The Orestad Traffic Passenger Demand Model

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Abstract. The passenger travel demand model for the greater Copenhagen area is a tour based nested logit model where the generation, distribution and mode choice models are connected via the measure of accessibility. The model is very detailed in all three levels and that is the main strength in the model forecasting power. The model validity is strongly proved by the fact that the forecasting results for 2000 exhibit a very good fit to the observed car and public transport traffic. The main aim of the paper is to provide a detailed description of the model. Secondly, an application of the model in a study of road pricing in Copenhagen is described in order to give an idea to the reader of how such a policy measure can be modelled as well as the plausible magnitude of changes caused by a road pricing system.

1   INTRODUCTION

The Orestad Traffic Model (OTM) is an operative traffic model for the greater Copenhagen area. The OTM consists of demand and assignment models for both passenger and freight transport. The first version of the model was developed in 1994. Since then the model has been continuously updated where the last two revisions took place in 1998 and 2000. The model version from 1998 is trip based while the latest version is tour based. The shift in the model paradigm proved to give large improvements in the model fit to the observed data and in the model forecasts.

The OTM has been applied in a number of major infrastructure projects in Copenhagen over the years. The model is originally built for predicting passenger demand of metro. Some other major projects where the OTM has been applied are the Harbour Tunnel project, the Stambusnet project (reorganisation of the bus service in Copenhagen) and the FORTRIN project (road pricing).

The main aim of the paper is to present the structure of the OTM passenger demand model (chapter 3). The OTM forecasting power is presented through the model's application in the project of road pricing (chapter 4). The model structure is explained in chapter 2 while the concluding remarks are given in chapter 5.

2   MODEL STRUCTURE

2.1   Data

The estimation procedure that is applied in the generation and in the mode choice models is based on disaggregate data. Disaggregate data in the OTM consists of revealed preference (RP) and stated preference (SP) data. The RP data is based on the Danish Transport Behaviour survey (TU data) from 1997, 1998 and 1999, in total 25,550 observations.

The OTM is originally built for the purpose of forecasting the traffic effects of the coming metro. That is one of the reasons why SP data has been completed since 1994. Secondly the SP data is completed for the purpose of increasing the quality of parameter estimates in the mode choice model, which essentially contributes to the calculation of more precise values of travel time. In total, 19,989 SP observations were available in the estimation of the mode choice model.

2.2   Model structure

The greater Copenhagen area is split into 601 zones in the OTM while the surrounding area is split into 17 port zones. The OTM passenger travel demand model consists of three main models, namely generation,

distribution and mode choice models. Apart of that, the OTM contains a model for external traffic and a model for traffic to and from Kastrup airport. The distribution model is conditional to the generation model, while the mode choice model is conditional to the distribution model. In the opposite direction the models are connected via the measure of accessibility, logsums. Due to the above, the OTM can be defined as a nested logit model. The OTM business (BS) segment is trip based while the commuter (HW), education (HE) and leisure (PR) segments are tour based. Split among four segments in the model is based on the assumption that travellers in these segments have essentially different values of travel time. Because of that, the changes in the traffic supply have different effects on the travel demand. The main reasons for the application of tour based modelling in the OTM are following:

- Tour based models work with non-symmetric generation-attraction matrices (and not with symmetric origin-destination matrices) and that allowed us to place the 'correct' modelling variables in the generation and distribution models. For instance, the car ownership variable is included in the tour based generation model. Similarly to that, the attractiveness of particular destinations in terms of the number of education places, shopping places and job places of different kind are taken into consideration in the tour based distribution model. In the (old) trip based OTM distribution model the only variable included in the model structure was the zone-to-zone distance. The tour based generation and distribution models give a considerably better fit to the observed data than the previous models.

- Parking costs are modelled in the mode choice model. A tour based model allows one to distinguish between the home zone, where the person as a rule does not pay for parking, and the non-home zone, where the parking costs must be paid. Home and non-home zones are not known in trip based models.

