MATSim Agent Heterogeneity and a One-Week Scenario

Andreas Horni

Kay W. Axhausen

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Institut für Verkehrsplanung und Transportsysteme
Institute for Transport Planning and Systems

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

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Andreas Horni
Institute for Transport
Planning and Systems (IVT)
ETH Zürich
CH-8093 Zürich
phone: +41-44-633 31 51
fax: +41-44-633 10 57
horni@ivt.baug.ethz.ch

Kay W. Axhausen
Institute for Transport
Planning and Systems (IVT)
ETH Zürich
CH-8093 Zürich
phone: +41-44-633 39 43
fax: +41-44-633 10 57
axhausen@ivt.baug.ethz.ch

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Abstract

This report describes two MATSim extensions: inclusion of individual values of time and money and a week-long simulation period. Speeding-up week-long simulation, mechanisms for warm-starting the simulation combined with an explicit termination criterion are implemented.

The extensions are applied in project *Surprice* to investigate equity effects with time-varying preferences in a road pricing context. First experiments' results are provided and technical implementation details are given.

Preferred citation style

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1 Problem and Goal

This paper's goal is, first, implementation of the simulation infrastructure and demand and supply generation for a week-long period and second, the inclusion of agent heterogeneity in terms of time and money values.

The project *Surprice* investigates variability of intra-personal travel preference variation, such as variation of value of time and money. The rationale for assuming temporal variation is the strong dependency of preferences on time-varying trip attributes, and not only on stable person attributes, such as income. Preference variation is assessed by model estimation performed by a different project group. Here, equity effects, described in Section 2.7 in a road pricing context are investigated quantitatively with MATSim.

2 Method

2.1 MATSim—In Brief

MATSim is an activity-based, extendable, open source, multi-agent simulation toolkit implemented in JAVA and designed for large-scale scenarios. It is a co-evolutionary model. A good overview of MATSim is given in Balmer *et al.* (2006) and its basic principle is illustrated in Figure 1. In competition for space-time slots on the transportation infrastructure with all other agents, every agent iteratively optimizes its daily activity chain by *trial and error*. Every agent possesses a fixed amount of day plans memory, where each plan is composed of a daily activity schedule and an associated utility value (in MATSim, called *plan score*).

Before plans are executed on the infrastructure in the network loading simulation (e. g., Cetin, 2005), a certain share of agents (usually around 10%) is allowed to select and clone a plan and to subsequently modify this cloned plan.

If an agent ends up with too many plans (usually set to 4-5 plans per agent), the plan with the lowest score (configurable) is removed from the agent's memory. One iteration is completed by evaluating the agent's day described by the selected and executed plan.

If an agent has obtained a new plan, as described above, then that plan is selected for execution in the subsequent network loading. If the agent has *not* obtained a new plan, then the agent selects from existing plans. The selection model is configurable. In many MATSim investigations, a weighted random choice based on a logit choice model is used.

In the current standard configuration, agents' attributes taken into account are age, mobility tools, occupancy, home and work location. Destinations are characterized by location, activity types, which can be performed there and service hours; here, day-of-week-specific service hours are applied as technically provided by Meister (2008). Income, value-of-time and public transport fares are not yet included by default in MATSim. MATSim validation is mainly based on road count data.

2.1.1 Utility Function

The plan score, using MATSim utility function, is compatible with micro-economic foundations. The basic utility function was formulated in Charypar and Nagel (2005) from the *Vickrey* model for road congestion as described in Vickrey (1969) and Arnott *et al.* (1993). Plan utility, described in detail in Charypar and Nagel (2005), is computed as the sum of all activity utilities $U_{act,q}$ plus the sum of all travel (dis)utilities $U_{travel,q}$.

$$U_{plan} = \sum_{q=1}^{n} U_{act,q} + \sum_{q=2}^{n} U_{travel,q}$$

The utility of an activity is defined by:

$$U_{act,q} = U_{dur,q} + U_{late.ar,q} \ ,$$

where:

- $U_{dur,q} = \beta_{dur} \times t_{typ,q} \times \ln(t_{dur,q}/t_{0,q}) =: f(t_{act})$ is the utility of performing activity q, where opening times of activity locations are taken into account. $t_{dur,q}$ is performed activity duration, β_{dur} is marginal utility of activity duration for its typical duration $t_{typ,q}$ and $t_{0,q}$ is minimal duration, or in other words, the duration for which utility starts to be positive.
- $U_{late.ar,q} = \beta_{late.ar} \times t_{late.ar,q}$ gives the disutility of late arrival, where $\beta_{late.ar}$ is marginal utility of lateness and $t_{late.ar,q}$ is lateness compared to planned times given in the agent's day plan.

There may also be additional penalties for staying not long enough, departing too early, or (beyond the implicit opportunity cost of time) for waiting. These are not used in the present paper.

Travel disutility is given as

$$U_{travel,q} = \beta_{travel,m,q} \times t_{travel,m,q} =: g(t_{travel}) \;, \tag{1}$$

where $\beta_{travel,m,q}$ is marginal utility of travel with the used mode m and $t_{travel,m,q}$ gives the mode-dependent travel costs between location of activity $q-1$ and q. The notion $f()$ and $g()$ is used in Section 2.2 and 2.7.

The applied parameter setting for this paper is described in Section 2.8.2.

2.2 Agent Heterogeneity — Agent Preferences

Individual agent attributes have been used in MATSim, for example in destination choice, by taking into account individual error terms (Horni *et al.,* 2012b), as boundary conditions for activity chain assignment during initial demand creation (Balmer *et al.,* 2009), or for mode choice, taking into account season tickets (Meister *et al.,* 2010, p.15). Apart from these few examples, MATSim agent heterogeneity is very low at the moment, while the system technically supports a full-blown agent-based approach. Usually, identical utility functions have been used for all agents. In this paper, a individual time α and money parameter γ are applied as follows.

$$U_{travel} = \alpha g(t_{travel}) + \gamma m$$

and

$$U_{act} = \alpha f(t_{act})$$

with t_{travel}, t_{act} being the travel and activity time respectively. $f()$ and $g()$ are defined as shown in Section 2.1.1. m are monetary expenditures composed of mode-specific travel costs and the road pricing costs. α and γ are dependent on the group the agent belongs to. Here, the group is defined by the household income class and preferences are defined as an example as follows.

$$\alpha = 0.5 \times i/8$$

and

$$\gamma = 0.5 + (8.0 - i)/8$$

with household income classes $i = 0..8$ given in the microcensus 2005 (Swiss Federal Statistical Office (BFS), 2006) as shown in Figure 2. The relationship between these parameters and income needs to be analyzed and calibrated.

In this paper, preference variation is applied as a random offset on these two parameters, which simulates unobserved trip-dependency of the preferences (Figure 3 and Section 2.7).

2.3 Implementation and Technical Details

Multiple approaches for simulating a week-long scenario are discussed in Ordóñez Medina *et al.* (2012). Another possible approach is for example Joubert *et al.* (2010) or also the non-optimizing approach of Märki *et al.* (2011). Here, approach 2 of Ordóñez Medina *et al.* (2012, p.8) is implemented, but extended by lagged variables, representing persons' experiences influencing the next day. In other words, the MATSim day cycle is *not* unwinded as shown in Figure 4. This approach is natural and efficient, curse of dimensionality, i.e., combinatorial explosion of search space can be avoided. However, the sequential day simulation needs to be enhanced in the future as transition between days is not captured accurately, which is particularly important for weekend leisure traffic, and, furthermore, some decisions made with longer time horizons, are might not modeled correctly and should be equilibrated with weekly instead of dayly iterations.

The preference variables α and γ can be interpreted as being derived from implicit weekly time and money budgets, representing a mechanism that goes beyond the simulation of single days. However, budget balancing is not explicit, but statistically driven (see Section 2.4) for more details).

Technically, the *Surprice* scenario consists of agents' day plans (*plans.xml*), a planning network (*network.xml*), activity locations (*facilities.xml*), road counts (*counts.xml*) and a configuration file (*config.xml*). Code for scenario creation and execution can be found at (1 in Section 5), and technical details of the Zurich scenario are available in Horni *et al.* (2011b).

MATSim offers different tolling schemes: link, distance, cordon, and area tolling. Its configuration is detailed at (2). Adding individual agent preferences makes adaptations necessary both in terms of scoring and routing.

2.4 Budgets

Travel time and money budgets and their stability and accurate observability (Kuhnimhof and Gringmuth, 2009, p.182) are subject of intense and sometimes controversial discussion (see e.g., Goodwin (1981), Gunn (1981), Mokhtarian and Chen (2004)). Nevertheless, in the first place, the budget concept is plausible, and it can easily be assumed that decisions are guided by budgets on different time-scales, meaning that budgets are balanced within different periods (Kuhnimhof and Gringmuth, 2009, p.179). Extending MATSim from an average work day period to a weekly horizon, which can be seen as the minimum work-leisure cycle, is probably necessary for investigating choices guided by longer-term budgets (see e.g., Ordóñez Medina *et al.* (2012)). In other words, applying a weekly horizon allows to explain time-variations instead of having them in the model as unobserved heterogeneity [1]. This is important as a large part of variability is usually intra-personal, i.e., temporal; Kuhnimhof and Gringmuth (2009) and Chikaraishi *et al.* (2010) report two thirds and more than half, respectively, of variance being intra-personal.

The budget concept is applied here as follows. Evidently, time and money budgets are dependent on income besides other factors. As shown in Section 2.2, agents' preferences α and γ are defined as a function of household income class. Thus, via the income link, agents' preferences express implicit budgets. As will be detailed in Section 2.7, a daily random offset is added to α and γ representing unobserved influences triggered by trip attributes α_{trip} and γ_{trip}. These daily fluctuations statistically balance over longer periods (illustrated in Figure 5), which can also be interpreted as budget balancing.

Pending empirical calibration can either be based on estimation or MATSim equilibration, where the later, makes weekly iterations necessary, which may are feasible with warm-starting the simulation. Similar to generation of activity chains, for budget estimation longitudinal data is required. Furthermore, application of estimated travel time budgets needs MATSim adaptation as it tends to underestimate travel times due to missing intersection dynamics and traffic signals. This means that calibration goes beyond simple budget adaptation.

2.5 Speedup: Warm-Start and Explicit Stopping Criterion

Simulating a week scenario means a huge computational effort. Fortunately, successive days' correlations due to persons' routines (e.g., Schlich and Axhausen (2003), Schlich *et al.* (2004), Kitamura *et al.* (2006)) can be employed to speed-up simulation. While exogenous choices remain fixed over the course of iterations, the endogenous choices—here: time, route and mode choice—are subject to MATSim equilibration. "Warm-starting" the simulation, as mentioned e.g., in Zilske *et al.* (2012, p.4), means efficiently initializing a MATSim day using the relaxed state of the previous day. This is done for all days except Monday and Saturday, as the weekend clearly shows different patterns.

