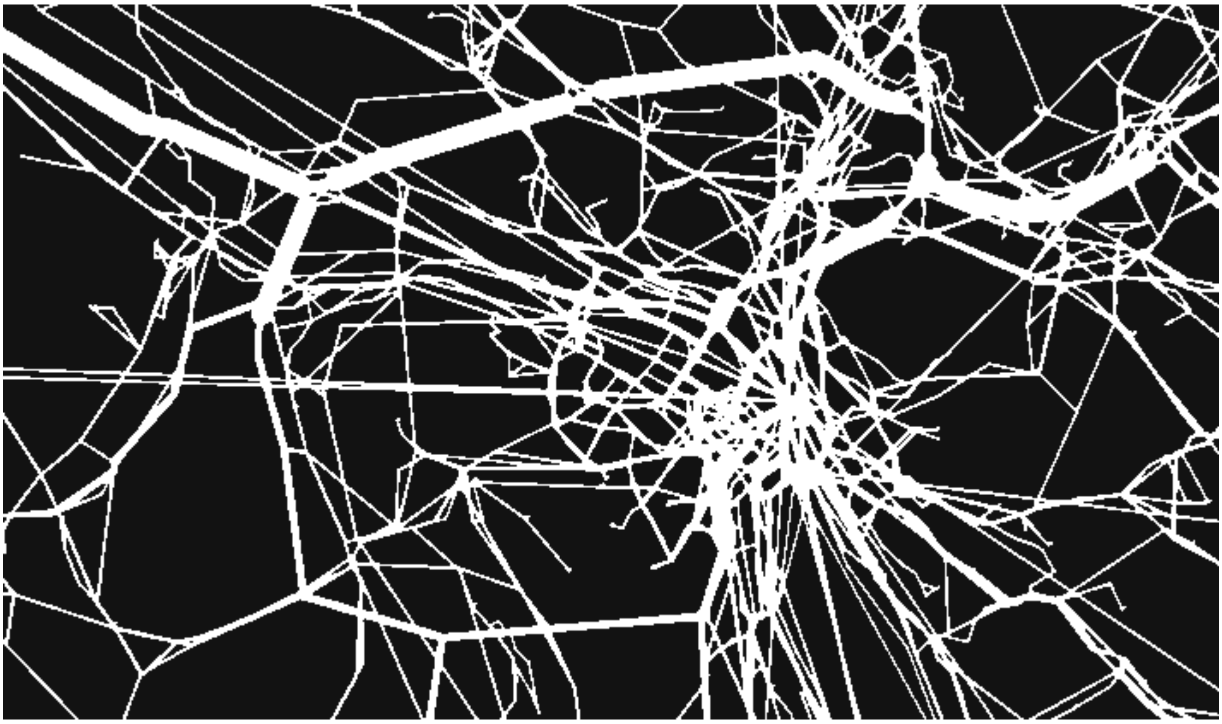

Road pricing: An analysis of equity effects with MATSim

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Abstract

Road pricing as a traffic management strategy is widely accepted to be an effective measure to reduce traffic, yet there are only few large-scale implemented urban pricing schemes. Perceived equity is an important factor among others in order to gain the acceptance needed for a realization of such. This paper investigates the impact of a cordon based pricing scheme for the city of Zurich on different income groups and transport modes, as well as spatial patterns. To do so, a peak-hour toll for entering and leaving the city is being simulated in the agent based simulation tool MATSim. The toll levels during the peak hours are varied until a desired reduction of 20 % of vehicle kilometers traveled within the cordon is achieved. Given this toll level, the impacts on traffic in- and outside of the cordon are analyzed. Further, the generated revenue is compared to the overall change of utility on an aggregated level and behavioral changes on municipal level as well as for individual agents and different user groups are analyzed in order to determine winners and losers of this pricing scheme for Zurich.

Keywords

Road pricing – Cordon pricing – Agent based modelling – Equity effects - Zurich

1. Introduction

Urban tolling schemes have been implemented in several cases around the world as a policy measure to mitigate the negative externalities of car traffic. In Europe, London and Stockholm have proven that when carefully planned and implemented, such measures can lead to an increase in social welfare. Both in London as in Stockholm the congestion reduction targets have been achieved and therefore these measures are mostly supported by the citizens inside of these areas (Eliasson 2014 & Richards, 2006). On the other hand, drivers see their liberties constrained by such measures and tend to oppose these measures. Opponents argue that lower income segments are mostly affected by these changes since the toll is a flat tax, impacting lower income households stronger than higher income households. Eliasson (2006) stated that in the Stockholm case one of the major concerns of the population besides the general aversion to paying for road usage, are equity concerns. Souche et al. (2015) states that cordon pricing can lead to inequalities in terms of accessibility and income distribution and Cools et al. (2011) lists the perceived fairness as one of the most important factors for the public acceptance. Richardson (1974) and Langmyhr (1997) among others show that these issues are not new problems, but exist since the first implementations of road pricing.