The OTM is a short-term forecasting model. The base year in the model is 1992. The base 1992 tour matrices are used in a pivot point procedure in both the generation, distribution and mode choice models. The pivot point procedure ensures that the model replicates realistically the travel patterns on the matrix level. This procedure has also an impact on the assignment model, which in turn produces realistic traffic flows on the road and rail networks compared to the counted traffic. The other model feature, which reflects the model short-term horizon, is an assumption that improvements in infrastructure generate induced traffic only in the PR segment. In a longer term one could assume that e.g. commuting traffic would also increase as a result of the improved infrastructure.

The structure of the OTM is shown in figure 1. Inputs to the demand model are zonal data and files of level of service (LOS). The zonal data describes the distribution of the population, jobs, education places, shopping places, car ownership and parking costs over the 601 zones. Zone-to-zone travel times as well as travel costs for each available mode are represented in LOS files. LOS files are produced in the car and public transport assignment procedures.

Once the LOS files and the zonal data are known the logsums are calculated for each zone pair in the mode choice model. The logsums in the mode choice model measure the obtainable accessibility from one zone to all other zones based on the present supply. The mode choice logsums are included in the distribution model, which becomes therefore dependent of the traffic supply. Similarly to that, logsums are calculated for each of the 601 internal zones in the distribution model. The logsums from the distribution model give a measure of generation power of each zone taking into consideration zonal jobs, education places, shopping places and distances between the zones. The distribution logsums are included in the generation model for private tours only allowing the effect of induced traffic to be measured in that segment.
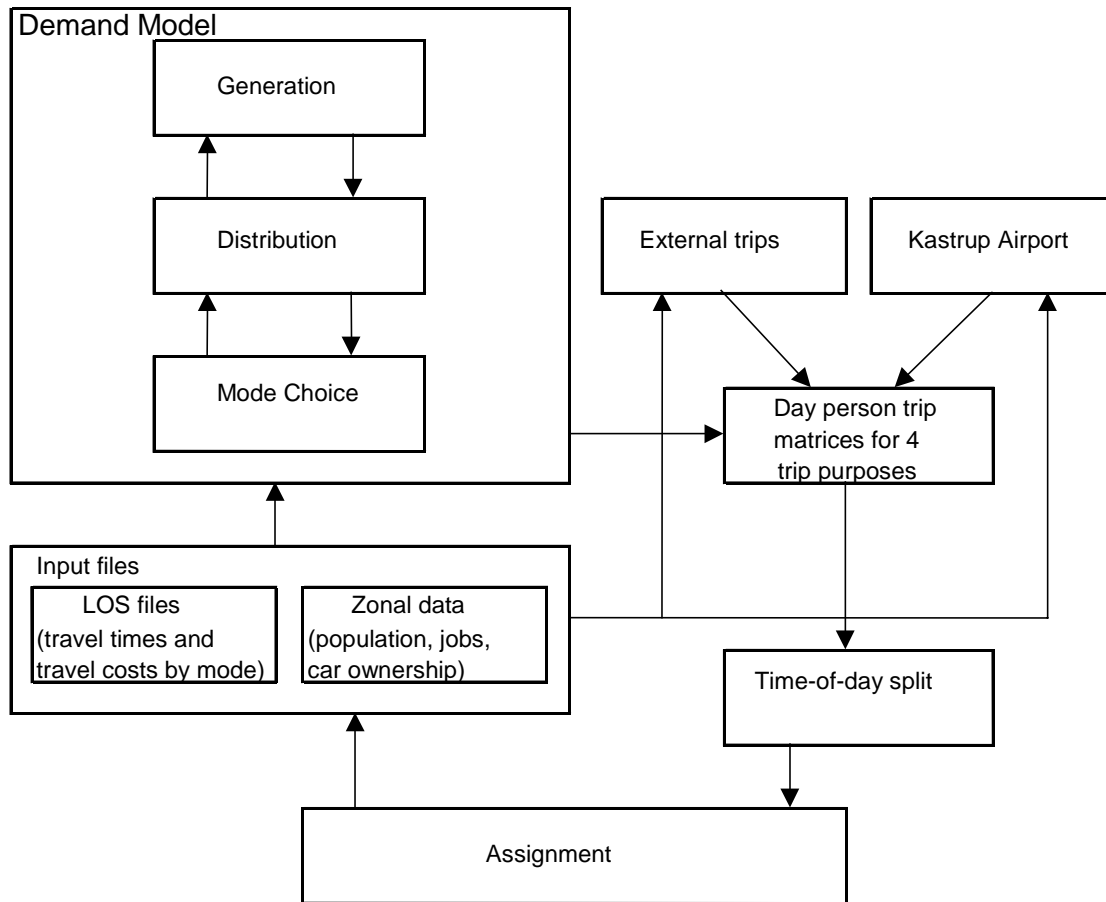
Figure 1 - The structure of the Orestad Traffic Model

