Income dependent economic evaluation and public acceptance of road user pricing

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Abstract

Road user pricing has often been stated to open up new possibilities to a more efficient allocation of limited road capacities in metropolitan areas, to a reduction of negative environmental effects and to raising additional funds for publicly financed projects. In this context, two major questions are frequently posed, one linked to economic evaluation and one concerning the project's public acceptance:

1. How to measure welfare effects of the policy?
2. Why is road user pricing often very unpopular?

This paper aims at linking economic evaluation to the understanding of implementation problems in a model that allows multiple choice dimensions simultaneously, such as route choice, mode choice and time choice. Therefore, a large-scale multi-agent microsimulation is used which is capable to simulate complete daily plans of several million individuals (agents). Within this model, agents optimize the utility of their daily plan with respect to a Random Utility Model (RUM). Therefore, this approach allows choice modeling and economic evaluation to be realised in a consistent framework. The utility functions are dependent on every agent's income and assume decreasing marginal utility of money, while the marginal utility of travel time is assumed to enter linearly.

For a real-world scenario of the Zurich metropolitan area in Switzerland, it is shown how agent react to a morning rush hour toll for eight different distance toll levels. Then, utility changes are calculated for every agent in order to identify winners and losers of the policy. Furthermore, agent specific utility changes due to the pricing schemes are valued following two different interpretations. For these, indicators of the overall welfare effect are calculated and compared. The results indicate that, first, the choice between the two interpretations of how to value utility changes might influence even the sign of the estimated welfare effect. Second, the distribution of welfare gains among the income range seems to be a possible indicator in order to identify acceptance problems of road user pricing. Finally, this approach could help policy makers to anticipate implementation problems and enable them to design and identify alternatives with higher public acceptance.

1 Introduction

Road user pricing has often been stated to open up new possibilities to a more efficient allocation of limited road capacities in metropolitan areas, to a reduction of negative environmental effects and to raising additional funds for publicly financed projects (e.g. Vickrey, 1969, 1973; Small, 1992; Lindsey and Verhoef, 2000). In this context, it has fequently been discussed how to measure the welfare effects resulting from the policy and how the consideration of decreasing marginal utilities of income might influence the results (Small, 1983; Herriges and Kling, 1999; Mackie et al., 2001; Bates, 2006; Franklin, 2006). Another open issue is why road user pricing is often not supported by a major part of the population (e.g. Schade and Schlag, 2000; Small and Gomez-Ibañez, 1998).

For real-world applications, these two questions are usually addressed by different research directions: welfare computations are done by economists using input data from aggregated state-of-the-practice transport planning tools or aggregated supply-demand functions and price elasticities (e.g. Bureau and Glachant, 2008). The major drawbacks of these approaches are that (i) typically only one choice dimension (route choice or mode choice) is considered as a reaction to a policy and that (ii) a constant marginal utility of money is assumed. Because of these limitations, welfare effects and the possible regressiveness of pricing schemes are likely to be underestimated (Jara-Díaz and Videla, 1989).

Implementation problems that are linked to a lack of public acceptance are often examined by psychologists. According to them, road user charges are unpopular because people do not trust the government to reinvest the collected money in a meaningful way and thus perceive the charge as an additional tax (Schade and Schlag, 2000). Furthermore, equity concerns are often mentioned in this context. However, the role of public acceptance has rarely been linked to the individual welfare effect that result from policy measures.

This paper aims at linking economic evaluation to the understanding of implementation problems in a model that allows multiple choice dimensions simultaneously, such as route choice, mode choice and time choice as well as continuously varying marginal utilities of money. Therefore, a large-scale multi-agent microsimulation is used which is capable to simulate complete daily plans of several million individuals (agents). Within this model, agents optimise the utility of their daily plan with respect to a Random Utility Model (RUM). Thus, this approach allows choice modeling and economic evaluation to be realised in a consistent framework. The utility functions are income dependent and assume decreasing marginal utility of income.

After introducing the simulation approach in Sec. 2 and defining a real-world scenario for the Zurich metropolitan area in Switzerland in Sec. 3, it is shown how agents react to a morning rush hour toll for eight different distance toll levels (Sec. 4.1). Then, in Sec. 4.2, agent specific utility changes due to the pricing schemes are valued in two ways. The resulting two different indicators for the overall welfare effect are calculated and compared. In Sec. 4.3, a possible dependency between the distribution of welfare effects among income deciles and implementation problems of road user pricing is analyzed. In

Sec. 5 the impact of this study on the methodology of economic appraisal schemes is discussed. The paper ends with a conclusion.

2 Simulation approach

This section aims at describing the simulation approach that is used in this paper. It then introduces the income dependent utility function.

At this point, only a brief overview of the software tool MATSim[1] can be given. For more detailed information, please refer to the Appendix or see Raney and Nagel (2006) or Balmer et al. (2005).

2.1 Simulation overview

In MATSim, each traveler of the real system is modeled as an individual agent. The approach consists of an iterative loop that has the following important steps:

1. **Plans generation**: All agents independently generate daily *plans*, that encode among other things his or her desired activities during a typical day as well as the transportation mode. Agents typically have more than one plan ("agent database"). With the current version of MATSim, there is always one plan for each mode.
2. **Traffic flow simulation**: All selected plans are simultaneously executed in the simulation of the physical system.
3. **Scoring**: All executed plans are scored by an *utility function* which is, in this paper, personalized for every individual by its income.
4. **Learning**: At the beginning of every iteration, some agents obtain new plans by modifying copies of existing plans. This is done by several *modules* that correspond to the choice dimensions available: time choice, route choice and mode choice. Agents choose between their plans according to a Random Utility Model (RUM).

The repetition of the iteration cycle coupled with the agent database enables the agents to improve their plans over many iterations. This is why it is also called **learning mechanism** which is described in more detail by Balmer et al. (2005). The iteration cycle continues until the system has reached a relaxed state. At this point, there is no quantitative measure of when the system is "relaxed"; we just allow the cycle to continue until the outcome is stable.

[1] Multi-Agent Transport Simulation, see www.matsim.org.

2.2 Utility function

There is some agreement in literature that income should be considered in transport policy analysis, see, e.g., Small (1983); Herriges and Kling (1999); Kockelman (2001); Mackie et al. (2001); Bates (2006, 1987); Franklin (2006). The argument essentially is that monetary price changes affect people with different income differently. This is usually addressed by estimating values of time for the income groups. In this paper, non-linear income dependent preferences are included in every agent's utility function.

