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Simultaneous modelling of access, egress & transit line choice for public transport

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Abstract

A public transport (PT) trip is a multimodal trip by nature: always complemented by an access and egress leg, for example cycling or walking to the PT stop. Introduction of shared modes increases the available access- and egress- options and thereby the PT system as a whole is possibly improved. In order to investigate those effects an extension is made to the traditional PT assignment algorithm, resulting in a simultaneous process of selecting the access-mode, stop choice, line choice, and egress-mode. A key advantage of our approach is that choices for mode chains are made independent on personal characteristics. This enables us to easily add new access- and egress- modes by only adjusting associated travel time and costs. Simulations for a use case in Amsterdam show that this enables us to complement the PT system with shared bikes, which is not possible in current transport models.

Keywords: public transport; transport model; access and egress; first mile last mile; choice modelling; multimodal trips.

1. Introduction

It is widely considered that the city of the future is a liveable city where cars play a less important role, resulting in a more prominent role for sustainable modes such as public transport, cycling and walking. Especially public transport is seen as an important mode to replace long-distance trips made previously by cars. An important aspect of public transport usage is the access and egress leg, also referred to as first and last mile. The access and egress legs complement the public transport trip into a chain of modes (Gentile et al., 2016). For example, one may first cycle to a train station nearby (access leg), then take a train or bus (public transport leg), followed by a last mile of walking to the final destination (egress leg). An efficient availability of access- and egress-modes can improve the public transport system as a whole tremendously, and therefore provide a more competing mode for cars . In the Netherlands, bicycles

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are already frequently used to access the train stations: 47 percent of the daily train users cycle to their access stations (Kager et al., 2016). By introducing shared mobility, new access- and egress-options are introduced and the public transport system as a whole might benefit, resulting in a modal shift towards public transport.

To estimate the effects of improving public transport (PT) by introducing new access and egress modes or improving existing ones, (macroscopic) transport models can be used. Traditionally, transport models first estimate who will use PT using a mode choice model, after which the trips are assigned to specific PT-stops and lines using a special PT-assignment algorithm (Brands et al., 2014). The decision on the exact mode chain (e.g., "bike-PT-walk" or "walk-PT-walk") is usually performed as part of the mode choice estimation. This is executed before the PT assignment is performed. This implies that for a small change in public transport access- and egress- (for example, a cheaper shared bike option) the complete mode choice model needs to be run again, which takes a lot of running time (e.g. 30 hours for the transport model of Amsterdam), and is a fundamental limitation of this approach.

In this paper we introduce a new approach for simultaneous modelling of access, egress, transit stop and transit line choice, inspired by the supernetwork concept (Carlier et al, 2003). Our approach integrates the choice for a specific mode chain as part of the public transport assignment process, and thereby it is not necessary to run the mode choice module for computing effects of improved access- and egress modes. The choices for mode chains, boarding and alight stops are based on utility functions, which we estimate based on data from the Dutch travel diary study. Only mode-specific characteristics are used during estimation, which enables us to add new, non-existing modes easily. The effectiveness of our approach is demonstrated in a realistic case study based on public transport network of Amsterdam. Using high-performance computing techniques on graphical cards we are able to compute the access, egress, stop and line choice in less than one minute. This enables policy makers to quickly study the effects of interventions, such as adding public transport stops and adding new modes for access and egress legs.

2. Public transport in current transport models

Transport models are used to compute current or future mobility behaviour. The focus in this study is on macroscopic transport models, that simulate behaviour on an aggregated level, where people are aggregated and described as a continuum. Usually, such a transport model consists of several stages, including destination choice, mode choice, and assignment.

During mode choice, the number of people that would like to travel with a certain mode is estimated using a utility function. This results in Origin-Destination trip matrices, containing the number of trips between each combination of Traffic Analysis Zones (TAZ) for a specific mode. If multiple possible access- and egress- modes for public transport are considered, this is in current transport models usually included as part of the mode choice. For example, the result of a mode choice algorithm might be six separate trip matrices: car (unimodal), bike (unimodal), walk-PT-walk, walk-PT-bike, bike-PT-walk and bike-PT-bike. To account for overlap between each of the PT mode chains, a nested logit can be applied. For each of the PT trip matrices, a public transport assignment is run. This results in network flows for each mode, for each link or transit line within the network.

