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Modeling intermodal travel behavior in an agent-based travel demand model

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Abstract

The topic of intermodal passenger mobility has become more important during the last 20 years. As mobility options increase in number and flexibility, it gets more and more attractive to combine multiple modes on single trips. In addition, intermodal travel behavior is expected to contribute to less car dependent mobility and transport sector's reduction of greenhouse gas emissions. Creating and improving the conditions for such a behavior requires planning with knowledge about influencing factors and highest resistances. Empirical evidence and behavioral models can support decisions on measures improving intermodal travel supply. This work presents an agent-based model approach containing intermodal travel behavior with regard to its most important decisions. It enables the combination of a multitude of modes and can be extended to even more modes. By combining many decisions and influences it is comprehensible and adaptable to different surveys and circumstances. We show that results are realistic and impacts are valid to be able to forecast effects of potential measures.

Keywords: agent-based; travel demand model; intermodal; mobiTopp

1. Introduction

Today's transportation debate is mainly related to the reduction of its contribution to global greenhouse gas, nitrate oxide, and local noise emissions. Further, transportation sectors land consumption is becoming more and more important in times of growing urbanization. Transport planners therefore rethink their planning practices and try to pave the way for more climate friendly technologies as well as a different travel behavior of residents. The latter often addresses a multimodal travel behavior having public transportation as its backbone and being supplemented by walking, cycling and a variety of sharing modes for particular occasions. The presence and usage of multiple transportation modes often comes along with an intermodal usage in combination with public transportation. Combining public transportation with private cars, known as park and ride or kiss and ride, with private bicycles, known as bike

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and ride, or with car-, bike- or e-scootersharing is expected to extend the range of public transportation in general and to improve its service quality [2]. Therefore, planners aim to connect relevant modes by an integrated intermodal information and booking platform and by a transfer support creating hubs with a variety of available transport modes and lots of service offers [16]. The sum of all measures is expected to enable a travel behavior less dependent on the personal car leading to a more sustainable transportation sector.

Planning for the overall transportation system requires planner's competence to understand the people's needs and a multitude of interrelated dependencies in technology, supply and behavior. Travel demand models are appropriate tools to test effects of an extended multimodal transportation supply or regulations limiting a certain behavior to design a transportation system for everyone's needs. These models have also the potential to simulate intermodal behavior in all its detail. State of the art models mainly focus on personal car traffic and public transportation. Only few detailed and more complex models set their focus on the demand modeling of pedestrians and cycle traffic. But for the combination of multiple transportation modes, the (potential) behavior of users in the context of an access to or an egress from public transportation needs to be integrated into the whole model that includes all modes.

The aim of this work is to model intermodal travel behavior with an influence on destination and travel mode choice in an agent-based travel demand model framework. To begin, existing empirical experiences and model approaches in the field of intermodal travel behavior are summarized. Based on this, desired effects on the behavior are defined to be able to forecast and test the expected results described in the section above. Further, the general model concept of intermodal behavior and the models as well as their foundation are described. An application in a regional travel demand model and its considered intermodal behavior is shown. Model results, their quality and the benefit of this intermodal extension in comparison to the model effort are critically assessed.

2. Literature Review and Model Requirements

There exist multiple definitions of intermodal travel behavior. Intermodality generally defines two or more travel modes being used within one trip whereby it is a special form of multimodality [3, 4]. Multimodal travel behavior means using different modes on different trips within a certain period (mostly one week). As a result, intermodal travel behavior can consist of a multitude of possible mode combinations whereas public transportation is seen as the most important in this context [5]. Some definitions set a minimum length for walking trips or even do not consider them as part of an intermodal trip chain as otherwise all trips would count as intermodal. [7].

Petersen [13] sets the availability of modes respectively the vehicles and the possibility to leave them behind as a prerequisite for intermodal behavior. Through publicly available modes and the support of safe and close parking at transfer locations, planners can promote this factor. The control of availability and usage conditions of private and public vehicles is therefore important for the modeling.