The functional form used for simulations is loosely based on Franklin (2006) and is similar to Kickhöfer (2009). A detailed derivation of this form and the estimation of the corresponding parameters are illustrated in Grether et al. (2009b). Hence, the utility functions of the two transport modes car and public transit (pt) are, according to (6) in the Appendix, given by:

$$\begin{aligned} U_{car,i,j} &= + \frac{1.86}{h} t_{*,i,j} \cdot \ln(\frac{t_{perf,i,j}}{t_{0,i,j}}) - \frac{4.58}{y_j} (c_{i,j,car} + c_{i,j,toll}) - \frac{0.97}{h} t_{i,j,car} \\ U_{pt,i,j} &= + \frac{1.86}{h} t_{*,i,j} \cdot \ln(\frac{t_{perf,i,j}}{t_{0,i,j}}) - \frac{4.58}{y_j} c_{i,j,pt} \end{aligned} \tag{1}$$

The first summand refers to Eq. (7), i.e. to the positive utility obtained from performing an activity, with $\beta_{perf} = +1.86/h$. With the second summand, mode and income dependency are introduced into the utility functions: y_j stands for the daily income of person j and $c_{i,j}$ is her monetary distance cost for traveling to activity i. The indices *car* and *pt* indicate the transportation mode. Toll costs ($c_{i,j,toll}$) apply when car is chosen for a trip and only when there are any tolled links on the route. Distance costs are calculated using a distance cost factor of 0.12 CHF/km for car and 0.28 CHF/km for pt respectively (given by Vrtic et al., 2007). While there is a third summand for car ($\beta_{tt,car} = -0.97/h$), picking up the linear disutility of travel time $t_{i,j}$, there is no equivalent expression in the pt utility function. Travel time in pt is nonetheless punished by the opportunity costs of time by missing out on positive utility of an activity (β_{perf}) which also implies additional negative utility for the car travel time. It was already pointed out in Grether et al. (2009b) that this implies for Zurich pt being the "higher value" mode.

By adding individual income to the utility function, strongly personalized preferences are modeled. Additionally, in a real-world scenario, trip distances and daily plans do also vary individually. Utilities are computed in "utils"; a conversion into units of money needs to be done separately in the context of economic policy appraisal (see Sec. 4.2).

3 Scenario

The income-dependent utility function is now applied to a large-scale, real-world scenario. The metropolitan area of Zurich, Switzerland, with about 1 million inhabitants is used.

The following paragraphs give a simplified description of the scenario and focus on differences to similar simulations done by Chen et al. (2008) where a full description for a reference scenario can be found.

In order to obtain robust results, the correctness and plausibility of the implementation of the income-dependent utility function was verified in a simple bottleneck model. It is similar to the well-known bottleneck scenario by Vickrey (1969) and later by Arnott et al. (1990). The new implementations were then calibrated against a reference scenario (Grether et al., 2009b).

3.1 Network and population

The network is a Swiss regional planning network that includes the major European transport corridors. It consists of 24 180 nodes and 60 492 links (see Fig. 1a).

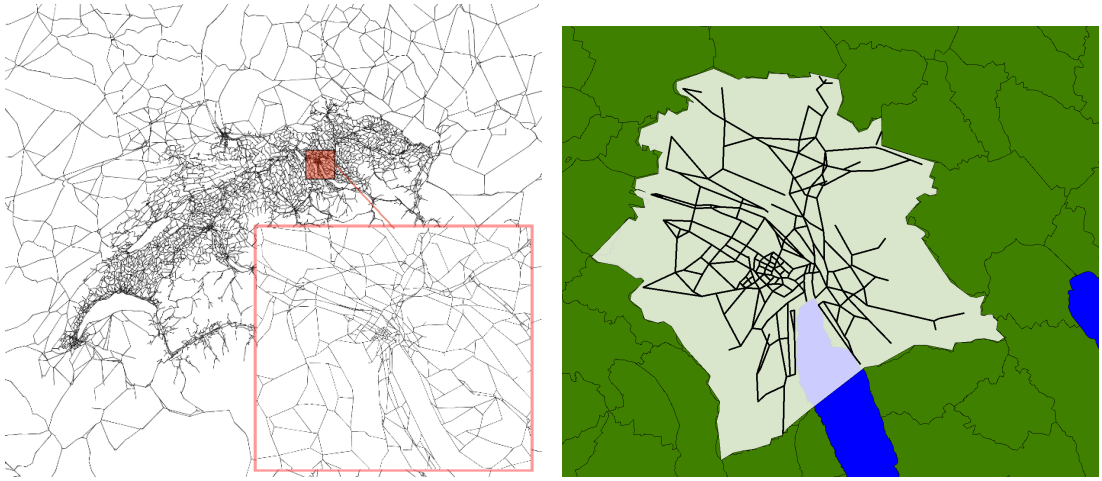
The travel demand consists of all travelers within Switzerland that are inside an imaginary 30 km boundary around Zurich at least once during their day (Chen et al., 2008; Vrtic et al., 2007). All agents have complete day plans with activities like *home*, *work*, *education*, *shopping*, *leisure*, based on microcensus information (SFSO, 2000, 2006). The time window during which activities can be performed is limited to certain hours of the day: *work* and *education* can be performed from 07:00 to 18:00, *shopping* from 08:00 to 20:00, while *home* and *leisure* have no restrictions. Each agent gets two plans based on the same activity pattern. The first plan only uses car as transportation mode, while the second plan uses only public transit.

In order to speed up computations, a random 10% sample is taken from the synthetic population for simulation, consisting of 181 725 agents. In this large-scale scenario, agents can modify their plans with respect to all three choice dimensions available as described in Sec. 2.1.

3.2 Income generation

Income is generated based on a Lorenz curve. Due to the lack of exact data the functional form of the Lorenz curve was approximated. Then the income curve, the first derivative of the Lorenz curve, was calculated (Kämpke, 2008).[2] To generate personal incomes for the agents, a random number between 0 and 1 is drawn from a uniform distribution. For this number, the corresponding value on the income curve is calculated and multiplied by the median income. Doing this for all members of the synthetic population, an income distribution was derived, similar to the distribution in reality.

[2] The Lorenz curve is $L(x) \propto \int_0^x y(\xi)\, d\xi$. Therefore, $L'(x) \propto y(x)$. The correct scaling is given by the fact that $y(0.5)$ is the median income.



