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Incorporating Passenger Load in Public Transport Systems and its Implementation in Nationwide Models

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Abstract

Reducing CO_2 emissions is crucial to climate change mitigation, but there has been little progress made in the transport sector. Public transport could make a significant contribution, which would require substantial changes in travel demand. In various national transport models proportionally increasing capacities have been assumed; this must be scrutinized in the light of urgency, long-term planning and construction processes and limited financial resources. This paper presents an approach that addresses previous obstacles to the integration of unchanged capacities, namely the lack of a detailed public transport service model and rapidly increasing computation times even in small networks. Based on widely available data on public transport supply and the consideration of previous studies on the relationship between variable vehicle load and the resulting costs for passengers, an extension for a nationwide transport model is developed. In two scenarios – a substantial reduction in local public transport fares and the introduction of a charge for motorized private transport – it is shown that significantly different demand effects occur when passenger load is considered.

Keywords: national transport model; transit ridership; vehicle capacity; in-vehicle comfort; seat load factor; crowding valuation; mode choice

1. Introduction

A vast majority of countries worldwide have committed themselves to reduce CO_2 emissions over the next decades for mitigating the anthropogenic climate change [17]. For achieving this the transport sector plays a crucial role, accounting for more than 21 % to the global CO_2 emissions in 2018 [4]. In addition to this objective, urban air pollution is an urgent problem to which traffic contributes significantly and has to be overcome in a short time due to national and European regulations [8]. Public transport systems are receiving a rising attention as a component of the transformation to greater sustainability. For a noticeable change in terms of modal share, the number of shifted trips

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must be of substantial size. With regard to earlier studies, two basic tendencies can be identified: Firstly, measures are examined which lead to a relatively small expected shift to public transport, so that the assumption that the number of passengers will not change significantly seems justified. Secondly, various studies analysed a medium to long-term steady state in which transport agencies react to increasing demand with a proportional rise in capacity. In contrast, only few models take into account vehicle load and the resulting demand effects in public transport: to the best of our knowledge, the passenger load in local and long-distance transport is only considered in the Switzerland transport model [21]. In the UK national model the functionality is present but inactive by default [6]. In Germany, capacity envisaged either for national train services only or in a stand-alone model for individual federal states or regions [19, 20]. In addition to the aforementioned assumptions, three main reasons for the lack of modelling of a changing vehicle load is given in the literature referred above:

- The data basis is insufficiently available or can only be obtained at great effort to determine capacities and loads
- Computation time increases rapidly with the number of line routes and vehicle journeys due to feedback loops
- Capacity effects are included in the public transport assignment by default. The methods used focus on the choice of route and departure time and do not take the destination and mode choice sufficiently into account

These aspects are particularly relevant for transport models with large study areas and extensive public transport systems. The following paper presents an approach that can address these issues. This is essential for the investigation of nationwide short and medium-term measures that are likely to have a high impact on the demand for public transport and will lead to a changing passenger load due to budget constraints and long periods of planning, procurement and construction of infrastructure and vehicles.

The applicability and relevance of the approach is shown by using two synthetic measures to bring about a significant change in the demand for public transport. One is an intramodal policy that attracts people to public transport by reducing passenger's costs by 50 %. This drastic reduction is in line with political discussions on a € 365 ticket. In the model, the validity of this ticket is limited to local public transport connections with a maximum travel distance of 100 km. The second measure is the deattraction of private transport by car due to a charge. For Germany, [28] pointed out that costs of € 0.04 per km for construction and maintenance of infrastructure is not covered by a single car driver, but by society. In order to internalize these costs, a mileage-based charge of this amount is being examined. The introduction of a charge on all roads will prevent bypassing effects and is coherent with a current initiative at European level to promote usage-based financing in the transport sector. Road pricing will be examined in combination with the reduction of fares to identify the effects of joint push and pull measures. The scenarios created are simulated twice: once under the assumption of a proportional increase in capacity leading to constant passenger loads. The second simulation involves unchanged capacity in comparison to reference, which causes changing load factors and a less favorable ride in crowded vehicles.

