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Equity Effects of Congestion Charges

An Exploratory Analysis with MATSim

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This paper shows an application of the multiagent, activity-based transport simulation MATSim to evaluate equity effects of a congestion charging scheme. A cordon pricing scheme was set up for a scenario of the city of Zurich, Switzerland, to conduct such an analysis. Equity is one of the most important barriers toward the implementation of a congestion charging system. After the challenges posed by equity evaluations are examined, it is shown that agent-based simulations with heterogeneous values of time allow for an increased level of detail in such evaluations. Such detail is achieved through a high level of disaggregation and with a 24-h simulation period. An important difference from traditional large-scale models is the low degree of correlation between travel time savings and welfare change. While traditional equity analysis is based on travel time savings, MATSim shows that choice dimensions not included in traditional models, such as departure time changes, can also play an important role in equity effects. The analysis of the results in light of evidence from the literature shows that agent-based models are a promising tool to conduct more complete equity evaluations not only of congestion charges but also of transport policies in general.

Urban congestion is the most important externality in urban transportation systems, and there is an almost unanimous agreement in society that this issue should be tackled (*1*). It has been difficult to implement effective, demand-oriented policies addressing this matter. Indeed, one effective strategy to mitigate congestion is road pricing (*2*). Singapore was the first country to implement it in the 1970s, but it is still regarded by citizens and politicians in many countries as an unconventional approach and thus faces strong resistance in society. This resistance is largely based on equity issues (*3*). The fear of double taxation, mobility limitations, and unfairness imposes a barrier toward the acceptability of congestion charging schemes (*4*). When the idea is brought up, those commuting by car toward tolled areas, typically feel they would be unfairly treated, while those living inside charging cordons would enjoy cleaner air, safer roads, and less congestion, all of which translate into an improved quality of life.

Hence it is not surprising that in a referendum on congestion charges held in 2006 in Stockholm County, Sweden, all of the residents of municipalities outside the tolling area voted against its implementation, while in the city of Stockholm supporters of the toll achieved a narrow majority with 53% of the votes (*5*). Past referendums in Gothenburg, Sweden; Manchester, England; and Edinburgh, Scotland, have rejected the implementation of congestion charging schemes, symbolizing public repudiation of such schemes. Attempts to implement such policies in the United States have also failed because of political objections, such as in New York and Seattle, Washington (*3*). Ungemah states that to proactively address these worries it is necessary for policy makers to address equity issues early in the process, increasing the transparency of the project and avoiding putting project proponents in a defensive position (*6*). Schade and Schlag state that the benefits of the charge and strategies to compensate for possible losses should be clarified to the public, with the goal of engaging stakeholders in a constructive dialogue with planners and politicians (*4*).

Predicting the distribution of these benefits and losses among individuals thus becomes an imperative to allow for a more rigorous examination of inequality issues and to proactively engage stakeholders in solutions to mitigate them. The acceptability of a congestion charging policy can be increased by making it clear to the public that although losses will indeed be incurred by the population in the short term, the revenue can be redistributed in such a way as to compensate for those losses and even exceed them in the long term. To effectively do so, a combination of qualitative and quantitative equity evaluations is needed (*7*). In this paper, a quantitative evaluation method is proposed; this method is based on the approach described by Bills et al. (*7*). The tool used for this purpose is the agent-based model MATSim. Agent-based models are particularly suited for such an analysis because they are based on disaggregated sociodemographic data and therefore allow for an in-depth analysis of gains and losses incurred for each individual. It is hoped that the combination of quantitative predictions and data visualization methods can shift the debate of an often contentious topic from a belief and perception-based one, toward a more pragmatic and result-oriented one.

This paper is organized as follows. The equity effects of road pricing schemes are discussed next, followed by an explanation of the approach to the challenges in modeling these effects. A case study in the city of Zurich, Switzerland, is then introduced, and results of the study are presented. Concluding remarks end the paper.

EQUITY CONCERNS IN CONGESTION PRICING

Equity, in a social justice context, can be defined as "the distribution of costs and benefits among members of society" (*8*). This definition is based on Rawls's theory of justice (*9*). Economists translate Rawls's social justice theory into two equity dimensions to analyze

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equity effects of policies. The first dimension, vertical equity, refers to Rawls's first principle, the difference principle, and analyzes how different groups fare in relation to one another. The second dimension, horizontal equity, refers to the principle of equal opportunities and analyzes how users from the same groups fare in relation to one another (*10*). When evaluating the equity effects of transport policies, the paper is referring to a concept of equity, which is based on Rawls's social justice theory. As transport planners, the authors are particularly interested in how vertically and horizontally distinctive social groups fare in regard to one another so that winners and losers of a policy can be spotted. On theoretical grounds this might sound straightforward, but assessing the equity effects of a transport policy or projects is not an easy task.