(a) Swiss road network, area of Zurich enlarged (b) hypothetical toll links in Zurich municipality

Figure 1: Scenario: Switzerland network with toll links for Zurich.

Region specific data is used for the Canton Zurich[3] area. A specific median is available for each municipality[4] of the state[5]. For every person living in Canton Zurich area, the municipality of the person's home location is identified. Then, the median income of this municipality is used for income calculation in conjunction with a Lorenz curve for the Canton Zurich.[6] The scenario focuses on the Zurich metropolitan area. Therefore, the income of persons living outside the borders of Canton Zurich is computed with the median income and the Lorenz curve of the Swiss Confederation.[7] The median income used for the Swiss Confederation is 43665 CHF per household and year. The y_i for Eq. (1) are obtained by (i) allocating the yearly household income individually to every agent, and (ii) dividing that number by 240 (working days per year) in order to obtain "daily income".

3.3 Policy design

In order to evaluate an example of road user pricing for the area of Zurich and the consequences with respect to public acceptance, a fictive distance-based city morning toll was designed. The toll area covers, as can be seen in Fig. 1b, all roads within the area

[3] A Swiss "Canton" is similar to a federal state.

[4] "Gemeinde" is the next lower administrative level, i.e. some kind of municipality.

[5] `http://www.statistik.zh.ch/themenportal/themen/daten_detail.php?id=759`, last access 30.10.2009

[6] `http://www.statistik.zh.ch/themenportal/themen/aktuell_detail.php?id=2752&tb=4&mt=0`, last access 30.10.2009

[7] `http://www.bfs.admin.ch/bfs/portal/de/index/themen/20/02/blank/dos/01/02.html`, last access 30.10.2009

of Zurich municipality, but does not include the motorways that lead into and partially around the city. Since these are owned by the Swiss Confederation and not by the city of Zurich, they can not easily be taken into account when the local government decides about the implementation of a city toll. In addition, this setup is also expected to lead to more concentrated car traffic flow on the motorways while pulling flows from residential areas. Therefore, in 2007, this road pricing scheme had been discussed to be implemented (Bundesrat (Government) of Switzerland, 2007).

Based on this toll road network, eight different toll levels are now simulated, starting from 0.35 CHF/km, in each step doubling, up to an almost prohibitive prize of 44.80 CHF/km.[8] The toll is implemented for the morning peak hour from 6:30 am to 9:00 am. This approach helps at finding a toll level near to the optimal toll for this particular system at this time of day only by observing welfare changes over different toll levels. From an economic point of view, the optimal toll is the one where the sum of monetized utility differences and toll payments is maximized.

3.4 Simulation Runs

First, a "preparatory run" is performed by running the simulation for 2000 iterations without any policy measure. For 1000 iterations, 10% of the agents perform "time adaptation" and 10% adapt their routes. The other 80% of the agents switch between their existing plans, which implicitly includes mode choice as explained in Sec. 2.1. This means, that during the first 1000 iterations, the *choice set* is being generated; during the second 1000 iterations, where time and route adaption are switched off, agents actually carry out their choice by only switching between existing options. In the following, the output after 2000 iterations is referred to as the *base case*.

After that, the distance toll is introduced for the subnetwork defined in Sec. 3.3. The simulation is run for another 200 iterations, starting from the final iteration of the base case. Again, during the first 100 iterations 10% of the agents perform "time adaptation" while another 10% of agents adapt routes. Agents, that neither adapt time nor route, switch between existing plans according to Eq. (8) which also includes the switch between transport modes. As for the base case, during the final 100 iterations only a fixed choice set is available.

4 Results

In this section, the simulation results are presented. Overall, nine scenarios have been analyzed, the base case and eight policy cases with increasing toll levels (see Sec. 3.3). In the following, direct observations of traffic conditions as well as the actual behaviour of

[8] 1 CHF = 1 Swiss Franc ≈ 0.70 Euro, 12.05.2010

the agents are discussed. Subsequently, in order to compare the different policies, the overall welfare effect is computed for two different interpretations of how to value the individual utility changes. Finally, the results are interpreted in the context of public acceptance of urban road pricing schemes. Please note that for reasons of clarity, not all nine simulation runs are always discussed; the analysis always contains the lowest and the highest toll level in order to get an idea about the range of possible impacts.

4.1 Traffic conditions

In the MATSim framework, agents have several possibilities to react to changes of the system, such as the introduction of a road pricing scheme. In this paper, they can (i) change their transport mode, (ii) change their car routes or (iii) adapt the departure time. So far, there is no location choice model implemented, and neither can agents drop activities from their schedule.

Picking up the first point, Fig. 2 shows a shift in the modal split as a consequence of the toll. The percentage of car trips between activities (= legs) monotonously drops from 61% in the base case to 57% for the highest toll. This effect is likely to be even more important when only looking at people who have an activity within the toll area.

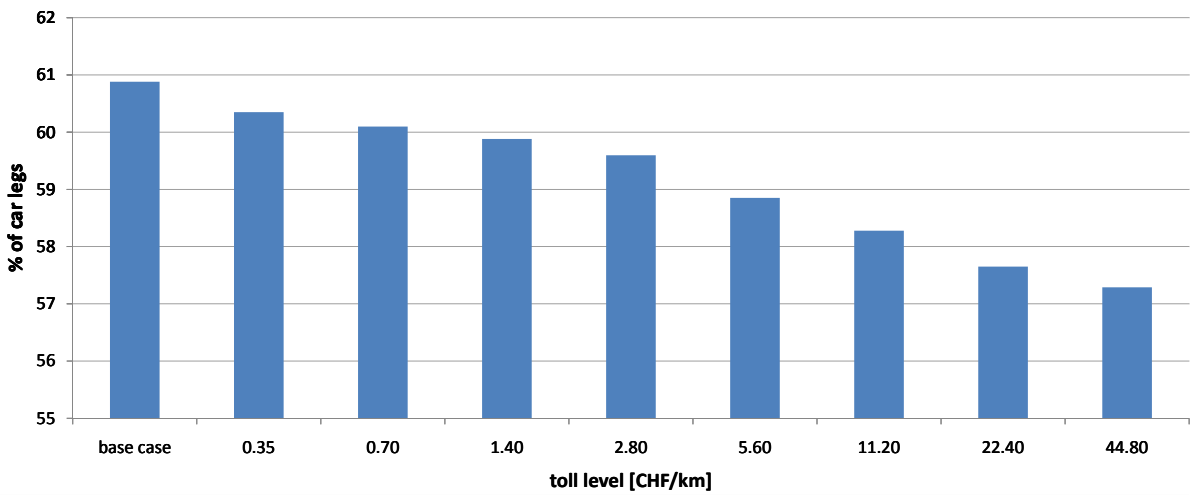


Figure 2: Percentage of car legs for the base case and the different toll levels; the remaining legs are public transit legs