When the logsums from the mode choice model and the distribution model are calculated the model system executes first the generation model, thereafter the distribution model and finally the mode choice model. Day matrices for four journey purposes are produced at that point. They are then split among three time-of-day matrices, namely matrices for morning peak (7a.m.-9a.m.), afternoon peak (3p.m.-5p.m.) and out-of-peak (the rest of the day) based on the observed time split existing in the base 1992 matrices. Before assigning on networks, the matrices for the HW, HE and PR purposes are transformed into trip matrices. These matrices, together with the BS trip matrices, are then amended by including the trips to and from the port zones as calculated in the external model. Finally trips to and from Kastrup airport, calculated in its own model, are included in the day trip matrices.

Car person trips are converted into vehicle trips by applying pre-defined car occupancy rates (which differ per segment) for the purpose of car assignment. The model system works therefore iteratively between the assignment and demand models, i.e. the assignment model is executed first (the production of LOS files), thereafter the demand model (the production of trip matrices) and finally the assignment model again (the calculation of traffic flows on the networks).

3   SUB-MODELS

3.1   Generation model

3.1.1   *Estimation procedure*

The OTM generation model is specified as a logit type model describing therefore the probability of making a tour in a specified time period. By making sure that the tour rate is small, which can be done by

expressing tour rates as the number of tours per hour (Paag and Daly), the OTM generation model can be specified as a logit model with the utility functions for alternatives *'tour'* and *'no-tour'* for origin zone i:

$$V_{tour,i} = \alpha + \sum_r \beta_r X_{r,i} + \beta_c X_{c,i} + \beta_l X_{l,i} \qquad (1)$$
$$V_{no\text{-}tour,i} = 0$$

In the $V_{tour,i}$ deterministic utility function for zone i, $X_{r,i}$ are 0/1 variables defined to be 1 for the actual type of employment (e.g., employee of higher, middle or lower level, self-employed, student, retired, not employed). $X_{c,i}$ stands for the number of cars per person in a household. Logsum variable for zone i, $X_{l,i}$, is included in the tour generation model for the PR segment allowing therefore for measuring the induced traffic. α is a constant that ensures that the total 1992 predicted tours is equal to the total 1992 observed tours. The OTM generation model is estimated from observed travel demand behaviour contained in the TU data.

3.1.2 Application procedure

The application procedure in the OTM generation model is based on the zonal data. In the zonal data it is known how many people of different employment (including students, retired persons and not employed persons) live in each zone. Apart from that, information regarding number of cars in zones are also available in the zonal data.

We define $S_{r,i}$ to be the zonal population shares of people of different occupations r living in zone i. The number of predicted tours by zone i for the forecasting year x, in a 24-hour horizon is then calculated in (2), where pop_i is population in zone i.

$$PredTr_i^x = 24\ pop_i\ [\exp(\alpha + \sum_r \beta_r S_{r,i} + \beta_c X_{c,i} + \beta_l X_{l,i})/(1 + \exp(\alpha + \sum_r \beta_r S_{r,i} + \beta_c X_{c,i} + \beta_l X_{l,i}))] \qquad (2)$$

The sum of $S_{r,i}$ for zone i equals 1. In this case, the following more simple formula holds approximately:

$$PredTr_i^x = 24\ pop_i \sum_r S_{r,i}\ /\ (1 + \exp(\alpha + \sum_r \beta_r + \beta_c X_{c,i} + \beta_l X_{l,i})) \qquad (3)$$

Similarly to equation (2), the predicted tours by zone i in the base year, $PredTr_i^{92}$ are calculated based on the 1992 zonal data and LOS.

