MODELING AND ANALYSIS OF ROAD PRICING SCHEMES

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ABSTRACT

There is considerable interest in introducing road pricing at the policy level throughout the world. Road pricing means restructuring the pricing schema to a more user charge based system and using this system to influence transport demand. The technical feasibility of road pricing has been proven in several cities and regions, but there remain questions regarding the transport demand effects of specific road pricing schemes. This research project developed models to establish the transport network and demand in Switzerland for the reference year 2030, then used these models to quantify the effects of six road pricing schemes on travel demand (destination, mode, route and departure time choice), and to estimate the impact of these road pricing schemes on land use, road safety and the environment.

RESUMO

Há um interesse considerável na adoção da tarifação rodoviária comopolítica de transportes ao redor do mundo. A tarifação rodoviária éconcebida como uma reestruturação no cálculo da tarifa para um sistema cobrança mais prático e como mecanismo de influência na demanda por transportes. A aplicabilidade desta técnica já foi provada largamente em cidades e regiões, contudo há ainda questões relacionadas sobre a reação da demanda a mudanças específicas na tarifação rodoviária. Este trabalho apresenta os resultados de modelos desenvolvidos para previsão da rede viária e demanda na Suíça para o ano de 2030, quantificar os efeitos de seis cenários tarifários na demanda (escolha do destino, do modo, da rota e do horário de partida), e estimar o impacto no uso do solo, segurança viária e meio ambiente.

1 INTRODUCTIONS

Many countries and regions are discussing the introduction of road pricing as a possible solution for growing transport and environment problems. Road pricing (also referred to as mobility pricing in Switzerland) means restructuring the pricing schema for motorized private transport (MPT) to a more user charge based system and using the system to influence transport demand.

In Switzerland there is considerable interest in road pricing at the policy level. The technical feasibility of road pricing has been proven in several foreign cities and regions, but there remain questions regarding the demand reactions to specific road pricing schemes. In summary, some fundamental facts on the impact and effectiveness of road pricing strategies are missing. The goal of this research project was to develop information to address this knowledge gap.

The research project developed a model to analyze six road pricing scenarios for passenger transport; freight transport was considered constant in the study. The study scenarios were defined to provide information on different control strategies and finance goals. Therefore, demand was expected to react differently for the different scenarios. The project goal was to quantify the passenger transport demand reactions under the different scenarios and to estimate the effects on land use, road safety and the environment. The calculation and interpretation considered the entire road network of Switzerland.

The study was conducted within the National Research Program "Mobility Pricing" from the Swiss Federal Road Office and based on the Swiss National Passenger Transport Model, NPTM, (Vrtic, Lohse, Fröhlich, Schiller, Schüssler, Teichert and Axhausen, 2007a). The discrete choice models were estimated in the program project B1 "Including travelling costs in the modelling of mobility behaviour" (Vrtic, Schüssler, Erath and Axhausen, 2007b). The mobility pricing scenarios were defined in the program project A2 "The role of Mobility Pricing in future transport financing" (Ecoplan and INFRAS, 2006).

2 METHODOLOGY

The first step in developing the road pricing model was to establish a reference case without road pricing. In this case the model describes the transport system and demand for the reference year 2030. The networks for road transport were established based on the NPTM and the planned motorway improvements according to Swiss Federal Road Office. The network and timetables for public transport were based on the year 2005 situation since no coordinated public transport timetable was available for the year 2030.

The NPTM was used to estimate the transport demand for the year 2030. Transport demand was based on existing origin/destination (OD) matrices from the year 2000 and projected changes to socio demographic conditions and land uses. The effect of transport system changes on demand in 2030 were not considered in the NPTM, therefore this had to be done as part of this project. These effects were estimated by applying the simultaneous destination and mode choice software tool VISEVA, the same method used in the NPTM. This allowed the researchers to consider possible destination and mode changes for the three transport modes considered in the study (private transport, public transport and walking).

Once the future networks and demand had been estimated, it was necessary to add the road pricing information to the network, in other words to establish the transport network changes that would be imposed through the introduction of road pricing. This was done by adding an additional cost element to specific network links.

Next, the VISUM 9.5 assignment software (PTV, 2006), the actualized OD matrices and the assignment parameters were used to calculate the skim matrices for different variables for every OD pair in the network; this was done both with and without road pricing. The skim matrices obtained in this process were then used to calculate the demand changes due to the introduction of road pricing. The transport system changes affect the demand stochastically and therefore the demand reaction must be calculated with related methods.