Route and departure time adaption could be analyzed independently, but at this point, a locally more differentiated indicator about the overall impact of the different toll levels on the actual traffic conditions is used: the average speed in central Zurich. Fig. 3 shows the average speed on all links in within a 2 km radius around the center of the city over time of day for several toll levels and for time bins of 5 minutes. For the base case (dark

blue line), it can be seen that the average car speed in this area drops from 42 km/h at 6:00 am to about 34 km/h at 6:30 am. It then raises again, up to round about 37 km/h, stays more or less constant until the afternoon peak starts at 4:00 pm.

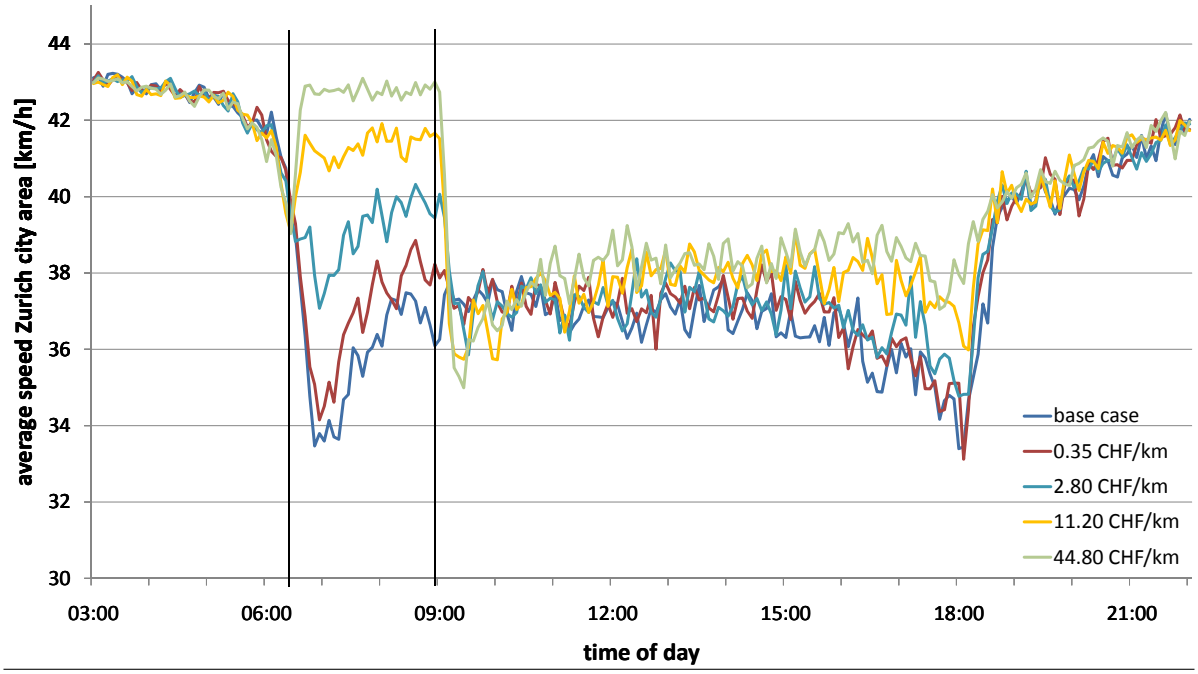


Figure 3: Average speed in Zurich city area over time of day for the base case and selected toll levels

For the first toll case, where agents have to pay 0.35 CHF/km, one can notice a slight improvement of the average speed in the morning hours from 7:00 am on, represented by the brown line in Fig. 3. With the toll level of 2.80 CHF/km (light blue line), this effect is even more important. Toll levels of 11.20 CHF/km and 44.80 CHF/km, represented by a yellow and light green line respectively, additionally influence the average speed in the afternoon peak in a positive way. Furthermore these high toll levels indicate that there might be a prohibitive toll level where no agent will take the car for traveling into or out of the city center. This fact is underlined by the decreasing number of people who pay toll during the day when raising the toll level: while for the lowest toll level, there are 11 016 agents paying toll, this number drops to only 1877 agents for the highest toll case, corresponding to only 6% or 1% of the whole population, respectively. Since the simulation uses a 10% sample of the full population, these numbers correspond to approximately 110 160 individuals for the lowest and 18 770 for the highest toll.

4.2 Economic evaluation

In literature, usually three major goals of road user pricing are stated: First, a more efficient allocation of limited road capacities in metropolitan areas. Second, a reduction of negative environmental effects. Third, the raising of additional funds what can be seen as an important step towards efficient financing of public transport infrastructure. The first two objectives have in common that they aim at internalizing external congestion and environmental costs of transportation into the utility calculations of individuals (e.g. Vickrey, 1969, 1973; Small, 1992; Lindsey and Verhoef, 2000). No matter whether politicians aim at realizing only one or even all of these goals, road user pricing schemes - as all policy measures - should make the system "better" than before. In this context, an economic policy appraisal is conducted: the impact of a policy on the welfare level and the welfare distribution of society needs to be understood.

When using a multi-agent approach, winner-looser analyses can directly be deduced from individual utility changes. In a second step, for economic evaluation, a conversion of utility changes into monetary values need to be found. This can be done *either* by first summing up all individual utility changes, and then monetarizing them, *or* by first converting individual utility changes into an individual willingness-to-pay/willingness-to-accept, and then summing up. The first option is in the following called "equitable interpretation" following the argument by Mackie et al. (2001) that "society needs to agree that the welfare of all individuals is equally important"; it is similar to a monetary valuation of "equivalent hours of leisure time" (Jara-Díaz et al., 2008); the second option corresponds to the classical Kaldor-Hicks criterion for economic investment (Kaldor, 1939; Hicks, 1939).

In the following subsections, it is shown that the choice between these two different interpretations for the welfare change highly influences the results of an economic evaluation. At this point, it is important to note that society needs to agree which interpretation to follow.