Literature shows that intermodal travel behavior depends on the socio-demographic background of the person. Younger age groups reveal a higher share of intermodal travelers. Further, working and having a higher education raises the probability whereas car availability reduces it. The dependence on public transportation going along with a higher intermodality is recognizable by the high share of transit passes. There is also a noticeable influence of purpose: working and leisure are more often intermodal and longer trips are more attractive for an intermodal combination [5, 11].

On the other hand, accessibility of transit stations and the number and quality of transit services are important for individuals choices whereby living in a dense urban structure mainly correlates with these parameters. Comparing personal and transport-related factors, the former appeared to be more important [11].

Still, both the personal context as well as the mobility needs and the spatial structure suggests the use of an agent-based modeling framework as the specific situation, situative mode availability and appropriateness mainly decides if an intermodal trip will be done and how it will be constructed. There are already some approaches and models focusing on the peculiarities of intermodal travel behavior. Gebhardt et al. [5] created a modeling framework integrating intermodal influence on decisions regarding home and workplace choice, on travel demand and on traffic flow. Travel demand is modeled with an intermodal mode choice containing public transportation in combination with walking, cycling and driving by integrating selected combinations in a nested choice set [8]. This was possible as a survey was available which enabled the comprehension of these combinations.

The attractiveness of a combination depends on chosen transfer locations depending on the availability of transport modes. Consequently, it is required to consider the most appropriate transfer locations during the choices or it is required to evaluate their suitability. Krajzewicz et al. evaluated possible transfers by total travel time and only considered the shortest trip [8]. A further challenge in modeling intermodal travel behavior is the interconnection of the intermodal mode choice and the related route choice. Meyer de Freitas et al. found path sampling for both choices to be too expensive and therefore avoided it by applying a recursive logit approach in a multimodal network of Zurich. However they mainly focused on the mode combinations and routes itself with a focus on the transportation supply not regarding individual's characteristics and general travel demand [11].

Taking the motivation of the interconnection of various transportation modes into account, the desired effect of a general improvement of public transportation or sharing modes need to be considered in the general model setup. This is relevant for the destination choice as destinations can become more attractive if access to e.g. public transportation stops and, consequently, accessibility in general improves. Besides, public transportation itself becomes more suitable in the following mode choice as additional access or egress options fill possible gaps. This enables the simulation of influences on the general travel behavior by only interconnecting multiple modes. Both, the general influence on public transportation accessibility and the simulation of access and egress trips is required for an analysis of intermodal travel behavior under varying circumstances.

Therefore, a two step mode choice is set: the main mode choice first decides the most important trip mode regarding distance based on aggregated information of all available intermodal combinations. Afterwards, the intermodal combination is constructed by choosing a convenient access and egress if the related main mode was chosen first. It is possible in both steps to consider personal and infrastructural influences to depict an appropriate individual behavior. Further, the approach enables flexibility to e.g. estimate models based on a local household travel survey without explicit intermodal information and to enrich travel mode choice with less costly access trip surveys. The described model requirements were integrated into the agent-based travel demand modeling framework mobiTopp. The model's general structure and the extension are described in the following section.

3. mobiTopp

mobiTopp [9, 10] is an agent-based travel demand modeling framework modeling every person, household and car of a study area over the period of one week. The framework consists of two modules: a long-term module and a short-term module. During the long-term module, all decisions which remain stable during the whole simulation period of one week will be modeled, e.g. the population, the activity patterns, locations for work and education and the ownership of cars as well as commuter tickets and other mobility tools. Afterwards, executing the short-term module, all agents are processed simultaneously by applying destination and mode choice models sequentially for each trip. A route choice is not applied in this context but can be done afterwards either by VISUM or MATSim[1].