The study considered six different road pricing scenarios (the scenarios are described in Section 4). The same road and public transport networks were used for all the scenarios, only the road pricing components differed. The road pricing components consist of:

- Fuel costs;
- Road charge; and,
- Public transport fare.

The introduction of road pricing forces the transport users to consider an additional attribute in their travel decisions, namely the road charge. The behavior changes caused by this attribute will depend on the road pricing definition; they can include changes to destination, mode, route or/and departure time. In order to quantify these changes discrete choice models and stochastic assignment methods must be used to estimate the different willingness to pay of users. The discrete choice models used in this research were estimated as part of the project B1 (Vrtic, Schüssler, Erath and Axhausen, 2007b) using SP data with a sample size of 1005 respondents. The alternative, using simplified methods based on the demand elasticity, was not used since these simplified methods can only provide rough estimations on a very aggregate level of road pricing impacts.

2.1 Mode choice changes

The introduction of road pricing changes the generalized costs and utility of travel, and therefore the mode choice changes should be calculated considering the changes on the utility for the different modes. In this research the pivot-point method for the Multi Nominal Logit model (MNL) (Ortuzar and Willumsen, 2001) was used to calculate the mode choice changes. It calculates the demand changes due to relative changes in the utility of the modes for each origin-destination pair. The pivot-point approach is suitable for estimating scenario demand based on the demand in the reference case and the changes in specific attributes between the reference case and the test scenario.

The formula for the pivot point method for an MNL is:

$$P_k^1 = \frac{P_k^0 \cdot e^{(V_k^1 - V_k^0)}}{\sum_i P_i^0 \cdot e^{(V_i^1 - V_i^0)}} \tag{1}$$

V_k^1-V_k^0	Utility difference for mode k
P_k^1	Demand proportion in scenario (status 1) for mode k
P_k^0	Demand proportion in reference case (status 0) for mode k
V_k^1	Utility in scenario (status 1) for mode k
V_k^0	Utility in reference case (status 0) for mode k

The utility functions for the two competing alternatives (MPT and PuT) for the mode choice are:

$$\begin{aligned} V_{\text{MPT}} &= ASC_{\text{MPT}} + \beta_{\text{Travel time MPT}} * \left(\frac{\text{Total costs}}{\text{Mean Total costs}}\right)^{\lambda_{\text{tc MPT}}} * \text{Travel time} \\ &+ \beta_{\text{Fuel cost}} * \left(\frac{\text{Travel time}}{\text{Mean Travel time}}\right)^{\lambda_{\text{tt\_fc}}} * \text{Fuel cost} + \beta_{\text{Charge}} * \left(\frac{\text{Travel Time}}{\text{Mean Travel time}}\right)^{\lambda_{\text{tt\_ch}}} * \text{Charge} \end{aligned} \tag{2}$$

$$\begin{aligned} V_{\text{PuT}} &= \beta_{\text{Access time}} * \text{Access time} + \beta_{\text{Number of transfers}} * \text{Number of transfers} \\ &+ \beta_{\text{Headway}} * \text{Headway} + \beta_{\text{Ride time}} * \left(\frac{\text{Fare}}{\text{Mean Fare}}\right)^{\lambda_{\text{rt\_fa}}} * \text{Ride time} \\ &+ \beta_{\text{Fare}} * \left(\frac{\text{Ride time}}{\text{Mean Ride time}}\right)^{\lambda_{\text{fa\_rt}}} * \text{Fare} \end{aligned} \tag{3}$$

Table 1 presents the parameters used for the mode choice model.

Table 1 Transport Mode Choice Parameters used in the Pivot-Point Method

Variable	Parameter
MPT ASC	0.21
MPT Travel time [h]	-2.26
MPT Fuel cost [CHF]	-0.08
MPT Road pricing charge [CHF]	-0.17
PuT Ride time [h]	-1.90
PuT Fare[CHF]	-0.10
PuT Access time [h]	-2.61
PuT Headway [h]	-0.56
PuT Number of transfers	-0.26
λ_MPT_Total costs	-0.10
λ_PuT_Ride time_Fare	-0.28
λ_MPT_Travel time_Fuel costs	-0.33
λ_MPT_Travel time_Charge	-0.35
λ_PuT_Fare_Ride time	-0.19

Source: Vrtic, Schüssler, Erath and Axhausen, 2007b

The utility functions contain non-linear terms (also called elasticity formulation Mackie, Jara-Diaz and Fowkes, 2001), therefore some variable means from the SP survey are considered in the utility function. The mode choice changes were considered in all scenarios.