4.2.1 "The equitable interpretation": valuing utility changes with the average monetary value of utility

As mentioned above, the "equitable interpretation" follows from the assumption that "society needs to agree that the welfare of all individuals is equally important" (Mackie et al., 2001). Summing up the individual utility changes ΔU_j results in

$$\Delta \tilde{U} := \sum_{j=1}^{n} \Delta U_j \ . \tag{2}$$

This includes the disutility of paying the toll, weighted for each individual by $4.58/y_j$, where y_j is individual income as introduced in Eq. (1). This is similar, but not identical,

to a conversion of utility changes into "equivalent hours of leisure time" (Jara-Díaz et al., 2008) before summing up.[9]

In addition, there is the toll revenue, $\sum_{j=1}^{n} c_{i,toll}$. The question now is how to combine these two numbers to come up with a single number for the welfare effect. One possibility is to use the average monetary value of utility, $\frac{1}{n}\sum_{j=1}^{n}\frac{y_j}{4.58}$. This results in

$$\Delta\tilde{W} := \left(\frac{\frac{1}{n}\sum_{j=1}^{n} y_j}{4.58}\right) \cdot \sum_{j=1}^{n} \Delta U_j + \sum_{j=1}^{n} c_{i,toll}, \tag{3}$$

where $\Delta\tilde{W}$ represents the overall welfare change for society that results from the policy. The first summand picks up the sum of monetized direct utility changes. It is calculated by the aggregated utility changes which is converted into money terms with the average monetary value of utility. The second summand corresponds to the toll payments.

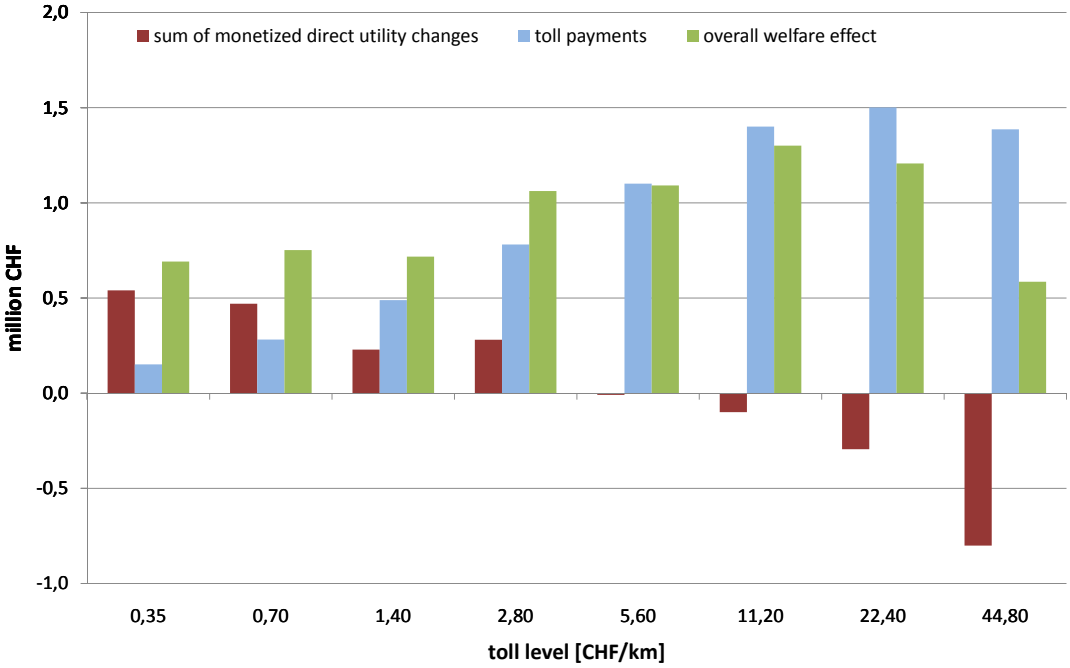
Leaving the toll payments aside for the moment, in Fig. 4a the red bars show the monetized direct utility changes corresponding with the first summand of Eq. (3) for the eight different toll levels. It can be seen that for toll levels up to 2.80 CHF/km, there is still a positive effect, a toll level of 5.60 CHF/km has almost no effect on the perceived welfare level while all toll levels from 11.20 CHF/km on lead to an welfare loss when excluding toll payments in the calculation. When taking into account the toll payments marked by blue bars in Fig. 4a, there is now a positive welfare effect for all toll levels (in green bars) since the toll payments overcompensate the perceived utility losses.

In practice, this approach is used within many transport project appraisal schemes: First summing up over all travel time savings, and then multiplying them with an average Value of Time (VoT).

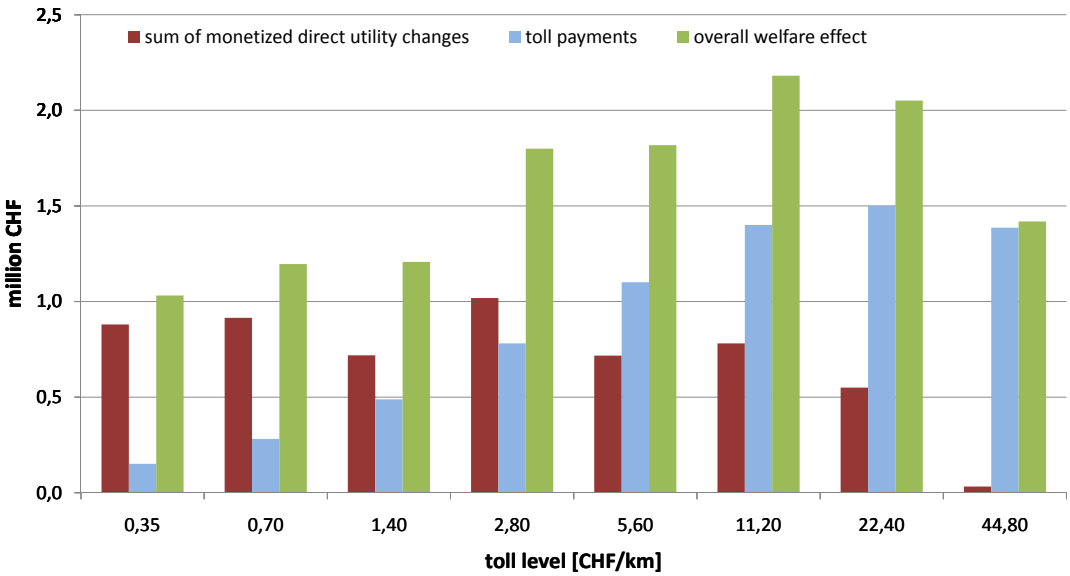
[9] The difference is that in our simulation, the marginal utilities of time vary between individuals: Individuals pressed for time have smaller $t_{perf,i}$, and therefore their marginal utility of time,

$$\frac{\partial}{\partial t_{perf,i}} \frac{1.86}{h} t_{*,i} \cdot \ln(\frac{t_{perf,i}}{t_{0,i}}) = \frac{1.86}{h} \frac{t_{*,i}}{t_{perf,i}} ,$$

is larger.