The simulation is performed with the national transport model for Germany (DEMO), which has been developed and applied for many years. The entire DEMO encompasses modules for short-distance transport, long-distance transport, freight transport, commercial service transport and network models (road, railroad and inland waterways). The latter are used to derive mode and origin-destination specific costs, but due to limited availability and the huge amount of data, public transport services are not included in all details. However, since such data are of high relevance for modelling travel demand, detailed travel cost and several time matrices (e. g. access, egress, in-vehicle) have been derived based on representative and extensive web-based queries. But it is important to note that no timetable information, specific vehicle routes or capacities for public transport are implemented in DEMO.

The approach presented in this paper was developed for considering capacity effects of public transport services for everyday travel. This travel demand is modeled by the DEMO module for short-distance passenger transport. For the topic discussed here, most relevant are trip purpose and mode specific utility functions that are based on a travel time study for Germany [1]. The estimated and in DEMO implemented functions for the utility U have non-linear parts of travel costs c and in-vehicle time t, α and β are parameters for cost evaluation, γ for numerical usability. The general form of the utility function is defined by equation 1. Further details are presented and discussed in several papers, e. g. [25, 26].

$$U = (\beta_t \cdot t + \alpha_t \cdot \ln(t + \gamma_t)) + (\beta_c \cdot c + \alpha_c \cdot \ln(c + \gamma_c)) \quad (1)$$

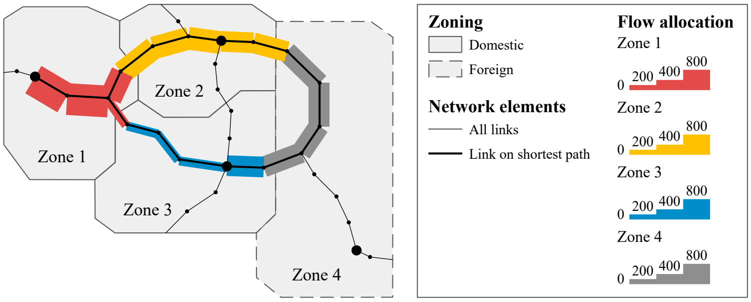

Fig. 1. Schematic illustration of the approach for allocating traffic flows by public transport to traffic analysis zones

2. Methodology

The approach presented does not require a detailed public transport model with the aforementioned drawbacks, but is based on known traffic flows, estimated vehicle loads and a deducted relationship between the loads and the costs obtained by changes in passenger load. The starting point is shown in fig. 1: traffic flows between traffic analysis zones (TAZ) are known from the calibrated demand model. The flows are assigned for each relation to the corresponding links on the shortest paths. The magnitude of transport demand per TAZ is determined by all flows on the links in this TAZ and their multiplication by the link lengths. Vehicle loads to be estimated in the building block described below are used to determine the supply in the reference by multiplicative inverse with the demand. In scenarios with variable capacities, a higher demand for public transport leads to a proportionally increasing supply and thus to unchanged load factors. When modelling scenarios with constant capacities, an increase in demand must result in raising costs due to crowding effects. This relationship is expressed by a value of time (VOT) factor and is described afterwards. The implementation in the existing destination and mode choice model is outlined at the end of this section.

2.1. Baseline data on vehicle loads

Vehicle loads result from the interplay of transport supply and demand, which can only be described in a simplified way due to limited data availability. For Germany, the Federal Statistical Office reports the distance travelled in passenger km per year, the number of available seat km as well as the the total number of seats and standings at the level of the federal states and the various public transport systems [14, 15]. For temporal differentiation, daily time series for supply and demand are estimated based on an analysis of transport agency data [13] and a national household survey on everyday traffic behaviour [9]. The heterogeneous spatial structure is taken into account by verified assumptions about the degree of availability of public transport systems. The reference shows an average seat load factor of 37 % over 24 hours and a peak load of 65 % between 7 and 8 a. m. in 2014, which is in line with the recommended target load in German public transport [18]. The spatial distribution of passenger load is heterogeneous: fig. 2 shows that the two largest cities Berlin and Hamburg have the highest peak loads of 161 % and 134 %, while the predominantly rural areas in Thuringia with an average of 39 % have significantly lower peak loads.

