: 1:100000).</b>
12	
13	<b>TABLE 1 Personalized Parameters</b>
14	
15	<b>TABLE 2 Choices of Private Vehicles and Parking Locations under Different Scenarios</b>

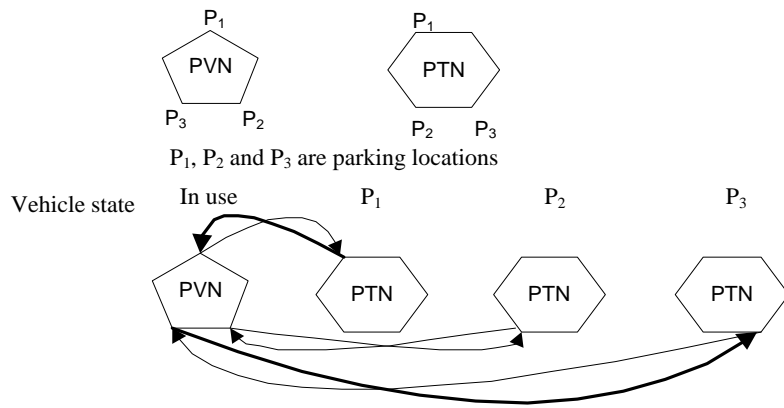


FIGURE (1.1)

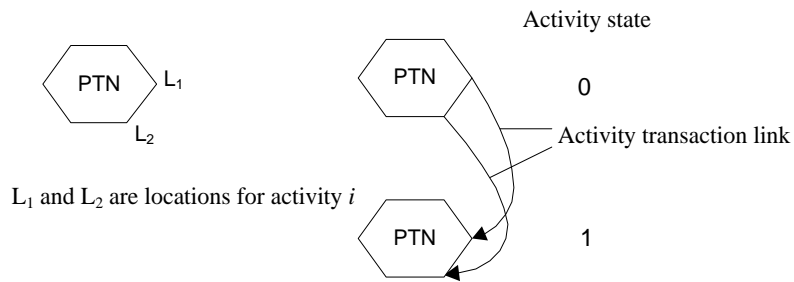
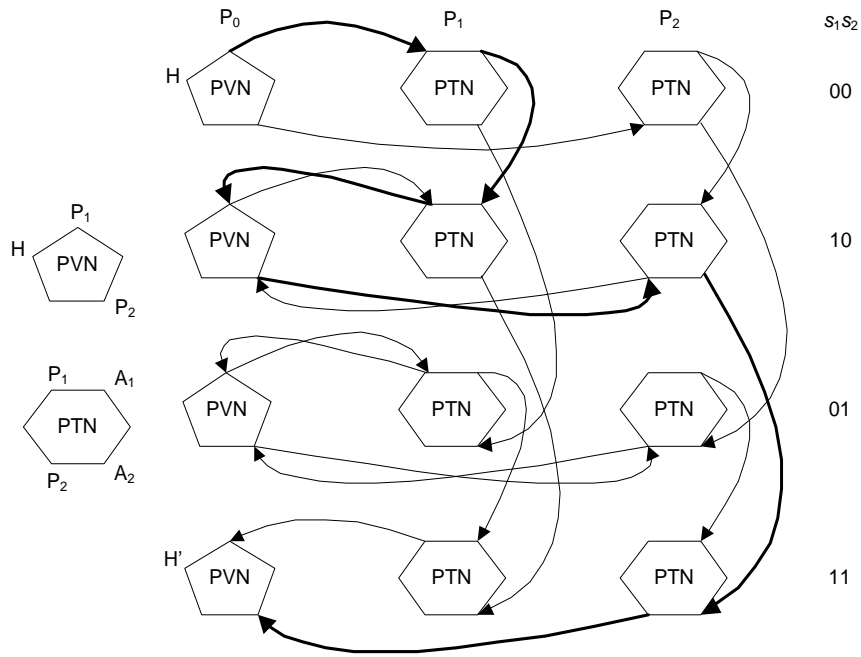


FIGURE (1.2)

**FIGURE 1 Example of Parking/Picking-up and Transaction Links.**

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**FIGURE 2 Example of Multi-state Supernetwork.**