[1] for a discussion of variability see e.g., Figure 6 and Horni *et al.* (2011a) and for a discussion of MATSim modeling of longer-term decisions see e.g., Horni *et al.* (2012a)

In this paper, a simple adaptation process is implemented (see code at 3 and 4). Comparing day i and day $i-1$, $activity_i$ is assigned the times of $activity_{i-1}$ if their types and position in the plan are are equal. If additionally location is identical for these activities and respective preceding activities, then also mode and route are copied. Per plan the process is started at first activity and stopped at first mismatch in terms of activity type. A first extension could be to initialize the rest of the routes with approach implemented at (5), who initializes routes on a loaded network instead of an empty network by using an incremental approach with so-called within-day replanning. More complex adaptation rules are possible, where adaptation may dependent on the similarity of plans. Examples for day plan similarity measures are as follows. Schlich (2001a) analyze individuals' daily schedules with the sequence alignment method, developed in genetics research. In Feil (2010), a *best-match operator* is described. However, this operator is mainly based on agent comparison rather than plan comparison and thus not perfectly suitable here. Further similarity measures can be found in e.g., Kitamura *et al.* (2006), Simma and Axhausen (2001), Schlich (2001b).

To produce a speed-up the warm-start must be combined with a stopping criterion. While stopping criteria have been researched (e.g., Meister (2011, Chapter 2)), the core MATSim implementation was based on a fixed number of iterations set by the modeler, guided by visual inspection of the total score improvement. An explicit termination criterion is now part of the code. In this paper (see code at 4), it is based on the population average score improvement of the agents' best plans (note that the score improvement of the currently executed plan is dependent on the replanning rate).

Importantly, the simulation must still be able to generate enough variability to cover the complete search space. Focusing on implementation, neither this variability analysis nor systematic speed-up analysis has been done for this paper, but left for future work.

2.6 Lag-Effects

Lagged variables are researched extensively in model estimation to explain temporal variation (Arellano and Honoré, 2001, Honoré and Kyriazidou, 2000, Kitamura and Bunch, 1989). Here, mode choice of previous day influences next day as shown in Figure 7, where preference is changed person-dependent. This can be interpreted as extending the agent memory to a weekly horizon. Rationales for strengthening or weakening preference are manifold (e.g.: "I do not necessarily need the car for shopping *every* day of the week" versus "I am used to a certain mode for shopping"), here it is simply meant as an example to illustrate technical infrastructure. In essence, introduction of lagged variables explains part of temporal variability which appears as unobserved heterogeneity in cross-sectional models. Lagged variables are here applied to the mode constants in the utility function as shown in Section 2.8.2. Calibration is pending.

2.7 Preference Variation Effects on Equity

Hypothesis of the project *Surprice* says that equity in road pricing context is probably larger than assumed until now as former analysis was based on models, where the value of time is only dependent on income. Adding temporal value of time variation, or, in more general, temporal preference variation, is expected to increase equity. The context of measuring and judging equity needs clarification, i.e., application of economic efficiency measures such as *Pareto* and *Bayesian* and related *Kaldor-Hicks* efficiency needs to be considered. Furthermore, basis of equity measurement related to subjectivity or objectivity needs to be clarified [2]. Problem of subjectivity is as follows. The utility function takes the form

$$U = \alpha f(t_{act}) - \alpha g(t_{travel}) - \gamma m + \epsilon,$$

where U is the utility, $f()$ and $g()$ are functions as defined above, α and γ are the time and money preferences as described above, m are monetary costs and ϵ are random error terms. Value of time is usually dependent on α/γ.

Assuming that wealthier persons have a higher value of time, and further assuming that road pricing decreases travel times by Δt, a larger utility gain is created for them as compared to poorer persons with otherwise identical situations, i.e.,

$$\alpha^{rich} f(t_{act} + \Delta t) - \alpha^{rich} g(t_{travel} - \Delta t) - \gamma^{rich} m > \alpha^{poor} f(t_{act} + \Delta t) - \alpha^{poor} g(t_{travel} - \Delta t) - \gamma^{poor} m.$$

On the other hand, under heavy traffic conditions U_{rich} might be smaller than U_{poor} as suffering in traffic jams decreases utility more for rich people having a higher value of time.

Evaluating utility and its changes in equity context is thus difficult, and a suitable comparison measure needs to be developed for the project.

Here, we focus on travel times. The effect of adding random disturbances α_{trip} and γ_{trip} to the preferences, representing unobserved dependencies on trip attributes is investigated. Rationale for random variations is assumption, that trip purposes at the given rough level of specification, cancel out within and between groups or even for single person's trip chains. Furthermore, for implementation simplicity, α_{trip}, despite its name, is applied to all trips of a specific person

[2] for a discussion of objective and subjective value of time see e.g., Ortúzar and Willumsen (2001, p.457), Hensher and Button (2000, p.504) or González (1997)

on a specific day, meaning that here this parameter should be called α_{day}. In a future version individual values should be applied per trip.

Clearly, in a linear context, these random offsets cancel out over the population and time or even over trip contexts of a person, such that rich and poor people, on average, are the same off. But in a non-linear context, which is usually assumed in transport systems, some effects possibly remain. For this test, microsimulation is particularly suitable, as the specific spatial settings and road pricing scheme can be considered with high resolution. In other words, the real-world microsimulation scenario explicitly takes into account spatial constraints maybe leading to system non-linearities. This allows testing to what extent persons, willing to pay for shorter travel times, actually are able to approach tolled infrastructure to reduce their travel times (see Figure 8). Additionally, application of lagged variables is tested, another potential source of non-linearity.

2.8 Scenarios

2.8.1 Small-Scale Toy Example

For rapid development and debugging, but not for results, a small-scale scenario is provided. On a chessboard network 6 TAZ with demand as shown in Figure 9 are defined. Road pricing is applied in the center zone. The scenario has been created using code at (6).

2.8.2 Real-World Zurich Scenario

The Zurich scenario is frequently used in MATSim development but also for projects in Swiss planning practice (e.g., Balmer *et al.,* 2009). Simulation scenario population is derived from the Swiss Census of Population 2000 (Swiss Federal Statistical Office (BFS), 2000). Here, a 1% sample of car traffic (including cross-border traffic) crossing the area delineated by a 30 km circle around the center of Zurich (Bellevue) is drawn, which results in 17'912 agents simulated. The activity location data set, comprising more than 10^6 locations is computed from the Swiss Census of Population 2000 and the Federal Enterprise Census 2001 (Swiss Federal Statistical Office (BFS), 2001). The network from the Swiss National Transport Model (Vrtic *et al.,* 2003)—a planning network—is used, consisting of 60'492 directed links and 24'180 nodes. Navigation networks, such as (Tele Atlas MultiNet, 2010, NAVTEQ, 2011), are readily applicable in MATSim.

To date, commonly, a single day was simulated, for which demand is derived from the National Travel Survey for the years 2000 and 2005 (Swiss Federal Statistical Office (BFS), 2006), reporting 33'000 independent person days for Switzerland overall.

For creation of a weekly scenario either longitudinal travel survey studies are required or algorithms creating prolonging surveyed periods such as Munizaga *et al.* (e.g., 2011), Doherty *et al.* (e.g., 2002), Kuhnimhof and Gringmuth (e.g., 2009), where still, e.g., Kuhnimhof and Gringmuth (2009) is calibrated by longitudinal surveys, here with the German Mobillity Panel (MOP). Prominent longitudinal surveys are *Mobidrive* (Zimmermann *et al.*, 2001), *Thurgau* (Löchl *et al.*, 2005) and *Uppsala* (Hanson and Huff, 1982). As this projects' models are estimated based on the *Thurgau* study, MATSim demand is also derived from this study. Clearly, results' transferability from the rural Thurgau region with the small city Frauenfeld to the urban/sub-urban Zurich agglomeration awaits analysis.

As described earlier, agent preferences are derived by person groups; here, income groups are chosen. Assigment of income group membership to agents is done randomly following the income distribution of microcensus (see Figure 2) showing a rather natural/plausible form than Thurgau data set (see Figure 10). In the future, incomes could be derived from EVE (Swiss Federal Statistical Office (BFS), 2007) possibly integrated with synthetic population generation (Müller, 2011).

In more detail, demand is prepared as follows. After filtering non-home-based plans, days containing trips with undefined modes, days containing inconsistent types and finally persons with incomplete weeks (see code at 7), 116 out of 230 persons are used. Activity types *home, work, shop, leisure, education* and *other* are used (see also Table 1) Type *other* is used here, different from the standard MATSim scenarios because of small sample size.

Choice dimensions are assigned as shown in Table 2. Modes taken into account are *car, pt, bike* and *walk*. Car mode is microsimulated, other modes are handled as pseudo-modes as described e.g., in Rieser and Nagel (2009, p.5). For model testing, traffic count data for 2004-2005 from automatic national, cantonal and municipal count data stations (e. g. ASTRA, 2006) are available.

Scenario was created using code at (8).

For the experiments, road pricing is included. A link-based regime is implemented, where between 6 AM and 8 PM all links with a speed limit of 60 km/h and above are tolled with 1 EUR in a 10 km radius area around Bellevue, a central place in Zurich.

Parameter Calibration

In this paper, the following utility function parameter setting is applied, which is loosely derived from Balmer *et al.* (2009, 2010), Horni *et al.* (2011b):

$\beta_{dur} = +6.0\ EUR/h$,

$\beta_{late.ar} = -18.0\ EUR/h$,

and

$\beta_{travel,\ car\ |\ pt} = -12.0\ EUR/h,\ \beta_{travel,\ walk\ |\ bike} = -6.0\ EUR/h.$

Following constants are used to calculate travel disutility:

$C_{car\ |\ pt\ |\ walk} = 0\ EUR,\ C_{bike} = -15.0\ EUR.$

For the usage of lagged variables these constants are adapted dependent on the main mode of the previous day as follows.

$C_{j,\ lagged} = C_j \times f_{lagged} + \phi \times (1.0 - f_{Lagged}),$

where j is the main mode used in the previous day, f_{lagged} is a uniform random variable between 0.5 and 1.5, and ϕ is a configurable scale factor, here set to 2.0. Public transport, bike and walk legs are "teleportet" and not microsimulated as described e.g., in Meister *et al.* (2010). Teleportation speeds of the modes are chosen as follows.

$v_{pt} = 5.56\ m/s,\ v_{bike} = 3.33\ m/s,\ v_{walk} = 0.83\ m/s,$

where the network distance is approximated as the beeline between the activities with a scale factor of 1.5. Distance costs are given as follows, with a *marginal cost of money* of 1 utility point per EUR.

$costs_{car} = 0.0005\ EUR/m,\ costs_{pt} = 0.00025\ EUR/m.$

The parameters α_{trip} and γ_{trip} are calculated as

$\alpha_{trip} = \tau \times (0.5 - r),$

and

$\gamma_{trip} = -\alpha_{trip},$

where r is a uniform random variable in the range between 0 and 1, and τ is a configurable factor, here set to 1.0.

Rough mode choice calibration is given in Table 3, where only distances and times, but not number of legs, are taken into account as in MATSim still access and egress walks are substantially underestimated. Average weekly values could be used in future and finer calibration.

The parameter $\alpha_{tot} = \alpha + \alpha_{trip}$ is applied to both travel times and activity participation times. Parameter $\gamma_{tot} = \gamma + \gamma_{trip}$ is applied to monetary travel costs.

Calibration has set mobility simulation flow capacity factor to 0.03, which is high compared to e.g., Balmer *et al.* (2009), but necessary for a stable score development without system-wide breakdowns (see Figure 11 and Rieser and Nagel (2008)).

3 Simulation Results

Following configurations are simulated:

- 0: no road pricing
- 1. road pricing
  - a: Applying preferences α, γ, without temporal preference variation.
  - b: Including preference variations $\alpha_{total} = \alpha + \alpha_{trip}$ and $\gamma_{total} = \gamma + \gamma_{trip}$.
  - c: Configuration *a* plus lagged variables.