(a) "Equitable interpretation": valuing utility changes with the average value of utility



(b) "Individual interpretation": valuing utility changes with the individual's value of utility

Figure 4: Different interpretations of the aggregated willingness-to-pay as an indicator for welfare change resulting from various toll levels: (i) monetary valuation of direct utility changes [red], (ii) toll payments [blue] and (iii) the overall welfare effect [green] as the sum of (i) and (ii). Results per typical workday and scaled to full population.

4.2.2 "The individual interpretation": valuing utility changes with the individual's monetary value of utility

Following the individual interpretation, the aggregated individual willingness-to-pay and the individual willingness-to-accept, respectively, can be used as an indicator to describe changes in the society's welfare level. Thanks to the multi-agent approach, it is possible to calculate the willingness-to-pay on any desired level of disaggregation. Thus, a conversion from units of utility into money terms is performed on an individual level with person specific values of utility that result from the individual utility functions introduced by Eq. (1). Therefore, the overall welfare change ΔW that results from the policy is given by:

$$\Delta W := \sum_{j=1}^{n} \Delta U_j \cdot \frac{y_j}{4.58} + \sum_{j=1}^{n} c_{j,toll} \tag{4}$$

Again, the first summand represents the sum of monetized direct utility changes. Here, it is dependent on the individual utility difference ΔU_j and on the reciprocal value of the income dependent marginal utility of money, $y_j/4.58$, where y_j is individual income. The second summand adds the overall toll payments that are naturally the same as in Eq. (3).

The sum of monetized direct utility changes is now shown by the red bars in Fig. 4b for the eight different toll levels. In contrast to the "equitable interpretation" from Fig. 4a, it can be seen that the effect stays strictly positive over all toll levels and turns out to be more important. When adding the toll payments marked as blue bars in order to calculate the overall welfare effect (green bars), one can notice that the welfare level naturally also stays positive for all toll levels and that the overall welfare effect has a more important amplitude than in the "equitable interpretation". Surprisingly, a toll level of 11.20 CHF/km maximizes ΔW for both interpretations.[10] However, it has been shown that within this multi-agent framework, the sum of the income-dependent individual willingness-to-pay can methodically be calculated and thus be used for project appraisal. Another advantage of this approach is that choice modeling and economic evaluation are implemented in a consistent way since the simulation output is directly used for evaluation.

To sum up, it can be followed that not only *the calculated level* of the welfare effect but even *the sign* of the overall effect might - under certain conditions - depend on the choice between the two different valuations of utility changes.

[10] This seems unrealistically high for a real system. It is likely that this has to do with the income that was generated from household data, but is, in this model, applied to individuals. Assuming that a division by two would approximately correct for this issue, then a toll level of 5.60 CHF/km would not seem fully implausible for the city of Zurich, especially if one recalls that this could be offset by a tax reduction.

4.3 Public acceptance

The main question in the context of public acceptance is whether results from the economic evaluation of toll schemes can be used so as to understand why road user pricing is often very unpopular. In order to answer this question, the "individual interpretation" is used. Note, that in the following the role of toll revenues is not further examined. The focus is now on the directly monetized utility gains resulting from the different toll levels that correspond to the first summand in Eq. (3).

For the two extreme toll levels of 0.35 CHF/km and 44.80 CHF/km, Fig. 5 breaks the overall monetized direct utility gains from Fig. 4b down to population deciles that are sorted by income. The dots represent the willingness-to-pay (when positive) or the willingness-to-accept (when negative) for direct utility gains or losses that people experience in the corresponding decile. Red dots for a toll level of 0.35 CHF/km, green dots for a toll level of 44.80 CHF/km. Remember that the monetized direct utility gains were calculated based on a person specific utility function and were averaged afterwards. The remaining toll levels lead to similar curve shapes in between these two.

