Model complexities and requirements for multimodal transport network design: Assessment of classical, state-of-the-practice, and state-of-the-research models

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ABSTRACT

In the aim for a more sustainable transport system, governments try to stimulate multimodal trip making by facilitating smooth transfers between modes. The assessment of related multimodal policy measures requires transport models that are capable of handling the complex nature of multimodality. This complexity sets requirements for adequate modeling of multimodal travel behavior and can be categorized into three classes related to the range and combinatorial complexity of the choice set, the mathematical complexity of the choice model, and the complexity in demand-supply interactions. Classical modeling approaches typically fail to meet these requirements while state-of-the-practice approaches only partly fulfill these. Hence, the hypothesis of this study is that application of such models in network design implies an ill decision-making process. Both approaches are therefore compared with the theoretically sound super-network approach. Requirements for multimodality are constructed, and all three models are tested regarding how these requirements can be met. The findings of this comparison are supported by realistic examples in the real-world transport network of the Amsterdam Metropolitan Area. It is shown that the theoretical shortcomings of classical and state-of-the-practice approach indeed result in incorrect predictions of multimodal travel behavior. The flexibility of the super-network approach, on the other hand, is capable of describing the expected impact of supply changes on travel behavior. This illustrates the urgency for applying sound multimodal modeling approaches in network design studies.

1. INTRODUCTION

In many highly urbanized regions around the world transport related costs due to travel time delay and unreliability of the transport system are considered as major problems. Furthermore, large traffic volumes induce sustainability problems in terms of usage of scarce space in cities, energy consumption and the emission of greenhouse gases. A shift to more sustainable modes of transport, such as bicycle and transit, is likely to alleviate these problems by reducing inefficient car usage. However, the strength of the transit system, offering high capacity connections between main nodes, is reduced by its limited flexibility. The generalized costs involved with access and egress, parking of private vehicles and transferring between modes is often too high to be competitive with the car. A more integrated multimodal network would offer smooth transfers and synchronization between all types of private and public transport modes. In such a multimodal network travelers can benefit from the strengths of both private (flexibility) and public (high capacity) modes. Improved integration and coordination of transport modes is likely to lead to more trips in which multiple modes are used between which travelers make a transfer. More multimodal trip making implies an increase in transit and bicycle access and egress shares, and thereby to a more sustainable transport system (1). Typical instruments to facilitate multimodal trips are the establishment of park-and-ride or bike-and-ride facilities, synchronization of transit services, providing multimodal travel information, and offering high quality transit services.

Transport models are key tools in decision-making processes regarding the implementation of such multimodal policy measures. When searching for effective policy measures, the application of transport models can range from the evaluation of few pre-defined scenarios based on expert judgment to solving a multi-objective network design problem. The urgency for models that are capable of handling multimodal trips is twofold. In the first place, multimodal trip making is expected to become more important in the future. Hence, this type of trips has to be taken into account for accurate modeling of travel behavior. Second, the policy objective to stimulate multimodal trip making requires tools to evaluate the impact of specific measures. Correct modeling of multimodal travel behavior, however, is not a straightforward task. Classical modeling approaches mostly fall short of adequately covering and describing the full combinatorial range across all available modes of transport. This deficiency results from a rather strict separation between private and transit modes, a split between the mode and route choice, little attention for access and egress modes, the lack of detailed transfer modeling, and the assumption of unlimited service capacities. Hence, these models are not capable of capturing the full complexity of the analysis and prediction of multimodal trip making.

In the literature two main approaches can be found to handle the complexity of multimodal trip making in transport models. The first approach pre-specifies mode chains as additional artificial modes (2)(3). Classical models can easily be adjusted to incorporate these additional mode chains, which forms the main reason for its popularity in practice. This approach will be referred to as the state-of-the-practice model. The second line of research focusses on the integration of all modes by means of the network representation (4)(5)(6). Routes generated through such a network do not only describe the sequence of links, but also the related mode or combination of modes that is used. The state-of-the-research super-network approach is based on such a multimodal network representation, a-priori generation of travel alternatives, and simultaneous

mode and route choice (7). The multimodal concept and sound theoretical underpinning makes this approach suitable for handling typical multimodal difficulties in transport modeling.