Destination and mode choice models are discrete choice models. Destination choice is based on traffic analysis zones. In each choice situation, the utility to all zones is calculated considering attractivity as well as the logsum of mode choice utilities of the alternatives. In mode choice, mobiTopp supports the basic modes walk, bike, car as driver, car as passenger and public transportation as well as carsharing [6], bikesharing, ridehailing and ridepooling modes [15]. For each choice situation, the choice set of all modes is restricted to the available ones with the help of a mode availability model. E.g., carsharing is only available if a car is present at the current location, the car is free to book and the agent is a customer of the respective company.

4. Model Implementation

Intermodal trips, in contrast to monomodal trips, require at least one transfer between two modes. As stated in Section 2, public transportation is a suitable main mode for intermodal trips. Considering other modes than walking as access or egress significantly increases the traveller's possibilities. Depending on the access or egress mode, a high number of possible transfers has to be considered. To reduce the choice set in this approach, possible transfers are chosen by weighing travel times of trip legs with a higher weight of access and egress, public transportation transfers and total costs by using the multimodal route search of PTV Visum. It further considers maximum shares of access and egress trips and limits transfers to desired stations. Those transfers can be calculated in advance. In our study,

we integrate intermodal trips into all decisions done in the short-term module. Therefore, the computational overhead calculating all transfers dynamically is comparably high. Using predefined transfers lowers the overhead significantly. Hence, we chose the approach and calculated transfers for all OD-pairs before running the short-term module.

4.1. Mode Availability Model

mobiTopp's default mode availability model filters the available modes based on a set of rules. Those rules are now extended to consider intermodal aspects of an OD-pair. First, a mode is only available as access or egress mode, if a suitable transfer exists in the predefined transfer mapping for the OD-pair under consideration.

Second, the availability of a car as either access or egress mode is checked. The car is only available as access mode, if the agent is at home and at least one car is available at home. The car is only available as egress mode, if the agent has used the car earlier as access mode on an intermodal trip. The same applies for a self owned bike. Bikesharing is available if the agent is a customer of a bikesharing company and a bike of this company is available in the current zone of the agent for access legs or in the egress transfer zone for egress legs. Further limitiations of availiability of other intermodal modes can be added by the same principles.

Third, the service area of the bikesharing company is checked. As with free-floating carsharing [6], a bikesharing bike can only be returned in the predefined service area. If the agent travels to a zone outside the service area and uses bikesharing as egress mode, the agent is forced to use the bike until coming back to the service area again. The choice set of modes is thus limited to bikesharing.

Forth, if an agent is moving to their home zone and has a vehicle parked somewhere, the agent must use the vehicle as egress mode. The agent is thus limited to an intermodal trip with a fixed egress mode. The way into the home zone could be the way home or to an other activity inside the home zone.

4.2. Intermodal Mode Choice

Destination and mode choice are executed sequentially. Parts of the mode choice are reused in destination choice. Thus, mode choice is explained first although destination choice is executed first. We split the intermodal mode choice into several parts. First, the main mode is selected. This is done by a mixed-logit model, considering individual preferences for modes and their related travel time as suggested by [10]. The utility function of public transportation exemplarily shown is defined as:

$$u_{pt,dest} = \beta_{time} * tt_{pt,dest} + \beta_{cost} * tc_{pt,dest} + \cdots + \beta_{logsum,acc} * logsum_{pt,dest,acc} + \beta_{logsum,egr} * logsum_{pt,dest,egr} \qquad (1)$$

where

$dest$ destination, selected during destination choice
$tt_{pt,dest}$ travel time in public transport to the destination *dest*
$tc_{pt,dest}$ travel cost in public transport to the destination *dest*

and the logsum is defined as:

$$logsum_{pt,dest,acc|egr} = log\left(\sum_{m \in modes} e^{u_{m,dest,acc|egr}} \right) \qquad (2)$$

where

$u_{m,dest,acc|egr}$ utility of the respective access or egress mode m to the destination *dest*

The model of the main mode choice includes the evaluation of time and costs, public transportation transfers, socio-demographic characteristics and mobility tools and spatial attributes like parking and topography. At this stage, utilites of all intermodal main modes additionally contain a logsum calculating the access and/ or egress accessibility (2). This is to consider access quality regarding all available modes already in the main mode choice. The available combinations are filtered out of the set of all combinations using the mode-availability model. Travel times and costs are weighted and averaged over the user's preference for each mode of transportation in the case that it can be used in different combinations. If, for example, several egress modes with different access times are available for the access

mode walk, each access time is weighted with the preference for the corresponding egress mode and averaged over the sum of all weights. The same calculation is applied to the egress mode. The resulting characteristic values of access and egress modes are used for the calculation of their utilities and the access and egress logsum.