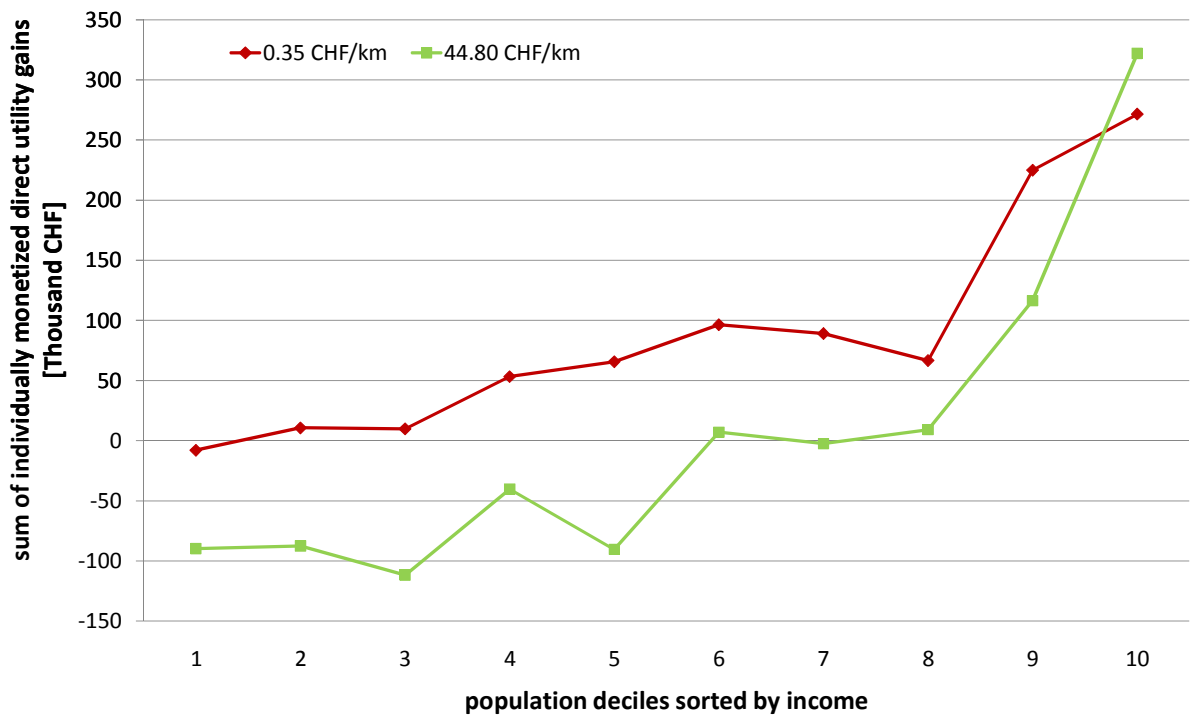


Figure 5: Sum of individually monetized direct utility gains due to the city toll over population deciles sorted by income: red dots for a toll level of 0.35 CHF/km, green dots for a toll level of 44.80 CHF/km; results for a typical workday and scaled to full population; the connecting lines only lead the eye.

At a closer look, one can see that for the high toll level, only the two highest income deciles have a positive willingness-to-pay for the toll. All other deciles either lose in terms of money or stay almost unchanged. This highlights an important implementation problem of policy measures in democratically organized societies: 50% of the population would be better off without the toll, 30% would have an almost unchanged utility level and for only 20% of the population monetized gains appear. This might be an important reason why a majority is likely to refuse the introduction of the policy even though it has an overall positive welfare effect. Moreover, the same might be true for the red curve even though almost all deciles gain in average: the toll could indeed be seen as an unequal reallocation of utility towards higher income groups.

5 Discussion

In the sections above we presented several implications of road user pricing in a real world scenario for the inner city of Zurich. Eight different toll levels were examined. We based our simulations on highly personalized utility functions with decreasing marginal utility of money. After finding quite intuitive and obvious consequences for traffic conditions and the actual behaviour of the agents in Sec. 4.1, we discussed in Sec. 4.2 two different interpretations for the valuation of utility changes. Both could be used when calculating the system's overall welfare change. Following the "equitable interpretation", individual utility changes can be converted into equivalent hours of leisure time or be directly summed up and monetized with the average value of utility. Following the "individual interpretation", a conversion from utility changes to the individual willingness-to-pay or willingness-to-accept is performed and an overall value is derived by summing these up. We showed that the choice between the two interpretations might even change the sign of welfare changes.

Somewhat curiously, in the "equitable interpretation", toll payments are no longer pure transfer payments to the state, but do have consequences on the welfare level. Considering only the toll payments, one obtains

$$\Delta\tilde{W}^{toll} := \left(\frac{\frac{1}{n}\sum_{j=1}^{n} y_j}{4.58}\right) \cdot \sum_{j=1}^{n}\left(\frac{4.58}{y_j}\, c_{j,toll}\right) = \frac{1}{n}\left(\sum_{j=1}^{n} y_j\right) \cdot \left(\sum_{j=1}^{n} \frac{c_{j,toll}}{y_j}\right) , \qquad (5)$$

which is in general not the same as $\sum_{j=1}^{n} c_{j,toll}$.

Finally in Sec. 4.3, we pointed out that road user pricing schemes might have regressive impacts on the welfare distribution of society. The same is likely for most of the investments in transport infrastructure that aim at shortening travel times (see Grether et al., 2009b, e.g.). In our opinion, this structural issue needs to be considered when evaluating public transport projects. In the case of road user pricing, such analysis might help to understand reasons for low public acceptance and also how to improve the acceptance of unpopular projects. The problem is quite obvious: financing infrastructure

projects by non-differentiated user fees leads to an regressive reallocation of welfare towards higher income groups. Financing projects e.g. by a progressive income tax might be more appropriate. Provided a progressive income tax system has been set up for making society more equal, then this tax would have to be even more progressive than the welfare reallocation by the transport projects. One possibility to address these issues might be the design of "policy packages" where policies are directly coupled with a redistribution scheme, e.g. of the toll payments. By doing so, it seems feasible to design packages that would meet broad public acceptance.

A property of the "individual interpretation" is the possibility to identify how the *individual perception* of welfare changes in terms of money is distributed among the members of society and how a package deal would need to be designed. This analysis can basically be done on every desired level of disaggregation: it is possible to combine multiple demographic attributes of the population of interest, e.g. by considering the geospatial distribution of winners and losers (see Grether et al., 2008). Therefore we think that multi-agent simulations could help to improve economic project appraisal and the understanding of problems that are linked to public acceptance.

6 Conclusion

This paper aimed at showing some new possibilities in the context of economic policy evaluation that are due to multi-agent microsimulations. In the model, agents optimize their daily plans with respect to individual preferences, individual income and activity locations. Based on this framework, a winner-loser analysis was performed by using individual utility differences. In order to evaluate the road pricing measure, these individual utility changes were monetized in two different ways by using the average or the individual value of utility, respectively. The marginal utility of money was assumed to be decreasing with income. The main findings in this paper are:

1. Income can and needs to be included in utility calculations for a better understanding of problems linked to acceptability.
2. Road user pricing might have regressive impacts on the welfare distribution of society. The same is likely for other investments in transportation infrastructure that aim at shortening travel time.
3. Multi-agent microsimulations allow to monetize utility changes based on individual preferences and attributes.
4. Valuing utility changes with an average value of utility leads to different results and might even change the sign of the welfare effect.
5. Toll payments are no longer pure transfer payments when valuing utility changes with the average value of utility, but have themself an effect on the welfare distribution of society.

6. With the help of the multi-agent approach, it seems feasible to study the effects of revenue recycling in more detail within future studies. "Policy packages" with compensating schemes could be simulated and analyzed in order to achieve broader public acceptance for unpopular transport policies.

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Appendix. Simulation details

The following paragraphs are ment to present more information about the MATSim simulation approach that is used in this paper. Every step of the iterative loop in Sec. 2.1 is now illustrated in more detail.