Due to substantial system adaptation and extension in short development time, results are preliminary and further plausibility checks are necessary. Additionally, results are based on single runs, while microsimulations should be based on ensemble runs for proper computation of statistical significance etc. (Horni *et al.,* 2011a). Furthermore, changing destinations is an important answer to a different supply situation due to e.g., road pricing. However, in this version destination choice is not included.

In Figure 12, 13 and Table 4, it can be seen that road pricing—as a trend with unclear statistical significance—decreases average trip travel times and (except for Tuesday) also car [3] trip travel distances. In a setting without destination choice, alternatively, longer travel distances and times to circumvent monetary costs could, a priori, be expected. Trip travel distances on tolled links is, as expected, decreased for the configuration 1.a (with road pricing) versus configuration 0 (without road pricing).

[3] Only *car* distances are reported as other modes' distances remain stable as they are not routed on the network.

In Figure 14, influence of preference variation can be seen. Trip travel times and distances and tolled travel distances are plotted against $\Delta\alpha_{tot} = -\Delta\gamma_{tot}$. Figure 14(a) shows that with increasing α travel times decrease as expected. In Figure 14(b), car travel distances increase with increasing alpha. This can either be due γ, which decreases with increasing α, or due mode switchers. The high values are also interesting in context of small population distance average changes between configurations and need further analysis. As expected, usage of tolled links increases with increase of α and decrease of γ respectively (Figure 14(c)).

In Figures 15, 16, and 17, and Table 4, it can be seen, that preference variation increases the spread in travel times and utilities (where car travel distances are quite stable), comparing run 1.a and 1.b. Interestingly, it can further be seen that travel times are all higher in configuration 1.b, reducing road pricing effect on travel times. Car travel distances and utilities have no trend.

To investigate project hypothesis, income classes have to be analyzed. Somewhat in contradiction to project hypothesis, Figure 18 shows higher travel times for lower income classes for configuration 1.b. This situation is identical for all days, thus, arbitrarily Wednesday is shown, here. The spread of travel times does not show a trend (Figure 19). One could here also think about analyzing subjective utilities, where, on the other hand this analysis is in danger to have exogeneity problems.

Influence of lagged variables is weak, here. More calibration investment might produce clearer results. For the comparison of configuration 1.a and 1.c (with lagged variables), Table 4 reports for the week average slightly higher trip travel times, car trip travel distances and tolled travel distance. However, for single days, no trend is visible. Figure 20 shows slightly larger spread, when including lagged variables.

For the 1% sample, 16 computation hours are required for the 7 days, using 6 threads of a Linux server, equipped with a current standard Intel Xeon(R) processor.

4 Conclusions and Outlook

In this paper, individual MATSim agent preferences are introduced. This, on the one hand, reveals the changes necessary in terms of scoring and replanning to add more agent heterogeneity in MATSim. On the other, problems as formulated in project *Surprice* can be analyzed.

One can a priori assume, that effects due to symmetrical preference variations do cancel out over population and time if system is linear. As MATSim is, in some parts probably linear (due to missing intersection dynamics, including traffic lights and due to queue simulation instead of car following simulation). Thus, effects may be smaller than observed in reality.

Assumed effects on equity as formulated in Section 2.7, *cannot* be confirmed here. On the contrary, preliminary results—surprisingly—indicate, that preference variation in road pricing context leads *on average* to even higher travel times for lower income groups (Figure 15). However, compared to the political weight of this statement, the time invested in plausibility checking, code testing, etc. is definitely not sufficient. Furthermore, concluding from single run results is yet common, nevertheless, dangerous and sometimes—dependent on spatial and temporal resolution—plain wrong.

Besides a more careful analysis in this vein, further improvements may concern public transport simulation instead of teleportation, application of lagged variables to further choice dimensions and time-slot-wiese as well as activity-wise, as well as its calibration, analysis of warm-start and termination criterion, and inclusion of destination choice in replanning. For shopping and leisure destination choice modeling, the introduced extension of MATSim by individual agent preferences and week simulation horizon is essential, as these choices are often based on individual longer-term time and money budgets.

5 Referenced Files and Folders

1. *playground.anhorni.surprice.**
2. *http://ci.matsim.org:8080/job/MATSim_contrib_M2/org.matsim.contrib$ roadpricing/javadoc/?*
3. *playground.anhorni.surprice.warmstart.AdaptNextDay*
4. *playground.anhorni.surprice.TerminationCriterionScoreBased*
5. *playground.christoph.controler.WithinDayInitialRoutesController*
6. *playground.anhorni.surprice.preprocess.miniscenario.**
7. *playground.anhorni.surprice.preprocess.rwscenario.ConvertThurgau2Plans*
8. *playground.anhorni.surprice.preprocess.rwscenario.**

6 Figures and Tables

Figure 1: **MATSim Principle:** Heart of MATSim model is iterative equilibration of demand and supply—representing a fixed point problem—by a co-evolutionary algorithm.

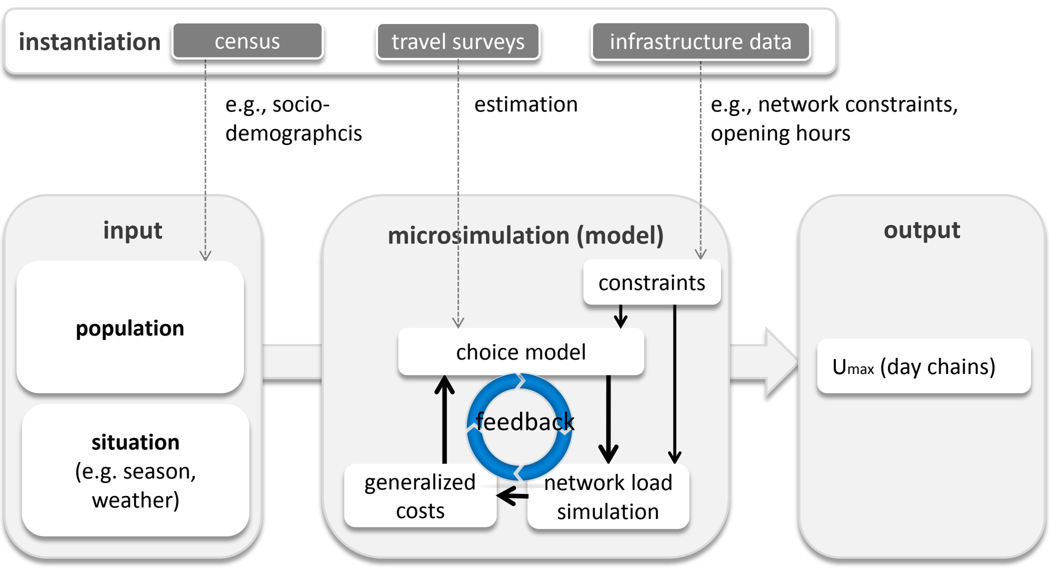


Figure 2: **Household Income Microcensus** (German)

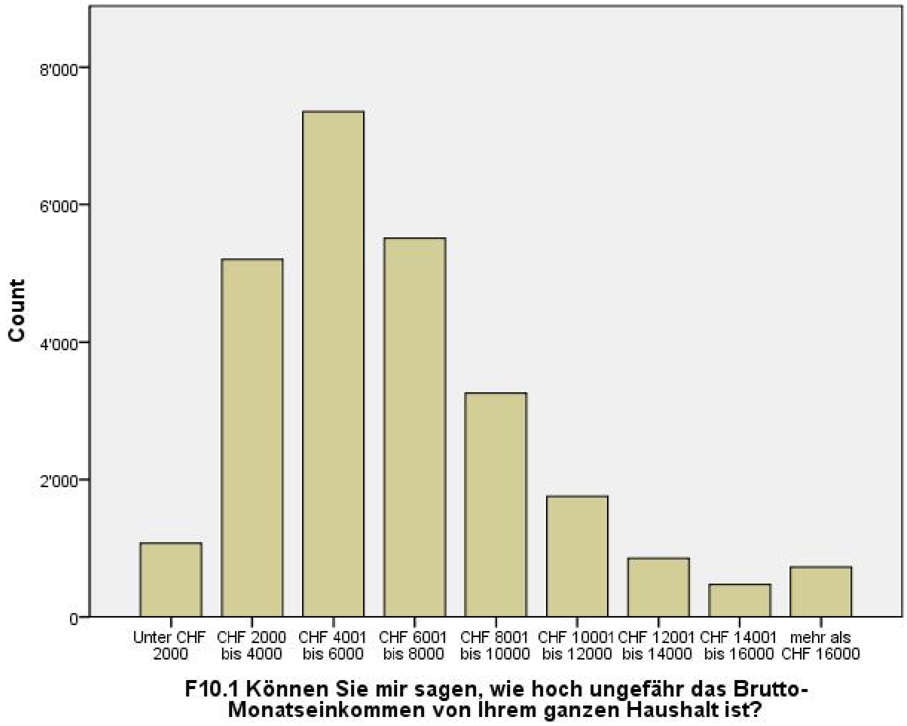


Figure 3: **Time-Dependent Preferences:** α_{tot} is dependent on income and trip characteristics, here modeled as unobserved heterogeneity.