The forecasted generated tours by zone i are finally calculated by applying a pivot point procedure as shown in equation (4).

$$T_i^x = M\ (PredTr_i^x\ /\ PredTr_i^{92}) \qquad (4)$$

where M is number of observed tours in zone i in the base year. If M and/or $PredTr_i^{92}$ is zero, minimum threshold values are assumed.

3.2 Distribution model

3.2.1 Estimation procedure

The OTM distribution model is estimated on the zonal data. The model is formulated as a logit model where the attraction of each destination zone is defined by a utility function. The model predicts therefore the proportions of tours between zones, given the average travel characteristics between zone pairs (e.g., travel distance for zone pairs) and zonal characteristics of the destination zone (i.e., attractiveness of the destination zone).

The distribution model is double constrained since it is constrained both at the origin zone and at the destination zone. The origin-constraint is ensured by setting a weight factor to be equal to the total number of tours generated by the origin zone. The number of tours generated by each zone is known from the basic 1992 matrices. The destination constraint is ensured by estimating destination specific constants in the destination utility functions. The destination specific constant ensures that number of tours which end in one destination zone, from all origin zones, is equal to observed number of tours ending in the particular destination zone.

Destination j-zone utility function, for a given origin-zone i, in the OTM distribution model has following shape:

$$V_{ij} = \ln(A_j) + \delta_{int} z_{ij} + \delta_{dist} f(d_{ij}) + \delta_l L_{ij} + \delta_j \qquad (5)$$

where A_j is a zonal variable (attractiveness) of the destination zone j. z_{ij} is a component that identifies whether the tour is intrazonal (i.e., $z_{ij} = 1$ if i=j, 0 otherwise). $f(d_{ij})$ is a function of distance between the zones. Non linear distance terms are estimated to improve the model fit. L_{ij} is the logsum variable calculated in the mode choice model, reflecting the accessibility between origin and destination zones. δ_j is a destination specific constant.

In the HW segment, the attractiveness A_j is defined to be equal to the number of available jobs in the zone. Similarly to that, in the HE segment A_j is defined to be equal to the number of study places in the zone. In the BS segment, attractiveness is set equal to number of trips to the destination zone. Attractiveness of the destination j-zone in the PR segment is defined to be equal to:

$$A_j = 17.8 J_{ls,j} + 17.8 J_{pi,j} + 34 J_{s1,j} + 3.5 J_{s2,j} + 109 J_{s3,j} \qquad (6)$$

where, $J_{ls,j}$ is the number liberal service jobs in destination zone j, $J_{pi,j}$ is the number public-institution jobs, $J_{s1,j}$ is the number of jobs in retail shops, $J_{s2,j}$ is the number if jobs in wholesale shops and $J_{s3,j}$ is number of jobs in supermarkets. Constants beside the jobs define that different branches attract different number of tours per employee. These constants are based on a project identifying the trip rates in the country (Danish Ministry of Transport).

3.2.2 Application procedure

The first step in the application of the distribution model in the forecasts consists of generating a base 1992 synthetic matrix T_{ij}^{92} by applying the estimated coefficients from equation (5). Applying the same weight factor as in the model estimation, the T_{ij}^{92} matrix produces the same total number of tours to each zone as the base 1992 observed matrix M_{ij}. The specific zone-to-zone tours (i.e., matrix cells) are however not the same in T_{ij}^{92} and M_{ij}. In order to minimise the difference between the observed 1992 zone-to-zone tours and the calculated 1992 zone-to-zone tours the destination utilities are extended with a correction factor E_{ij}. E_{ij} is calculated in a pivot point procedure:

$$E_{ij} = \log (M_{ij} / T_{ij}^{92}) \qquad (7)$$

The j zone destination utility, for a given origin zone i, is now defined to be:

$$V_{ij} = \ln(A_j) + \delta_{int} z_{ij} + \delta_{dist} f(d_{ij}) + \delta_l L_{ij} + \delta_j + E_{ij} \qquad (8)$$