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- 5

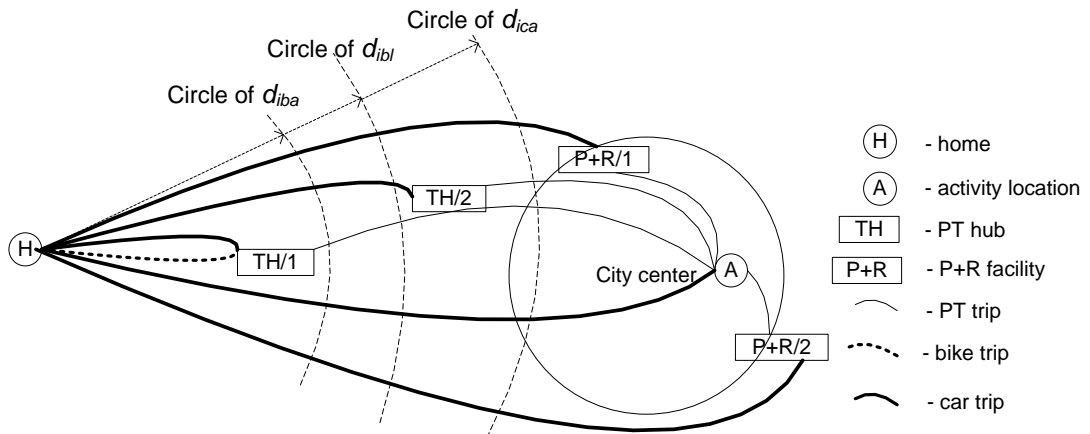
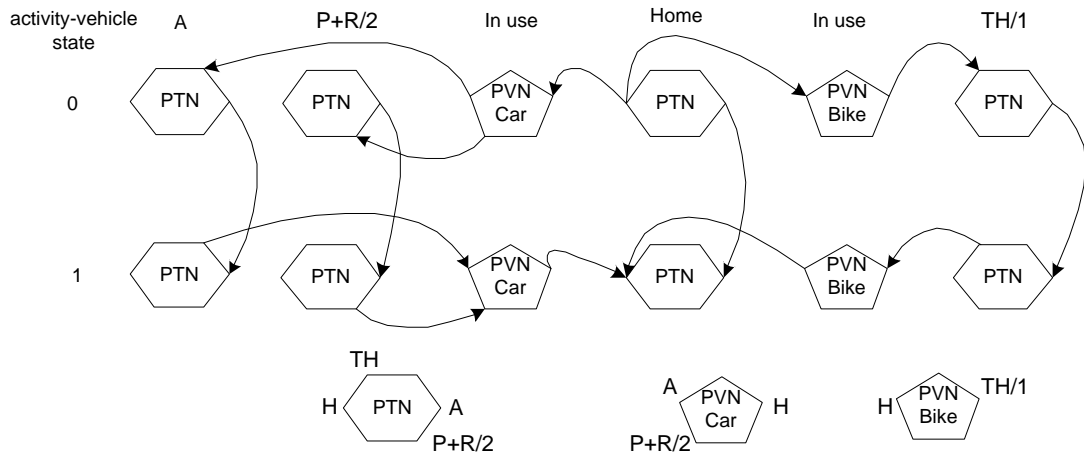


FIGURE 3 Example of Location Considered for Parking.

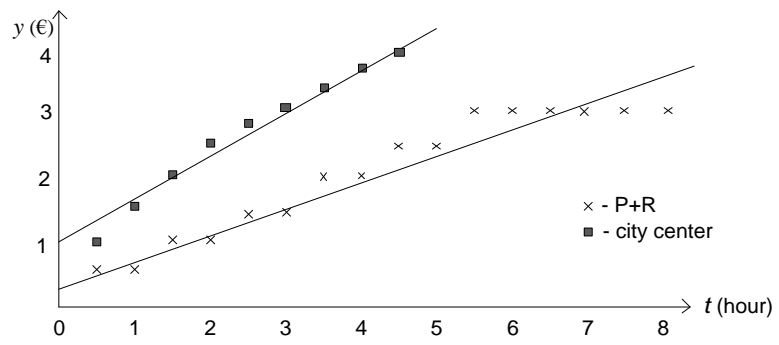
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**FIGURE 4 Example of Action Space of a Traveller.**