2.2 Destination choice

Two scenarios, namely the Scenario B – Zone Charging and Scenario D – Zone-Network-Zone Charging, include cordon charges for entering and leaving certain cities. Therefore it was expected that in addition to mode choice changes these scenarios would also have destination choice changes. In order to model these effects the original demand model (VISEVA) of the NPTM was used, because in the Stated Preference (SP) survey used to develop the model no destination choice parameters were considered.

2.3 Route choice

A stochastic assignment method was used in all scenarios to evaluate route choice in order to fully consider the variation in the willingness to pay and perception errors of automobile drivers (Bovy and Stern, 1990). In a stochastic assignment the choice set per iteration for a given O/D-pair is calculated with a variation with a given distribution of the impedance of the links (PTV, 2006). After the choice set was generated, the demand was distributed on the identified routes according to a choice model (here MNL). Furthermore, the independence of each route is considered (Cascetta, 2001).

The NPTM estimates the impedance of a route between two given zones as a combination of connectors and links impedance (turning impedance is not specified in the NPTM). The link impedance consists of the following three elements:

1. Travel time on link
2. Link length (converted first to fuel cost per km and then to time value using value of travel time savings (VTTS))
3. Road charge (converted with VTTS to time value)

The truck traffic is considered as preload on the network. Since the research was designed to evaluate person travel impacts of road charging scenarios, truck traffic was pre-loaded on the network and did not vary between scenarios.

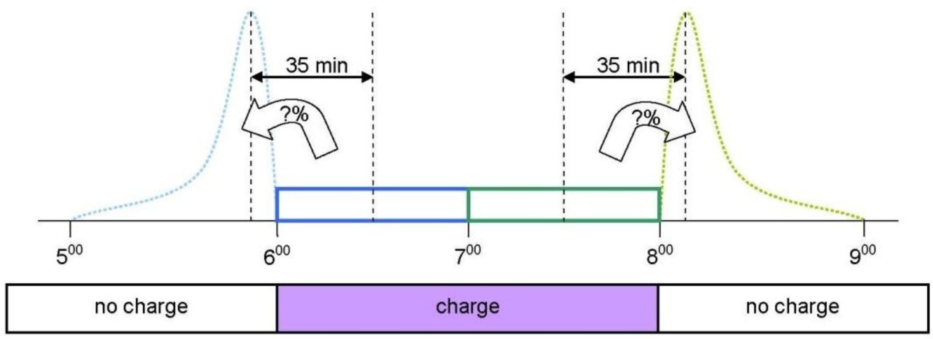
In the PuT model, the time table based assignment procedure (PTV, 2006) was used to estimate route choice. Fare adjustments were not necessary since in all scenarios fares were considered constant and Scenario E2 included a general public transport fare increase, respectively.

2.4 Departure time choice

In order to model the departure time choice, the dynamic NPTM with O/D-Matrices per hour, the corresponding skim matrices per hour and the parameters for departure choice were used. This information allows estimation of the time adjustments of travel demand caused by utility changes due to time dependent charges (Marchal, 2001).

The pivot-point method can be used here as well, since the number of MPT trips per hour and the utility per O/D-pair are known for the reference case, and the utility per O/D-pair for the alternative scenario is also known. The only assumption needed is the time gap between the center of gravity of the demand distribution for the one hour matrix with charging and the demand shift to the hour before or afterwards without charge. This is shown in Figure 1.

Figure 1 Schema of departure time choice



It is assumed that the demand per hour in the reference case is equally distributed. With the introduction of a time dependent road pricing charge, the demand shifts partially to a skewed distribution into the hour before the road pricing takes effect (and the hour after the road pricing ends), because the consumer wants travel at a time close to his optimal (without road charging) departure time. Therefore the assumption for the time gap was chosen with 35 min.

This means that automobile drivers must make a tradeoff between:

- paying the charge and traveling at the desired hour, or

- not paying the charge and traveling either earlier (Parameter = -0.35) or later (Parameter = -0.78) than desired.