Plans generation

An agent's daily plan contains information about his planned activity types and locations, about duration and other time constraints of every activity, as well as the mode, route, the desired departure time and the expected travel time of every intervening trip (= leg). Initial plans are usually generated based on microcensus information and/or other surveys. The plan that was reported by an individual, is in the first step marked as "selected". An alternative plan for non-selected transportation mode(s) is constructed.

Traffic flow simulation

The traffic flow simulation executes all selected plans simultaneously in the physical environment and provides output describing what happened to each individual agent during the execution of its plan. It differentiates between car and public transit plans: The *car traffic flow simulation* is implemented as a queue simulation, where each street (= link) is represented as a first-in first-out queue with two restrictions (Gawron, 1998; Cetin et al., 2003): First, each agent has to remain for a certain time on the link, corresponding to the free speed travel time. Second, a link storage capacity is defined which limits the number of agents on the link; if it is filled up, no more agents can enter this link.

The *public transit simulation* simply assumes that traveling takes twice as long as traveling by car on the fastest route in an empty network[11] and that the travel distance is 1.5 times the beeline distance between the activity locations. Public transit is assumed to run continuously and without capacity restrictions (Grether et al., 2009a; Rieser et al., 2009).

This approach is due to the fact that, for the Zurich scenario, there is not enough data available yet for simulating public transit with high resolution, e.g. based on bus or metro lines and the underlying shedules.

The output of the traffic flow simulation is a list that describes for every agent different events, e.g. entering or leaving a link, arriving or leaving an activity. The events data

[11] This is based on the (informally stated) goal of the Berlin public transit company to generally achieve door-to-door travel times that are no longer than twice as long as car travel times. This, in turn, is based on the observation that non-captive travelers can be recruited into public transit when it is faster than this benchmark (Reinhold, 2006).

includes agent ID, time and location (link or node ID). It is therefore quite easy to grab very detailed information and to calculate indicators such as travel time or costs per link (which is used by the router), trip travel time, trip length, percentage of congestion, and many more.

Scoring plans

In order to compare plans, it is necessary to assign a quantitative score to the performance of each plan. In this work, in order to be consistent with economic theory, a simple utility-based approach is used. The elements of our approach are as follows:

- The total score[12] of a plan is computed as the sum of individual contributions:

$$U_{total} = \sum_{i=1}^{n} U_{perf,i} + \sum_{i=1}^{n} U_{tr,i} \ , \tag{6}$$

  where U_{total} is the total utility for a given plan; n is the number of activities, which equals the number of trips (the first and the last activity are counted as the same); $U_{perf,i}$ is the (positive) utility earned for performing activity i and $U_{tr,i}$ is the (usually negative) utility earned for traveling during trip i.

- A logarithmic form is used for the positive utility earned by performing an activity:

$$U_{perf,i}(t_{perf,i}) = \beta_{perf} \cdot t_{*,i} \cdot \ln\left(\frac{t_{perf,i}}{t_{0,i}}\right) \tag{7}$$

  where t_{perf} is the actual performed duration of the activity, t_* is the "typical" duration of an activity, and β_{perf} is the marginal utility of an activity at its typical duration. β_{perf} is the same for all activities, since in equilibrium all activities at their typical duration need to have the same marginal utility. $t_{0,i}$ is a scaling parameter that is related both to the minimum duration and to the importance of an activity. As long as dropping activities from the plan is not allowed, $t_{0,i}$ has essentially no effect.

- The (dis)utility of traveling used in this paper is estimated from survey data. It is, at this point, not any more a homogenous function for all agents but it depends on the agent's individual income as well as on his time, mode and route choice. The functional form is explained in Sec. 2.2.

In principle, arriving early or late could be punished. There is, however, no immediate need for doing so since this is already indirectly punished by foregoing the reward that could be accumulated by performing an activity instead (opportunity cost of time). In consequence, the marginal utility of waiting or being late is $-\beta_{perf}$.

[12] Note that the terms "score" and "utility" refer to the same absolute value. "Utility" is the common expression in economic evaluation and is therefore used in this paper.

The learning mechanism

A plan can be modified by various **modules** that correspond to different choice dimensions. These modules are customizable, they can be independently switched on or off or even be replaced by other modules. In this paper, three different choice dimensions are considered: time choice, route choice and mode choice that are implemented as follows:

1. **Time allocation module**: This module is called to change the timing of an agent's plan. A simple approach is used which just applies a random "mutation" to the duration attributes of the agent's activities (Balmer et al., 2005).
2. **Router module**: The router is a time-dependent best path algorithm (Lefebvre and Balmer, 2007), using for every link generalized costs of the previous iteration.
3. **Mode choice**: This choice dimension is not represented by its own module, but instead by making sure that every agent has at least one *car* and at least one *public transit* plan (Grether et al., 2009a; Rieser et al., 2009).

The modules base their decisions on the output of the traffic flow simulation (e.g. knowledge of congestion) using **feedback** from the multi-agent simulation structure (Kaufman et al., 1991; Bottom, 2000). This sets up an iteration cycle which runs the traffic flow simulation with the seclected plans for the agents, then uses the choice modules to generate new plans; these are again fed into the traffic flow simulation, etc., until consistency between the modules is reached. The feedback cycle is controlled by the **agent database**, which also keeps track of multiple plans generated by each agent.

In every iteration, 20% of the agents generate new plans by copying an existing plan and then modifying the copy in equal parts of 10% either within the time allocation or the router module. All other agents select one of their existing plans. The probability to change from the selected plan to a randomly chosen plan is calculated according to

$$p_{change} = min(1, \alpha \cdot e^{\beta \cdot (s_{random} - s_{current})/2}) \ , \tag{8}$$

where

- α: The probability to change if both plans have the same score, set to 1%
- β: A sensitivity parameter, set to 2
- $s_{\{random,current\}}$: The score of the current/random plan

In the steady state, this model is equivalent to the standard multinomial logit model $p_j = \frac{e^{\beta \cdot s_j}}{\sum_i e^{\beta \cdot s_i}}$, where p_j is the probability for plan j to be selected.

The repetition of the iteration cycle coupled with the agent database enables the agents to improve their plans over many iterations. This is why it is also called **learning mechanism** which is described in more detail by Balmer et al. (2005). As the number of plans is limited for every agent by memory constraints, the plan with the worst

performance is deleted when a new plan is added to a person that already has reached the maximum number of plans. The iteration cycle continues until the system has reached a relaxed state. At this point, there is no quantitative measure of when the system is "relaxed"; we just allow the cycle to continue until the outcome is stable.

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