If the choice is a monomodal trip, the mode choice is finished and the agent proceeds as normal in mobiTopp. Otherwise, mode choice continues with the second step: selecting the access and egress modes. Access and egress modes are selected in sequence. As the first selected mode will influence the second one, the order in which those decisions are taken are first determined. The criteria to decide is the average beeline distance of all accesses or egresses whereas a longer distance is considered to be more important. Afterwards, the access and egress modes are chosen. The decision is taken by a multinomial logit model only regarding available access or egress trips. It considers travel time and costs as well as personal attributes to enable a realistic choice. This model has already been used in the losum calculation of the main mode choice (2). All combinations of access and egress legs are evaluated to select one.

4.3. Destination Choice

The intermodal destination choice is based on a multinomial logit model. The utility function contains attributes of the relation between origin and destination depending on the set of possible modes. The utility function is defined as:

$$u_{dest} = \beta_{attractivity} * log(attractivity_{dest}) + \beta_{pt} * logsum_{pt,dest} + \beta_{drive} * logsum_{drive,dest} +$$
$$\beta_{pt\_fix} * logsum_{pt,fix\_dest} + \beta_{drive\_fix} * logsum_{drive,fix\_dest} \tag{3}$$

$dest$ represents a destination evaluated by the utility function. fix_dest is the next fixed destination, i.e. home, work or education. Logsums are calculated as in mode choice.

The integration of the intermodal combinations has the consequence that the complexity of the destination choice increases significantly as the logsums contain intermodal information. The destination choice without intermodal routes scales linearly to the number of possible destinations, since a fixed number of modes is used in the calculation of $logsum_{pt}$. This results in a complexity of $O(n)$, where n represents the number of destinations. For intermodal combinations with one transfer, the intermodal extension expands this to $O(n \times m)$, where m is the number of possible access or egress modes. For intermodal trips with two transfers, the complexity increases to $O(n \times m \times k)$, where m is the number of possible access modes and k is the number of possible egress modes. As the access and egress mode choice set is typically the same, the complexity of the intermodal destination choice is $O(n \times m^j)$, where m is the number of possible access or egress modes and j is the number of transfers.

4.4. Intermodal Trips

With the introduction of intermodal trips, the atomic nature of trips in mobiTopp has to be split up further. Therefore, an *intermodal trip* is introduced. An intermodal trip is build up of multiple parts called *leg*s. A leg can contain any kind of monomodal trip. The number of legs per trip is currently limited to three, an access leg, a main leg, and an egress leg. According to travel surveys, trips with more than three legs are rare.

A trip in mobiTopp undergoes three transitions: prepare, start, and finish. During the preparation of a trip, the needed vehicle for the trip is reserved. This is done either by taking an already parked vehicle, when the user has to reuse it, or by reserving a new vehicle of the household or of one of the mobility providers. In case of an intermodal trip, the preparation is executed for all legs at the beginning of the whole trip. Carsharing cars or bikesharing bikes are thus reserved or booked at the beginning of the trip. Due to this, all legs of a trip are viable. It is impossible to fail starting the next leg because a shared vehicle is unavailable.

Afterwards, the trip is executed. During the execution of the trip an agent is moved from origin to destination using the specified modes and the behavior implemented in the trip. The vehicle for the main or egress mode is reserved until it is used. At the end, the trip is finished. Finishing the trip involves returning the vehicles and logging the trip. In case of an intermodal trip, all legs of a trip are finished together.