EQUITY ANALYSIS IN CONGESTION PRICING

In the United States (*11*) and in Europe (*12*) equity issues are often not part of the evaluation of transport policies or projects and are therefore not addressed in the planning process. In a way, transport projects and many policies are inherently unequal since they are usually confined to a geographic area. If a Rawlsian social justice distributive approach were strictly followed, projects that have the highest marginal gains for those most impaired should be prioritized. Changing the order of cause and effect, one can argue that the identification of groups of individuals most negatively affected by a policy can allow for compensatory measures targeting them. Different approaches have been proposed to evaluate the equity effects of transport policies.

Economic welfare evaluation is the most common approach. In its simplest form, it measures only welfare gains or losses owing to toll payments. More comprehensive measurements also take into account redistributions of trips (e.g., departure time changes resulting from the toll) and travel time changes. A complete welfare analysis, nevertheless, should also evaluate how the redistribution of toll revenues affects different groups. Studies by de Palma and Lindsey (*13*), Eliasson and Mattsson (*14*), Franklin (*15*), and Santos and Rojey (*16*) show that depending on how the revenues are redistributed, congestion taxes can be either regressive or progressive. The conclusion drawn by these authors is that when the redistribution of revenues is ignored, a congestion charge will always reduce social welfare across all groups, although in different proportions. The prediction of equity effects without accounting for revenue redistribution, the so-called first order equity effect, is useful in proposing redistribution strategies and to therefore achieve equitable second order effects, that is, after redistribution is accounted for.

A different approach to perform equity evaluations is based on accessibility measures. Because of the higher complexity of accessibility evaluations in transport models, studies with this approach are less common than welfare-based ones. Accessibility studies seek to answer the question of whether some groups will suffer from worse access conditions than others and to what extent that factor poses a hindrance to their mobility (*8*). The problem with this approach is that accessibility measures are less straightforward than welfare-based measures. While the latter may be based on the traditional cost–benefit method, accessibility studies can use a wide range of measurements and tools. As Litman remarks, the problem arises from different ways of defining what accessibility equity for groups or individuals means, which in turn leads to different definitions and units of measurement (*17*).

MODELING EQUITY EFFECTS WITH AGENT-BASED MODELS

Most of the existing studies analyzing equity effects of congestion pricing schemes make use of traditional large-scale models based on the four-step process. Logit models do indeed provide the possibility for evaluating consumer surplus changes (*18*). That is the case for studies conducted by Eliasson and Mattsson (*14*), Santos and Rojey (*16*), and Di Ciommo and Lucas (*19*). Franklin shows a method based on nonparametric equations to compare outcomes across groups (*20*). Franklin (*15*) and Currie and Delbosc (*21*) propose a method based on structural equation modeling. These models show similar results, namely, a small decrease in welfare across all groups of road users and a larger effect on high-income users. However, these models have some notable disadvantages. The first limitation is that they require a certain level of aggregation of travelers before simulations are conducted, thus, ignoring effects that emerge from the large amount of interaction between agents. The second limitation is that welfare equity analysis with four-step models allows for welfare to be based only on the disutility of traveling, that is, on changes in travel times owing to changes in destination, mode, and route choices at an aggregate level. These models ignore other choice variables such as the relocation of activities in the trip chain (since they are based on static origin–destination matrices) and departure times. Both limitations pose a high degree of abstraction and, as such, a limitation on the modeling of adaption strategies of travelers when faced with a congestion charging scheme.

A possible way to overcome these limitations is to use agent-based simulations. They are part of a class of models that is encountering increasing popularity in transportation research. Of the several key features of this approach [for a general discussion see, for example, Macal and North (*22*)], some are particularly relevant in the context of the discussion above and can indeed address the mentioned limitations by representing (*a*) travelers (agents) on the individual level with personal attributes that are consistently maintained over all of the simulation and (*b*) goal-oriented agents that can autonomously modify their behavior according to utility functions, which can include elements beyond travel disutility and can even be individualized. Based on such considerations, an existing agent-based transport simulation was used in this study. Details on this modeling tool are provided below.