The hypothesis in this study is that the application of state-of-the-practice transport models in network design still implies an ill decision-making process. Therefore, the main objective of this paper is to illustrate that using such models will lead to counterproductive or sub-optimal decisions by policy makers regarding the implementation of multimodal network measures. To this end, both the classical transport model and state-of-the-practice model are compared to the so-called super-network approach. All three models are applied to assess the impact of a series of typical multimodal supply measures in the real-world case study of the Metropolitan Area of Amsterdam. It is shown that state-of-the-practice models are not able to properly predict the impact of travel behavior to network changes as shown by the super-network model. The analyses of the dissimilarities in assignment results of the different models provide insight into the theoretical and conceptual shortcomings of currently used approaches.

This paper starts in Section 2 by introducing the model complexities that emerge in multimodal networks and concisely discussing how this relates to the developments in this field. Next, in Section 3, the models that are discussed in this paper are described, i.e., the classical model, the state-of-the-practice model, and the super-network model. The case study is subject of Section 4. After a short description of the case study, an overview of the evaluated multimodal supply measures is given. Thereafter, a conceptual comparison between the models is made and findings are supported by examples from the case study. The paper ends with some final remarks and conclusions in Section 5.

2. MULTIMODAL TRANSPORT MODELING

Urban regions are typically characterized by dense concentrations of housing, employment and facilities, the availability of a variety of transport modes, high costs for parking due the scarcity of space, and congested road networks. These characteristics provide optimal conditions for multimodal trip making. This multimodality has to be accounted for when assessing the transport systems' performance, and even more so, when evaluating typical multimodal policy measures. The nature of multimodal travel behavior introduces some complexity that is absent in unimodal transport prediction. Multimodal networks, in which continuous (private) and discontinuous (transit) modes are integrated, offer a large number of travel alternatives differing in mode or mode combinations, access and egress location, transfer facilities, and routes. The attractiveness of such an alternative depends, among others, on the combination of modes used, their composition within the full trip, and their mutual overlap with other alternatives. When modeling travelers' choices this complexity has to be taken into account as well as when considering the interactions between travel demand and network supply. This additional complexity sets requirements that should be met by transport modeling tools in order to adequately describe multimodal travel behavior. While state-of-the-practice transport models generally meet some of these requirements, other requirements have been discussed in the literature that are not yet fully adopted in practice. This latter category of requirements will be discussed in the section below.

2.1 Modeling requirements

The requirements that are specific to modeling multimodality can be categorized into three classes, each relating to a particular issue of the assignment process: the range and combinatorial complexity of the choice set, the mathematical complexity of the choice model, and the complexity in demand-supply interactions. In this study the total travel demand is assumed to be given and inelastic (i.e., independent of network performance). The requirements described here relate to the assignment of these travelers to the multimodal network, thus modeling travelers' mode choices and route choices. The requirements discussed in the ensuing of this section are categorically shown in the first two columns of the overview in Figure 3 in Section 3.4.

Range and combinatorial complexity of the choice set

In a multimodal network multiple modes of transport and transit services, as well as transfer facilities connecting them, are available to the traveler. A multimodal transport model should be able to predict the usage of the full range of modes and mode chains. Routes in which several modes or services are combined can be feasible alternatives and as such need to be considered (*representativeness of the choice set*). However, not every mode chain is feasible. Generally, travelers have no motorized private modes available at the station. A trip composition train-car-train is therefore rather unlikely. Such unfeasible travel alternatives should be excluded from the set of considered travel alternatives (*realism of the choice set*). Furthermore, the attractiveness of a trip leg can depend on the trip composition as a whole. For example, the costs for using a bicycle as access or egress mode are usually different at the home-side than at the activity-side of a trip. Where a bicycle is usually available for free at the home-side, a bicycle needs to be rented or parked in advance at the activity-side of a trip, implying extra costs (*trip dependent leg properties*).

Mathematical complexity of the choice model

The structure of multimodal transport networks is generally more complex than their unimodal counterparts. The planning of a trip in a large multimodal network might involve multiple choices related to the various available modes, transport services, and transit boarding and alighting locations. These additional choice dimensions make it much harder to describe the underlying behavioral choice process in a mathematical (tractable) way. The mode and route choices cannot be seen as two distinct choices anymore as they are heavily correlated. Travel alternatives describe both the spatial routes that are taken as well as the chains of modes that are being used. From a behavioral point of view the mode and route choices become integrated into a single simultaneous choice process (*choice dependencies*). In addition, the increased complexity of the network implies bigger differences in travelers' knowledge and perception of travel alternatives and their attributes as well as more variation in travelers' preferences. In general, it is more realistic to model the route choice in a stochastic way rather than performing a deterministic assignment. In modeling multimodal trips this issue becomes even more urgent (*heterogeneous perception and preferences*). Explicitly modeling the choice between travel alternatives, however, introduces another problem. Mode, services or space related unobserved route attributes could have rather complex correlation patterns. This overlap has to be accounted for when predicting route shares (*correlated alternatives*). Travelers have intrinsic preferences for certain modes that are not represented by any observed attributes. Using the metro, for example, is usually valued less onerous than travelling by car. Besides the attributes of a trip leg, these preferences for a leg can also depend on the trip composition as a whole. Using the bicycle