The utility function will be now shown for the hour from 5 to 6 a.m. (without charge) and from 6 to 7 a.m. (with charge). A demand shift can only occur to the hour from 5 to 6 a.m. because in the hour later (7 to 8 a.m.) also has a charge.

$$\begin{aligned} V_{5\text{-}6\text{ a.m.}} &= \beta_{\text{travel time}} * \text{Travel time}_{5\text{-}6\text{ a.m.}} + \beta_{\text{Fuel cost}} * \left(\frac{\text{Travel time}}{\text{mean Travel time}}\right)^{\lambda_{\text{tt\_fc}}} * \text{ Fuel cost}_{5\text{-}6\text{ a.m.}} \\ &+ \beta_{\text{Charge}} * \left(\frac{\text{Travel time}}{\text{mean Travel time}}\right)^{\lambda_{\text{tt\_ch}}} * \text{Charge}_{5\text{-}6\text{ a.m.}} + \beta_{\text{Earlier}} * \text{Earlier} \end{aligned} \tag{4}$$

$$\begin{aligned} V_{6\text{-}7\text{ a.m.}} &= \beta_{\text{Travel time}} * \text{Travel time}_{6\text{-}7\text{ a.m.}} + \beta_{\text{Fuel cost}} * \left(\frac{\text{Travel time}}{\text{Mean Travel time}}\right)^{\lambda_{\text{tt\_fc}}} * \text{ Fuel cost}_{6\text{-}7\text{ a.m.}} \\ &+ \beta_{\text{Charge}} * \left(\frac{\text{Travel Time}}{\text{Mean Travel time}}\right)^{\lambda_{\text{tt\_ch}}} * \text{Charge}_{6\text{-}7\text{ a.m.}} + \beta_{\text{Later}} * \text{Later} \end{aligned} \tag{5}$$

3 RESULTS

The research considered the following six scenarios:

Scenario A – Object Charging – This scenario implements an object (charging new build road links) and value (charging existing road lanes) pricing schema on selected links. The charge per kilometer amount is chosen to maximize gross income.

Scenario B – Zone Charging – This is a cordon pricing system, where every vehicle crossing the municipal border of one of the eleven largest Swiss cities during the peak periods (6:00-8:00 and 16:00-18:00) pays a fee of 3 Swiss Francs (CHF).

Scenario C – Network Charging – This scenario consists of charging vehicles a fee of 4 Rappen (1/100 of a Swiss Franc – Rp.) per vehicle-km traveled on the national network (mainly motorways) and the highway network of importance (in total approximate 5,000 km). At the same time the fuel price is reduced by 12 Rp/liter.

Scenario D – Zone-Network-Zone Charging – This scenario combines scenarios B (zone model) and C (network charging model).

Scenario E1 – Area Charging – This scenario consists of charging vehicles 4 Rp per vehicle-km traveled for the entire Swiss road network and lowering the fuel price by 30 Rp per liter.

Scenario E2 - Area Charging – This scenario considers much higher transport costs. It consists of increasing the cost to 15 Rp per vehicle-km, lowering the fuel price by 30 Rp per liter, and increasing the price for public transport to be equal to the variable price for motorized private transport (therefore increasing the public transport price per km by more than 50%).

Table 2 summarizes the demand reactions to these six scenarios in comparison to the reference case for 2030 and also the data for the year 2000.

Table 2 Estimated Impact of Road Pricing on Travel Demand

in millions per day	MPT trips	PuT trips	MPT vehicle-km	MPT person-km	PuT person-km
NPTM 2000	11.194	1.885	114.1	165.4	45.0
Reference Case 2030	13.630	2.579	145.8	201.3	67.5
Sc. A (Object Charging)	13.626	2.581	145.4	200.7	67.6
Sc. B (Zone Charging)	13.557	2.650	144.0	198.8	72.4
Sc. C (Network Charging)	13.571	2.636	140.0	193.1	71.4
Sc. D (Zone-Network-Zone Charging)	13.495	2.712	137.3	189.5	76.3
Sc. E1 (Area Charging)	13.523	2.684	139.6	192.6	72.1
Sc. E2 (Area Charging)	13.403	2.803	130.7	180.4	75.1
Relative change compared to reference case in %					
NPTM 2000	-17.9	-26.9	-21.7	-17.9	-33.2
Sc. A (Object Charging)	0.0	+0.1	-0.3	-0.3	+0.2
Sc. B (Zone Charging)	-0.5	+2.7	-1.2	-1.2	+7.3
Sc. C (Network Charging)	-0.4	+2.2	-4.0	-4.0	+5.8
Sc. D (Zone-Network-Zone Charging)	-1.0	+5.2	-5.9	-5.9	+13.1
Sc. E1 (Area Charging)	-0.8	+4.1	-4.3	-4.3	+6.9
Sc. E2 (Area Charging)	-1.7	+8.7	-10.4	-10.4	+11.3

