Heterogeneous values of time in a multimodal context: An activity- and agent-based simulation approach

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Motivation and context

Heterogeneous user preferences (e.g. value of time, activity scheduling, perception of comfort, physical conditions) matter:

- Equity and redistribution effects
- Mean value is not always representative (Winners vs. Losers)
- Self-organization effects

Challenges

- Modelling of multiple heterogeneity dimensions
- Lack of data

Alternative approach

- Agent-based simulation with Stochastic User Equilibrium (e.g. MATSim)
MATSim: Multi-Agent Transport Simulation

- Stochastic User Equilibrium
- Boundary/initial conditions (land use, transport network, demographics, etc.)
- List of choice dimensions that are adapted
- Parallel Queue Model Approach and **fully integrated public transport simulation**
- Time step: 1sec over 24h period

**Choice dimensions**
- Route choice
- Mode Choice
- Departure time choice
- (Secondary activity-location choice)

**Constraints**
- Flow and storage capacity of the network
- Bus vehicle capacity
- Dwell times

Initial demand modeling

Supply data
Facilities
Population
Demand

Initial demand

Execution
Scoring
Replanning

Relaxed demand

Relaxation process

Evaluation
Heterogeneity in VOT

\( \alpha \): Value of Time  \( \beta \): Schedule delay early  \( \gamma \) – Schedule delay late

**Proportional Heterogeneity:** \( \alpha, \beta, \gamma \) vary proportionally \( \Rightarrow \mu, \eta, \lambda = \text{const.} \)
- usually strongly income dependent

**\( \alpha \) - Heterogeneity:** \( \mu = \frac{\alpha}{\beta} \) varies \( (\eta = \text{const.}) \)
e.g. type of job, family situation

**\( \gamma \) - Heterogeneity:** \( \eta = \frac{\gamma}{\beta} \) and \( \lambda = \frac{\alpha}{\gamma} \) vary \( (\mu = \text{const.}) \)
e.g. shift workers vs. flexible hours

\[
\mu = \frac{\alpha}{\beta} \quad \eta = \frac{\gamma}{\beta} \quad \lambda = \frac{\alpha}{\gamma}
\]

Introducing Heterogeneous Values of Time in MATSim

Marginal Value of Time in an activity – based context:

\[ mVTTS_a = \frac{mUTTS_a}{\beta_{a}^{mon}} = -\beta_{a}^{trv(i)} + \beta_{a}^{act(i+1)} \cdot \frac{t_{typ(i+1)}}{t_{i+1}} \]

Using continuous interaction from Axhausen et al. (2008):

\[ f(y, x) = \beta_{x} \left( \frac{y}{\hat{y}} \right)^{\lambda_{y,x}} x, \]

\[ mVTTS = \frac{-\beta_{mode}^{trv} + \beta_{act}^{inc} \cdot \frac{t_{typ}}{t}}{\beta_{a}^{mon}} \]

\[ = \frac{-\beta_{mode}^{trv} + \beta_{act}^{inc} \cdot \frac{t_{typ}}{t}}{\beta_{mon} \left( \frac{inc}{inc} \right)^{\lambda_{inc,mon}}} \]

\[ = \frac{-\beta_{TT,mode}^{inc} \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} + \beta_{act}^{inc} \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} \cdot \frac{t_{typ}}{t}}{\beta_{mon}}. \]

Heterogeneity in Values of Time as a consequence of different marginal utilities for activity performance and disutility of traveling. Marginal utility of money stays constant.
Value of Time and Schedule Delay in MATSim

\[ mVTT_S_a = \frac{mUTT_S_a}{\beta_m^{mon}} = -\beta_{trv}^{trv(i)} + \beta_a^{act(i+1)} \cdot \frac{t_{trv(i+1)}}{t_{i+1}} \]

\[ \alpha = mVTT_S \cdot \beta^{mon} = -\beta_{trv} + \beta^{act} \]

\[ \beta = \beta^{act} \]

\[ \gamma = \beta^{late} \]

Proportional heterogeneity

\[ \alpha = -\beta_{trv} + \beta^{act} = -\beta_{cost}^{trv} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} + \beta_{const}^{act} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} \]

\[ \beta = \beta^{act} = \beta_{const}^{act} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} \]

\[ \gamma = \beta_{const}^{late} \cdot \beta^{act} = \beta_{const}^{late} \cdot \beta_{const}^{act} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} \]

\[ \alpha - \text{heterogeneity} \]

\[ \alpha = -\beta_{trv} + \beta^{act} = -\beta_{cost}^{trv} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} + \beta_{const}^{act} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} \]

\[ \beta = \zeta_{\beta} \cdot \beta^{act} = \zeta_{\beta} \cdot \beta_{const}^{act} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} \]

\[ \gamma = \eta \cdot \beta \]

\[ \gamma - \text{heterogeneity} \]

\[ \alpha = -\beta_{trv} + \beta^{act} = -\beta_{cost}^{trv} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} + \beta_{const}^{act} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} \]

\[ \beta = \beta^{act} = \beta_{const}^{act} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} \]

\[ \gamma = \zeta_{\gamma} \cdot \beta^{act} = \zeta_{\gamma} \cdot \beta_{const}^{act} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} \]
Simulation setup: Corridor scenario

- 20km corridor with bus network (Bus stop every 600m)
- Home location density
- Work locations density

- 8000 agents
- Home – Work – Home activity chains
- Distance between bus stops: 600m
- Bus headway: 5 min
- Bus capacity: 90 (MAN NL323F)
- Bus length: 7.5m
- Dwell time per passenger: 1 sec
### Behavioural and monetary parameters and activity constrains