TOOL: MATSim

MATSim is an open source, activity-based, multiagent simulator of travel demand and supply implemented in Java, codeveloped at ETH Zürich and TU-Berlin (*23*). It is modular and designed to handle large-scale scenarios (*24*). In MATSim, each agent has a daily activity chain (a plan). In an iterative process, on the basis of a coevolutionary algorithm, each agent tries to maximize its daily plan's score by changing routes, modes, end times, and locations of leisure and shopping activities (location of work activities and the home location are fixed). These variables represent the search space of the coevolutionary algorithm and make up the agents' choice dimensions. The coevolutionary algorithm is conducted during the replanning module. Replanning is performed after each iteration. In this module, a share of all agents is allowed to conduct the replanning and search for a new plan according to predefined evolution strategies. Those agents that are not chosen for replanning select one

plan from their memory based on a logit model, in which a plan with a higher score has a larger probability of being chosen and therefore executed. Iterations are performed until an equilibrium state is reached. In practical terms, that state is reached when the average scores (or utility) of the agent's conducted plans stay (approximately) constant from one iteration to the next. The evolution of scores for an individual agent depends on its interaction with other agents in the simulated area. This iteration between agents is performed in the MobSim (mobility simulator) module, which is a queue-based traffic simulator in which agents compete for space–time slots in the transport infrastructure (*23*). After each iteration, a scoring function (Equation 1) is used to calculate the score of the executed plan for the agent. This score can be interpreted in its econometric meaning as in classic random utility theory (*25*). MATSim is thus a coevolutionary utility maximization model, in opposition to sequential, rule-based models (*23*). The mechanism of the model thus makes the achievement of a high level of granularity possible, which improves the level of detail of the analysis of the equity effects of transport policy (*24*). In addition, it means that MATSim also takes into account cross correlations between different socioeconomic variables, such as age, gender, income, and car ownership, which is impossible with classic large-scale models. The aggregation of results into groups and categories is conducted only after the simulation. Simulation outputs contain detailed information on scores as well as the executed plan of each agent, thus enabling agent-by-agent comparisons between a scenario with and one without a congestion charge (*24*). Since these models are usually based on census data, they reflect the socioeconomic and demographic diversity of a population and its behavior more faithfully.

$$S_{\text{plan}} = \sum_{i=1}^{n} \left(S_{\text{activity},i} + S_{\text{travel},i} \right) \tag{1}$$

where

n = number of activities,
$S_{\text{activity},i}$ = score of performing ith activity, and
$S_{\text{travel},i}$ = score of trip performed to reach ith activity.

A detailed description of the terms in Equation 1 is available in Axhausen et al. (*23,* p. 29). The fact that the equation links individuals' activities and travel patterns leads to a better representation of travel conditions on activities and travel choices. MATSim is therefore better suited for evaluating pricing scenarios, especially time-dependent ones as in the case of congestion charging schemes, since the simulation time frame encompasses an entire day (*26*). A simulation with such a high level of detail, combined with well-documented performance metrics (scores) for each agent, allows planners to easily assess benefits or disadvantages resulting from changes in the transport system for individual agents. Differences in scores can point to potential winners and losers from the scheme. The available socioeconomic data of these individuals then allows planners to group agents according to different categories. The availability of activity locations also allows planners to combine numerical data with raster data and therefore conduct a geographic equity analysis. MATSim thus allows for a thorough horizontal (based on geographic inequities of similar groups) as well as vertical (based on inequities between different socioeconomic groups and individuals) equity analysis of a congestion charging scheme.

ZURICH CASE STUDY

In this work, a first order equity analysis was conducted for a congestion charging scheme in Zurich. Zurich was chosen as there is an already calibrated and extensively used MATSim model for this city as well as the necessary socioeconomic data depth for conducting the required analysis. The calibration of the scenario was done by adjusting scoring function parameters to fit the output of the simulation to empirical data in regard to modal split and distance distributions, whereas traffic count data were used for validation (*23,* p. 375). The model (called a "scenario" in MATSim) contains agents living within a 30-km radius around the center of Zurich. The scenario's population consists of 162,179 agents (10% of the real population living in this area). To have realistic traffic flows in the scenario, the capacities of the road network (here a navigation network was used) were also scaled down to 10%. The cordon was designed as a circle with a radius of 4,530 m around the center of Zurich. Every agent crossing this cordon by car has to pay the toll. Other possible modes are transit and human powered modes (biking and walking).