as an access or egress mode has a different impact on the attractiveness of the full trip than when the bicycle is used as the main mode. Similarly, the attractiveness of travelling by train is higher when one can board or alight at an intercity station (8). This is independent of the hierarchic level of the train service (stop, regional, or Intercity) being used (*trip dependent leg attractiveness*).

Complexity in demand-supply interactions

When the travel demand is high and peak periods are heavily loaded the usage of both the physical infrastructure and transit services will impact the (experienced) travel times. The consideration of alternatives in which multiple (private and transit) modes are combined introduces correlations in travel times and demand flows between different modes of transport. Higher travel times on the car network might impact the share of park and ride alternatives. As a consequence, the quality of the transit network is influenced by the usage of the car network (*demand-supply interaction between alternatives*). Another constraint is the available number of parking places at bike and ride and, in particular, park and ride facilities. More travelers using such a facility will raise walking times to and from the parking location at first. Eventually, no more vehicles can be parked when the available capacity is met (*capacity of transfer locations*). The resistance of making a transfer follows from, among others, parking costs, parking time, walking time, and the risk of missing a transit connection. These transfer related costs are a substantial part of the total generalized costs of a full trip. To predict the impact of (changes in) transfer attributes they have to be modeled explicitly (*performance of transfer movements*).

3. MODEL FORMULATIONS AND COMPARISON

In the previous section three main modeling approaches were distinguished: the classical approach, the state-of-the-practice approach, and the super-network approach. For the following comparative analyses, the corresponding operational models that follow the classical approach and state-of-the-practice approach are used (regarding methods and model parameters) according to their current implementation for the considered study area. An operational model of the super-network approach has been implemented specifically for this study based on methods and parameters reported from earlier studies and, where needed, re-calibrated with aggregated data for the case study area. Each of the models are described in the following subsections.

3.1 The classical model

The classical model is based on a strict separation between private and transit modes and does not meet the requirements for multimodality. Yet, the model is included here in the case study comparison to show the consequences of ignoring multimodal trips. In the ensuing, the classical model is described according to the network definition, modal split, and network assignment, while the main concepts of this model are shown on the left-hand side in Figure 1.

The multimodal transportation network consists of the infrastructure network defined by nodes and links, and the transit service network defined by lines and stops. Links have characteristics such as speed and capacity, while lines have characteristics such as frequency, travel time, and the network link(s) that are traversed. Transportation zones are used to denote origins and destinations, and form a subset of the network nodes. These zones are connected through connector links representing access and egress to the network. Connector links to the road

network enable pedestrians, bicycles, and cars, while connector links to the transit stops only allow for walking. Therefore, although private and transit modes can share the same links, they are dealt with as being two separate networks.

Figure 1 – The classical modeling approach (left) and the state-of-the-practice approach (right)

The total (inelastic) transport demand is distributed over the two main modes: car and transit. Bicycle traffic is here ignored as a main mode of transport as the considered demand describes interregional trips. The mode shares are computed using a standard multinomial logit model based on random utility maximization (9), where the error terms are assumed to capture effects of taste variation, knowledge limitations and perception differences across the population. In the traffic assignment, car trips are assigned according to the assumption of the deterministic user equilibrium, hence assuming that drivers have perfect information in their route choice. Route costs are based on the weighted sum of the travel distance and travel time, where travel times are modeled according to the BPR function. The equilibrium is computationally reached through applying the Frank-Wolfe algorithm, where enumeration of the route choice set is not needed.