The fact that a toll is a flat tax means that lower segments of society pay a larger share of their income when crossing the cordon. This potentially leads to only low income people being forced to change their behavior while leaving high income individuals to enjoy emptier roads without changing their behavior. In modelling terms, we would expect higher income people to have their utility increased by the toll while seeing low income people have their utility decreased. Another criticism is that congestion taxes favor the population living inside of the cordon. Indeed, in the case of Stockholm the congestion decrease outside of the cordon is insignificant and in some cases the charge even led to an increase (Eliasson, 2009).

When simulating the implementation of congestion charging, the main concern is the evaluation of traffic changes. Experts are mostly concerned with the change in traffic dynamics, specially, were traffic will increase and decrease. While such analysis is paramount in the design of such a policy and the basis of determining the necessary operational interventions in the system, not much attention has been given to equity effects. Horni and Axhausen (2014) have worked on the modeling of inequalities with MATSim, and Börjesson et al. (2013) performed equity effects analyses based on value of travel time (VOT) based on a revealed preference logit model in Switzerland. The contribution of this paper consists in an application of MATSim to analyze winners and losers of a congestion pricing scheme for the city of Zurich.

According to Ernst Basler & Partner (2008), current traffic volumes in Zurich do not justify such an extensive measure as road pricing at the moment but predict that the latter could improve the traffic situation in the city of Zurich from the year 2025 on, given the current population and car ownership growth. Even if this is not yet the case, foresightful planning is crucial because of the far-reaching impacts on society.

In this paper, the policy goal of the cordon pricing scheme for Zurich was set to a reduction of vehicle kilometers travelled (VKT) in the inner city by 20%. This arbitrary value was chosen since it is of the same magnitude of traffic reduction in London (Richards, 2006) and Stockholm (Eliasson, 2014). Both cities experienced, respectively, a VKT reduction of 15% and 16%. Börjesson et. al (2014) states that the effects on traffic volume and adaption costs are surprisingly stable with respect to changes in the transportation system and that the transferability of the impacts to other networks is a reasonable assumption. A reduction in vehicle kilometers driven (VKT) is expected to reduce externalities such as air pollution (due to less cars travelling and higher speeds), traffic accidents as well as less maintenance costs on the network due to wear and tear of roads (Richards, 2006).

2. Methodology

The analysis of the effects of a macroscopic traffic management strategy on a microscopic level requires a simulation tool, which allows simulating large models, yet does not aggregate traffic flows and decisions. The state of the art multi-agent simulation software MATSim holds exactly these properties. This activity-based model is designed to simulate an agent's complete day and gives each agent the freedom to change departure time, route, mode as well as location of shopping and leisure activities. While the destination of leisure and shopping activities can be changed, the home and work location of each agent is fixed. In an iterative process, the plans of each agent get modified until the average population score stabilizes. (Horni, Nagel, Axhausen 2016).

The scoring function used in MATSim can be seen in (2). Each agent tries to maximize its own score by changing mode, departure time, route and location of shopping and leisure activities. The first term of the equation represents the utility of performing activities, which the agent tries to maximize, by lengthening its duration. The second term represents the disutility or negative utility of travelling. This disutility is different for different modes and is, of course, also dependent on the time spent travelling, which the agent tries to minimize.

$$S_{plan} = \sum_{q=0}^{N-1} S_{act,q} + \sum_{q=0}^{N-1} S_{trav,mode(q)} \tag{2}$$

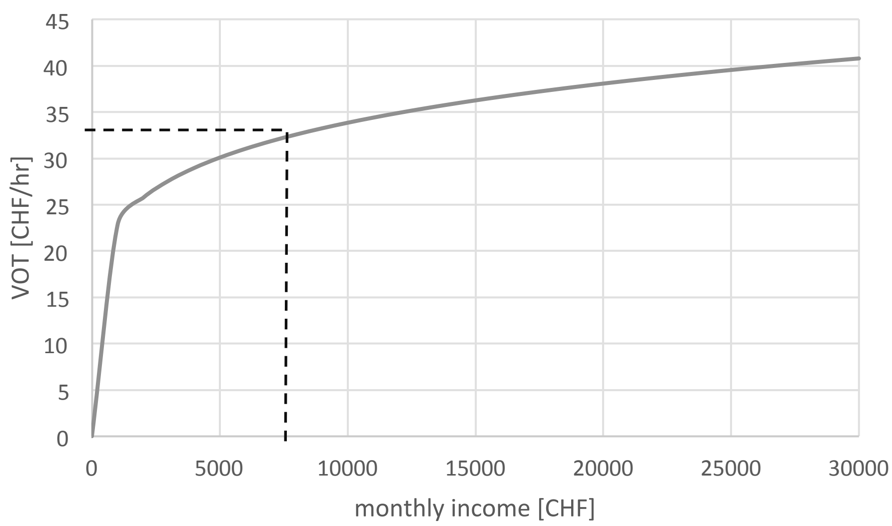
Determining the effects of a financial measure imposed on a whole population regarding equity effects requires more than the present demographic information. It is crucial to include the value of time (VOT) as road pricing intents to provide shorter travel times in exchange for monetary compensation. Depending on many factors such as trip purpose, mode, income and distance it is difficult to determine the VOT of every agent prior to the simulation. With income being the only parameter independent of the simulation it was used as a proxy variable to calculate the VOT. In order to get an income for each agent, income data aggregated on household level from a different microcensus was extracted and matched with the one used in the model, using the home location as a linkage. The household income was divided by the number of agents that are employed and assigned to these agents. Unemployed agents got assigned an income of 2.500 CHF in order to model a certain value of time to avoid decisions being made independently of their financial consequences.