2.2. Relationship between passenger load and costs

Increased vehicle utilization in public transport means that there is less space available for the passenger and that the person may have to stand. This is equivalent to fewer options for the use of in-vehicle time and can be reflected in an additional cost term. Formulating and quantifying these costs can be done in different ways, but consistency with utility theory can be produced straightforward with a VOT factor [11]. Travel time is included in the utility function with an individual-specific valuation (the VOT), so that the changed perception of travelling as a result of crowding can be expressed using the factor. In this research field, several stated (SP) and revealed preference (RP) studies are carried out, whereby the findings cannot be summarized without contradiction. In the specification of their regression models [10, 16, 27] assume for RP data a linear relationship between vehicle load and costs. [3, 22, 24] suggest that the VOT factor is rising more strongly at high loads and therefore presume a non-linear relationship for the analysis of

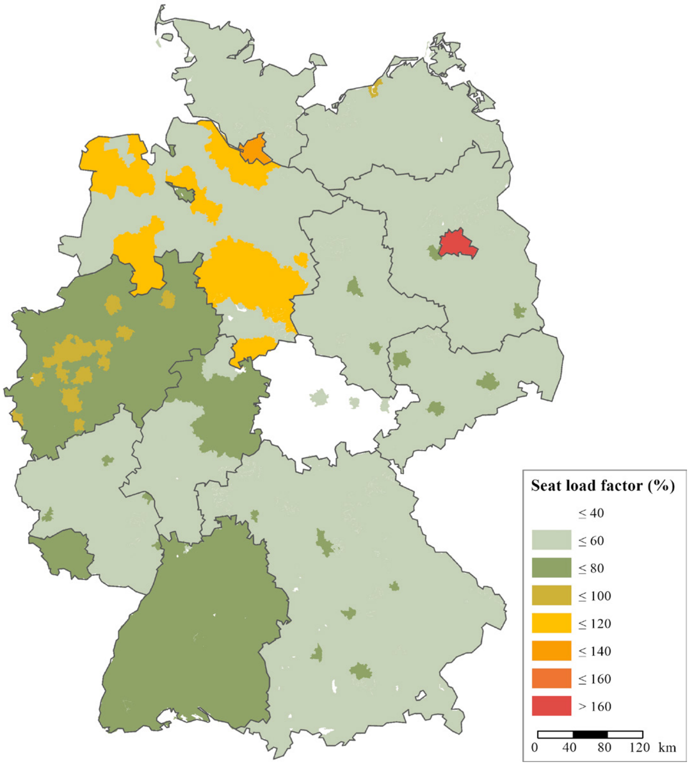

Fig. 2. Spatial distribution of peak passenger load in Germany, reference

SP and RP data. [2, 5, 23] suppose a threshold: the VOT factor only increases above a certain passenger load, below the assessment of the travel time does not change.

The developed function 2 of seat load factor s and the VOT factor is shown in fig. 3 and represents a possible solution in the corridor given by the mentioned literature. The points of discontinuity are defined on the recommendations in the literature and typical vehicle layouts of public transport in Germany. Nevertheless, other piecewise defined functions are conceivable, so that the function must be validated on the basis of further investigations.

$$\text{VOT factor} = \begin{cases} 1, & s \leq 0.25 \\ 0.36s + 0.92 & 0.25 < s \leq 1.50 \\ 1.31s - 0.5 & 1.50 < s \leq 2.1 \\ 2.25 & s > 2.1 \end{cases} \tag{2}$$

Three characteristic ranges can be distinguished:

- Standard: the seat load factor in Germany varies typically between 0 % to 150 % even at peak times, with higher values occurring only rarely (see fig. 2). In a facing seating arrangement, which is very common in Germany, a 25 % seat load corresponds to an average occupation of one person per group of seats. People travelling together choose seats which are close together, so that boarding passengers still find empty seats that are not adjacent. The vehicle is perceived as empty, the VOT factor remains at 1. If the seat load rises, passengers increasingly have to share a seating group or decide to stand next to the doors. If it is considered that travellers perceive the relative change in the VOT in the same way (but in absolute terms differently due to a different VOT, as in DEMO modelled), than the marginal passenger in this situation is indifferent between standing and sitting. Strongly dependent on the specific vehicle type (ratio of standing and seating areas, number and arrangement of door areas per vehicle), this perception ends about 150 %, the VOT factor increases moderately.