For the assignment of transit trips, the combinatorial constraints due to the line-bound character of transit lines typically allows for enumeration of choice sets. Travelers' preferences are explicitly taken into account by the principle of optimal strategies (10) in a stochastic assignment. Optimal strategies imply that travelers choose a set of alternatives that can be optimal rather than choosing a single route. This set of alternatives includes all feasible alternatives between a boarding station and the destination and is also referred to as a hyper-path. During their trip they choose which service lines to board, based on actual arrival times of transit vehicles. In the assignment first a set of candidate alighting stops is defined based on maximum walking distances to the trip destination. Thereafter a branch-and-bound building algorithm is applied backwardly construct the hyper-path. Per stop that is reached, the expected travel time is calculated as the sum of the in-vehicle times (of all calling lines) weighted by their boarding probability and the expected weighting times. Boarding probabilities are calculated through a logit model in which travel times are multiplied by line frequency. The waiting time at a stop is

calculated as half of the headway of the combined frequency of all lines that can be used. When all candidate boarding-stops are reached a logit model is applied to distribute travelers over these stops based on the generalized costs of the hyper-path serving this stop. The generalized costs are a weighted sum of monetary costs, in-vehicle time, access time, egress time, waiting time and the number of transfers that has to be made. Hence, the average generalized costs used in the mode choice are the sum of the generalized costs per hyper-path weighted by their choice boarding stop probability. Conceptually, the assignment could be repeated several times with updated perceived travel times to reflect vehicle crowding and reach equilibrium. However, this is seldom done in practice since it would dramatically increase the computation time.

3.2 The state-of-the-practice approach

The state-of-practice model is basically an extension of the classical model, mainly differing in the fact that a set of mode chains is pre-specified. To this end, transferring between private (bicycle and car) and transit modes is now allowed at transit stops, and corresponding connecting links between road network nodes and transit stops are included in the network representation. The modes that can traverse such a link determine the feasible transfers at the transit stop. In general, transfers from bicycle are assumed to be possible at any stop, while car transfers are only possible at a limited set of pre-defined stops. The construction of the transit hyper-path follows exactly the same procedure, but note that the branch-and-bound algorithm has to be repeated for every egress mode, as the set of candidate stops depends on the maximum egress distance by this mode. In the model used here, the following mode chains are distinguished as separate modes: walk-transit-walk, bicycle-transit-walk, car-transit-walk, walk-transit-bicycle, and walk-transit-car. These pre-specified mode chains consist of two or more modes, but are modeled as an additional artificial mode. Therefore, mode choice is now applied to a wider set of modes.

The generalized costs of each mode chain are calculated similar to the functions used in the classical model. However, due to the correlations in the mode chains the multinomial logit model cannot be used to determined mode shares. This correlation between the unobserved attributes of these alternatives will lead to an overestimation of the transit shares. To account for this the modal split is calculated using a nested logit model (11) with two nests m , corresponding to car trips and chained trips using transit. Nest parameters are estimated to capture the correlation within a nest (while assuming that the nests are uncorrelated). This nested procedure is shown on the right-hand side in Figure 1.

3.3 The super-network approach

The (generic) term of super-network approach is here used to indicate (the family of) models that include three main modeling components: construction of an integrated multi-modal network representation (the super-network), a-priori generation of the choice set, and simultaneous mode and route choice modeling (7). In this section each of this components is concisely discussed. The modeling framework is shown in Figure 2.

The network representation in the classical model is the starting point of the automatic super-network construction. This super-network is for this case study built up in five layers: heavy transit, light transit, pedestrian, bicycle and car. Instead of allowing (infrastructure) links to be used by multiple modes, these network links now appear in multiple layers (corresponding to

1 modes), and in transit layers are duplicated for every transit service traversing this link. The five
 2 layers are integrated into a single network by adding artificial transfer links, connecting the
 3 pedestrian network to the remaining layers. These transfer links represent transfer possibilities
 4 and hence their cost function is based on attributes such as fixed transit costs, parking time, and
 5 parking costs. Private transport layers (car and bicycle) are connected to the pedestrian layer at
 6 locations where these vehicles can be parked, for example, centroids, parking lots and park-and-
 7 ride facilities. At stops and stations the pedestrian layer is connected to transit layers. All origin
 8 and destination zone centroids are located in the pedestrian layer implying that a transfer
 9 between modes always involves the pedestrian network and thus includes walking. To limit the
 10 computation time for the choice set generation both transit layers are simplified by the
 11 construction direct links between boarding an alighting stops (12). Given that stop properties are
 12 represented through transfer links and lines are modeled as a set of (directed) links, the network
 13 representation collapses to a set of nodes and links.
 14

Figure 2 – The super-network approach

18 In contrast to the classical and state-of-the-practice model, the super-network model follows a
 19 path-based approach. That is, the set of alternatives is constructed before the assignment step.
 20 The choice set is generated by first extracting a subset of available routes, usually done through
 21 repeated shortest-path searches with randomized attribute values and preference parameters. For
 22 reasons of mode variety, mode-specific route sets are generated and then concatenated into full
 23 multimodal travel alternatives. Furthermore, to improve the computational efficiency the full set
 24 of feasible routes filtered imposing a set of logical, feasibility and behavioral constraints. Finally,
 25 dominated (i.e., non-competitive) routes and routes showing large overlap with more attractive

alternatives are excluded from the set. In a second step, for each user class (in this study only home-activity or activity-home) specific attributes are assigned to the generated routes.