The next step was to convert these income values into a VOT for each agent. Based on existing surveys and models of VOT for Switzerland (Axhausen, König 2006), a simplified conversion (1) was established. Instead of using trip purpose, mode, distance and income, a VOT only for car usage dependent on income was implemented.

$$VOT \left[\frac{CHF}{hr}\right] = (\frac{income}{avg.income})^{0.1697} * 32{,}52 \left[\frac{CHF}{hr}\right] \quad (1)$$

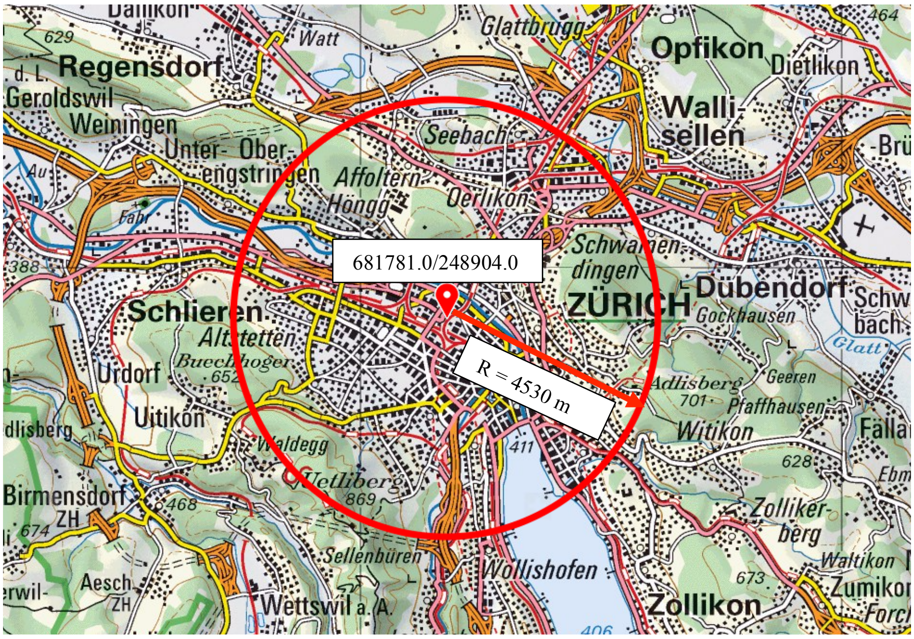
The relationship between monthly income and VOT is shown in Fig. 2.1. One can see that with an average income of the population of approx. 7.950 CHF per month an agent gets the standard value of 32,52 CHF per hour assigned.

Figure 2.1 VOT distribution with respect to income



With these new values of time, the model had to be recalibrated to make sure it represents the current mode share in the observed area. The cordon in this scenario was set to include not only the central business district of Zurich but also the neighborhoods Oerlikon, Affoltern and Altstetten, in order to scale up the benefits, but not crossing the ring road around the city. The toll was implemented into the model by charging every vehicle entering one of the links crossed by the cordon, in both directions. The configuration of the cordon is illustrated in Figure 2.2.

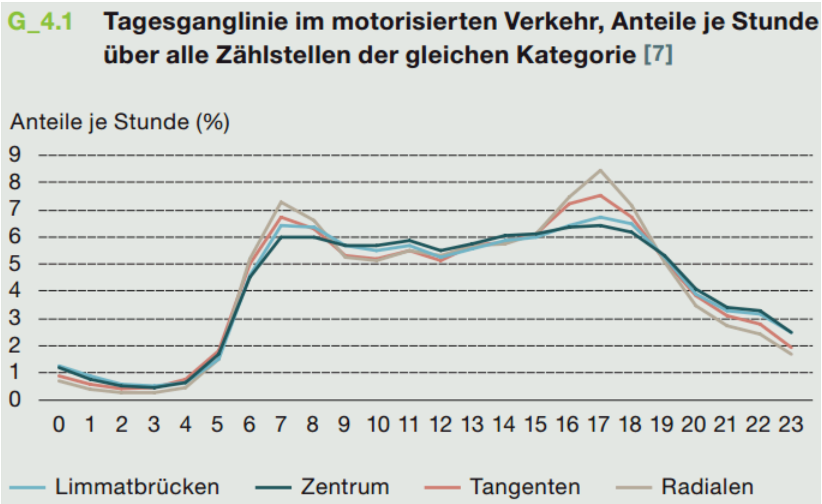
Figure 2.2 Cordon with radius and center location



Source: map.geo.admin.ch

In order to break down the traffic peaks in the morning, the toll is being charged during the morning and evening traffic peak hours in each direction, entering and leaving the city. The times during which the toll is charged are based on the time variation curve of a set of four representative links in Zurich (Figure 2.3) and are set to 5:30 – 9:00 in the morning and 15:30 – 19:00 in the afternoon, while crossing the cordon during other times is free of charge.