As shown in Table 2, the number of public transport trips per workday was 27% lower and the number of private vehicle trips 18% lower in 2000 than in the reference year 2030. The total distance traveled in Switzerland, measured in person-kilometers (P-km), was 33% lower for public transport and 18% lower for motorized private transport in 2000 than in the reference year 2030. The motorized private transport vehicle-km was calculated based on the assumption that average vehicle occupancy decreases from 1.45 persons (2000) to 1.38 persons (2030).

The model results for the road pricing scenarios are meaningful and show the expected effects. As shown in Table 2, the demand shift from private vehicle transport to public transport is moderate; this is because the additional road pricing charge is compensated for by the reduction in fuel prices for private transport in most scenarios.

The research also showed the impact of road pricing on road safety and the environment. Tables 3 and 4 summarize the estimated impacts of the road pricing scenarios on road safety and the environment. To illustrate the changes on the road network the volumes difference plots for three scenarios is included in discussion starting after Table 4.

Table 3 Estimated Annual Impact of Road Pricing on Road Safety and Environment

Per year	Accidents	Casualties	CO2 [tons]	NOx [tons]	PM 10 [tons]
Reference Case 2030	37'557	18'527	10'472'000	17'233	2'901
Sc. A (Object Charging)	37'539	18'533	10'444'000	17'200	2'891
Sc. B (Zone Charging)	36'902	18'260	10'365'000	17'112	2'865
Sc. C (Network Charging)	37'399	18'656	10'064'000	16'735	2'742
Sc. D (Zone-Network-Zone)	36'663	18'348	9'912'000	16'560	2'691
Sc. E1 (Area Charging)	36'615	18'112	10'114'000	16'814	2'782
Sc. E2 (Area Charging)	35'664	17'755	9'586'000	16'185	2'597
Relative change compared to reference case in %					
Sc. A (Object Charging)	-0.1	-0.1	-0.3	-0.2	-0.4
Sc. B (Zone Charging)	-1.7	-1.4	-1.0	-0.7	-1.3
Sc. C (Network Charging)	-0.4	0.7	-3.9	-2.9	-5.5
Sc. D (Zone-Network-Zone)	-2.4	-1.0	-5.4	-3.9	-7.3
Sc. E1 (Area Charging)	-2.5	-2.2	-3.4	-2.4	-4.1
Sc. E2 (Area Charging)	-5.0	-4.2	-8.5	-6.1	-10.5