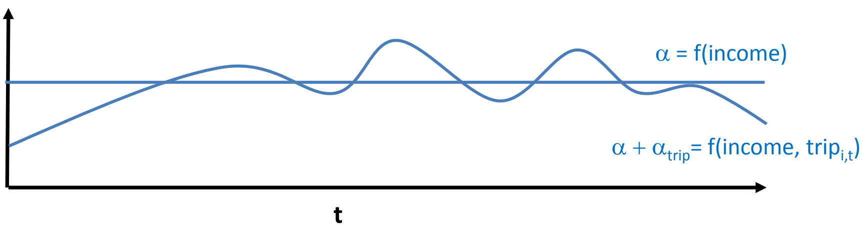


Figure 4: **Week Scenario Implementation**

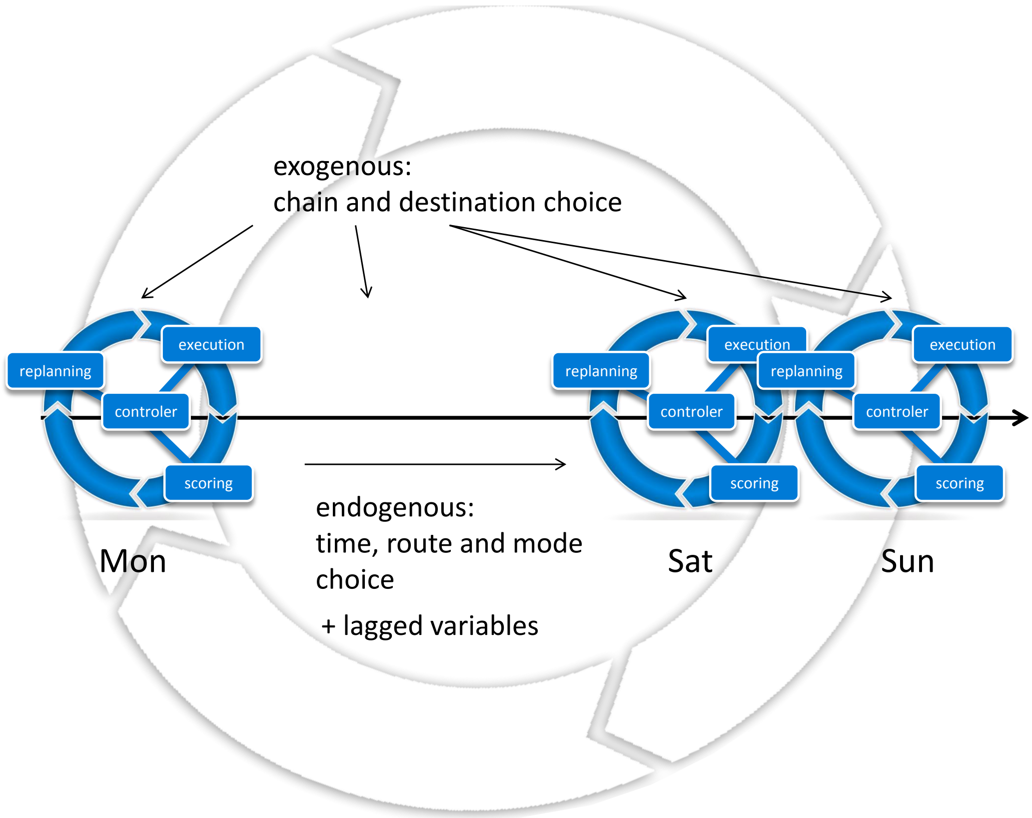


Figure 5: **Budgets:** Balancing of budgets over time is illustrated. As argumented earlier, implicit budgets are a different representation of travel time and money values. While averaged over the week (as an example) travel time budget (TTB) is lower and travel money budget (TMB) is higher for rich people on single days this might be different with varying preferences, leading to effects in road pricing contexts not modeled adequately with stable preferences models. Here, for example, different to the week average, $TTB_{rich} > TTB_{poor}$ for TUE-WED and $TMB_{rich} < TMB_{poor}$ for MON-WED, on WED poor people have higher TMB than TTB on the generalized costs unit axis.

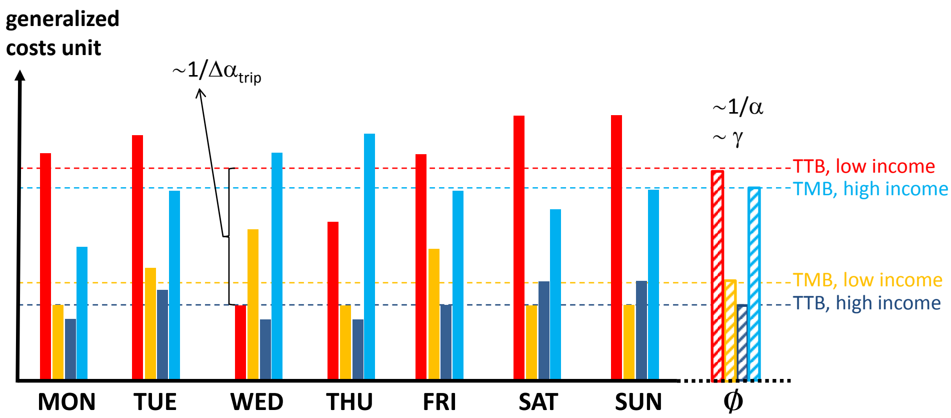


Figure 6: **Variability:** Total Variability, or output variability, optimally given by ensemble runs, results from input and model variability, both composed of explained and unexplained heterogeneity, quantified with β and ϵ respectively. Here, model variability comes from time, route, and mode choice, and input variability is generated by activity and destination choice. Temporal variability is explained by the week chains and lagged variables.

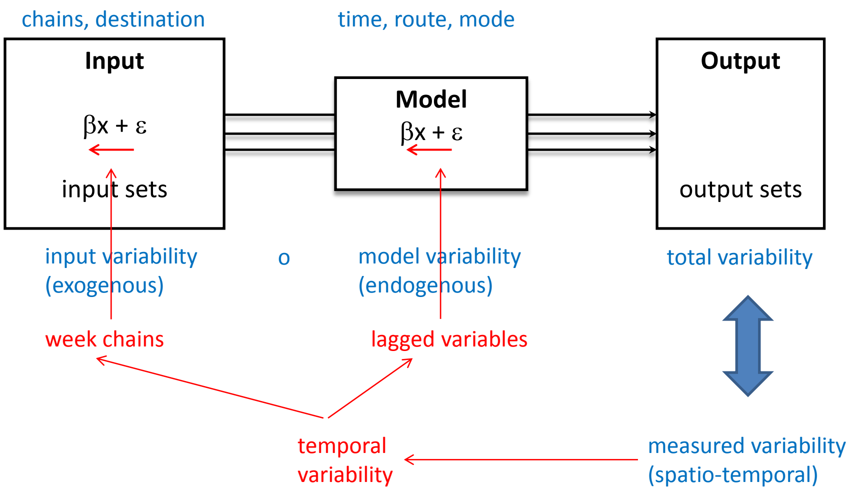


Figure 7: **MATSim Utility Function Including Lagged Variables:** $U_{act,t}$ denotes activity utility for day t and $U_{travel,t}$ denotes travel (dis-)utility for day t. α, γ are income-dependent individual preferences, where α_{trip} and γ_{trip} are the unobserved random fluctuations. $mode_{main,t-1}$, used for lagged effects, is main mode of previous day, here given as most often counted mode for a person day. Other measures, such as highest travel time could be used for main mode definition.

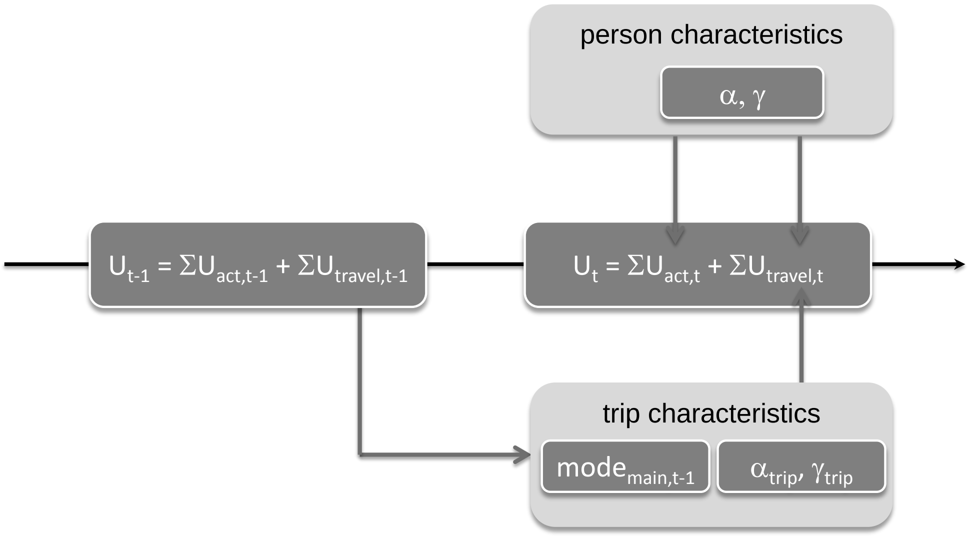


Figure 8: **Road Pricing Losers/Winners:** Evidently, the main reason to use microsimulation is large influence of spatial configuration, including road pricing scheme, on accessibility of tolled infrastructure. An example is shown, potentially leading to net winners and losers due to road pricing, independent of income. Here, *RP* stands for road pricing and *tt* stands for travel time.

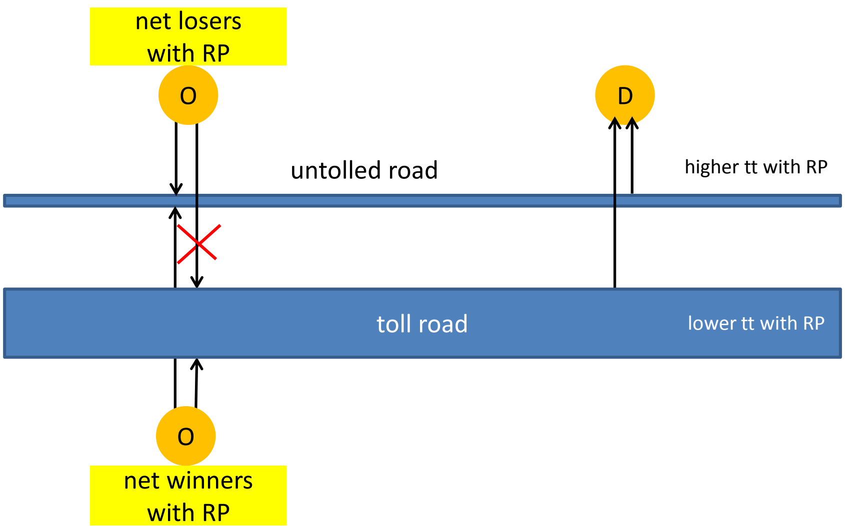


Figure 9: **Toy Scenario:** 6 TAZ with configurable amount of demand as marked with blue arrows. Area charging is done in the center zone. Road network is a chessboard with configurable density.