The value for the toll was set to achieve a reduction in vehicle kilometers traveled (VKT) by at least 20% during peak times inside the cordon. Therefore, several preliminary simulation runs were performed to test different toll levels with the goal of achieving the desired level of reduction. The value of the toll that provided the set goal was 4.07 Swiss francs ($4.14, July 2016).

A 20% VKT reduction was the aim because it is in the same order of magnitude as reductions observed in Stockholm (*27*) and in London (*28*). Stockholm, similar to Zurich, also has a high car-ownership rate as well as good quality transit infrastructure. Moreover, both Zurich and Stockholm have a relatively high concentration of jobs and shopping activities in their central areas. While each city has its own unique characteristics, it is a reasonable assumption that traffic reduction effects stemming from congestion charging are transferable (*29*).

Modeling of Inequalities

As a default, MATSim considers only a small set of an agent's attributes. Parameters of the scoring function are set to the same level for all agents. As the interest is in equity effects, it is important to include income-based values of time, so that income inequalities are accounted for in the scoring function and therefore influence the agent's choices. Income inequalities are incorporated into the model through values of travel time by car. An exponential function explaining the income value of the travel–time relationship was used; it was based on empirical studies of the value of travel times in Switzerland (*30*). This approach constitutes a simplification as values of travel time do not depend only on income but also on destination, travel mode, travel distance, time of day, and travel purpose (*31*).

Method

The analysis conducted here follows the method proposed by Bills et al. for quantitative equity analysis with activity-based models (*7*). This analysis consists of the following steps:

1. Divide the population into groups,
2. Calculate equity indicators, and
3. Calculate percentage changes in the measured values between the baseline scenario and the scenario with the implemented policy.

A first division into groups was made according to geographic- and income-based categories. To understand the reasons for the changes, further groupings of the population based on changes in behavior (e.g., changed departure time or not) were made. The main indicator for winners and losers of the policy is the percentage score difference for each agent between the scenario before and after the implementation of the toll (Equation 2). The difference is affected most by changes in the traveling part of the scoring function, but since the traveling part of the scoring function has a smaller weight than the activity part, the absolute change in score is rather low.

$$\text{score difference} = \frac{S_{\text{plan, toll}} - S_{\text{plan, no toll}}}{S_{\text{plan}}} \tag{2}$$

The application of this method allows one to evaluate first order equity effects of the congestion pricing scheme. Such an analysis does not provide a complete forecast of equity effects, but can play a decisive role for determining second order effects since it allows policy makers and designers of the system to estimate potential winners and losers in early project phases. Equity concerns can therefore be addressed, and mitigation strategies for the most disadvantaged groups can be proposed.

RESULTS

The toll value of 4.07 Swiss francs achieved a traffic (VKT) reduction of 23.7% during the morning peak and 24.3% during the evening peak. At the same time, an overall VKT reduction of −1.14% was achieved during the entire day for the scenario. The number of cars crossing the cordon during peak times was reduced by 45% (value averaged across both peaks). Mode shares were 20.1% for transit, 44% for car, and 35.9% for human powered modes in the entire scenario. After the toll implementation, there was a mode shift of 1% from car to transit. The average score change of the agents was −0.186% (SD = 6.204%) and average global travel times were reduced by 1.697% (SD = 22.678%).

While appearing to be controversial, the average decrease in score, despite an average decrease in travel time, results from the fact that the scoring function is much more sensitive to changes in activity duration and schedule delay than to travel times. An average decrease in overall welfare is also found by Eliasson and Mattsson (*14*), Santos and Rojey (*16*), Di Ciommo and Lucas (*19*), Franklin (*15, 20*), Currie and Delbosc (*21*), and Franklin et al. (*32*), therefore indicating that at a general level, the negative effect of the congestion charge is being captured by MATSim. The first best theory also foresees such negative effects (*31*). Welfare in this context represents an individual score and is not related to social welfare.

The hypothesis of the toll being regressive or progressive had to be refuted at a significance level of 95%. Although the regressivity of tolls before any redistribution of revenues is found in studies conducted with traditional large-scale models, no clear income-dependent trend is observed here (*14, 15*). Studies on welfare effects of the congestion charging schemes in London (*28*) and Stockholm (*32*) are also unclear in regard to the regressivity of the toll.