In the assignment, attributes of the generated route-mode alternatives are iteratively updated to account for the effect of predicted links flows, transit vehicle occupation, and parking capacity constraints. The attributes contributing to the generalized costs of a route-mode alternative relate to level of service (e.g., travel time and costs), intrinsic preferences for specific modes and stations (i.e., mode and stop specific constants), intrinsic preferences for specific alternative type distinguishing train, bus/tram/metro, car, and park-and-ride (i.e., alternative specific constant). The shares in travel demand for each route-mode alternative are then computed using the paired combinatorial logit model (13) capturing the complex overlap among alternatives. This model allows different correlation between any pair of alternatives, while still retaining the advantages of a closed form expression. Here, correlations are related to trip type (mode chains), spatial structure (physical links), and transport services (modes and stations).

4. CONCEPTUAL AND QUANTITATIVE MODEL COMPARISON

In this section the classical model (CL), the state-of-the-practice model (PR), and the super-network model (SN) are discussed as to how they perform in light of the requirements for multimodality. In the introduction it was hypothesized that shortcomings of the classical and state-of-the-practice models are not only theoretical, but may imply wrong decision-making when the impact of multimodal policy measures is assessed. To illustrate this, a series of examples from the real-network of the Amsterdam Metropolitan Area are shown. Each example relates to a specific multimodal policy measure that is assessed by all three models. The results of these assignments are then used to support the findings of the conceptual comparison. Columns three to five in Figure 3 indicate whether a requirement is fully met (Y), partly met (P), or not met (N). It can directly be noted that the classical model fails to meet almost all requirements. This is expected, given that this approach conceptually excludes multimodal trips. When a requirement can principally be met by state-of-the-practice models, but is typically refrained from for computational reasons, this is indicated in the figure. The model requirements and how they are met are discussed below following the same categories introduced earlier. First the case study with the real-world examples is introduced.

4.1 Introduction of the case study

The case study area covers the Amsterdam Metropolitan Area in The Netherlands (Figure 4). This area has an extensive multimodal network with pedestrian, bicycle, car and transit infrastructure. Transit consists of bus, tram, light rail, bus rapid transit, metro, interliner, local train, regional train and intercity train. Bicycles can be parked at most stops and stations, and transit stops facilitate park-and-ride transfers. Such an integrated network clearly illustrates the need for a multimodal modeling approach. Origins and destinations are aggregated into 102 transportation zones. Important commercial areas are the city centers of Amsterdam and Haarlem, the business district in the southern part of Amsterdam, the harbor area and airport Schiphol. Other areas are mainly residential, but still small or medium scale commercial activities can be found.

Figure 3 - The list of requirements and their evaluation within the case study

Four hypothetical multimodal policy measures are selected, as indicated in Figure 4. The first one concerns the opening of a *new train station in Amsterdam-West* on the rail track between Amsterdam and Haarlem. This station is located between the residential area of Amsterdam Sloterveer and the Amsterdam harbor. This additional stop comes at the costs of 2 minutes of additional travel time for through going passengers. The second example is the introduction of a *direct bus connection between Almere and Amsterdam South*. This bus line serves several neighborhoods in Almere with a frequency of 4 busses per hour. Using the motorway, the travel time is nearly twice as long as that of the parallel train service, however, access and egress times are reduced. Measure 3 regards the *upgrade of the station of Hoofddorp to an intercity station*. This involves an additional stop for the 6 intercity train services that are running every hour (in both directions) between The Hague, Amsterdam and Almere. This additional stop comes at the costs of 3 minutes extra travel time for through going passengers. Finally, a new *park and ride*

facility in Amstelveen is introduced, connected to the metro line to Amsterdam central station. Each multimodal policy measure is evaluated on itself by each of the three models. Table 1 gives an overview of relevant assignment results.