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_{act}$</td>
<td>$+ 0.48 \text{ utlis/h}$</td>
</tr>
<tr>
<td>$\beta_{tr,car}$</td>
<td>$- 0.48 \text{ utlis/h}$</td>
</tr>
<tr>
<td>$\beta_{tr,pt}$</td>
<td>$-0.66 \text{ utlis/h}$</td>
</tr>
<tr>
<td>$\beta_{tr,walk}$</td>
<td>$-1.401 \text{ utlis/h}$</td>
</tr>
<tr>
<td>$\beta_{wait,pt}$</td>
<td>$-1.458 \text{ utlis/h}$</td>
</tr>
<tr>
<td>$\beta_{cost}$</td>
<td>$-0.062 \text{ utlis/$}$</td>
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<tr>
<td>$\beta_{0,car}$</td>
<td>$-0.562 \text{ utlis}$</td>
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<tr>
<td>$\beta_{0,pt}$</td>
<td>$-0.124 \text{ utlis}$</td>
</tr>
<tr>
<td>$\beta_{0,walk}$</td>
<td>$0.0 \text{ utlis}$</td>
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</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT Fare</td>
<td>$2 \text{ $/trip}$</td>
</tr>
<tr>
<td>Car cost per km</td>
<td>$0.2 \text{ $/km}$</td>
</tr>
<tr>
<td>Parking cost</td>
<td>$6 \text{ $/trip} (= 12 \text{ $/day})$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Activity</th>
<th>Typical duration</th>
<th>Opening time</th>
<th>Latest start time</th>
<th>Earliest end time</th>
<th>Closing time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home</td>
<td>14h</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Work</td>
<td>9.5h</td>
<td>8.00am</td>
<td>9.00am</td>
<td>6.00pm</td>
<td>7.00pm</td>
</tr>
</tbody>
</table>


Income-based heterogeneity in VOT

Modeling of value of time heterogeneity based on household income: continuous interaction from Axhausen et al. (2008):

\[ f(y, x) = \beta_x \left( \frac{y}{\hat{y}} \right)^{\hat{y}, x} x, \]

Axhausen et al. (2008) estimate $\lambda = 0.1697$ for $\left(\frac{\text{inc}}{\text{inc}_\text{mon}}\right)^{\lambda_{\text{inc},\text{mon}}}$.

Different degrees of heterogeneity are tested for $\eta^* \lambda_{\text{inc},\text{mon}}$ with $n = 0, 1, 2, 3, 5$.

Adding $\alpha$ heterogeneity

Joint probability density distribution for VOT $\alpha$ and $\alpha / \beta$

$n = 1$

$n = 3$
Adding $\gamma$ heterogeneity

Joint probability density distribution for schedule delay late $\gamma$ and $\gamma/\beta$
Congestion pricing: first – best toll approximation


$$\text{External cost: } C(t_0) \approx t^e(t_0) - \tau^\text{free} - t_0.$$  

Queue encountered when entering the link at $t_0$ to dissolve at $t^e(t_0)$

Time bins in MATSim implementation: 5 min
Economic evaluation

**Social Welfare** = Consumer Surplus + Toll Revenue + PT Fare Revenue + PT Operation Cost

**Logsum** (Expected Maximum Utility)

\[ V_J = \frac{1}{\mu} \cdot \ln \sum_{j=1}^{J} e^{\mu V_j} \]

**Choice Set Generation:**
Chosen alternative, activity shift +1hr, -1hr, activity extension +1hr, -1hr, mode shift (total of 14 alternatives)
Evaluation using a pseudo – simulation approach

**Bus operation cost** according to Australian Transport Council (2006)

\[ C = (d_{vkm} \cdot c_{vkm} + t_{vh} \cdot c_{vh}) \cdot O + N_v \cdot c_{vday} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_{vkm}$</td>
<td>0.006 \cdot \text{capacity} + 0.513 [$/vkm]$</td>
</tr>
<tr>
<td>$c_{vday}$</td>
<td>1.6064 \cdot \text{capacity} + 22.622 [$/vday]$</td>
</tr>
<tr>
<td>$c_{vh}$</td>
<td>33 [$/vh]$</td>
</tr>
<tr>
<td>$O$</td>
<td>1.21</td>
</tr>
</tbody>
</table>
Social Welfare and Consumer Surplus before and after pricing

Social welfare

No bus service

2 min bus headway

Consumer surplus
Changes in Welfare and Consumer Surplus after congestion pricing

Social welfare

Consumer surplus
Changes in Consumer Surplus vs. Income

No bus service

2 min headway
Spread of consumer surplus changes

(a) $\alpha$ heterogeneity, no bus service

(b) $\alpha$ heterogeneity, 2 min headway
Changes in Consumer Surplus vs. $\alpha$ and $\beta / \alpha$ and $\gamma$

$\alpha$ heterogeneity, $n = 5$

$\gamma$ heterogeneity, $n = 5$
Key Findings and Outlook

- Significant self-organization effect with alternative mode of transport and heterogeneous user preferences
- Relative welfare gains from congestion pricing diminishes with increasing user heterogeneity given availability of alternative mode
- Changes in consumer surplus are strongly dependent on availability and service level of alternatives
- Public transport users can be the one who loose from congestion pricing in case mode shift leads to crowding and associated delays

Future Work

- Transfer to a realistic medium to large scale scenario (e.g. Sioux Falls, Singapore)
- Questions of spatial inequality
- Combination of different heterogeneity characteristics (Value of Time, Schedule Delay, Trip Distances, Activity Types)