5. Application to Study Area

The described model steps have been integrated into the agent-based travel demand modeling framework mobiTopp and applied to the region of Karlsruhe located in the southwest of Germany. It consists of urban and rural areas interconnected by a comparably well developed public transportation system. As the region of Karlsruhe is located at Germany's border to France, the planning area includes as well districts of the neighboring Departement "Grand-Est". In total, the population consists of about 1.9 million agents belonging to about 880,000 households. The study area itself has a diameter of about 100 kilometers and is split up into 2,400 traffic analysis zones. During the simulation period of one week, all agents conduct over 50 million trips. The simulations were processed on an Intel Xeon E-2288G with 3.7 Ghz and used up to 76 GB of RAM. The simulations took about 7 hours without the intermodal extension and about 257 hours with the intermodal extension. Especially the intermodal influence in destination choice is computationally intensive as the intermodal logsum is calculated for all possible destinations of a trip.

Relevant modes and mode combinations were delimited to capture the essential intermodal travel behavior. Related literature and our empirical base suggests that public transportation is the important main mode being supplemented by access trips other than walking [5, 11, 12]. Considered transport modes are walking, cycling, car as driver, car as passenger, bikesharing, free-floating carsharing, and ridepooling. All possible combinations of public transportation with these modes were taken into account and reviewed in the context of its use case:

- Does the availability of transportation modes generally allow the combination? (e.g. an own car is usually only available as an access from home and on the way back home)
- Does the supply of a transportation mode support its intermodal usage? (e.g. free-floating carsharing's service area in the related model is limited to the inner city area, whereas access to public transportation is unlikely)
- Is data available or can related behavior be observed?

Their implementation requires the modeling of related decisions based on a suitable database. Its core is represented by the national household survey *Mobilität in Deutschland (MiD)* containing an intermodal trip sample [12]. A local stated choice survey on access trips to public transportation stops supplements the database. The survey was intentionally conducted to capture related access and egress trips.

The observed behavior corresponds with the modeled behavior in terms of trip frequency, trip distance, trip modes, and further attributes. A further analysis of access and egress trips reveals that both their distances and their modes match the results of the intermodal trip sample of *MiD* which can be seen in Fig. 1(a). Still, the sample contains nation-wide results whereby a comparison in detail is only possible to a certain degree. A similar evaluation was done for intermodal carsharing trips.