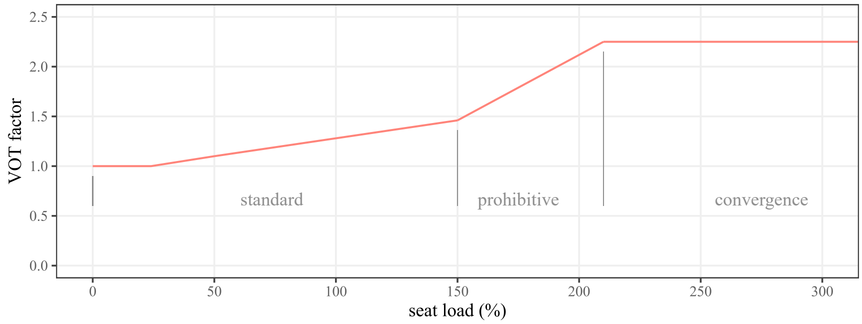

Fig. 3. Graph of the deducted function between seat load and VOT factor

- Prohibitive: the number of standing passengers in the aisle is growing, and boarding and alighting are becoming difficult. The crowding has a strong restraining effect, expressed by a considerably growing VOT factor. The upper limit has been set to 210 %, as this is the average ratio between the total number of standing and seating places and the number of seats as declared by transport agencies. In Germany, higher load factors at peak times are rarely observed, even though in an international comparison significantly higher levels of demand occur.
- Convergence: after the maximum capacity has been exceeded, a further range is introduced for computational reasons. Since the evaluations of the in-vehicle time resulting from load factors influence the destination and mode choice, an iterative calculation is necessary. This computation is terminated when the change in load factor between two iterations falls below a threshold value.

2.3. Adaption of the utility function for incorporating crowding in destination and mode choice

The perceived costs due to changed crowding on a relation are composed of the individual costs per crossed TAZ. In this approach the interzonal composition is implemented by a weighted average VOT factor δ, in which the sums of the link lengths within a TAZ represent the weights. Two special cases must be considered: firstly, shortest paths that pass through foreign territory for which no vehicle loads are known (see fig. 1). For this it is assumed that no additional costs incurred for this segment. Secondly, for intrazonal relations it is expected that the shortest path runs within the TAZ. This results in an origin-destination VOT factor matrix $\boldsymbol{\delta}$. The VOT is calculated by the partial derivatives of the utility function by travel time and costs. Equation 3 shows the adjustments to take the VOT factor per relation δ for the in-vehicle time t into account. The utility function for costs c remains unchanged when applying δ.

$$U = \delta \cdot (\beta_t \cdot t + \alpha_t \cdot \ln(t + \gamma_t)) + (\beta_c \cdot c + \alpha_c \cdot \ln(c + \gamma_c)) \tag{3}$$

3. Results

At the national level, the results indicate a significant impact of the measures on the mode choice in all four scenarios. The model reactions are as expected, and it should be noted that the magnitude varies considerably with and without a varying passenger load. The outcome of the conventional model approach, which assumes constant vehicle loads, is shown on the left side of fig. 4. By halving fares without further measures, the mode share of public transport would increase from 9 % in the reference to about 11 %, which corresponds to 2.4 bn additional trips per year. Approximately two thirds would be shifted from car travel (1.5 bn avoided trips), the remainder coming from non-motorized modes. The distances travelled by public transport would increase by almost 29 bn to 141 bn passenger km per year. The introduction of a supplementary charge on roads would raise the share of public transport to almost 12 %, while travelling by car would decrease significantly from 55 % to less than 52 %. The charge would also ensure that the environmentally friendly modes of walking and cycling benefit; they could slightly increase their share. The approach presented allows important insights for transport agencies and the public administration: to avoid overcrowding effects, the capacities must be enlarged by 28 % on a statewide level, if the charge is introduced. A detailed examination reveals