Finally, the forecasted number of tours between zones i and j is calculated applying formula (9):

$$T_{ij}^x = T_i^x \exp(V_{ij}) / \sum_j \exp(V_{ij}) \qquad (9)$$

3.3 Mode choice model

3.3.1 VOT and model calibration

The OTM mode choice model is structurally the same as in some previous Danish large scale models, for instance the Great Belt model (Daly, Rohr and Jovicic), the Copenhagen-Ringsted model (Nielsen and Jovicic) and the Harbour Tunnel model (Paag and Daly). The theoretical background for the model estimation based on the simultaneous application of RP and SP data is described in Bradley and Daly (1992). The OTM mode choice model is based on a large set of RP and SP data.

The obtained values of travel time (VOT), in DKK per hour in 1992 prices, are shown in table 1 for all journey purposes. The BS segment has the highest VOT while the HE segment has the lowest VOT due to the income effect of the participants in these two segments. This finding is confirmed in the UK VOT project (UK Department of Transport). The private trips are a mix of trips with different purposes and VOT. The UK project also found that VOT for shopping was lower than the VOT when travelling on holiday. This mix of different trip purposes in the OTM PR segment resulted in obtaining similar VOT in

the HW and PR segments (again a finding that is confirmed by the UK VOT project). The bus in-vehicle VOT is as a rule higher than the VOT for train, metro and light-rail due to the difference in comfort. Value of in-vehicle travel time is lower than both access-egress VOT, and waiting and interchanging VOT because the time spent in train/bus can be somewhat usefully applied, e.g. reading. Access-egress time is usually short and it is spent on foot or bike. Therefore, it cannot be used for other purposes than reaching the main mode of transport on the trip. The waiting and interchanging time is weighted most negatively (approximately two times the in-vehicle VOT) because it can cause delays at the arrival at the destination. It is interesting to see that the model for the PR segment predicts higher VOT for bike/walk trips up to 30 minutes than for trips longer than 30 minutes. This happens probably due to the fact that longer walk/bike trips is a purpose in itself (e.g., bike excursion) while shorter trips are related to some activities (e.g., shopping).

	HW	PR	HE	BS
Access-egress time	47.8	52.2	18.6	146.8
Waiting and interchanging time	63.8	68.8	20.0	190.3
Bus in-vehicle time	38.1	28.3	10.2	85.7
Train in-vehicle time	26.2	16.9	9.5	85.7
Metro in-vehicle time	17.5	24.5	10.1	85.7
Light-rail in-vehicle time	25.4	24.5	10.1	85.7
Car free-flow time	18.7	23.0	9.1	46.8
Car congested time	64.0	59.4	26.4	130.8
Parking searching time	83.9	28.2	53.2	112.8
Parking costs	1.132	1.132	1.132	1.132
Walk/bike time (up to 30 min.)	51.9	105.5	23.8	-
Walk/bike time (over 30 min.)	145.5	74.7	48.7	-

Table 1 – VOT in DKK per hour, 1992 prices

The value of 1.132 for parking costs should be understood in the way that respondents in the RP/SP surveys weighted the parking costs 13.2% higher than driving costs. This is probably due to the fact that while driving costs are more or less included in the home budget, the parking costs are real out-of-pocket costs, i.e. coins that must be available for paying the parking, and that is in most cases an annoying factor.

Car-driver, car-passenger, bus, train, walk, bike, light-rail and metro modes are defined in the model structure. In order to obtain the same mode shares as in the observed 1992 matrices a set of correction factors are estimated in the calibration of the mode choice models while constraining the coefficients for time and cost. Because the observed matrices distinguish only between car, public transport, bike and walk alternatives it was necessary to apply the same correction factor for car-driver and car-passenger alternatives as well as for bus and train alternatives. The correction factor for mode m is calculated in an iterative procedure following the equation:

$$\text{CorrFactor}_m = \ln (T_m^{92} / M_m) \tag{10}$$

where T_m^{92} is the calculated sum of tours/trips for mode m ($T_m^{92} = \sum_{ij} T_{ij,m}^{92}$) and M_m is the observed sum of tours/trips for mode m based on the 1992 matrices. In each new run the correction factors add to their previous value.