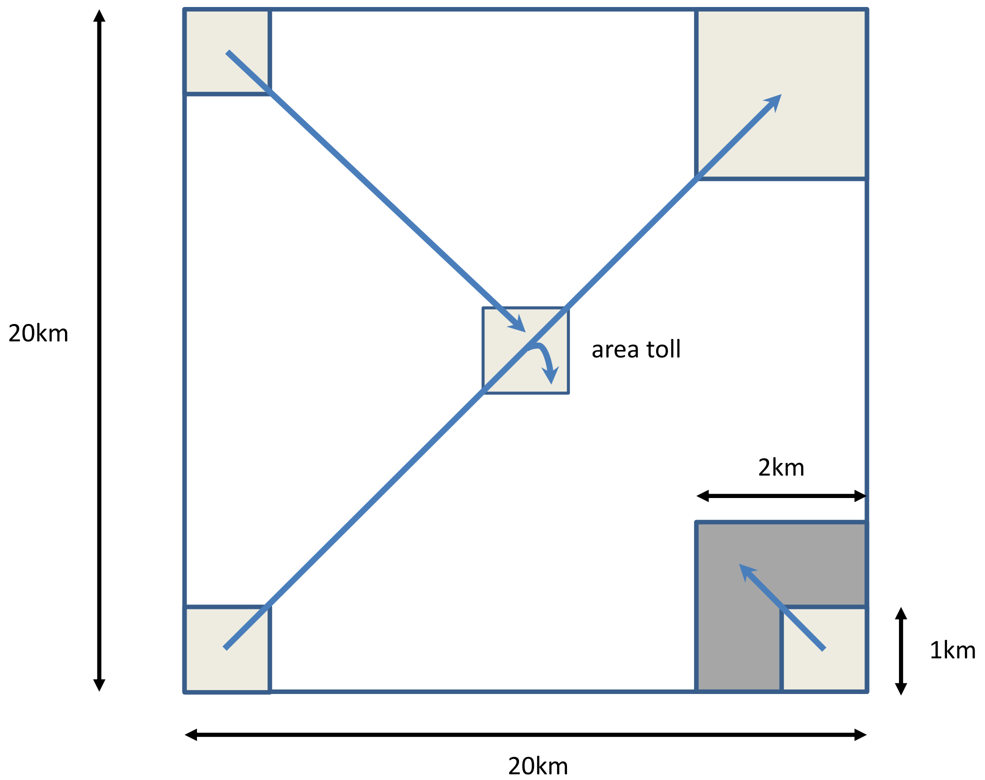


Figure 10: **Household Income Thurgau**

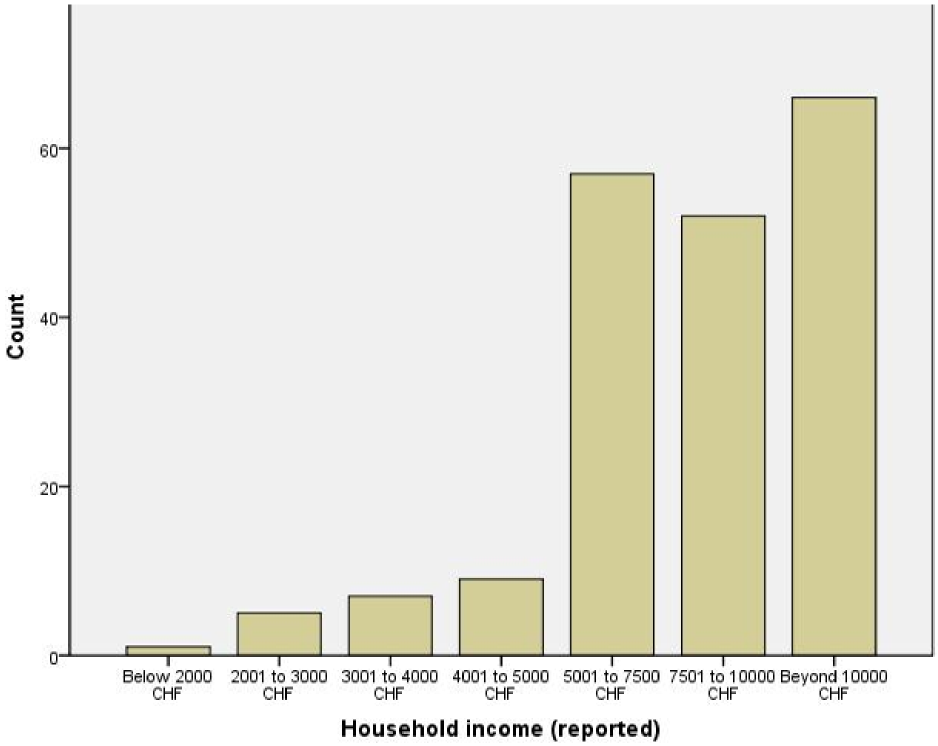


Figure 11: **Wednesday Average Score Development:** Score fluctuations indicate substantial bottlenecks in the network given the calibrated flow capacity factor. In other words, a slightly lower flow capacity factor can lead to unnatural network-wide breakdowns and should be avoided.

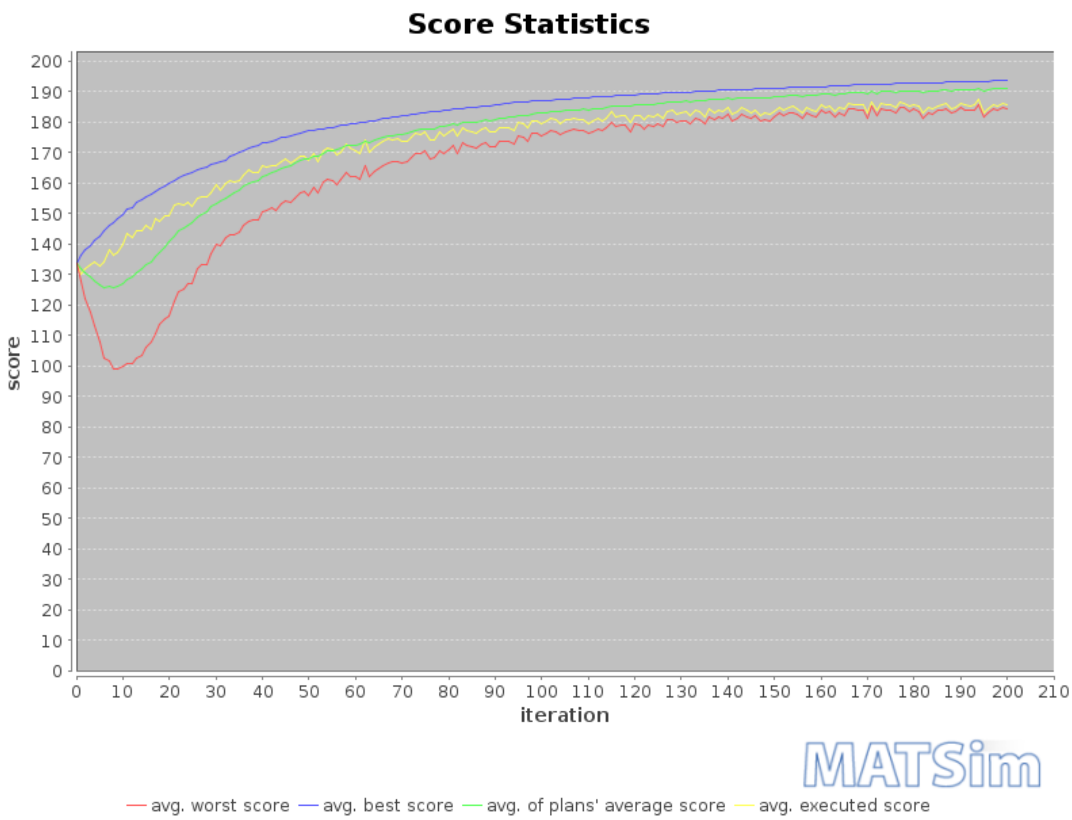
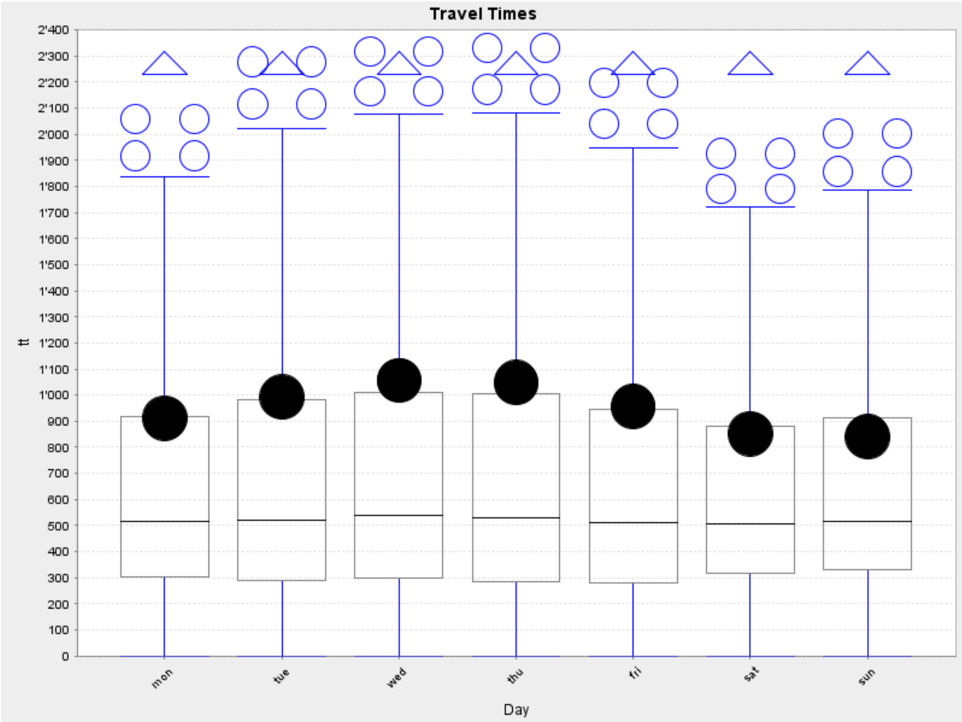


Figure 12: **Trip Travel Times** [s]

(a) Configuration 0



(b) Configuration 1.a

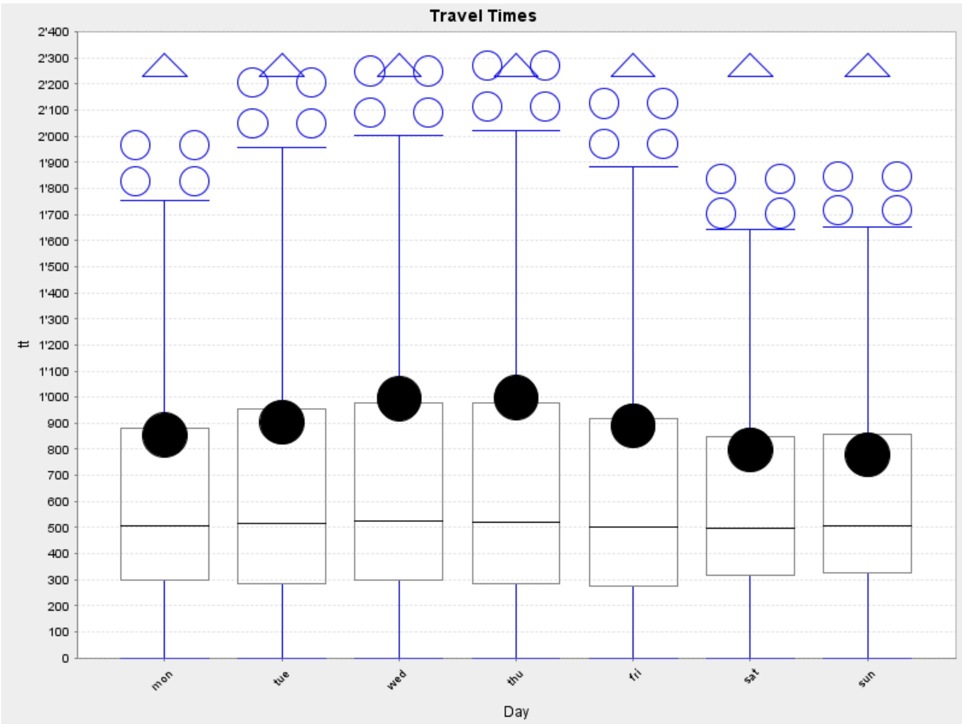
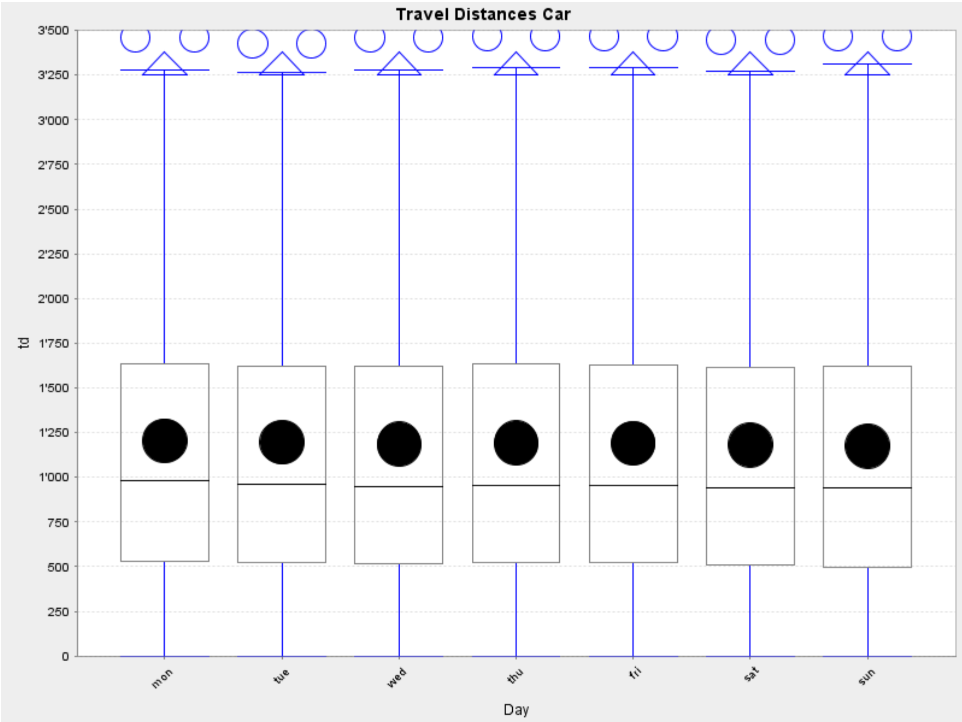