The most negatively affected municipalities are located right outside the cordon (Figure 1). The determining factor for these negative scores is a high level of car commuters toward the cordon

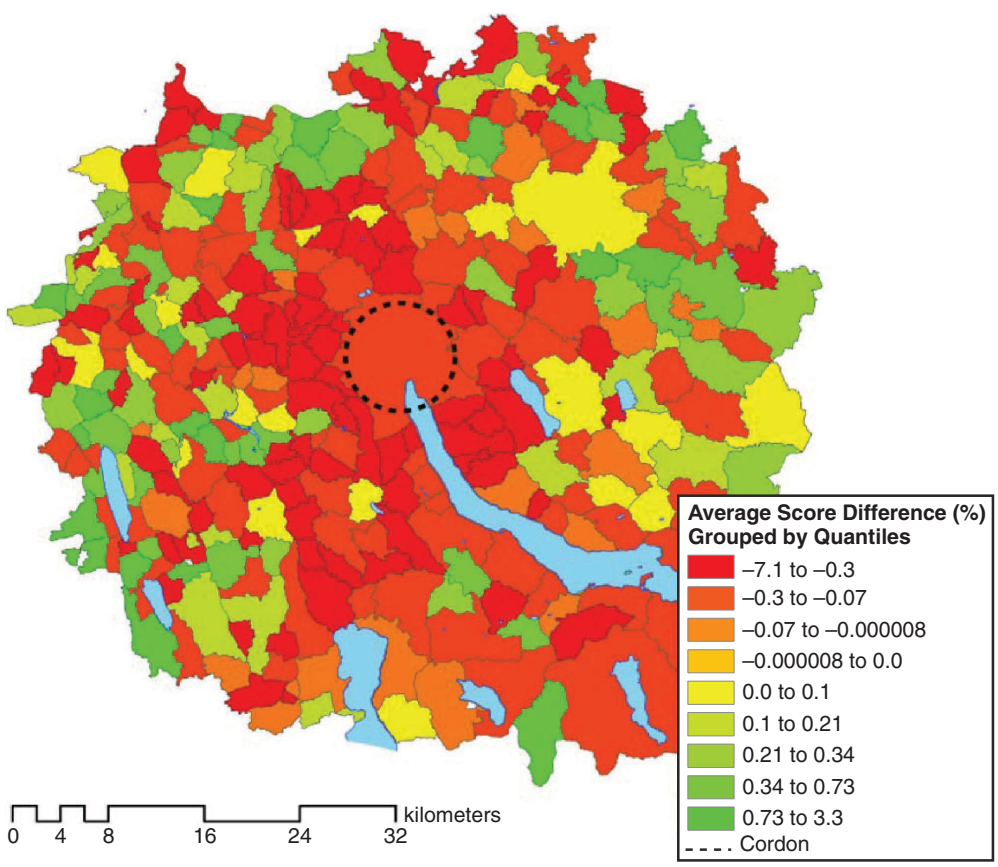

FIGURE 1 Average score difference for each municipality in scenario.

area. Municipalities with average positive score changes are located farther away from it. These positive scores are determined by two factors. First, an extremely low percentage (8.4%) of these agents have to commute toward the cordon area. Second, these agents increase the share of car trips by 0.7%. There appears to be an intricate spatial relationship between winners and losers in those areas. Agents living in neighboring municipalities with higher commuting rates to the cordon area free road space by changing travel mode or departure times. Agents not commuting toward the cordon but to areas close to it, therefore, benefit from more road space by traveling faster by car to their workplaces. Red areas in Figure 1 are characterized by a higher percentage of agents commuting toward the tolled area (42.5%) and a decrease of 4.4% in the share of trips with cars. While 45.0% of agents commuting toward the cordon made use of the car before the toll, the percentage decreased to 35.7% after its implementation.

The pattern observed in Figure 1 is a proof of the effectiveness of the toll since it is precisely the automobile oriented mobility status quo it is designed to change and at the same time an indicator of the groups that will most fiercely oppose the toll. When the spatial pattern of winners and losers is evaluated, it thus becomes evident that municipalities with a high share of commuters to the city fare substantially worse than those with very low shares of commuters to those areas. Unsurprisingly, suburban male car commuters are the people that are most likely to oppose congestion charging measures (*33*). The behavioral change of this group has a rebound effect on some agents outside the cordon, who are increasing their scores. These usually do not commute by car to the cordon area, and if they commute by car to other areas than the cordon, they profit from more road space since many commuters to the city shift from car to other modes.

Table 1 shows the vertical equity effects (by comparing rows) and horizontal equity effects (by comparing columns) and provides a deeper insight into the winners and losers of the toll implementation. Patterns of vertical inequalities become evident only when comparisons are made between gender and car-ownership status. Income does not appear to be a significant variable for explaining score changes. For all income groups, car owners fare worse than transit users. Higher income transit users fare better when they commute to the city. This result is not expected because a lower level of service owing to a higher ridership in the transit system toward the inner city is expected after the introduction of the toll. The higher utility of higher income transit users reflects a limitation of the model used for this study, which did not take into account measures such as, for example, crowding.