Figure 2.3 Daily time variation curve for Zurich



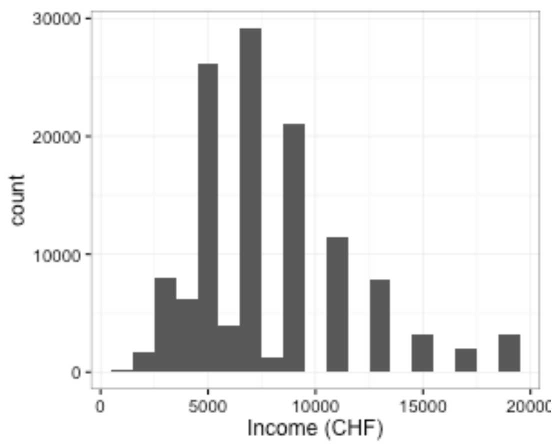
Source: Stadt Zürich (2012)

To define the exact amount that needs to be charged, several runs of the model where performed while increasing the toll by 1,35 CHF each run. The toll value that produced at least a 20% traffic reduction within the peak times inside of the cordon was then selected. This value was 4,07 CHF.

3. Scenario

A scenario in MATSim consists of a synthetic population and location of activities based on microcensus data. The scenario used for the present work encompasses a radius of 30 kilometers from the city center of Zurich (see Figure 4.1) and models the behavior of 162.157 agents, representing a 10% sample of the population in this area. Each agent holds an initial plan as well as demographic information about home and work location, gender, age, employment, driver's license and car availability. The data source is the national census of 2000 and the travel diaries of 2005. The income data is from a 2010 census. A histogram of the income and VOT for the population is shown in Figure 3.1. After the simulation the data was treated to exclude agents younger than 18 years and the few, which had a zero score. The remaining data set, on which the analyses were performed, includes 125.455 agents.

Figure 3.1 VOT and Income Distribution of the agents.



4. Results

This section is divided in two parts. First, general results of the pricing scheme are presented. Second, the analysis of inequality effects is made.

4.1 General Results

The toll value of 4,07 CHF achieved a traffic (VKT) reduction of 23,7% during the morning peak and 24,3% during the evening peak. With the toll, VKT inside the cordon are 776.685km during morning peak and 890.728km during evening peak. At the same time, a general VKT reduction during the whole day of -1,14% was observed for the entire scenario. Any increase in traffic outside of the cordon, therefore does not overshadow the VKT reduction achieved by it. The traffic inside the cordon is shown in Figure 4.1. The amount of vehicles crossing the cordon during peak and off-peak times both before and after the implementation of the toll is displayed in Table 4.1.

Figure 4.1 Traffic volumes inside of the cordon before and after implementing the toll.

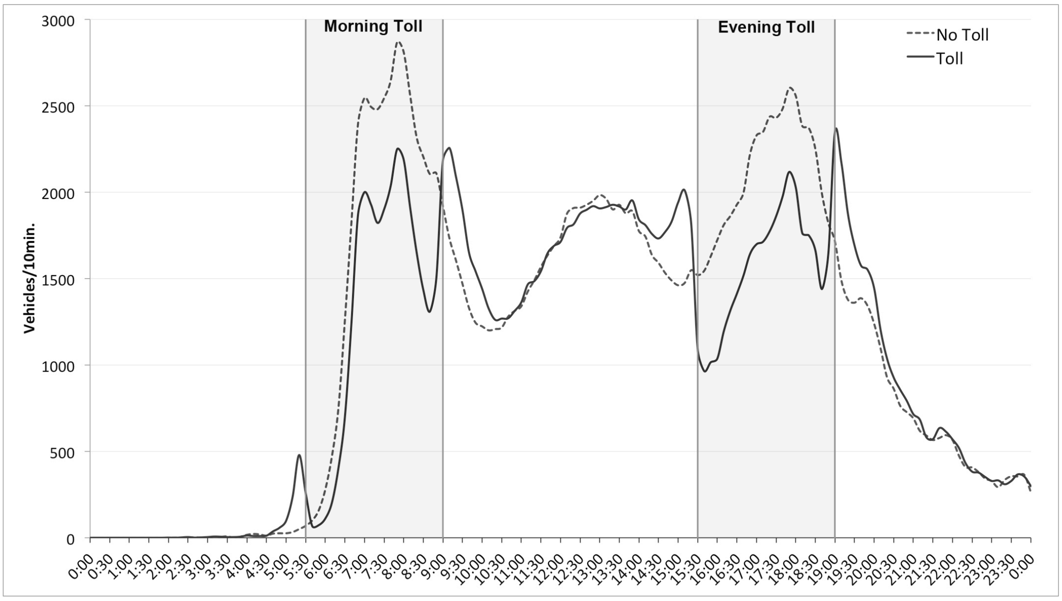


Table 4.1 Vehicles crossing the cordon in both scenarios.