There are two main types of public transport assignment algorithms: schedule-based and frequency-based (Gentile et al., 2016). In a schedule-based service it is assumed that the operator publishes full information about the timetable and passengers are able to plan their complete trip before departure and the assignment algorithm is usually applied for operational or real-time management. In a frequency-based service only the stop sequence and frequency of each line is available, and this is generally used in strategic, macroscopic models, aimed for determining average loads. In this work we focus on frequency-based public transport assignment.

A frequency-based public transport assignment algorithm is more complex than a conventional car assignment algorithm such as All-Or-Nothing or Volume Averaging (Ortúzar & Willumsen, 2011). First of all, the network is more complex, as shown in Fig. 1. It includes multiple transfer options, transit lines between the stops and several access and egress options to reach a stop can be identified. Second, the time needs to be considered in a more complex way than assigning a car trip, because of the time table or frequency of transit lines, resulting in waiting and transfer time. Third, the generalized costs are not just a combination of travel time and costs, but might have different ratios for valuing access-, egress-, waiting and travel time, as well as include transfer penalties or difficult tariff structures.

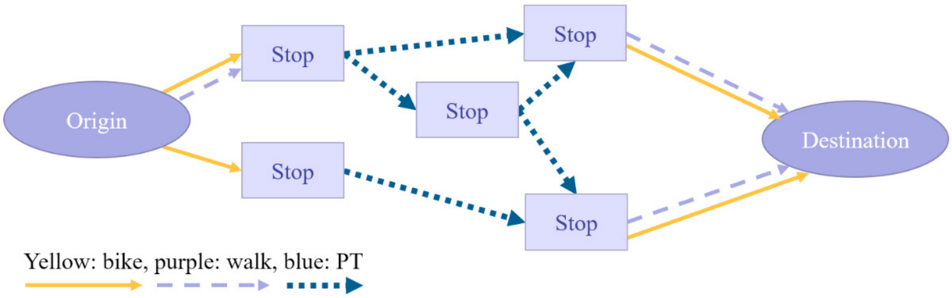

Fig. 1: The complexity of the transit line, transit stop, access and egress choice in public transport: each stop can be reached by 0 or more modes, and between stops multiple routes (with or without transfers) are possible.

To account for these aspects, a public transport assignment algorithm consists of three steps: stop selection, path-building (backward search) and assignment (forward search). In stop selection, a limited set of reachable stops at the origin and destination are composed, for example using a maximum walking distance or minimum amount of stops of a certain type (Brands et al., 2014). During path-building a backward shortest path algorithm is used. This algorithm searches for all possible routes starting at the destination. The last assignment phase consists of a forward search being run on the pre-processed network. This determines which part of the travellers will choose for which route to reach the destination. Usually, it is assumed that travellers will board the first public transport vehicle arriving at their current stop, and additionally the arrival of vehicles and travellers on the stop are evenly distributed over time. This process is repeated for each of the different mode chains, each having a separate trip matrix. Capacity of public transport vehicles is generally not included as part of a frequency-based public transport algorithm, i.e. the algorithm assumes that all vehicles have unlimited passenger capacity.

3. Methodology for public transport access and egress modelling

We propose to include public transport access and egress modelling as part of the public transport assignment, independent of the overall mode choice. This implies that the mode choice part of a transport model only needs to estimate the total number of public transport travellers, and not their specific mode chain of access- and egress legs. Additionally, within the assignment part of the transport model, the public transport assignment algorithm only needs to be run once, instead of for every combination of mode chains. The public transport assignment algorithm then performs a simultaneous mode chain, transit line and stop choice.

In Section 3.1 we discuss how utilities for public transport mode chains can be derived, in order to compute the mode chain choice. In Section 3.2 we discuss how we can extend the public transport assignment algorithm by including this choice for mode chains after the backward search stage of the algorithm. We conclude the section with a numerical example which illustrates the approach using a small network.