The influence of gender on score differences is not as evident as car ownership, but it is present. By comparing car-owning males and females, it is clear that men are more affected, whether it be positively or negatively. Eliasson and Mattsson (*14*), Franklin (*15*), and Richards (*28*) also find that men experience higher effects from the tolls. The reason for this is simple: men have higher car ownership and usage rates. Gender is therefore a proxy for a more significant explanatory variable for vertical inequity: car ownership. The lower score differences of women and transit users are echoed by

TABLE 1 Average Score Differences by Group

	Lives Outside Cordon (%)			Lives Inside Cordon (%)			
Trait	Works Outside	Works Inside	Total	Works Outside	Works Inside	Total	Grand Total (%)
High income	0.03	−1.18	−0.16	−0.54	0.13	−0.20	−0.17
No car available	0.04	0.19	0.06	−0.45	0.19	−0.16	−0.01
Female	−0.04	0.12	−0.02	−0.02	0.18	0.06	0.00
Male	0.21	0.28	0.22	−1.42	0.21	−0.57	−0.02
Car available	0.02	−1.35	−0.20	−0.58	0.10	−0.22	−0.20
Female	0.04	−1.05	−0.11	−0.18	0.05	−0.06	−0.10
Male	0.00	−1.58	−0.28	−0.97	0.15	−0.35	−0.29
Medium-high income	−0.07	−1.22	−0.25	−0.69	0.41	−0.16	−0.24
No car available	0.17	0.28	0.18	−0.17	0.16	−0.04	0.12
Female	0.23	0.36	0.24	−0.31	0.10	−0.16	0.12
Male	0.04	0.15	0.06	0.17	0.22	0.19	0.10
Car available	−0.12	−1.42	−0.33	−0.95	0.49	−0.21	−0.31
Female	−0.04	−1.19	−0.19	−0.56	0.66	0.05	−0.16
Male	−0.20	−1.58	−0.45	−1.33	0.34	−0.44	−0.45
Medium-low income	0.00	−1.38	−0.20	−0.41	0.36	−0.03	−0.17
No car available	−0.09	−0.42	−0.13	0.01	0.15	0.07	−0.07
Female	−0.04	−0.42	−0.08	0.07	0.28	0.15	−0.01
Male	−0.21	−0.43	−0.24	−0.14	−0.03	−0.09	−0.19
Car available	0.02	−1.51	−0.22	−0.62	0.43	−0.07	−0.19
Female	0.00	−1.23	−0.16	−0.35	0.51	0.08	−0.12
Male	0.05	−1.70	−0.27	−0.89	0.36	−0.20	−0.26
Low income	−0.03	−1.26	−0.21	−0.51	0.32	−0.10	−0.19
No car available	−0.01	−0.38	−0.06	0.01	0.39	0.16	0.02
Female	0.05	−0.52	−0.01	−0.05	0.39	0.10	0.02
Male	−0.14	−0.17	−0.14	0.15	0.40	0.27	0.00
Car available	−0.03	−1.40	−0.24	−0.78	0.30	−0.21	−0.24
Female	−0.03	−1.22	−0.19	−0.23	0.30	0.03	−0.15
Male	−0.03	−1.53	−0.30	−1.30	0.30	−0.41	−0.32
Grand total	−0.01	−1.27	−0.20	−0.52	0.31	−0.11	−0.19

higher support of congestion tolling schemes stemming from these groups (*34*). Horizontal inequalities, on the other hand, account for higher score contrasts.

The commuting patterns appear to be a determinant factor for score changes, as observed in other studies (*14, 16, 35*). Table 1 also shows patterns that are not accounted for in Figure 1, most important, the positive welfare effect experienced by those living and working inside the cordon. Those commuting toward the inner city, however, are the ones most negatively affected by the toll. This finding has two main reasons: car ownership as well as car use is higher outside the cordon area. High car ownership is a behavioral factor, which also has its roots in the dispersed urban structure of suburban municipalities.

These areas are dominated by sprawled low-rise settlements and are not as well connected to the fast mass transit systems, therefore increasing the utility of using a car to commute to work. The model therefore confirms the most evident equity effect of congestion charges: the winners are those living and conducting their activities inside the cordon and the losers are those living outside it and commuting toward it by car.