3.3.2   Application procedure

The first step in the application of the mode choice models in the forecasts consists of generating a base 1992 matrix of calculated mode probabilities $PP_{ij,m}^{92}$. This is easily done by calculating the values of mode

utility functions applying the estimated coefficients and the appropriate variable values from the 1992 files of level of service. Similarly to that the observed 1992 mode probabilities $MP_{ij,m}$ are calculated based on the observed 1992 matrices.

Having defined the new supply new zone-to-zone travel times and travel costs are calculated in the assignment procedure. These values are stored in the new files of level of service. Forecasting mode probabilities $PP_{ij,m}^x$ are now calculated for each transport mode m on a zone-to-zone level as both the coefficient values and the variables are known in the mode utilities. A pivot point procedure is applied again in order to calculate the future trips/tours between zones i and j, by car, walk, bike and public transport modes:

$$T_{ij,m}^x = MP_{ij,m} (PP_{ij,m}^x / PP_{ij,m}^{92}) T_{ij}^x \tag{11}$$

3.4 Model for external traffic and Kastrup model

Through trips (trips between the port zones) and trips with only one leg in port zones are modelled in an external model. Out of 17 port zones 15 are handled in a simple model for external traffic. The remaining two port zones for Kastrup airport are dealt with in a separate model.

For the base year 1992 port zone trips are based on traffic counts and distribution of trips within greater Copenhagen area is estimated from matrix adjustment procedures. The Kastrup model is based on data from a SP survey that was conducted at both the domestic and international terminals at Kastrup airport in the end of 1998. In total 150 interviews were completed with passengers. These data are applied in predicting the mode choices for trips to/from airport zones. Only two modes of transport are interesting in this model, i.e. car and public transport modes. The model operates only with PR and BS segments. The obtained VOT in the model are somewhat higher than the VOT from the mode choice model presented in table 1. In the forecasting scenario, the deterministic utility functions for car and public transport modes are calculated from LOS. Car and public transport forecasting probabilities for each zone pair are therefore easily calculated. The day matrices calculated in (11) are finally corrected for the port zone traffic as calculated in these two models.

4 ROAD PRICING PROJECT

One of the recently finished projects where the OTM is applied is a study of road pricing in Denmark (the FORTRIN project). The base scenario in the model calculations is the year 2000 situation without road pricing. Sums of the person day trip matrices by modes of transport and trip purposes are shown in table 2. Year 2000 matrices are calculated taking care of all infrastructure improvements since 1992. Secondly, zonal data for 2000 are established based on the official figures from different ministries. Finally, car occupancy rates are updated from 1992 to 2000 as well as travel costs.

Before running different road pricing scenarios, the model was tested against observed traffic from 2000. The average divergence between forecasted car traffic and observed car traffic on 13 screen lines was 4% while the largest difference was –11%. The difference between forecasted and observed public transport passengers was 13% on average for 15 screen lines. The relative higher difference for public transport is partly due to smaller amount of public transport users than car users.

	HW	HE	BS	PR	Total
Car	950,000	59,000	883,000	1,289,000	3,181,000
Bike	514,000	302,000	54,000	360,000	1,230,000
Walk	200,000	36,000	51,000	935,000	1,222,000
Public transport	453,000	66,000	15,000	431,000	965,000
Total by purpose	2,117,000	463,000	1,003,000	3,015,000	6,598,000

Table 2 – Person trips in the base 2000 matrices by mode and trip purpose

One of the investigated scenarios in the study is based on allowing for road pricing distinguishing between geographic areas, and main and secondary types of roads. Road pricing is graduated in the way that it costs more to drive in the city centre than in the periphery as well as it costs more to drive on secondary roads than on the main roads. By introducing road pricing directly on the road network for each road link, the zone-to-zone extra driving costs are calculated in the LOS files based on the car assignment model. New LOS files are then applied in the calculation of logsums that influence both the destination choice (due to the changed accessibility) and the negative induced traffic in the PR generation model.