3.1. Mode chain choices

To model the (simultaneous) mode and route choice, a nested-logit choice model (NL) is adopted to calculate the probability of each stop combination and mode chain alternative (e.g. bike-PT-walk). Here we assume the mode chains are correlated. This is valid since their main mode is the same, which is the public transport. Another assumption is that each stop combination is independent. This is also valid since each stop is located differently.

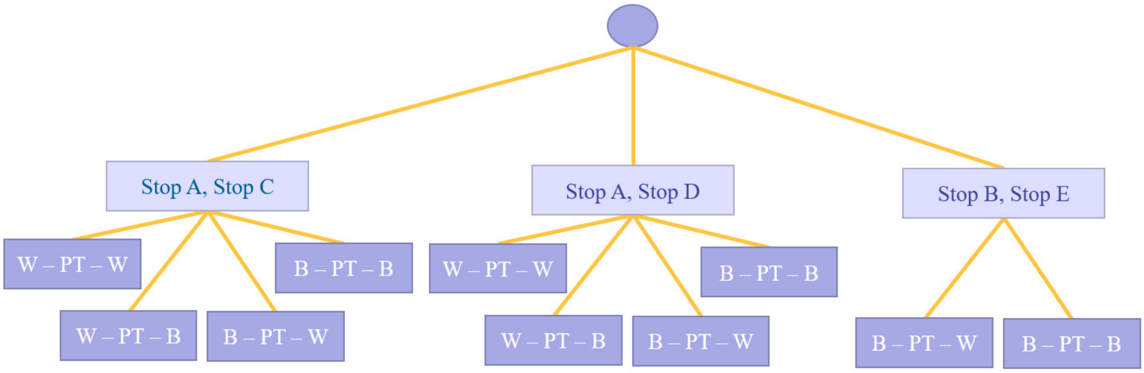

Fig. 2: Nested logit model for stop combinations and mode chain choice. The 4 possible stop combinations are derived from Fig. 3 (B: bike, W: walk, PT: public transport)

As shown in Fig. 2, the higher level nests represent the public transport stop combinations. Within each nest, the PT based mode chains are connected whose composite utility is used to for the utility of stop combination alternatives. This structure is analogous to a destination-mode choice model (Castiglione, Bradley, & Gliebe, 2015).

Since the mode chain utility function is applied in the assignment phase of the transport model, no data on population characteristics is available. Only a trip matrix containing the input from origin to destination is available. Therefore, only trip characteristic such as in-vehicle travel time, access and egress time are used in the utility function. Stop-related attributes (such as number of shops or bike parking) are also not considered in the utility function due to a lack of data of both existence and usage by travellers. Also costs are not considered, because of a lack of public transport costs per km. However, this attribute can easily be included in future.

The utility function of a mode chain is then defined as:

$$V_{s,s'}^{i,j} = ASC_m + \beta_{i\in m} T_{o,s}^{i} + \beta_m T_{s,s'} + \beta_{j\in m} T_{s',d}^{j} + \beta_w T_{wait} + \beta_N N$$

In this utility function, i represents the access modality of the mode chain m and j represents the egress modality of the mode chain. For instance, for a mode chain walk-pt-bike, i is the walking mode and j is the bike mode. s is one of the access stop candidates and s' is one of the egress stop candidates. In the utility function, ASC_m is the alternative specific constant of mode chain m, representing the utility not explicitly listed in the equation. $T_{o,s}^{i}$ is the travel time of access leg from origin zone o to the boarding stop s using mode i, $T_{s,s'}$ is the travel time between s and s' using public transport, and $T_{s',d}^{j}$ is the egress leg from alighting stop to destination zone d using mode j. T_{wait} is the total waiting time in a trip. N is the number of transfers traveling from boarding stop s to alighting stop s'.

3.2. Integrating mode chain choices in public transport algorithms

A mode chain consists of an access mode i and an egress mode j, defining a chain i-pt-j. During the public transport assignment process, mode chain choices are performed for each (o, d) pair, in which o is an origin zone and d is a destination zone. For the trips between origin o and destination d, denoted by $Q(o, d)$ it needs to be decided which stops in the network are used, and which chains i-pt-j are used by travellers. This means that the total number of trips $Q(o, d)$ is subdivided over mode chains and stops.