	Without Toll			With Toll		
	Mor. Peak	Eve. peak	Whole day	Mor. Peak	Eve. peak	Whole day
Living inside cordon	516	2.408	4.664	204	1.253	3.896
Living outside cordon	8.789	9.622	16.147	4.787	6.079	14.500
Total	9.305	12.030	20.811	4.991	7.332	18.396

These results prove that the toll achieved its goal of reducing vehicles kilometers travelled in the inner city of Zurich as well as the externalities associated to it. The average score of the agents changed from 183.9765 to 183.5072, a -0,255% difference. 68.062 agents saw their scores decrease while the rest saw an increase in their scores. Another observed change is in mode share, despite being small. The scenario without toll had 20,1% of the agents travelling by public transport, 44% by car and 35,9% by slow modes. After the toll, there was a shift of 1% from car to public transport.

4.2 Inequalities

Now, we turn to analyze who got off better or worse by the toll as well as which agents adapted their behavior the most. Table 4.2 summarizes groups of agents ranked by relative score change. Figure 4.1, shows the relative score change for the smallest administrative units in the scenario.

Table 4.2 Relative score change by income category and home location.

Relative score change (%)	Lives in cordon	Income Category	Mean Income (CHF)	# Agents
-0.2408	No	Medium	8.492,3	50.478
-0.2035	No	Low	4.678,0	37.062
-0.1133	Yes	Medium	8.299,8	12.428
-0.1030	Yes	High	14.934,2	2.863
-0.1024	Yes	Low	4.642,2	9.179
-0.0820	No	High	15.119,5	13.445

Figure 4.1 Percentage average score difference classified by quantiles.

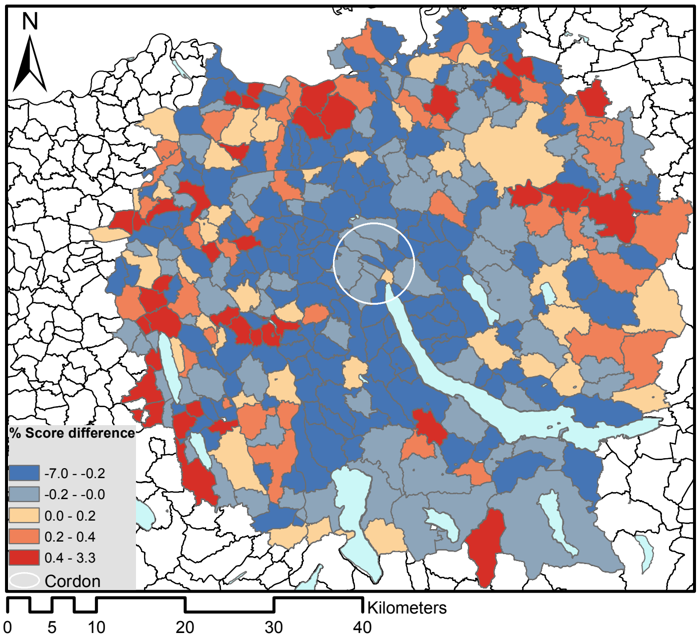


Table 4.2 shows that those with a medium income experience the highest impact of the toll the most. This is in tune with Richard's observations of the effects of the London charge. Medium income citizens were most affected because they could afford driving, but were much more willing to adapt to the charge (changing departure times or switching to transit) than low income people, which already used transit, or high income people, to whom the extra cost of the toll did not play a big role in their decision (Richards, 2006).

Figure 4.1 shows a clear spatial pattern of winners and losers. With only one region inside the cordon experiencing average score increases, the agents located in regions outside, but close to the city, suffer the most from the toll. The ones best off, are the ones further away from the cordon area. This suggests that these agents are inserted into other regional economies, i.e. they do not predominantly work inside of the cordon. As a matter of fact, the 30km radius which defines the scenario also includes important cities in the Swiss national context such as Winterthur to the northeast, Zug in the south and Baden in the West. Agents living far from Zurich and not working there are therefore more likely only to be conducting shopping and leisure trips into the cordon area. Both of the inequalities evidenced above provide an insight into the winners and losers of the tolling scheme.

In order to make an assessment of patterns, the agents were grouped into categories based on primary activity location as well as behavioral patterns. A list of 138 combinations was summarized into groups ranked by relative score change (see Table 4.3).

Table 4.3 Frequencies of occurrences of "TRUE" answers to each variable in the relative score change group.

Relative score change (%)	# Agents	Live inside	Work inside	Car before toll	Car after toll	Cross cordon	Changed dep. time
-13.0 - -1.3	14.555	47,62%	40,48%	100,00%	50,00%	76,19%	54,76%
-1.3 - 0	42.142	58,82%	41,18%	70,59%	54,90%	58,82%	35,29%
0 - 0.3	60.126	70,00%	40,00%	60,00%	50,00%	30,00%	0,00%
0.3 - 4.5	8.773	63,64%	68,18%	27,27%	77,27%	63,64%	0,00%

Fixed activity location do not seem to have a big impact on the relative score change. Those living inside the cordon tend to have a higher score, but differences are small. The difference seems to be even lower for work locations. Behavioral patterns, however, appear to be much more significant. There is a correlation between car usage and score difference. Those who suffered most from the toll, were also those who used car mostly. Besides having to pay the toll, many agents in this group also changed to another mode of transport. Interestingly, for the agents with the highest utility gains, the inverse happened: they switched to the car. These are most probably two agent groups: the ones travelling within the cordon, which make use of more available road space and those crossing the cordon with an income high enough to pay for the toll to gain speed and make use of the higher travel time reliability.