Table 2 confirms the correlation between higher car ownership rates and score losses. Besides higher car ownership rates, worse-off agents also show substantial behavior differences from those faring better. Commuters who used to cross the cordon at peak times, many of whom adapt to the toll by changing their departure times or changing modes, are the most affected agents. Those that do not reduce their score by adapting are penalized by having to pay the toll. The change in behavior imposed by the toll on car drivers is thus an important factor. By changing departure time to avoid the toll, agents are incurring the danger of higher traffic volumes right before and right after the tolling windows, increasing their travel time and schedule delay. Those paying the toll enjoy shorter travel times as well as a reduction in schedule delay, but also have to bear the financial burden of paying for those advantages.

Table 2 also shows that besides car ownership, the negative scores are the result of increased travel times, change of mode, and departure times. Substantial departure time changes were also observed in London and Stockholm after toll implementation (*14, 15, 28*). Longer travel times, however, are partly explained by higher levels of traffic right before and after tolling windows, both within and just outside the cordon and partly through longer travel times with transit than with car. A time dimension in the simulation and the evolution of traffic states throughout the day provides a larger set of choice possibilities and adaptation strategies for the agents. The simulation of a time dimension, which plays a substantial role in behavioral adaptation of travelers to real-world congestion charges, is possible only with agent- or activity-based models, but not with the classic four-step model. This shortcoming of the four-step model led planners to underestimate behavioral adaptation of travelers in regard to departure times in Stockholm (*27*). While VKT inside the cordon was reduced during tolling periods in the simulation, it increased by up to 200% during the half hour right before and right after the toll. The increased traffic toward or outward from the cordon area during these short periods is a reason for increased travel times and therefore score losses of agents changing their departure times to avoid the toll.

Plan changes during the course of a daily simulation period, as well as land use and commute patterns, show that equity analysis of congestion charges and transport policies in general have to allow for a higher degree of complexity than an analysis based on mere travel time savings of different groups. Figure 2 shows that in average terms, there is indeed a decrease in score associated with an increase in travel times, but it is not substantial. In the area of the graph where most of the data points are located, there even appears to exist an increase in scores with increasing travel times. The density plots of each variable show how travel time changes are highly concentrated around the vertical axis. Indeed, the r-squared value of .0104 for the fitting curve is extremely low. The apparent counterintuitive relationship between travel time and score changes around the center of the graph as well as the lack of a significant fit between both variables shows that travel time alone cannot be seen as an explanatory variable for score changes. The combination of all decision dimensions of each individual agent results in a heterogeneous spatiotemporal behavior, making it difficult to draw deterministic conclusions with regard to the causes of score changes at an aggregate level. However, since the weighting of activity durations and even schedule delay is much higher than for traveling (up to 10 times depending on mode), further research will also focus on those aspects.

CONCLUSION

The equity effects analysis presented in this paper shows that score variations in MATSim do not stem exclusively from travel time savings and that no obvious correlation can be observed between score changes and income. Rather than based on continuous variables, score changes seem to be correlated mostly to car usage and com-

TABLE 2 Behavioral Changes of Agents Crossing the Cordon Before Toll Implementation

Behavioral Aspect	>3%	1.5% to 3%	0% to 1.5%	−1.5% to 0%	−3% to −1.5%	<–3%	Average
Crossed cordon with car	70.2%	68.9%	64.3%	80.1%	91.2%	86.4%	78.1%
Agents that crossed during peak times before toll	30.8%	32.0%	29.2%	48.6%	68.1%	55.5%	46.5%
Agents changing departure time	19.0%	19.8%	17.9%	25.7%	41.0%	40.0%	27.5%
Difference of car travel time as share of total travel time	0.9%	0.1%	–3.3%	–10.0%	–16.6%	–14.9%	–9.0%
Average of car trips as share of total trips	–1.4%	–4.0%	–8.1%	–14.9%	–16.0%	–9.7%	–10.6%
Average travel time change	4.9%	2.1%	5.7%	15.3%	30.0%	38.6%	17.1%
Agents paying evening toll	23.4%	17.7%	14.5%	26.5%	32.6%	23.8%	24.0%
Agents paying morning toll	21.7%	24.9%	18.1%	29.5%	39.1%	22.1%	27.1%
Agents changing from car to other modes	4.1%	5.0%	5.0%	10.5%	15.7%	13.6%	9.9%
Car ownership	74.8%	74.1%	72.0%	83.2%	91.2%	87.0%	81.6%