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4



**FIGURE 5 Example of Parking Price Profile.**

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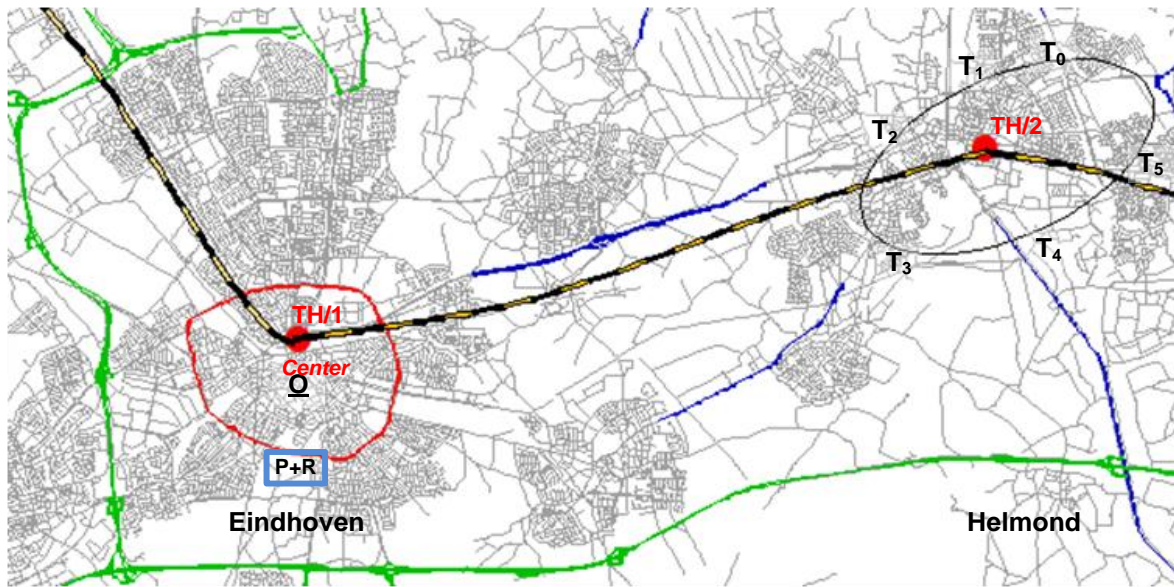


FIGURE 6 Eindhoven-Helmond Corridor (Scale: 1:100000).

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**TABLE 1 Personalized Parameters**

Time (minute)										Quality	Cost (€)
travel					transition				transaction		
walk	bike	bus	train	car	Board & wait	alight	park	pick	activity	activity	(all)
$\beta_{iwt}$	$\beta_{ibt}$	$\beta_{iptt}^{Bus}$	$\beta_{iptt}^{Train}$	$\beta_{ict}$	$\beta_{ibdt}$	$\beta_{iatl}$	$\beta_{ipkt}$	$\beta_{ipct}$	$\beta_{icat}$	$\beta_{icas}$	$\beta_{i-c}$
1.5	1.3	1.05	1.15	0.85	1.2	0	1	1	1	0.33	4.45

1  
2  
3  
4  
5

1  
2**TABLE 2 Choices of Private Vehicles and Parking Locations under Different Scenarios**

traveler\scenario	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
T <sub>0</sub>	-	-	B	B	-	-	B	B	B	B	B	B
T <sub>1</sub>	-	-	-	B	B	B	B	B	B	B	B	B
T <sub>2</sub>	-	-	-	-	-	-	-	TH/1	TH/1	-	-	-
T <sub>3</sub>	-	-	-	-	-	-	-	TH/1	TH/1	-	-	-
T <sub>4</sub>	-	-	-	B	-	-	-	-	TH/1	-	-	-
T <sub>5</sub>	-	-	-	-	-	-	-	-	TH/1	B	B	B

3  
4