Change in departure times to avoid toll charges is also a behavior related to score reductions. Impressively, none of the agents with increased score, changed their crossing time of the cordon to avoid charges. Since this classification does not distinguish the ones in the "Changed dep. time" group between ones crossing only during peak traffic times and off-peak time, open questions remain about the behavior of these agents. It might show that those which increased their score did not cross the cordon at peak times before the tolling, or didn't cross the cordon at all. It is also possible, albeit unlikely, that they remained crossing at peak times, while utility gains from travel time savings and reliability were higher than the disutility of paying for the toll. Nevertheless adapting to the toll by changing crossing time to avoid it seems to incur a great loss of utility.

Further on, special attention was given to the agents which live inside the cordon, since those are supposed to be the most affected by the scheme. In fact, this proved to be true only for those that also work inside of the cordon area. This group consist of 49,3% of all agents living inside the cordon and experienced an average 0,31% increase in their scores (those working outside experienced an average -0,51% score decrease). 83% of these agents did not change their transport mode. 6.003 agents continued to use car and 3.898 stayed with other modes. The most probable explanation for these increases for agents both living and working in the cordon is a decrease in congestion within peak hours, allowing for faster speeds. Conversely, those which experienced the highest score increase (up to +10% relative score change), were the ones who moved from other modes to car. This high increase is a result of the high valuation of travel times by car in the scoring functions. The population which profited from this was less than 500 agents though and this phenomenon is not very relevant.

When looking at those who live outside the cordon, the average score change was -1,27% for those working inside of the cordon and -0,02% for those not crossing the cordon. The necessity to cross the cordon, established by a work location inside of it is a determinant factor influencing score losses. Our attention will now turn to the agents crossing the cordon in both the simulations with and without the toll (Table 4.4). These are 26.540 agents. 19.856 agents crossing in both scenarios live outside the cordon and out of these 15.391 work inside the cordon. Out of these 26.540, 18.082 agents crossed the cordon by car before and after the toll.

Table 4.4 Behavioral changes for agents crossing the cordon (only groups with >1.000 agents which decreased their score).

Relative score change (%)	# Agents	Income category	Paid toll	Changed dep. time to avoid toll	Car before	Car after
-1,818	1.479	Medium	Yes	No	TRUE	TRUE
-1,764	1.217	Low	Yes	No	TRUE	TRUE
-1,762	3.299	Medium	Yes	Yes	TRUE	TRUE
-1,687	2.044	Medium	No	Yes	TRUE	TRUE
-1,671	2.543	Low	Yes	Yes	TRUE	TRUE
-1,404	1.543	Low	No	Yes	TRUE	TRUE
-0,407	2.438	Medium	No	No	TRUE	TRUE
-0,314	1.786	Low	No	No	TRUE	TRUE
-0,064	1.963	Low	No	No	FALSE	FALSE
-0,038	2.736	Medium	No	No	FALSE	FALSE

Table 4.4 confirms the observation made for Table 4.3, that is, those crossing the toll with car suffer the most when paying the toll at morning or evening peak, or changing their crossing

time at morning or evening peak. Interestingly, most of the agents chose not to change to other modes. Indeed, taking all agents crossing the cordon before and after the toll, only 11,5% changed from car to another mode. This magnitude is in tune with observed values in Stockholm and London, though (Eliasson, 2014 & Richards, 2006). What is also evident by Table 4.4 is the fact that it is mostly middle and low income groups crossing the toll, which are affected by it.

The results analyzed so far have shown that the behavioral patterns expected from a cordon toll in Zurich would have similar effects to the previous experiences in London and Stockholm, with mode or departure time shifts being undertaken by the ones crossing the cordon to try to alleviate for it. Car users crossing the cordon appear to be the main losers from this policy, while winners appear to be agents both living and working inside the cordon area, despite their mode choice. While Table 4.2 showed income levels for the agents, the other tables restrained from doing so, since income levels were relatively stable across relative score change groups. The following section evaluates if income, materialized in the model through value of time, can be an explanatory variable for score differences before and after the toll. No income influence is observed when plotted against relative score change for the entire population. This is expected, since in absolute average the density of income and relative score changes are very concentrated around the median. Therefore the most affected agent groups were analyzed:

Group 1: Those living outside the cordon and commuting to work inside the cordon by car and paying toll. 7.421 agents belong to this group.

Group 2: Those living inside the cordon and commuting to work outside the cordon by car and paying toll. 1.281 agents belong to this group.

Group 3: Those undertaking all their activities inside the cordon. 11.122 agents belong to this group.

In Figures 4.2, 4.3 and 4.4, income is plotted against the referenced score change. The data points were plotted together with a fitted curve and a 95% confidence interval.

Figure 4.2 Group 1, divided into agents who changed departure time to avoid the toll and not.