To analyze the sensitivity of the total model on an improvement of pubic transportation accessibility, a scenario was built with an additional bikesharing service area and additional bikes. By this measure, the number of bikes doubled increasing from about 540 to over 1000 and the service area not only includes the city of Karlsruhe and some small bikesharing systems in neighboring municipalities but also larger bikesharing systems in all towns of the region. Only looking at bikesharing trips their number almost doubles from about 650 to almost 1250 trips per day which leads to the assumption that there is still demand which can not be supplied yet. This also applies for intermodal bikesharing trips to or from a public transportation stop. Further, public transportation benefits from its improved accessibility: there is a slight increase of 0.02 % of public transportation share in the total planning area noticeable representing about 280 trips per day or about 150 trips per additional bike per year. These trips shift mainly from the private use of cars as driver or passenger. Nevertheless, walking trips decrease as well, but only slightly. It is assumed that according to usual trip distances of walking trips, the improved bikesharing supply causes a shift from especially walking and short public transportation trips to bikesharing. A more detailed analysis of benefiting OD-relations on the level of municipalities reveals a high growth of public transportation where bikesharing supply has been extended. The growth in these municipalities is above the average growth in the whole region. This both counts for incoming and outgoing trips and especially concerns municipalities not having any bikesharing supply before. Karlsruhe shows a higher growth in outgoing trips, as the regional availability of biksharing has been improved more intensely whereas the smaller towns show a higher increase of incoming public transportation. The increase in outgoing public transportation trips is shown in Fig. 1(b).
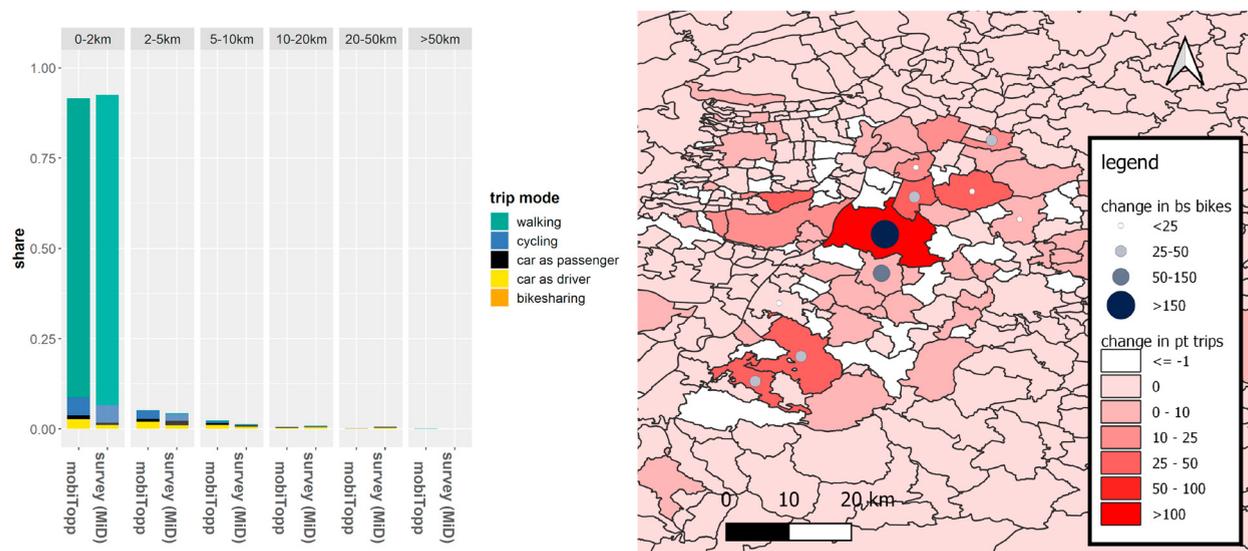
Fig. 1: (a) Modal splits of access and egress trips by distance in model (mobiTopp) compared to survey data (MiD); (b) change in public transportation trips and additional bikesharing supply

6. Conclusion

Having included intermodal alternatives in destination and mode choice, we consider intermodal travel behavior in all decisions in the short-term module of mobiTopp. We showed that with the implementation of intermodal mode choice decisions in the agent-based travel demand modeling framework mobiTopp, we were able to simulate influences on main mode choice decisions caused by changes in access and egress modes. The findings on the general improvement reveal effects to appear in desired areas support the validity of the integrated effects. Although the growth rates are comparatively low we assume stochastic effects to be small. Their analysis will be subject of investigation in our ongoing work. Further, due to the agent-based nature of mobiTopp, all legs of each intermodal trip are simulated and therefore can also be analyzed separately.

Considering more intermodal combinations would already be possible but with a further increase in computation effort. This would also require an extended survey database covering more access and egress modes to multiple main modes and further aspects regarding the intermodal transfer under more diverse circumstances. Further, the predefined transfer locations restrict the model regarding individual preferences and situational availability.

However, due to its modular structure, the model implementation can easily be improved step-by-step in the future. First, the computational efforts have to be minimized, so more combinations can be considered in the simulation. Second, the transfer locations for the intermodal alternatives need to be determined dynamically during the simulation. Third, besides public transport as main mode, we have to enable intermodel trips for other main modes as well. So far, this is already done for station-based carsharing in ongoing work. Station-based carsharing has an intermodal nature as well, as related stations usually are reached by multiple transport modes. All possible combinations of carsharing with either an access or an egress mode are taken into account. The carsharing survey and its analysis is described in more detail by Reiffer et al.[14] whereas the survey on public transportation access trips used in this work is comparable to the carsharing survey.

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