Prior to starting the assignment process, we first identify public transport stops that people may use to depart from or arrive in a specific zone z. For this purpose we take the road networks for each modality i, and execute a breadth-first search from zone z. All stops that are encountered during this search are added to a set S_z. Additional constraints can be imposed on the search. For example, typically people are not willing to walk a very long distance to reach a public transport stop, so the selected stops can be limited to the stops that can be reached within a limited amount of time. Additionally, an additional requirement can be imposed on the search to ensure that the set S_z contains e.g. a train station for each zone z. In addition to the set S_z, we also determine the travel time for the access leg from zone

z to stop s with modality i during this search, which is denoted by $T_{z,s}^{i}$. For the egress leg from stop to zone, this travel time is denoted by $T_{s,z}^{i}$.

The public transport assignment procedure executes a backward search stage, during which the public transport travel times $T_{s,s'}$ between stop s and s' is determined for each pair of stops, as discussed in the previous section. In addition to the travel times, additional bookkeeping can be performed to keep track of e.g. the travel distances between stops and the number of transfers. After the backward search stage, the mode chain choices can be performed based on the travel times $T_{s,s'}$ and based on the travel times $T_{z,s}^{i}$ that were precomputed prior to executing the assignment algorithm. For each (o, d) pair we determine the mode chain choices using a nested logit, as defined in the following procedure:

1. Retrieve the candidate access stops S_o and egress stops S_d.
2. For each $s \in S_o$ and $s' \in S_d$: compute utility $V_{s,s'}^{i,j}$ for each access modality i and egress modality j. An example utility function is $V_{s,s'}^{i,j} = -1 \cdot (T_{o,s}^{i} + T_{s,s'} + T_{s',d}^{j})$, which only considers travel time. More details on the utility function can be found in Section 3.1.
3. Determine the composite utility of all mode chains nested for each combination of stops. For each $s \in S_o$ and $s' \in S_d$ we compute $V_{s,s'} = \theta * \ln \sum_{i,j} e^{V_{s,s'}^{i,j}/\theta}$, in which $0 < \theta \leq 1$ is a dispersion parameter reflecting the correlation between mode chains.
4. The fraction of trips traveling from $s \in S_o^{i}$ to $s' \in S_d^{i}$ is obtained by computing $P(s, s') = e^{V_{s,s'}} / \sum_{p \in S_o, q \in S_d} e^{V_{p,q}}$. This is a simplified nested-logit equation as there are no stop related attributes available in the study, only the composite utility of mode chain is included.
5. For each combination of stops $s \in S_o^{i}$ to $s' \in S_d^{i}$ the fraction of trips traveling using chain i-pt-j is equal to $P(s, s') \cdot (e^{V_{s,s'}^{i,j}} / \sum_{p,q} e^{V_{s,s'}^{p,q}})$, in which the sum enumerates all chains p-pt-q.

The procedure presented above defines the fraction of trips that travels between a specific combination of public transport stops. The number of trips can be obtained by computing $P(s, s') \cdot Q(o, d)$. The procedure is repeated for each (o, d) pair, after which the forward pass of the assignment algorithm can be performed. A numerical example of the process is included at the end of this section.

The mode chain choice is executed for each pair of zones, and for each such pair all relevant combinations of stops are enumerated, which is a computationally demanding process in a realistically-sized public transport network. In our implementation we parallelized the computation using CUDA, which is a parallel computing platform which enables us to run the computations in a parallel thread for each (o, d) pair. Details on this implementation are beyond the scope of this article.