Figure 4 – The Amsterdam Metropolitan Area

Table 1 – Case study results

Case study example	Assignment results	Classical model	State-of-the-practice-model	Super-network model
New station Amsterdam West	Station Amsterdam West:			
	Boardings and alightings (non-car access/egress)	0	128	102
	Boardings and alightings (car access/egress)	0	9	16
	Corridor Amsterdam-Haarlem:			
	Car shift (%)	+ 2.5	+ 4.8	+ 4.2
	Transit shift (%)	- 2.5	- 4.8	- 4.2
	- Private access modes (%)	0	61	54
	- Private egress modes (%)	0	19	26
	- Private modes at both ends (%)	0	0	1

New parallel bus service Amsterdam Zuid-Almere	Corridor Amsterdam Zuid-Almere:			
	Travelers by train	5054	7714	6533
	Travelers by the new bus service	661	394	278
Upgrade station Hoofddorp to intercity status	Station Hoofddorp			
	Boardings and alightings intercity	1536	2224	2032
	- Taken from stop train users (%)	44	57	51
	- Taken from other modes (%)	56	43	49
	Rise in number of boardings and alightings (%)	32	20	34
	Decline in stop train boardings and alightings (%)	25	26	15
New park-and-ride facility in Amstelveen	Park-and-ride facility Amstelveen			
	Park-and-ride users (unlimited capacity)	-	525	434
	- Taken from car alternatives (%)	-	48	61
	- Taken from transit alternatives (%)	-	52	39
	Park-and-ride users (max. capacity = 200)	-	-	201
	Park-and-ride users (parking costs 2 euro/h)	-	-	76
	Park-and-ride users (walking distance 300 meter)	-	-	167

4.2 Range and combinatorial complexity of the choice set

In the state-of-the-practice model the full combinatorial range of access and egress mode combinations can be specified. However, the number of additional mode chains is usually limited to reduce computation time and memory usage. In the super-network approach, all constraints on mode composition are dropped. The results for the new station in Amsterdam West show that the new station hardly attracts any travelers in the classical model. This is caused by the relatively remote location of the station, excluding walking as a feasible access and egress alternative. The state-of-the-practice model and super-network approach predict more boarding and alighting movements, but the benefits of this station are questionable. Especially since the new station causes a shift to car on the corridor Haarlem-Amsterdam as a result of the increased transit in-vehicle times. The introduction of a new parallel bus service between Amsterdam-Zuid and Almere also shows the effect of ignoring other access and egress modes. The classical model predicts a considerable number of travelers taking the bus. As walking is the only access and egress mode, bus stops will be easier to reach than the station, compensating for the additional in-vehicle time. This effect will be much smaller in reality, as bicycle provides a good alternative to reach the station. The number of predicted bus travelers is indeed much smaller in the state-of-the-practice model and the super-network model. In the park-and-ride example the classical model completely ignores the new park-and-ride facility and thus this combination of private and public modes as a feasible alternative (*representativeness of the choice set*). Dropping all constraints on mode composition in the super-network approach may lead to the inclusion of unfeasible routes. Hence, in case of a shortest-path based algorithm, a filter process is needed afterwards. In the state-of-the-practice model, the branch-and-bound algorithm for transit and shortest-path search within the car network automatically exclude unfeasible mode compositions (*realism of the choice set*). For pre-specified mode chains in the state-of-the-practice model no trip dependent attributes can be taken into account. A distinction between trip-ends can only be made if it is assumed that all trips start at the home-end (morning peak) or the activity-end

(afternoon peak). In that case bicycle could be valued differently in a walk-transit-bicycle chain than in a bicycle-transit-walk chain. The super-network approach is much more flexible as routes are a-priori generated. Leg attributes can be updated any time while taking properties of the full trip into account. Furthermore, a distinction is made between the home and activity side of trip. The attributes of a route can thus easily be adapted to its position with the full trip. For the new station in Amsterdam West, also the shares of private transport modes as access and egress are shown (for the complete corridor Amsterdam-Haarlem). The state-of-the-practice model assumes all trips to be in the home-activity direction. As the availability of private modes is higher at the home-end, the share of private modes as access is much higher than at the egress side. In the super-network models these shares are more balanced because a distinction between home-activity and activity-home trips has been made (*trip dependent leg properties*).