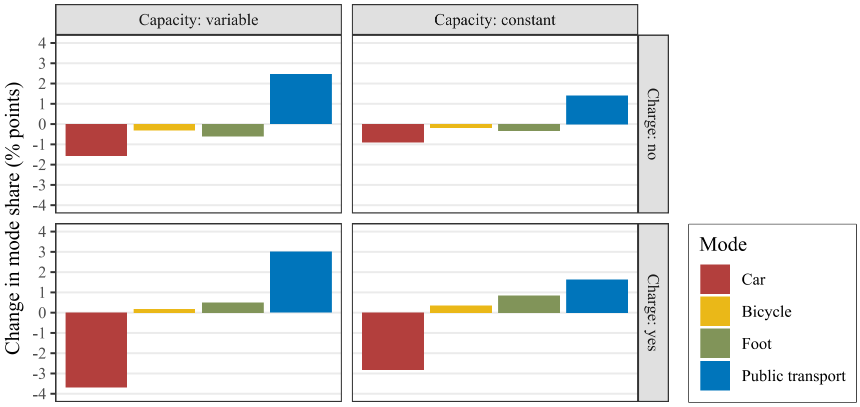

Fig. 4. Mode share changes in scenarios with 50 % reduction in fares

a range of variation: the largest expansion is required in Bremen and Brandenburg (about 31 %), while in Saarland the existing public transport service needs to be expanded by 22 % in order to keep the level of service.

The modal shifts in scenarios with constant capacities and thus a variable vehicle load are shown on the right side of fig. 4. The fare reduction without a charge would only lead to a 1.4 % point increase in the number of trips taken by public transport. The distances travelled by public transport would increase by 15 bn km per year, while motorized private transport would decrease by about 9.6 bn km per year. On average, peak vehicle load rises from 65 % in the reference to around 73 % in a scenario without an additional charge. Regional differences can be seen: Berlin shows the smallest increase with 3 % points, while North Rhine-Westphalia and Lower Saxony experience the highest growth of 10 % points. The consideration of constant capacities in a scenario with fare reduction and a charge has remarkable effects on the mode shares. Analogous to the scenario with variable capacities, the charge would lead to a greater reduction in trips by car (−2.8 % points) and an increase in trips by public transport (1.6 % points). Beyond this, the model results suggest that the number of trips by non-motorized modes would be significantly higher with regard to a scenario with variable capacities (1.2 % over 0.7 %).

The approach is capable of providing fine-grained estimates of changes in the seat load for the TAZ in scenarios with constant capacities. This is shown in fig. 5. An increase in passenger load can be observed in all federal states (average load of 76 %), but in Berlin the relative increase is the lowest (2 %). Although the public transport supply is extensive, Berlin's seat loads are in the prohibitive range of function 2, so that passengers would benefit only little from the fare reduction. Passengers in other federal states gain more, the specific vehicle load is determined by the interplay of numerous factors such as the transport supply, the activity pairs and the destination and mode choice.

4. Discussion

To evaluate the acceptability of the model's responses, it is useful to consider demand elasticities e. They are calculated in equation 4 by changing the costs C (here the reduction of public transport fares) by a global proportionate amount and monitoring the changes in travel made T by the corresponding mode [7]:

$$e = \frac{\log(T_1) - \log(T_0)}{\log(C_1) - \log(C_0)} \tag{4}$$

The resulting arc elasticities are in the range of what can be expected. In a scenario with variable capacities the elasticity is calculated to −0.36 based on the number of trips, in a scenario with constant capacities and thus overcrowding effects the elasticity amounts to −0.22. It should be pointed out that the 50 % reduction in fares represents a limiting case for which little empirical evidence is available. Furthermore, fare increases have been investigated more frequently in the literature. The review by [2] gives a short run elasticity range of −0.3 to −0.58 for UK depending on the public transport system, for non-UK countries the range is −0.29 to −0.38. Elasticities in the long run are about two