3.3. Illustration example

We illustrate this model via an example calculation for the situation shown in Fig. 3. Suppose there are 100 trips between two zones. Close to the origin zone there are two stop alternatives. Stop A is be accessed by 3 minutes walking or 1 minute by bike, while stop B is only accessible by bike in 5 minutes by bike (because the walking time is too long). At the destination side, both walking and bike are possible. It requires 4, 3 and 2 minutes walking from stop C, D and E to destination, respectively. If traveling by bike, the travel time is 1.5, 1 and 0.6 minute, respectively. For illustration purpose, only total travel time is taken into consideration in the utility function and the beta for the travel time is set to 0.05. Table 1 shows the computation of $P(s, s')$ as described in Section 3.2. The first two columns show the candidate stops close the origin and destination zones, respectively. The third column lists the possible mode chain between each stop combination. The fourth column lists the total travel time from origin to destination. The next three columns shows the log sum of all mode chains, fraction of each stop combination and the fraction of trips using a specific stop combination and mode chain. These three columns corresponds to step 3, 4 and 5 described in Section 3.2, respectively. The last column shows the number of trips traveling from a specific boarding stop to a specific alighting stop using a specific mode chain, i.e. the fraction multiplied by 100 trips.

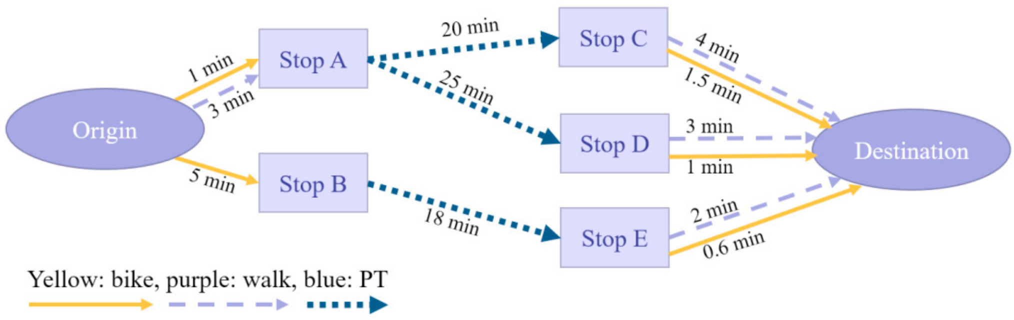

Fig. 3: Example route

Table 1: Illustration example of how trips between an OD pair are divided among every stop combination and mode chain alternative. (B: bike, W: walk, PT: public transport)

Access stop	Egress stop	Mode chain	Total travel time [min]	$V_{s,s'}$	$P(s,s')$	Fraction of trips	# of Trips
Stop A	Stop C	W – PT – W	27	-0,53796	0,40	8%	8
		W – PT – B	24,5			10%	10
		B – PT – W	25			10%	10
		B – PT – B	22,5			12%	12
	Stop D	W – PT – W	32	-0,78796	0,3117	6%	6
		W – PT – B	29,5			8%	8
		B – PT – W	30			8%	8
		B – PT – B	27,5			10%	10
Stop B	Stop E	B – PT – W	25	-0,8672	0,288	13%	13
		B – PT – B	23,6			15%	15

4. Case study: public transport in Amsterdam

4.1. Estimation utility function

The parameters of the utility function for public transport mode chains are estimated by combining data on selected mode chains as reported in the Dutch travel diary study ODiN 2019, the actual routes of all multimodal trips that were available for that specific origin and destination using OpenTripPlanner[1], and all train stations from OpenStreetMap[2]. More specifically, for this study we estimated choice parameters for four mode chains: walk-PT-walk, walk-PT-bike, bike-PT-walk, and bike-PT-bike. In total 4900 observations are used for estimation, which is 80% of 6125 observations. The observation data is extended to search 6 candidate stops within a certain radius of the origin and destination. For the 36 stop combinations, the travel time, distance, waiting time and number of transfers for each of the 4 mode chain alternatives are stored. This dataset is used to estimate the parameters using Biogeme[3].