4.3 Mathematical complexity of the choice model

Mode and route choice are still two separated steps in the state-of-the-practice model. The mode choice is first modeled by a nested logit model, after which the route choice is modeled individually for every chain including transit. In the super-network approach travelers are assigned to the network in a single assignment procedure by a paired combinatorial logit model. Hence, the share per mode chain is not modeled in a separate step, but follows from the cumulative flow of all alternatives yielding this mode chain (*choice dependencies*). This choice model is part of a stochastic user equilibrium assignment, taking into account differences in preferences, perception and network familiarity. This requires sufficient spatial, multimodal and preferential variation in the choice set, which is realized by the doubly stochastic shortest-path based generation algorithm. The state-of-the-practice approach only explicitly models the route choice within transit mode chains (*heterogeneous perception and preferences*). In this route choice overlap between alternatives is ignored. An extra stop, for example, will attract too many travelers if a zone is already served by the same transit services at other boarding stops. Only the correlation between unobserved terms related to the inclusion of transit modes is accounted for by the nested logit model. As car travelers are assigned to the network in a deterministic way, overlap among routes is no issue. A-priori choice set generation in the super-network approach allows for easy incorporation of correlation between alternatives. Overlap between mode types, as well as physical and service overlap between every pair of routes is accounted for by the paired combinatorial logit model. This can be seen from the park-and-ride example. In the super-network model most of the park-and-ride users are subtracted from the car. This stems from the correlation parameters between trip types. Park-and-ride and car alternatives have a higher mutual correlation than park-and-ride and transit alternatives. In the state-of-the-practice nested logit model, however, this correlation cannot be accounted for (*correlated alternatives*).

Another advantage of a-priori choice set generation is that route-based preference parameters can be applied. Mode specific constants can be attached to legs depending on their role within the full trip, while station specific constants can be added to represent the attractiveness of boarding and alighting stops. Within the state-of-the-practice model intrinsic preferences for certain modes are not explicitly modeled. Only a mode specific constant for car or transit chains can be included. Furthermore, the transfer penalties mentioned before can also be used to represent differences in the attractiveness of boarding a certain mode or hierarchical station level. These pragmatic solutions, however, have little explanatory value and cannot be directly transferred to other network settings. An upgrade of station Hoofddorp to intercity status shows the effect of

station specific preferences. Part of the travelers that now make use of the intercity used to travel by stop train while another part did not board or alight at station Hoofddorp before. This is predicted by all three models. However, the super-network approach also shows another effect. While the share of travelers switching from stop train to intercity is comparable, the number of stop train travelers does not decline as much as the other models predict. This means that new stop train travelers are attracted as well by the new status of station Hoofddorp (*trip dependent leg attractiveness*).

4.4 Complexity in demand-supply interactions

The congestion on the road caused by car drivers in unimodal trips impacts the attractiveness of park-and-ride alternatives in the state-of-the-art model. This interaction, however, only works in one way. After the assignment of travelers to transit chains including car as access or egress, flows and resulting travel times on the road are not updated. In the super-network approach the demand-supply interaction are automatically accounted for due to the fact that the assignment covers all modes and mode combinations. That is, the choice among the full range of alternatives is modeled as a single choice (*demand-supply interaction between alternatives*). In this model, limited car parking is modeled through a BPR-type function. Parking times increase slowly when the capacity is approximated, while grow rapidly (to infinity) when the capacity is exceeded. Capacity limitations are not directly taken into account in the state-of-the-art model. A penalty might be assigned to the utility of using car as access or egress. However, this penalty is not influenced by the occupation rate of the parking facility. This is shown by the introduction of a park-and-ride facility in Amstelveen. The state-of-the-practice model shows the potential of such a parking facility, but clearly over-predicts the number of users. The super-network model corrects for this and shows that all parking places will be used (*capacity of transfer locations*). Through the same penalty, other transfer related attributes are accounted for. Walking time, parking costs, parking time, and fixed transit costs are all represented by the same penalty. The impact of a single attribute can thus not be easily assessed. In the super-network these transfer related attributes are represented by artificial transfer links. As all transfers go via the pedestrian network, walking is automatically included as well. For the park-and-ride example, also the impacts of parking costs and longer walking distances have been assessed. Only the super-network allows the specification of these attributes and indeed shows a decline in park-and-ride usage. These results might be reproducible by the state-of-the-practice model but only by defining a new transfer penalty (*performance of transfer movements*).