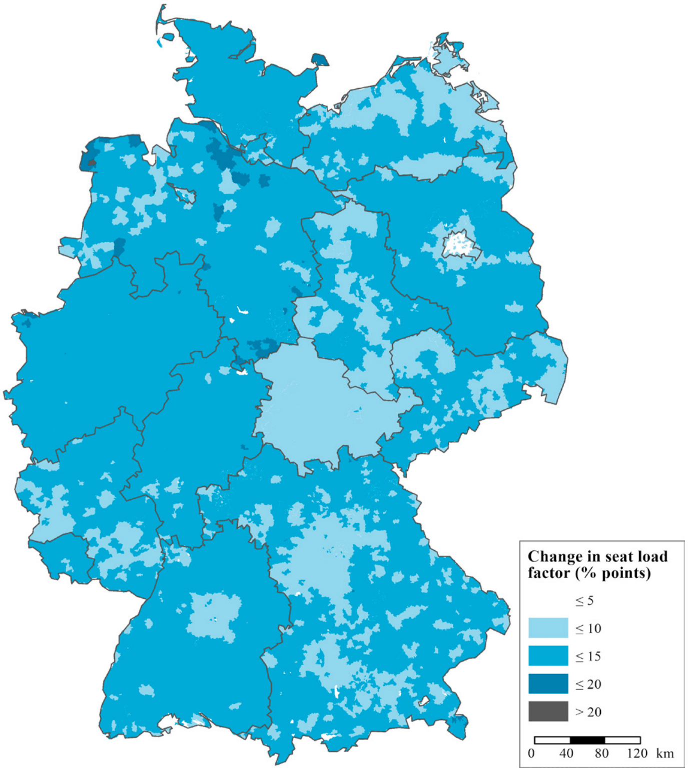

Fig. 5. Spatial distribution of peak passenger load with 50 % reduction in fares, constant capacities in public transport and a charge for car travel

times higher. [12] points out that there are significant differences between the elasticities off-peak (−0.11 to −0.84) and peak times (−0.04 to −0.32). Currently, the focus of the approach's implementation is on the peak hour, the daily and annual values are extrapolated from this. As a result, the effect of vehicle load on destination and mode choice tends to be overestimated, nevertheless it is shown which general impacts and intensities can be expected.

Due to the aggregated input data and the approach of calculating vehicle loads at TAZ level, there are uncertainties regarding the passenger load at peak hour. Between individual public transport lines and vehicles there may be fluctuating load factors, which are not completely taken into account by assuming an average crowding level. The model results provide valuable indications of the extent to which passenger load could increase under given conditions; local and more detailed investigations are then required for transport planning issues. Accompanying studies after implementation of the measures can generate important data on validation and calibration for further refinements.

5. Conclusion

The modelling of vehicle capacities in public transport and the change of load factors due to an increasing demand on nationwide level is challenging. Often the detailed data basis is missing or due to rapidly increasing computation times the passenger load is not taken into account. It was shown that in scenarios where no capacity expansion can be assumed, vehicle load should be considered in order to estimate correctly the effects on demand. This can be done with a simplified approach that relates public transport demand and seat loads in a TAZ to a VOT factor, which in turn is included in the destination and mode choice. The approach is also suitable for issues in which the necessary increase in public transport supply is to be investigated so that a constant passenger load can be ensured when policies are taken. The analysis of the synthetic measures shows considerable modal shifts, so that substantial CO_2 reductions can be expected even with unchanged capacities. If additional adjustments are made to the public transport service (e. g. by running more coaches per train), further significant contributions to climate change mitigation are expected.

Expanding public transport services or reducing fares drastically will require a considerable allocation of resources with distributional effects and thus a decision at political level. Since the efficient use of funds plays an important role in this context, a welfare analysis can provide an assessment of the costs and benefits of the examined measures. DEMO allows the modelling and impact analysis of a wide range of measures and provides interfaces on which a microeconomic analysis can be based. A future study could, for instance, investigate the economic implications of the presented fare reduction with and without an expansion of the transport supply and the resulting changes in vehicle load.

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