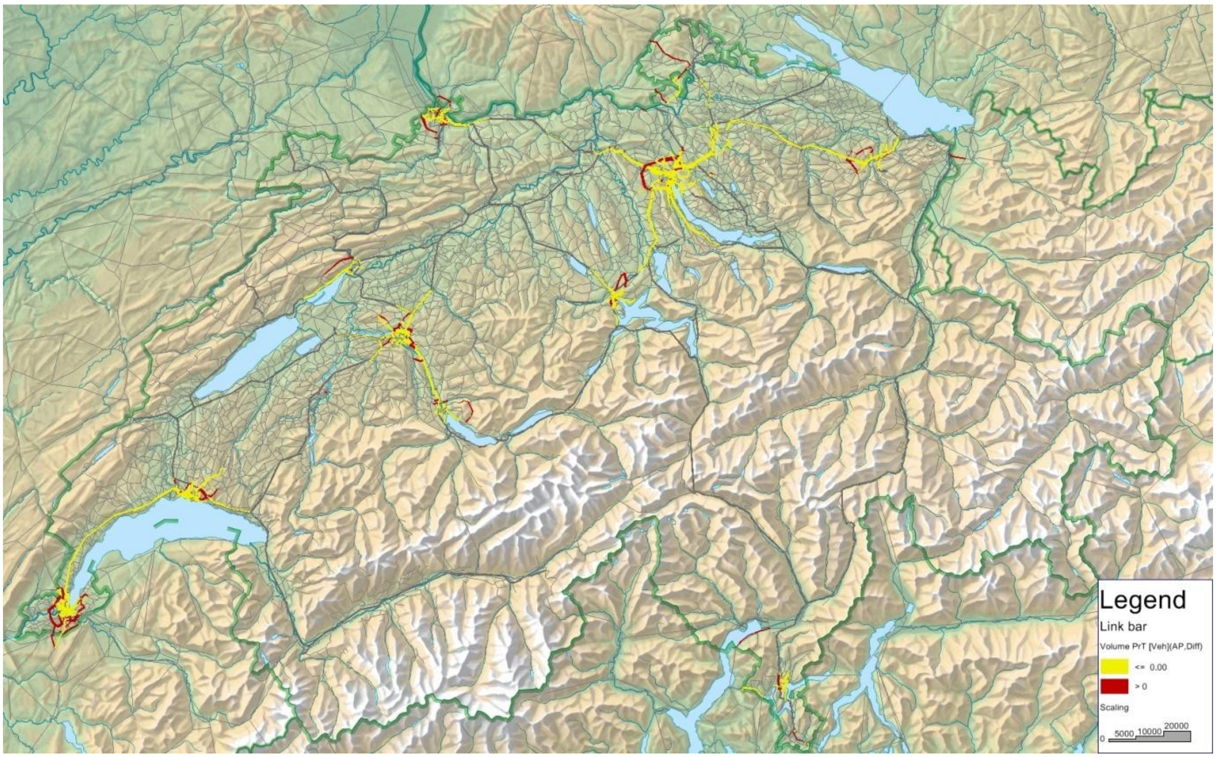
Table 4 Change in Noise Impact on Links in Built-up Areas

Scenario	Decline > 1 dBA (1)	Increase>1 dBA (2)	Difference (2)-(1)
Sc. A (Object Charging)	30.8 km	35.8 km	+5.0 km
Sc. B (Zone Charging)	131.1 km	64.0 km	-67.1 km
Sc. C (Network Charging)	78.1 km	181.7 km	+103.6 km
Sc. D (Zone-Network-Zone)	121.6 km	160.6 km	+39.0 km
Sc. E1 (Area Charging)	63.1 km	62.8 km	-0.3 km
Sc. E2 (Area Charging)	99.7 km	155.1 km	+55.4 km

As shown in the results, scenario A (object charging) has only a small impact on travel demand; this is because of its definition and the required comparability to the other scenarios. The effects are local and the mode shift is very small.