Figure 13: **Car Trip Travel Distances** $[m]$

(a) Configuration 0



(b) Configuration 1.a

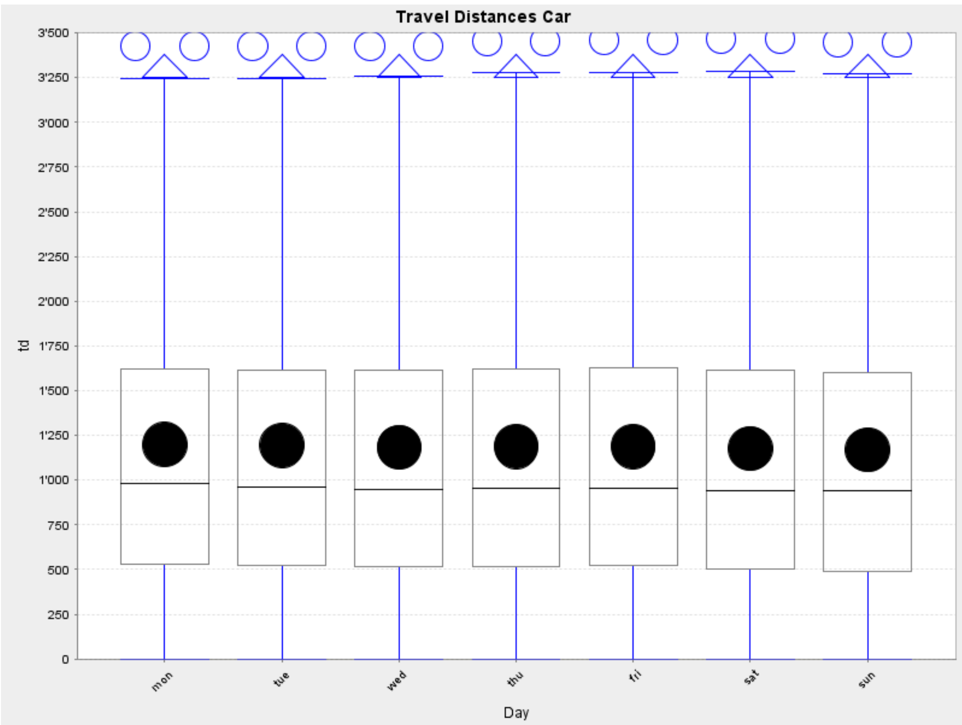
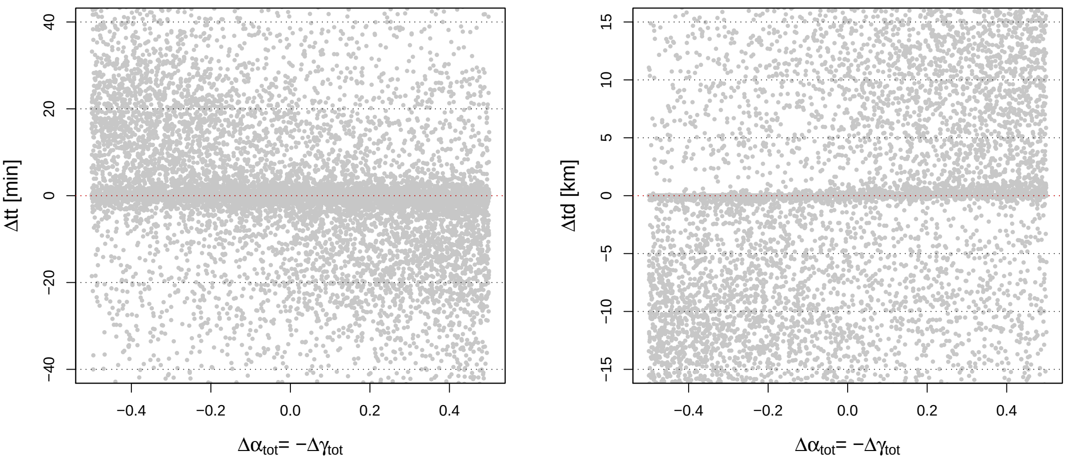


Figure 14: **Preference Variation:** Comparison per Person of Configuration 1.a and 1.b

(a) Trip Travel Times [*min*]

(b) Car Trip Travel Distances [*km*]



(c) Toll Trip Travel Distances [*km*]

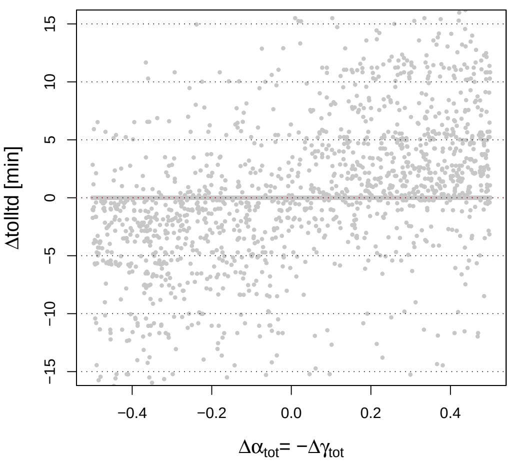
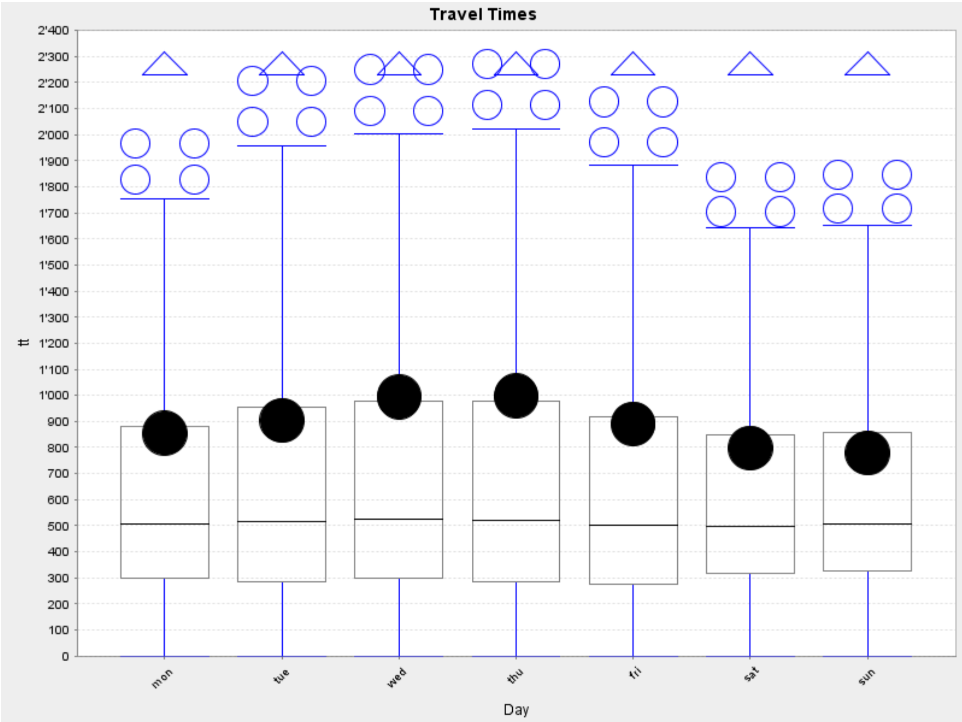


Figure 15: **Trip Travel Times** [*s*]

(a) Configuration 1.a



(b) Configuration 1.b

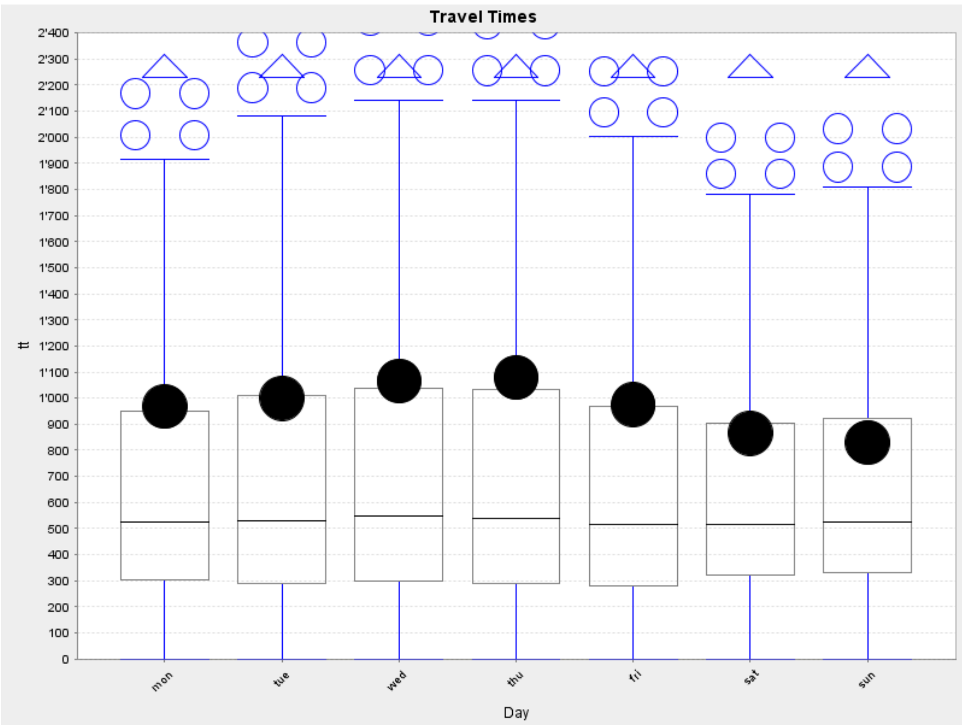
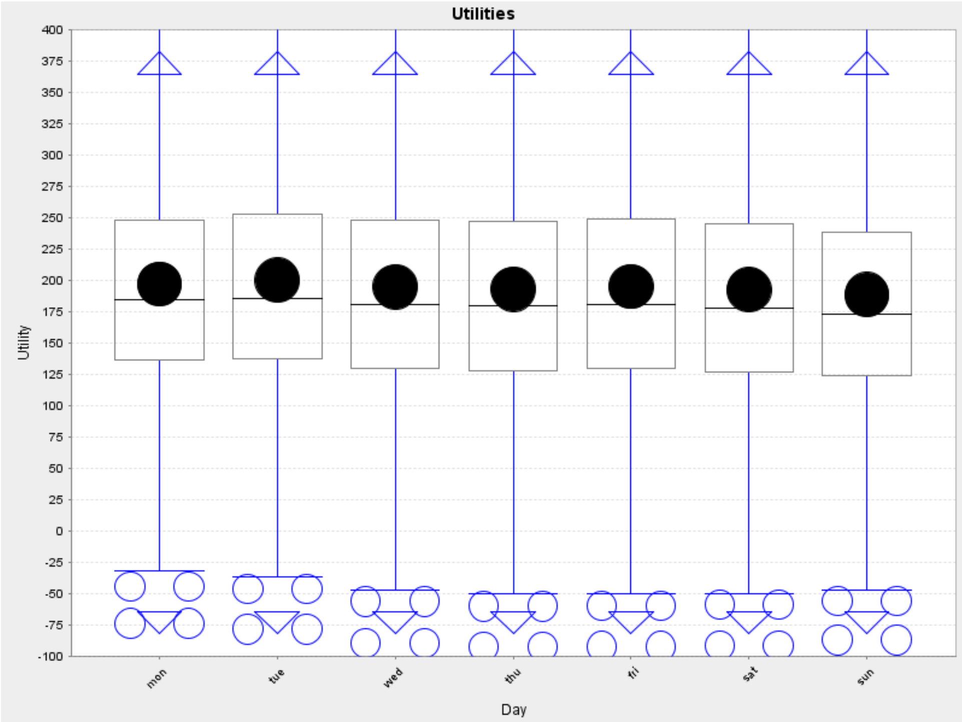