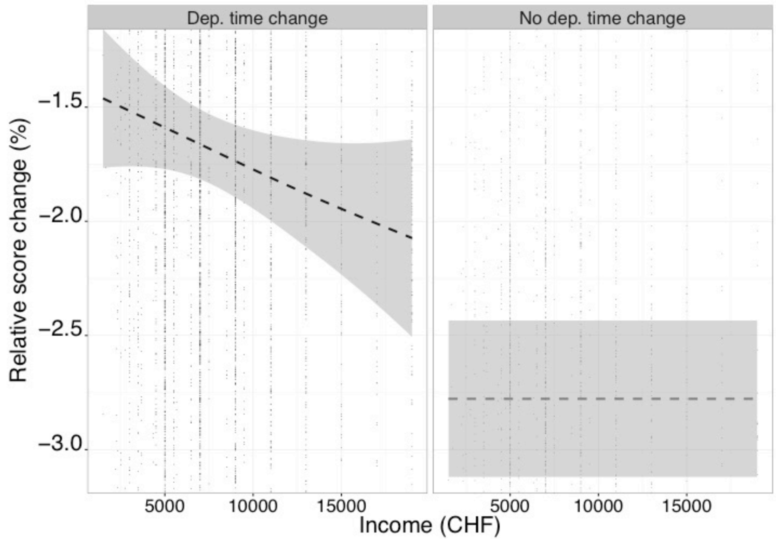


Figure 4.3 Group 2, divided into those who changed crossing time and not.

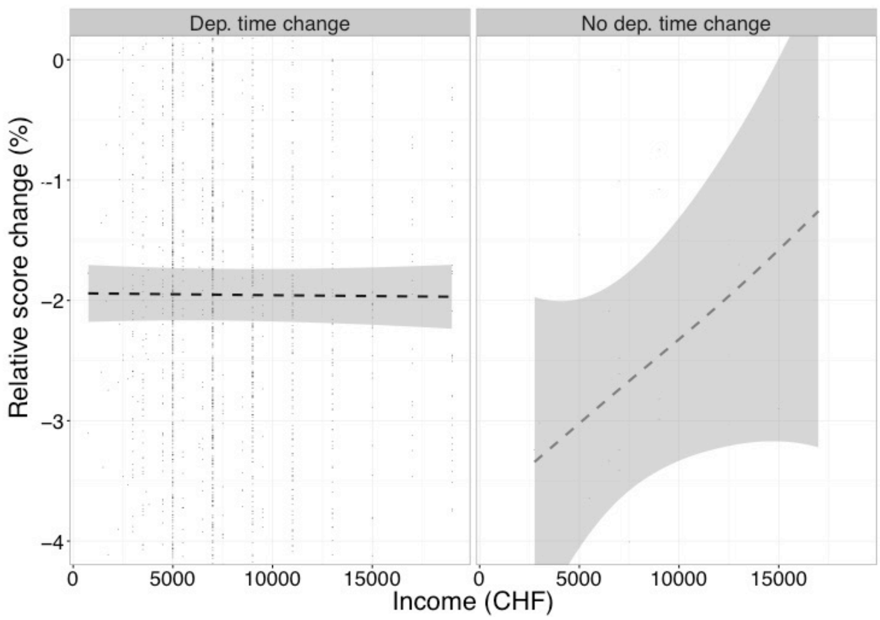
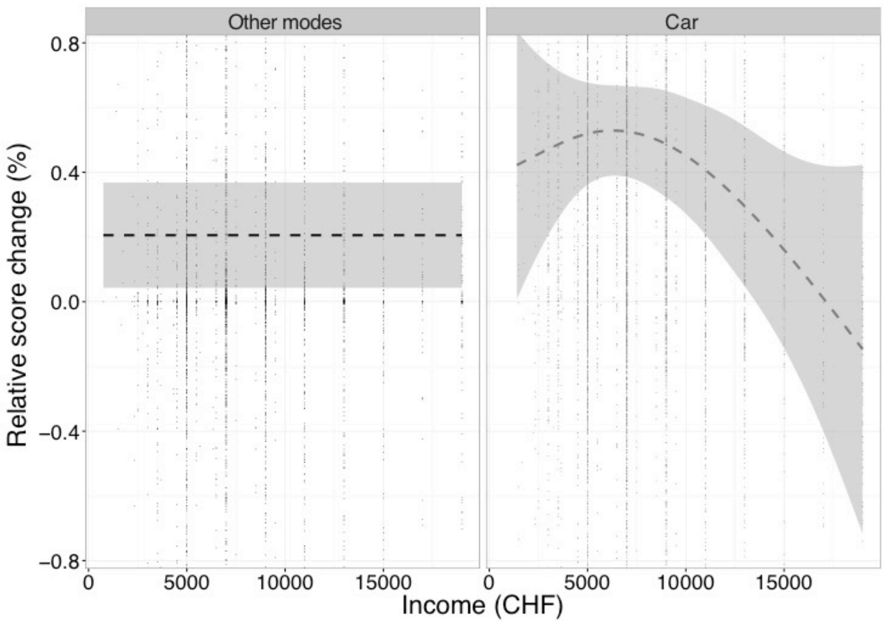


Figure 4.4 Group 3, divided into those who used and did not use the car.