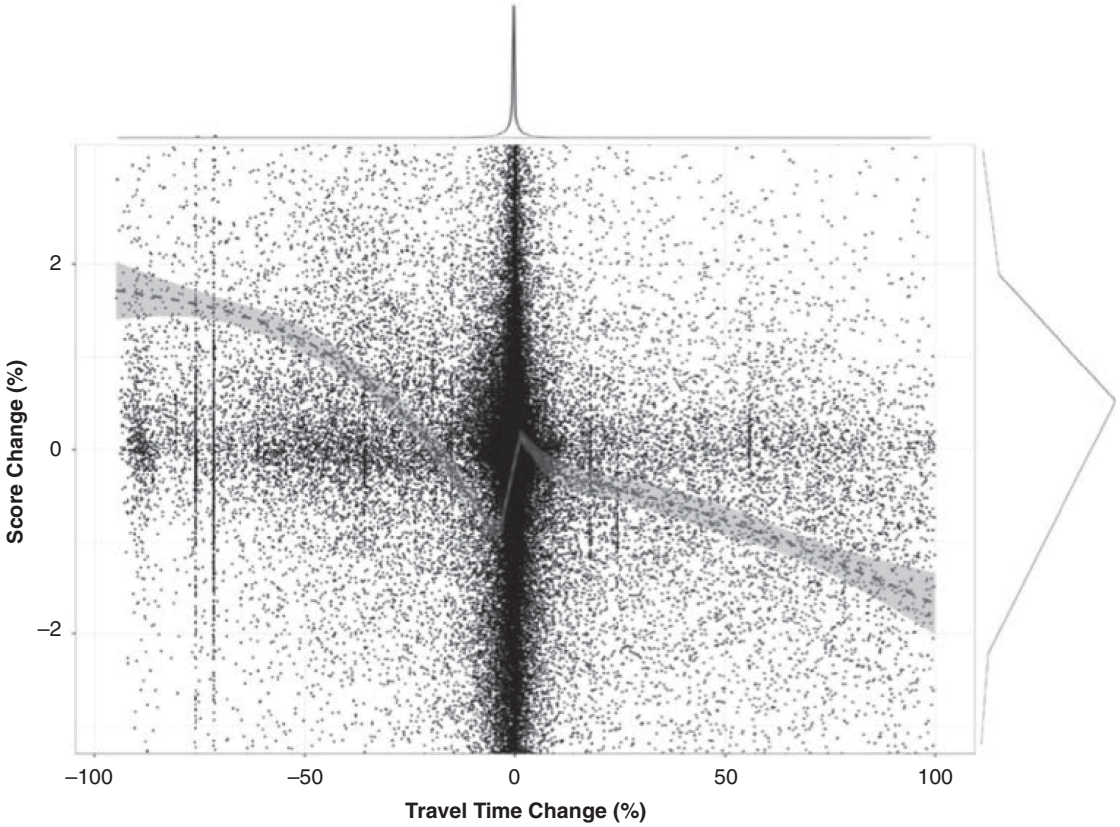

FIGURE 2 Travel time and score changes with densities of each variable.

muting patterns. Owing to the toll, within-day change of plans of car users as well as their commuting patterns are explanatory factors for negative score changes. While the results presented for Zurich are circumstantial, horizontal and vertical equity effects reflect findings from previous equity analyses in Stockholm and London (*27, 28, 32*). The cross correlation of different socioeconomic variables could be observed thanks to MATSim's features and, in particular, to (*a*) the highest possible level of disaggregation, (*b*) a full day simulation with interactions between agents, and (*c*) the possibility for the agents to rearrange their daily plans. The similarities of observed equity effects in London and Stockholm with those predicted for Zurich in the simulations are indications of the worthiness of MATSim for such analyses.

The first order equity effect analysis presented here is an important tool to enable planners and policy makers to address equity issues in the cordon design and in the revenue redistribution. Agent-based models are also important in a wider context of basing transport policies on welfare gains, which encompass more dimensions than travel time savings.

In future work, all time-dependent variables will be income based, not just the values of time. Furthermore, the value of time will be varied across different activities and travel modes in the scoring function. By doing so, it is hoped that the accuracy of estimated equity effects will improve by allowing for a higher degree of behavioral heterogeneity in the population. Moreover, the use of a transport supply scenario with detailed transit scheduling should be part of any future work for capacity constraint to be explicitly modeled in the transit system. Finally, the effect of activity patterns on score changes, such as activity duration and relocation (for secondary activities), has to be examined.

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