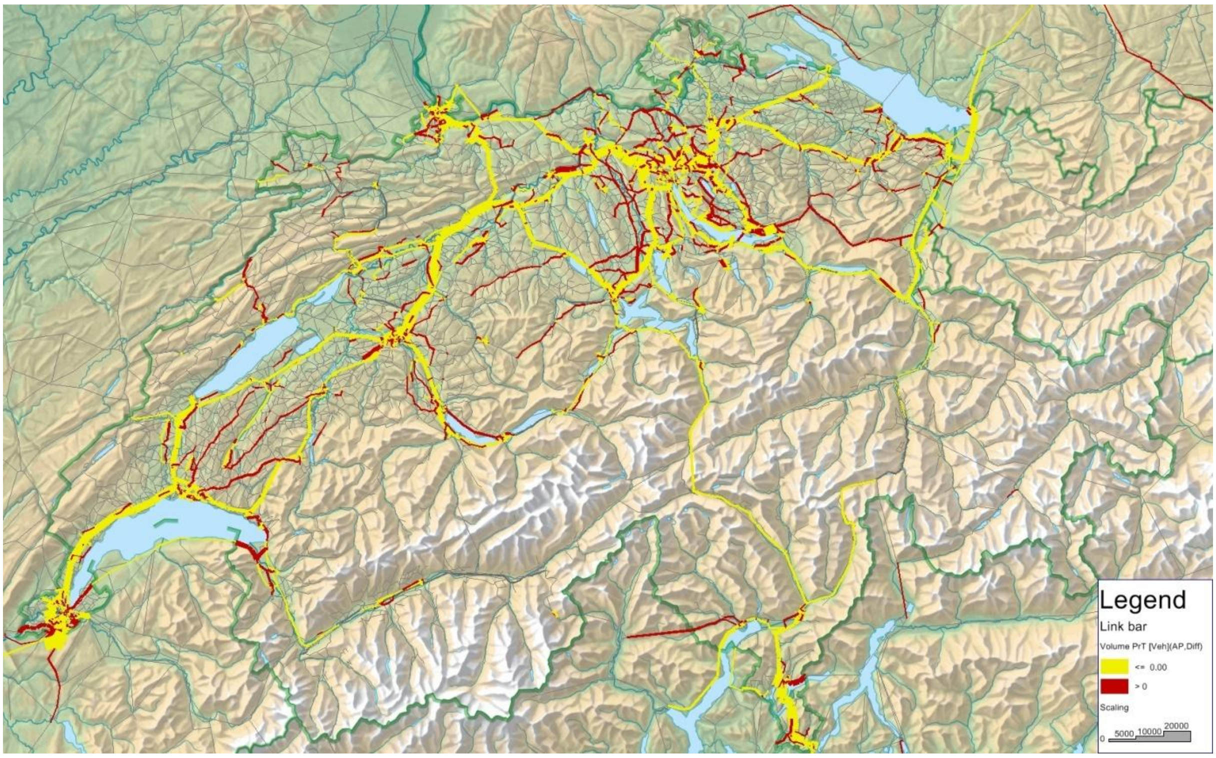
In scenario B (zone charging) the effects in metropolitan areas are clearly visible (compare Figure 2). There is a shift in the destination choice of motorized private transport trips within the pricing zones, a mode shift to public transport and a flattening of the peak hour traffic. Furthermore, there is stronger road traffic flow on links bypassing the pricing zones. This scenario also shows an improvement in road safety and reduction in noise impacts. Public transport gains passengers around the cities with zone charges on the radial lines in the peak hours as people switch to PuT to avoid the charge. This means also, possible additional investments could be necessary in the public transport networks. In this scenario, the effect on land use can be directly controlled by placement of the pricing zone borders, which indicates that the effects of the road pricing schemes are local and of low intensity.

Figure 2 MPT Scenario B (Zone Charging): Difference plot to reference case



In scenario C (network charging) the mode share for public transport on longer trips increases and demand on the motorway network is shifted to the highway network (see Figure 3). Furthermore, this scenario increases traffic flow in the built-up areas. The inbound, outbound, and through (transit) private vehicle traffic is also influenced in its route choice and redirected to links outside Switzerland. The shift of private vehicle traffic from the national network of motorways and national routes to the local network leads to an increase in the noise level and reduced road safety. The average daily speed on motorways increases in the metropolitan areas. The gain of passengers for public transport is concentrated on interregional and national connections.