Car LOS files with road pricing have also effect on the mode choice model, where the car-driver and car-passenger utility functions are extended in order to take care of the extra costs. Some of the SP data completed for the purpose of Harbour Tunnel project (Paag and Daly) includes SP information about the effect of tolls. The main conclusion of the data analysis is that respondents accept tolls essentially in the same way as driving costs. Due to that conclusion the car-driver and car-passenger utilities are extended in the way that both the zone-to-zone driving costs and zone-to-zone road pricing are multiplied by the same cost coefficient estimated in the mode choice model. Sums of the person day trip matrices by modes of transport and trip purposes for road pricing scenario are shown in table 3. In parentheses are shown percentage differences between the calculated trips in the scenario with road pricing and in the basic scenario.

Person trips by car drop by approximately 6% due to the introduced road pricing. Car driving cost in-mode elasticity in OTM is –0.11. Both some older and recent international research in this area has pointed out the same findings. Ben-Akiva and Lerman have calculated in-mode car travel cost elasticity to range between –0.10 (joint logit model) and –0.14 (nested logit model). Storchmann has recently calculated that the fuel price elasticity in Germany is –0.10. It should be noted here that OTM's elasticity of –0.11 and Storchmann's elasticity are short-term elasticities, which according to the literature are lower than long-term elasticities (Goodwin).

	HW	HE	BS	PR	Total
Car	872,000 (-8.2%)	39,000 (-33.2%)	883,000 (0.0%)	1,202,000 (-6.7%)	2,996,000 (-5.8%)
Bike	548,000 (+6.6%)	316,000 (+4.6%)	54,000 (0.0%)	378,000 (+5.0%)	1,296,000 (+5.4%)
Walk	212,000 (+6.0%)	38,000 (+5.6%)	51,000 (0.0%)	978,000 (+4.6%)	1,279,000 (+4.7%)
Public transport	485,000 (+7.1%)	70,000 (+6.1%)	15,000 (0.0%)	452,000 (+4.9%)	1,022,000 (+5.9%)
Total by purpose	2,117,000 (0.0%)	463,000 (0.0%)	1,003,000 (0.0%)	3,010,000 (-0.2%)	6,593,000 (-0.1%)

Table 3 – Person trips in the matrices with road pricing by mode and trip purpose

Looking by segments, the HE segment is affected largely due to the relatively low VOT, but this segment is rather unimportant for car traffic. On the other side, the business travellers are inferior to the extra costs as their VOT are high. The average drop of car traffic of 6% is largely influenced by the calculated decrease in the HW and PR segments, which in sum represent more than 70% of the entire car traffic.

After assigning the car matrices on the road network it is calculated that the vehicle-kilometres are reduced in average 11%, from 25.8 million vehicle-kilometres in the base scenario to 23 million vehicle-kilometres in the road pricing scenario. Comparing the vehicle-kilometres reduction of 11% with the car person traffic reduction of 5.8% it can be concluded that with an increase in driving costs it is first of all

longer car trips that change destination and mode. A similar observation has been found in a project for the Stockholm area, where reduction in the vehicle-kilometres is 13%.

Most of the shifted car trips moved to the public transport modes while the least moved to be walkers. The reduced accessibility between the zones resulted in a negative induced traffic in the segment for private trips. The magnitude of the induced traffic is 0.2% or 5,000 car trips.

5   CONCLUDING REMARKS

The OTM is a nested logit model where logsums connect the mode choice model with the distribution model and the generation model. The tour based modelling approach that is applied in the OTM allows inclusion of a large number of explanatory variables in both the generation, distribution and mode choice models and that is the main strength in the model forecasting power. The applied pivot point procedures, in all three levels of the OTM demand model, ensure that the model replicates very well the base traffic flows on the matrix level. The model forecasting results for 2000 prove to fit very well the counted traffic on some pre-defined screen lines. The model validity is also proved through a comparison of some of the model results with the similar international figures. For instance, the OTM car driving costs elasticity equals –0.11, a level found in similar projects in USA and Germany. In one of the defined scenarios in the study of road pricing the vehicle-kilometres dropped for approximately 11%, which is in line with the results from a similar project in Stockholm.

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