Figure 16: **Day Plan Utilities**

(a) Configuration 1.a



(b) Configuration 1.b

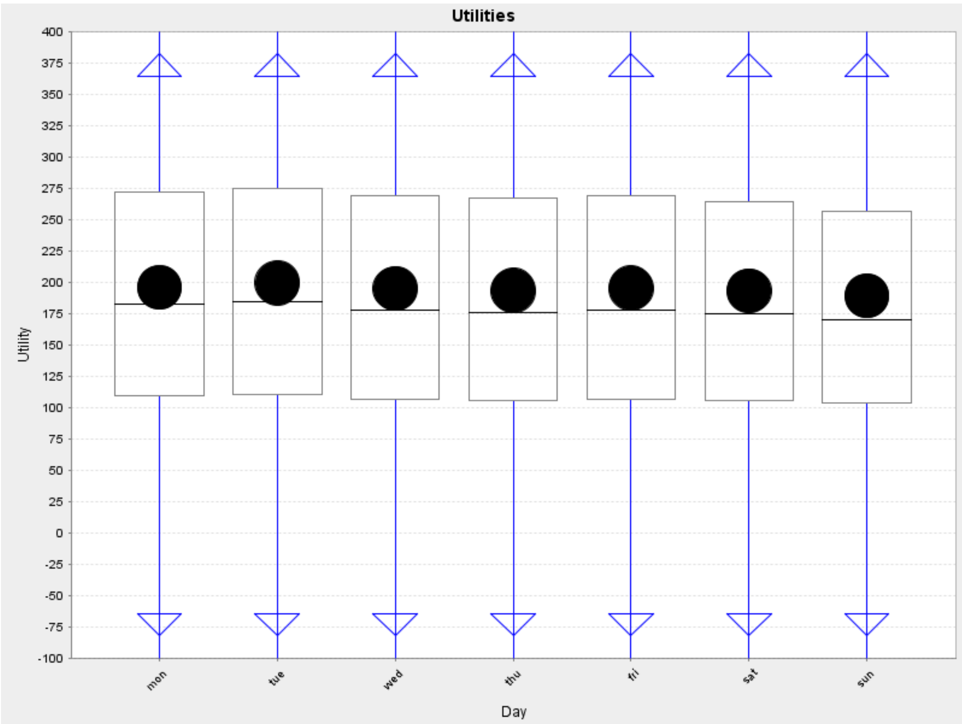
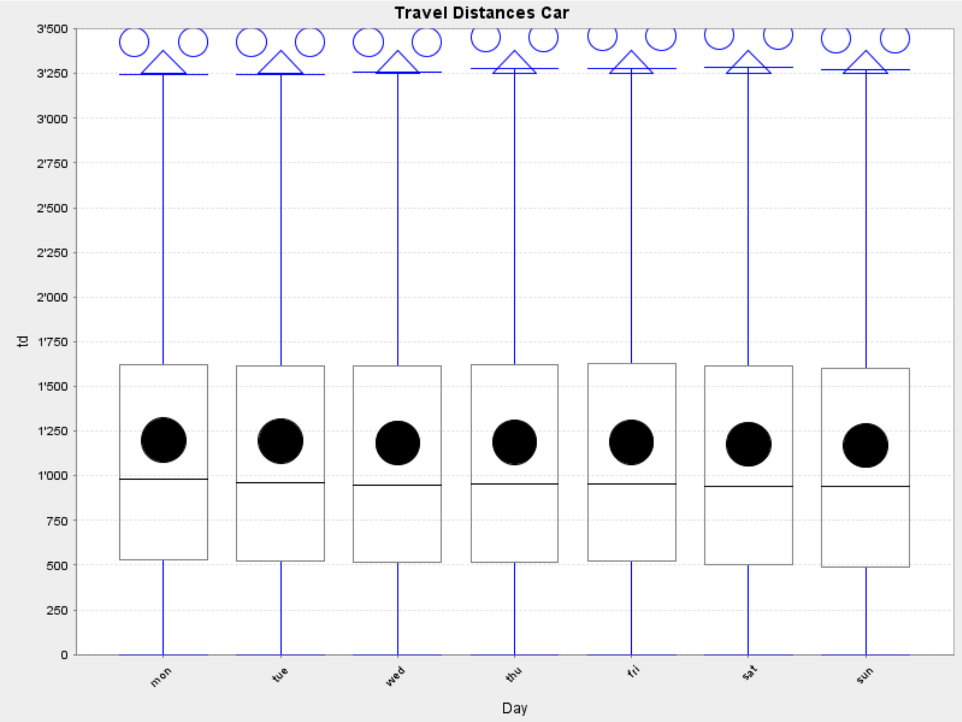


Figure 17: **Car Trip Travel Distances** [*m*]

(a) Configuration 1.a



(b) Configuration 1.b

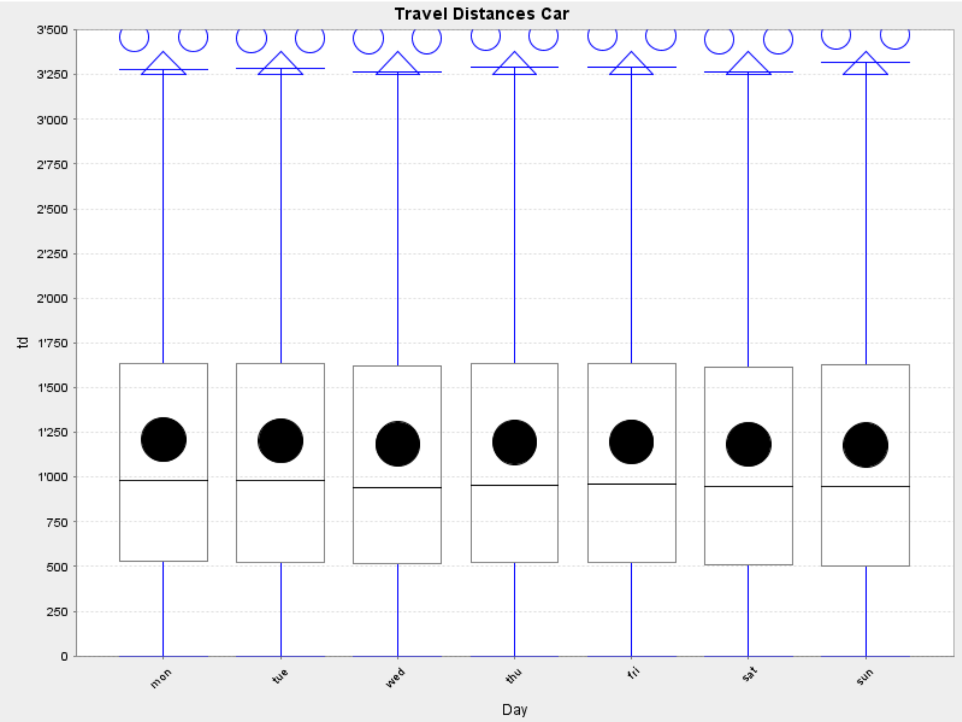
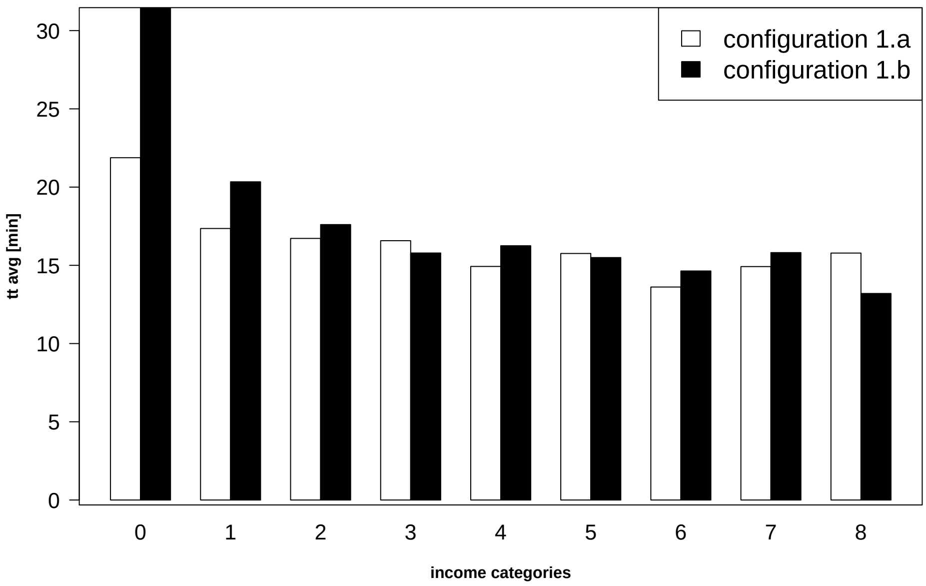


Figure 18: **Trip Travel Times per Income Class:** Average and Median [*min*]

(a) Average



(b) Median

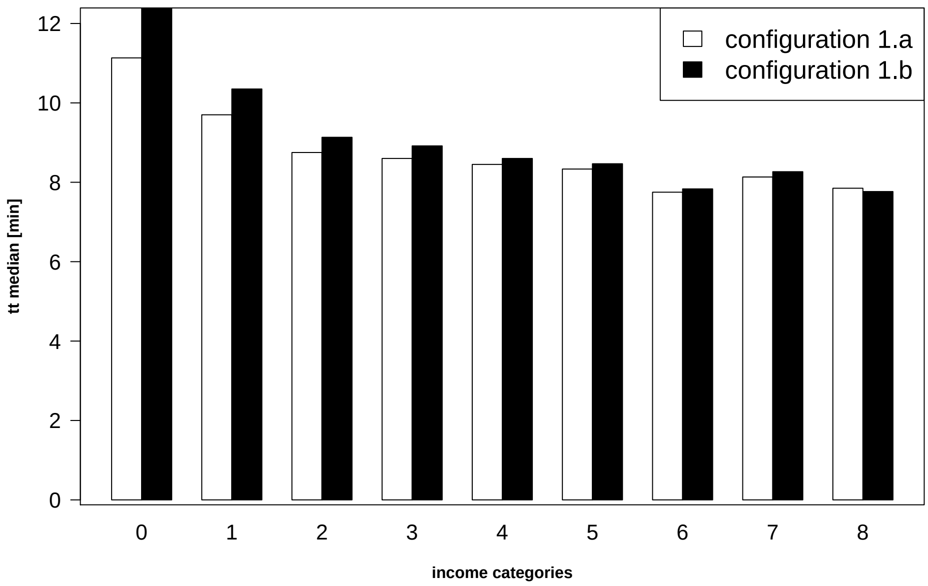
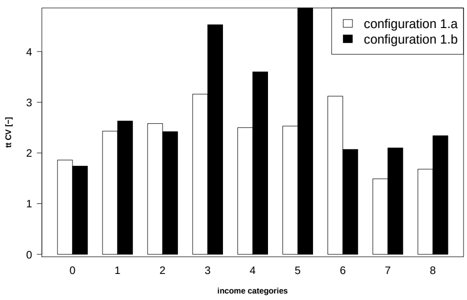
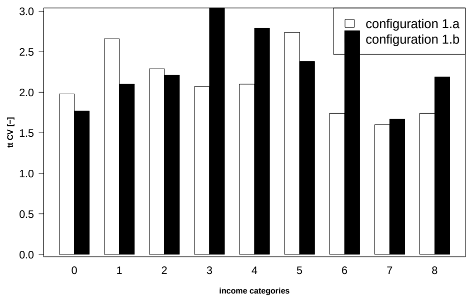