Figure 3 MPT Scenario C (Network Charging): Difference plot to reference case



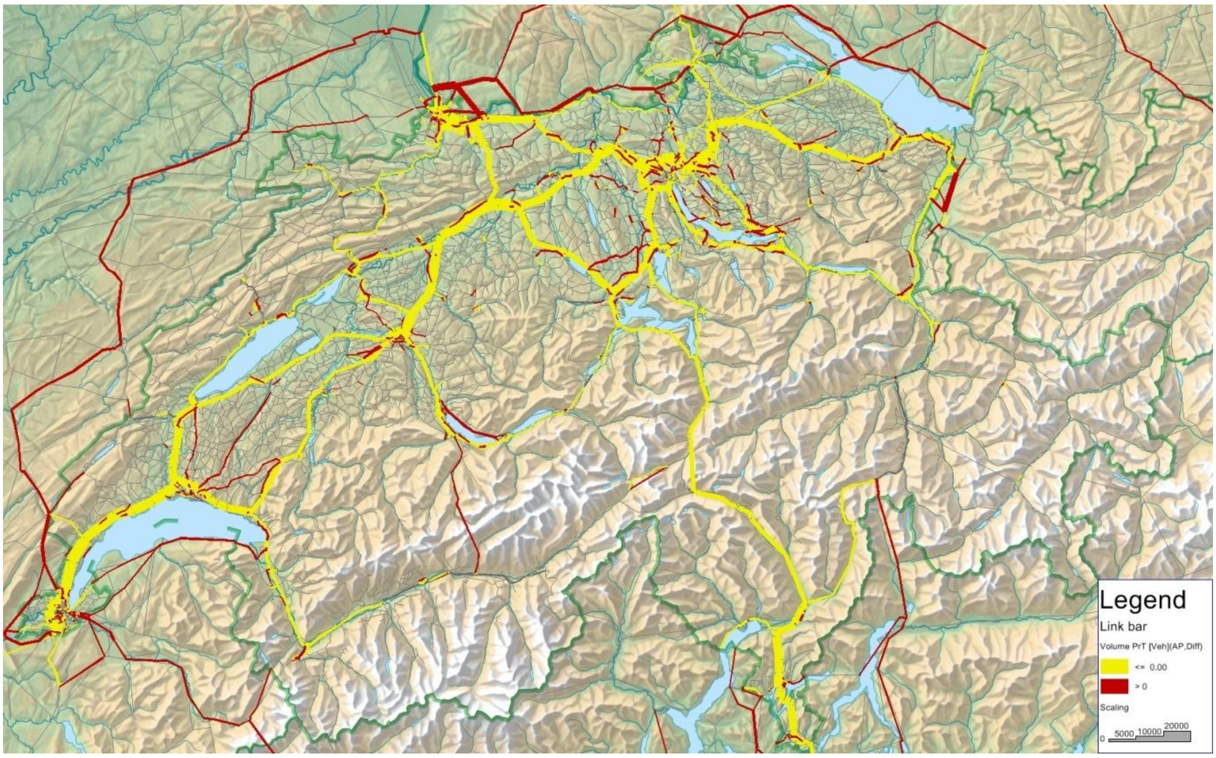
Scenario D (zone-network-zone charging) combines scenario B and C and lowers the vehicle flows in the metropolitan areas as well as on the motorways. In this scenario, the effects of Scenario B and C partly cancel each other out. For example, the noise impacts worsen slightly while there is a small improvement in road safety. The daily average speed on motorways increases. Public transport gains passengers on the radial lines around pricing zones as well as on the interregional and national connections.

Scenario E1 (network charging) has only moderate effects on the mode choice because of the low increase in the road charge and the simultaneous lowering of the fuel price. There is a mode shift from private vehicles to public transport as well as rerouting of inbound, outbound and transit private vehicle trips. The scenario has very small impacts on environment and road safety and these are distributed uniformly spatially. There is a small increase in the daily average speed on motorways and a small decrease on highways.

In scenario E2 (network charging) the significant increase in cost causes a shift from private vehicle trips to public transport trips (compare Figure 4). The distance sensitivity of the route choice is higher, which leads to an increased loading of the highway network, as well as to a massive rerouting of inbound, outbound and transit trips to links outside Switzerland.

The shifting of private vehicle trips on the highway network can cause undesirable road safety and noise impacts. The average daily speed increases significantly in certain segments of the motorway network, such as the Gotthard tunnel while the average speed on the highway network decreases. The public transport system strongly gains on interregional and national connections. The model results for scenario E2 also show, that even with the highest road prices of all scenarios, private vehicle mileage for 2030 would be higher than year 2000 estimates.

Figure 4 MPT E2 (Area Charging): Difference plot to reference case



4 CONCLUSIONS

Road pricing has been successfully implemented in many countries and regions. However, research has demonstrated that road pricing schemes must be very carefully planned to be successful (for e.g. CURACAO, 2009). A key part of the planning effort is evaluating the impacts of road pricing on travel demand.

In Switzerland there is considerable interest in road pricing at the policy level and therefore the Swiss Federal Road Office wanted to evaluate the impacts of six alternative road pricing scenarios on the country’s private and public transport demand. Specifically they wanted to better understand the impact of road pricing on the choice of destination, mode, route and departure time as well as the resulting impacts on the environment, road safety and land use.

Therefore, this research project developed models to establish the transport network and demand for the reference year 2030 and then used these models to quantify the effects of six road pricing scenarios on travel demand, and to estimate the impact on land use, road safety and the environment. The model results for the road pricing scenarios are meaningful and show the expected effects. In general the models show that demand shift from motorized private transport to public transport is moderate, but this is because the road pricing charge was compensated for by the reduction in fuel prices for private transport in most scenarios. The research results and model could be useful for testing additional road pricing scenarios for cities or regions and other research projects.

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