5. CONCLUDING REMARKS

In this paper the suitability of transport models to assess multimodal transport systems was tested. To this end, the classical model, the state-of-the-practice model and the super-network approach have been compared. This paper makes three contributions. First of all, specific requirements for modeling multimodality were formulated and categorized in three classes: the range and combinatorial complexity of the choice set, the mathematical complexity of the choice model, and the complexity in demand-supply-interactions. Each of the three models was tested against the multimodal requirements to provide insight into their strengths and shortcomings for modeling multimodal trips. The results of this conceptual comparison show that state-of-the-practice models still fall short in handling the behavioral complexity of multimodal trip making. Second, the hypothesis that using classical and state-of-the-practice models may imply wrong

decisions in the design process was illustrated by several examples in the real-world network of Amsterdam Metropolitan Area. The differences in assignment results confirm this hypothesis. In relatively simple transport models requirements are either ignored or inefficiently dealt with. Third, newly developed state-of-the-research models are shown to be a promising alternative. The presented super-network approach reproduces expected travel behavior in response to network supply changes. Through the flexibility of the network representation, a-priori choice set generation, and advanced choice models this modeling approach meets the multimodal modeling requirements.

It has been shown that decision makers might base their choices on systematically incorrect demand predictions. Two potential directions for further research remain that are both related to the impact of such an ill-decision making process on actual design choices. Firstly, all examples relate to small parts of the case study area. On this local scale, differences in assignment results are substantial. However, more research is needed to indicate whether these effects might be negligible at the full network scale or indeed systematically bias the assignment results leading to wrong decisions being made. Secondly, a translation from assignment results to design criteria has to be made. Decisions are generally based on derived network characteristics, such as travel time, energy consumption, car usage in urban areas and the emission of greenhouse gases. Wrong prediction of network usage does not necessarily imply a change in such decision criteria.

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REFERENCES

- (1) Ministry of Infrastructure and Environment, Stuctuurvisie Infrastructuur en Ruimte (SVIR), *Den Haag, The Netherlands*, 2012
- (2) Florian, M. J, and J. Wu and S. He, A multiclass multimode variable demand network equilibrium model with hierarchical logit structures, *Proceedings of the PTRC Conference*, pp. 211-224, 2000
- (3) Zhou X., H. S. Mahmassani, and K. Zhang, Dynamic micro-assignment modeling approach for integrated multimodal urban corridor management, *Transportation Research Part C: Emerging Technologies*, Vol. 16, No. 2, pp. 167-186, 2008
- (4) Sheffi, Y. and W. B. Powell, An algorithm for the equilibrium assignment problem with random link times, *Networks*, Vol. 12, No. 2, pp. 191-207, 1982
- (5) Abdelghany, K. F. S., and H.S. Mahmassani, Dynamic trip assignment simulation model for intermodal transportation networks, *Transportation Research Record: Journal of the Transportation Research Board*, No. 1771, pp. 52-60, 2000
- (6) Liao, F., T. Arentze, and H. Timmermans, Super-network approach for multimodal and multi-activity travel planning, *Transportation Research Record: Journal of the Transportation Research Board*, No. 2175, pp. 38-46, 2010

- 1 (7) Benjamins, M., C. Lindveld, and R. van Nes, Multimodal travel choice modeling: a super-
2 network approach, *Proceedings of the 81st Transportation Research Board Annual*
3 *Meeting, Washington D.C.*, 2002
- 4 (8) Bovy, P. H. L., and S. Hoogendoorn-Lanser, Modeling route choice in multimodal
5 networks, *Proceedings of the 10th International Conference on Travel Behavior Research*,
6 Lucerne, 2003
- 7 (9) McFadden, D., Conditional logit analysis of qualitative choice behavior, *In: Zarembka,*
8 *P. (ed), Frontiers in Econometrics, Academic Press, New York*, 1973
- 9 (10) Spiess H, and M. Florian, Optimal strategies: A new assignment model for transit
10 networks, *Transportation Research Part B: Methodological*, Vol. 23, No. 2, 1989
- 11 (11) Ben-Akiva, M., and M. Bierlaire, Discrete choice methods and their application to short
12 term travel decisions, *In: Hall R (ed), Handbook of Transportation Science, Kluwer*, pp. 5-
13 34, 1999
- 14 (12) De Cea, J., and J. E. Fernández, Transit assignment for congested public transport systems:
15 an equilibrium model, *Transportation Science*, Vol. 27, No. 2, pp. 19-34, 1993
- 16 (13) Koppelman, F. S., and C. H. Wen, The paired combinatorial logit model: properties,
17 estimation and application, *Transportation Research Record Part B*, Vol. 34, pp. 75-89,
18 2000