Figure 19: **Coefficient of Variation of Trip Travel Times per Income Class** [−]

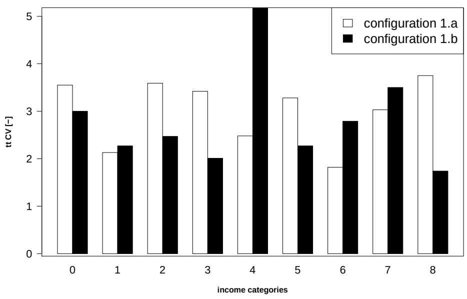
(a) Monday



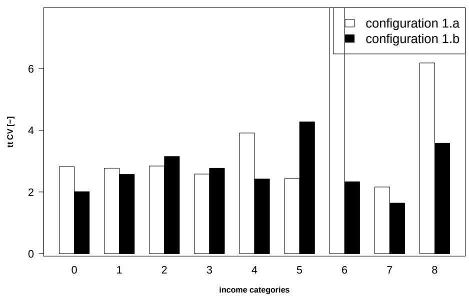
(b) Tuesday



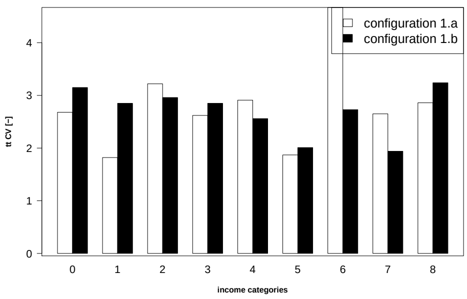
(c) Wednesday



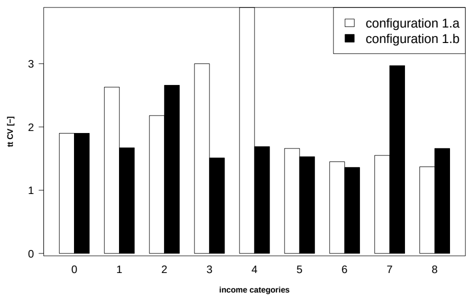
(d) Thursday



(e) Friday



(f) Saturday



(g) Sunday

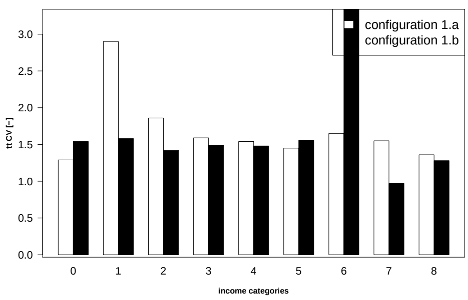


Table 1: **Number of Activities**

day	home	work	shop	leisure	education	other	Σ
mon	2.89	0.68	0.34	0.56	0.66	0.51	5.63
tue	2.90	0.75	0.36	0.64	0.64	0.54	5.83
wed	2.66	0.64	0.30	0.81	0.43	0.35	5.19
thu	2.77	0.72	0.42	0.60	0.57	0.40	5.49
fri	2.92	0.70	0.57	0.66	0.55	0.45	5.84
sat	2.64	0.16	0.59	1.13	0.05	0.30	4.86
sun	2.32	0.06	0.03	1.49	0.00	0.26	4.15

Table 2: **Choice Dimensions**

activity chains	derived from Thurgau data
home and work locations	derived from Swiss Census of Population
shopping, leisure, other and education locations	assigned according to neighborhood search (Balmer *et al.*, 2009, p.36)
times	derived from Thurgau study for initial demand and later subjected to MATSim equilibration
routes	MATSim equilibration only
modes	Starting MATSim equilibration with cars only and then performing sub-tour mode choice, defined in the footnote in Meister *et al.* (2010, p.10)

Table 3: **Mode Shares:** Given in [%] per day, according to microcensus (Swiss Federal Statistical Office (BFS), 2006, p.38), {Marti and Waldvogel (2003, p.12)}, and (MATSim Wednesday)

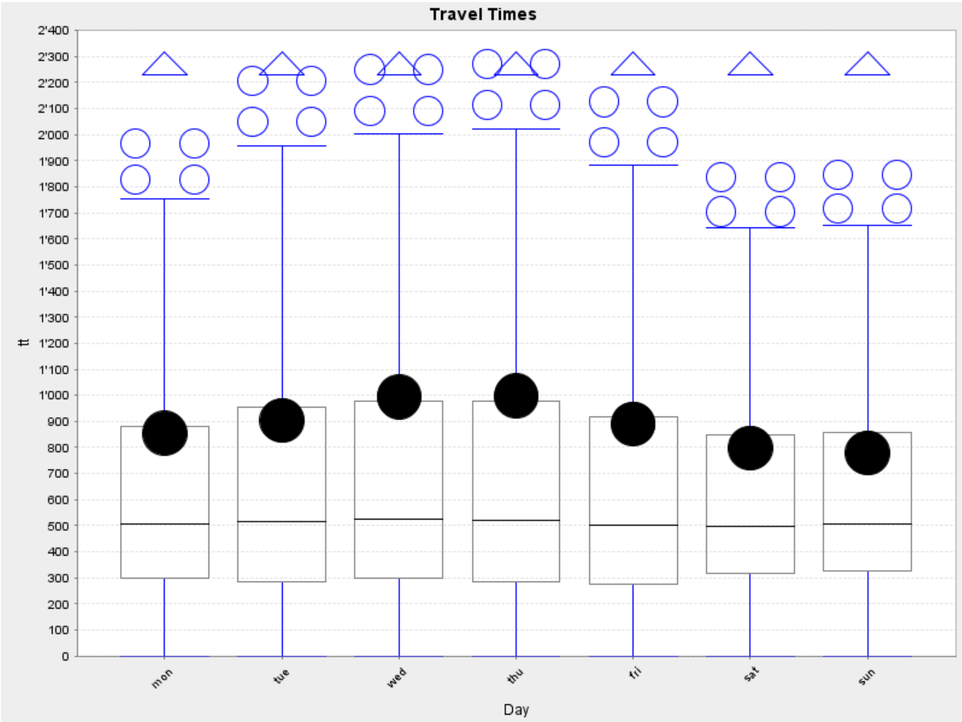
mode	distance	time	legs
car	68.8 {69.5} (69.2)	40.7 {43.6} (33.3)	37.1 {41.6}
pt	20.4 {17.7} (23.4)	11.1 {11.4} (29.4)	11.5 {10.3}
bike	2.1 {2.5} (4.0)	4.7 {5.6} (8.8)	5.3 {6.0}
walk	5.5 {4.6} (3.3)	39.7 {34.3} (28.4)	44.9 {40.1}
other	3.2 {5.6} (-)	3.8 {5.2} (-)	1.2 {2.0}

Table 4: **Average Values**

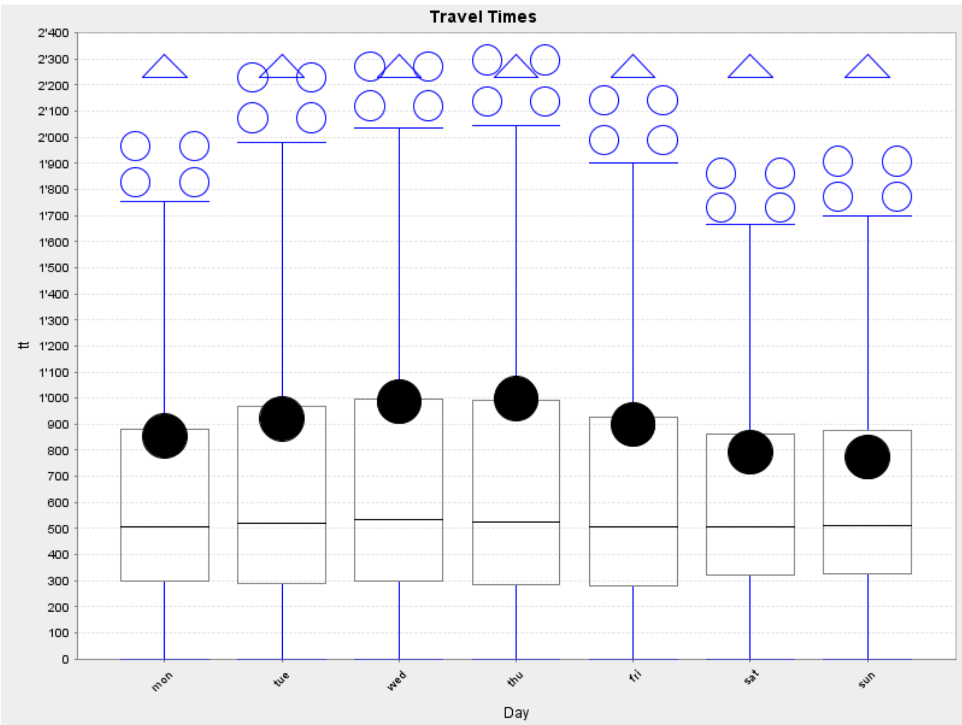
Configuration	**Mon**	**Due**	**Wed**	**Thu**	**Fri**	**Sat**	**Sun**	⊘
Average Trip Travel Times [s]								
0	911	993	1057	1048	957	852	841	951
1.a	855	904	994	998	891	798	779	888
1.b	968	999	1066	1079	975	865	830	969
1.c	855	921	986	998	899	793	773	889
Average Car Trip Travel Distances [m]								
0	9052	8932	9289	9194	8447	6437	5892	8178
1.a	8998	8970	9163	9181	8423	6393	5838	8138
1.b	8908	8883	9206	9082	8402	6409	5869	8109
1.c	8998	8997	9269	9188	8493	6444	5848	8177
Average Car Trip Travel Distances on Toll Links [m]								
0	3088	2662	2843	2681	2412	1890	1734	2473
1.a	2907	2584	2683	2589	2391	1856	1511	2360
1.b	3050	2597	2778	2635	2380	1815	1674	2418
1.c	2907	2621	2765	2563	2378	1819	1549	2371

Figure 20: **Trip Travel Times** [s]

(a) Configuration 1.a



(b) Configuration 1.c



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