[1] https://www.opentripplanner.org/, TNO has built up its own service for internal use.
[2] https://www.openstreetmap.org/
[3] https://biogeme.epfl.ch/

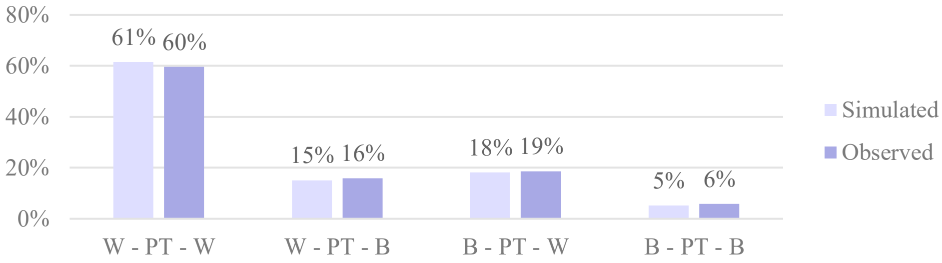

Fig. 4: Modal split of simulated compared to observed, for each mode chain. (B: bike, W: walk, PT: public transport)

After getting the estimated parameters, the mode choice of the leftover 20% of the dataset is simulated and compared with their observed modes. As shown in **Error! Reference source not found.**, the estimated mode chains match quite well with the observations. The estimated parameters are integrated in the PT assignment model. Due to the page size limit, further details on the model estimation are not reported here but are available from the authors on request.

4.2. Application in the transport model of Amsterdam

The public transport assignment with mode chains is demonstrated on a cut-out of the transport model of the municipality of Amsterdam (2021), for the time period morning peak and study year 2020. The used macroscopic transport model consists of 3035 Traffic Analysis Zones, 642 transit lines and 3071 transit line stops. About 200,000 public transport trips are performed. By default, walking and cycling are possible as both access and egress modes. Due to implementation using high performance computing techniques, a fast computation time of the public transport assignment of less than 1 minute is reached.

Two scenarios have been run: a reference scenario, and a scenario where shared bikes are added as a possible egress mode in the city centre of Amsterdam. Due to the flexible structure, it is possible to add new access and egress modes and investigate their impact without re-estimating the whole mode choice model. For shared bikes, it is assumed that the same parameters are used as a normal bike, except for the availability and a decreased speed (as a representation of transport costs). No capacity-constraints of shared bikes are considered, i.e., it is assumed that a shared bike operator will place as many bikes as required on the street available for usage.

The resulting egress choices per stop are shown in Fig. 5. It can be seen that during the morning peak, walking is mostly used as the egress mode in the city centre of Amsterdam. This is logical, since most people have their bike at home and not at the destination. With the addition of shared bikes, a lot of people shift toward this mode, mostly replacing trips previously made walking. The exact number of trips per mode chain are shown in Table 2. It can be seen that the egress part of mode chains Walk-PT-Walk and Bike-PT-Walk are partly replaced by shared bike. This shows that there is a high potential for a shared bike system within the city of Amsterdam, as well as that our introduced public transport algorithm enables to investigate alike changes in the public transport usage, toward multimodal hub.

Table 2: Number of trips per mode chain for the reference scenario and the scenario with shared bikes enabled in the city centre of Amsterdam, rounded to 1000 trips (W=Walk, B=Bike, SB=Shared Bike, PT=Public transport.

	W-PT-W	W-PT-B	W-PT-SB	B-PT-W	B-PT-B	B-PT-SB
Reference scenario	139,000	10,000	0	58,000	5,000	0
Shared bikes in city centre	134,000	9,000	6,000	55,000	5,000	3,000

Fig. 5: Computed public transit egress choice for the reference scenario during the morning peak (left), and a situation where shared bikes are made available (right). The pie charts are located at each transit line stops and show the percentage of each egress mode being used.

5. Conclusions and future work

In this paper we introduce a novel approach to add the public transport access and egress choice within the public transport assignment model, resulting in a simultaneous process of selecting the access-mode, the stop choice, the line choice, and the egress-mode. Compared to the state of the art in public transport modelling, a key advantage of our approach is that choices for mode chains can be made dependent on the characteristics of the access leg, public transport leg and egress leg. We have demonstrated the effectiveness of our approach in a case study in the city of Amsterdam, which shows that our approach enables studying the effects of current and new access modalities and egress modalities, and their role in the entire public transport system. Future work includes further validation using modal split data and integrating within a hub module, being able to model all multimodal hub travels. Additionally, we would like to investigate how to incorporate constraints for limited availability of shared modes in our model.

Acknowledgements

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