There is a different pattern between groups 1 and 2. For those living inside the cordon, income seems to play no role to their loss in utility. On the other hand, agents from group 1 show an interesting pattern. There appears to exist a negative linear correlation between income and relative score change for agents changing their departure time to avoid the toll. Since all of the trips in the group are done by car, it is understandable that high income individuals, through higher value of time, are also more affected by disutilities incurred by their behavioral change. This seems to be a contradiction to Richard's (2006) conclusion about London's medium income residents being most affect by the toll. There are two different patterns to be observed though. Richard's observations refer to all individuals crossing the cordon by car. In average, medium income agents are indeed mostly affected in the model (Table 4.2). For those commuting into the inner city and avoiding to pay the toll, the higher disutility of high income individuals changing their crossing times is most possibly explained by the higher traffic around the peak times (Figure 4.1). Since these agents have a higher value of time, a higher traffic incurs more time spent travelling, reducing the overall score more significantly for those agents. More analysis needs to be done to evaluate how much the departure times changed and how a traffic increase increased the travel time of agents in this group

The ones with no departure time change in group 1 have a stable relative score decrease across all income categories. This contradicts the expectation that those with lower income would be mostly affected by the toll. On the other hand, it is understandable from a computational point of view. Travelling disutility is only a part of the scoring function, which does not take different values of time for the activities undertaken by agents (which make for the largest part of the score). Therefore when all agents pay the toll, the impact is evened out across income categories.

Group 2 shows a different pattern. The relative score change is more significant for those changing departure time than for group 1. The reason for that might also be correlated to increased travel times, on the other hand the difference between the two groups is not too great. A detailed look into traffic going to and from the inner city would be necessary to acess whether there are higher traffic increases, in relative terms, in one of both directions. Unfortunately, the steep fitted line observed for those that didn't change departure time in group 2 is too little to allow for any further examinations.

For group 3, those living and performing all activities inside the cordon, the left hand graph is plotted only to allow a direct score change comparison to those travelling with car. As there is no income based factor in their scoring function, they will not see their relative score change as a function of income. For those travelling by car though, there is a smaller impact on score changes for those with higher income. This result contradicts expectations. Since those who live and work in the cordon travel mostly at peak times, the traffic reduction inside the cordon at these times should, analogous to what happened to the agents changing departure time in group 1, improve scores of higher income individuals more significantly. In order to conclude the reasons for this pattern, further examination of the influence of other parameters, such as average travel distances for each income category and if in the replanning phases of the iteration, significant changes were made concerning the departure times for these agents.

5. Conclusion

The proposed cordon pricing achieved the desired goal of reducing VKT inside the cordon during peak hours and therefore reducing congestion as well as negative externalities of car traffic. These positive impacts also extended to the entire scenario, moving trips from car to public transport and reducing VKT. In average, there was a decrease in the agents scores. While this reflects a decrease in personal utility, the scoring function does not take into account the economic principle of social cost internalization, which is the aim of road pricing schemes. The score change available from this analysis therefore excludes the possibility of performing a comprehensive cost benefit analysis and with it, a proper evaluation of real implementation measures. At the same time, the availability of scores for individual agents, enables a detailed evaluation of winners and losers of the scheme, a main policy concern, around which much of political debates occurs in the road pricing thematic.

By looking at winners and losers, the proposed scheme for Zurich has similar patterns to those observed in similar schemes, namely London and Stockholm. Agents which are drivers and have their homes or work, respectively inside or outside the cordon are the ones most negatively affected by the toll, which is expected since they are forced to cross the cordon, mostly around peak times. They decrease their score by either having to pay the toll or having to change their plans to avoid it. The further away agents live from the cordon, the less they are affected by it since they have less of a need to commute towards Zurich. Clear winners, on the other side, are residents which live inside the inner city, but do not need to cross the cordon. They enjoy less traffic, increased travel speeds and better reliability on the planned activity times.

An income-based analysis of the reference score changes shows that income only plays a role for agents living outside, working inside the cordon and adapting departure times in order not to pay the toll and those performing their activities inside the cordon. While the fittings have large confidence intervals, they show some understandable correlations. Grouping the income data by classes nevertheless shows that low income and even more significantly medium income agents crossing the toll suffer from it.

The work presented here shows that MATSim is a suitable decision making tool for road pricing schemes when it comes to evaluating the winners and losers of such a policy.

6. Future work

Albeit the results appear consistent with real world observations, a deeper analysis of the results should be undertaken in order to determine other relevant factors behind the score decreases of the agents. While travel times increases and the toll itself, are clear factors, the influence of the toll on activities, such as their duration and arrival delays is important. Another very important factor which has to be analyzed, is the travelled distance, since the negative part of the scoring function is dependent on travel time. An income based value of travel time should also be extended to other modes, in order to increase the degree of representation of the scenario and better simulate real behavior. Regarding the evaluation of the benefits of the toll itself, an interesting research would be to measure not only personal benefit, but also the social benefit from such a policy such as travel time savings and accessibility measures.

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