Heterogeneous values of time in a multimodal context: An activity- and agent-based simulation approach
Artem Chakirov
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:** \( \alpha \) varies, \( \beta, \gamma = \text{const.} \)  \( (\mu, \lambda \neq \text{const.}, \eta = \text{const.}) \)
  e.g. type of job, family situation

**\( \gamma \) - Heterogeneity:** \( \alpha, \beta = \text{const.}, \gamma = \text{varies} \)  \( (\eta, \mu, \lambda \neq \text{const.}, \mu = \text{const.}) \)
  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

\[ mVTTS_a = \frac{mUTTS_a}{\beta_{a,\text{mon}}} = -\frac{\beta_{\text{mode}}^{\text{trv}} + \beta_{\text{act}} \cdot \frac{t_{\text{typ}}}{t}}{\beta_{a,\text{mon}}} \]

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

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

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

\[ = \frac{\beta_{\text{mon}} \left( \frac{\text{inc}}{\text{inc}} \right)^{\lambda_{\text{inc,mon}}}}{\beta_{\text{mon}} \left( \frac{\text{inc}}{\text{inc}} \right)^{-\lambda_{\text{inc,mon}}}} \]

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


Value of Time and Schedule Delay in MATSim

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

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

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

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

Proportional heterogeneity

\[ \beta^{trv} = \beta^{trv}_{cost} \cdot \left( \frac{inc}{inc} \right)^{-\lambda_{inc,mon}} \]

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

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

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

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

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

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

\[ \beta^{early} = \beta^{early}_{const} \]

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

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

\[ \beta^{trv} = \beta^{trv}_{const} \]

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

\[ \beta^{early} = \beta^{early}_{const} \]

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

Corridor scenario

- 20km corridor with bus network (Bus stop every 600m)
- 12000 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>+0.96 [utils/h]</td>
</tr>
<tr>
<td>$\beta_{tr, car}$</td>
<td>0.0 [utils/h]</td>
</tr>
<tr>
<td>$\beta_{tr, pt}$</td>
<td>-0.18 [utils/h]</td>
</tr>
<tr>
<td>$\beta_{tr, walk}$</td>
<td>-1.14 [utils/h]</td>
</tr>
<tr>
<td>$\beta_{wait, pt}$</td>
<td>-0.18 [utils/h]</td>
</tr>
<tr>
<td>$\beta_{cost}$</td>
<td>-0.062 [utils/$]</td>
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<tr>
<td>$\beta_{0, car}$</td>
<td>-0.562 [utils]</td>
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<tr>
<td>$\beta_{0, pt}$</td>
<td>0.0 [utils/$]</td>
</tr>
<tr>
<td>$\beta_{0, walk}$</td>
<td>0.0 [utils/$]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PT Fare</td>
<td>2 $</td>
</tr>
<tr>
<td>Car cost per km</td>
<td>0.4 $/km</td>
</tr>
<tr>
<td>Parking cost</td>
<td>6$/trip</td>
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</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 Morning</td>
<td>8h</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Work</td>
<td>8h</td>
<td>8.00am</td>
<td>9.00am</td>
<td>5.00pm</td>
<td>6.00pm</td>
</tr>
<tr>
<td>Home Evening</td>
<td>6h</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>


Income distribution from Sioux Falls synthetic population

Income-based heterogeneity in VOT

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

Different degree of heterogeneity are tested for $\eta^* \lambda_{\text{inc,mon}}$ with $n = 0, 1, 2, 3, 5, 10$.

Lorenz curves

First – best pricing implemented according to

**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 dissolves at \( t^e(t_0) \)
First Results
Change in realized consumer welfare in % (all toll is returned)

Proportional heterogeneity

$\alpha$- heterogeneity

$\gamma$- heterogeneity
Schedule delay cost

Proportional heterogeneity

First-best toll

No Toll

α - heterogeneity

γ - heterogeneity

TTC_morning
TTC_evening
SDC_morning
SDC_evening
First-Best Toll Benefits with Proportional Heterogeneity (relative)

Changes in Consumer Surplus in %

Changes in Consumer Welfare in %
Car Mode shares – Proportional Heterogeneity

No Toll

First-best toll
Morning Departure Times vs. Income

Homogeneous VOT  Prop hetero n=1  Prop hetero n=3  Alpha hetero n=1  Alpha hetero n=3
Evening Departure Times vs. Income

Homogeneous

Prop hetero n=1

Prop hetero n=3

Alpha hetero n=1

Alpha hetero n=3

No Toll

First-best toll
Outlook

• Systematic comparison to transportation economics literature (e.g. Verhoef, van den Berg)

• 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)
Toll revenue variations during the last 50 iterations

(a) Proportional

(b) Alpha

(c) Gamma

(d) Alpha Proportional
First-Best Toll Benefits with Proportional Heterogeneity (absolute)

Changes in Consumer Surplus

Income Groups

Changes in Consumer Welfare

Income Groups