Accounting for Spatial Dependency in Joint Models of Motorized and Non-motorized Travel

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Spatial Dependency

- Tobler’s (1970) First Law of Geography:
  "Everything is related to everything else, but near things are more related than distant things"

- Individuals located closer to each other are likely to share similarity in
  - Physical environment
  - Social environment

- Implications on travel modeling
Recent Policy Focus

- Auto $\Rightarrow$ Multimodal $\Rightarrow$ Active Travel
- Congestion, air quality, climate change, obesity/health
- Built environment design
- Seeking win-win solutions:
  - Reduced auto use
  - Increased walking/biking
Built Environment Impacts

- Net effect of these BE measures on both motorized and non-motorized travel?
- Which BE strategies are most beneficial to the society?

<table>
<thead>
<tr>
<th></th>
<th>Increase</th>
<th>Decrease</th>
<th>Same</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Motorized</td>
<td></td>
<td></td>
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<tr>
<td>Travel</td>
<td></td>
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<tr>
<td>Motorized</td>
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<tr>
<td>Travel</td>
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</tbody>
</table>

Win-Win!
Existing Literature

- Most studies do not provide needed insight into the trade-offs between motorized and non-motorized travel
- Empirical evidence on the impacts of BE remains very mixed
- Little sensitivity analysis of how benefit estimates vary by modeling methods
Modeling Framework

- Extends from Guo et al (2007), which was frequency-based
- Dependent variables:
  - daily vehicle miles traveled (VMT), and
  - miles walked/biked (MWB)
Independent Regression

VMT: \[ y_1 = X_1 \beta_1 + \epsilon_1 \]

MWB: \[ y_2 = X_2 \beta_2 + \epsilon_2 \]

\[ \epsilon_1 \sim N(\mu, \sigma_1^2) \]

\[ \epsilon_2 \sim N(\mu, \sigma_2^2) \]

COV \( \epsilon_1, \epsilon_2 \) = 0
Independent Regression

VMT: \[ y_1 = X_1 \beta_1 + \varepsilon_1 \]

MWB: \[ y_2 = X_2 \beta_2 + \varepsilon_2 \]

Model Estimation

\[
\hat{\beta}_{1,\text{OLS}} = \left( X_1' X_1 \right)^{-1} X_1' y_1
\]

\[
\hat{\beta}_{2,\text{OLS}} = \left( X_2' X_2 \right)^{-1} X_2' y_2
\]
Seemingly Unrelated Regression

VMT: \( y_1 = X_1 \beta_1 + \varepsilon_1 \)

MWB: \( y_2 = X_2 \beta_2 + \varepsilon_2 \)

\[
\begin{bmatrix}
  y_1 \\
  y_2
\end{bmatrix}
= \begin{bmatrix}
  X_1 & 0 \\
  0 & X_2
\end{bmatrix}
\begin{bmatrix}
  \beta_1 \\
  \beta_2
\end{bmatrix}
+ \begin{bmatrix}
  \varepsilon_1 \\
  \varepsilon_2
\end{bmatrix}
\]

\[
Y = X\beta + \varepsilon
\]

Stacked Form

\[
E \begin{bmatrix}
  \varepsilon'
\end{bmatrix} = \Omega = \Sigma \otimes I, \quad \Sigma = \begin{bmatrix}
  \sigma_1^2 & \sigma_{12} \\
  \sigma_{21} & \sigma_2^2
\end{bmatrix}
\]
Seemingly Unrelated Regression

\[ Y = X\beta + \varepsilon \]

\[ E \left[ \varepsilon' \right] = \Omega = \Sigma \otimes I, \Sigma = \begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{21} & \sigma_2^2 \end{bmatrix} \]

Model Estimation

\[ \hat{\beta}_{GLS} = \left[ X' \left( \sum^{-1} \otimes I \right) X \right]^{-1} X' \left( \sum^{-1} \otimes I \right) \hat{Y} \]
Spatial Seemingly Unrelated Regression

VMT: \[ y_1 = X_1\beta_1 + \varepsilon_1, \quad \varepsilon_1 = \lambda_1 W_1 \varepsilon_1 + \mu_1 \]

MWB: \[ y_2 = X_2\beta_2 + \varepsilon_2, \quad \varepsilon_2 = \lambda_2 W_2 \varepsilon_2 + \mu_2 \]

Inter-person correlation due to spatial dependence

Rewrite

\[ \varepsilon_1 = \begin{pmatrix} \mu_1 \end{pmatrix} - \lambda_1 W_1 \begin{pmatrix} \mu_1 \end{pmatrix} = B_1^{-1} \mu_1 \]

\[ \varepsilon_2 = \begin{pmatrix} \mu_2 \end{pmatrix} - \lambda_2 W_2 \begin{pmatrix} \mu_2 \end{pmatrix} = B_2^{-1} \mu_2 \]

\[ Y = X\beta + \varepsilon \]

Stacked Form

\[ E \begin{bmatrix} \varepsilon' \end{bmatrix} = \Omega = B^{-1} \begin{pmatrix} \varepsilon \otimes I_N \end{pmatrix} B_2^{-1}', \quad B = \begin{bmatrix} B_1 & 0 \\ 0 & B_2 \end{bmatrix} \]
Spatial Seemingly Unrelated Regression

\[ Y = X\beta + \varepsilon \]

\[ E \left[ \varepsilon' \varepsilon \right] = \Omega = B^{-1} \otimes I_N \hat{B}^{-1}, \quad B = \begin{bmatrix} B_1 & 0 \\ 0 & B_2 \end{bmatrix} \]

Model Estimation

Iterative procedure to optimize the following log-likelihood function:

\[ L = -\frac{1}{2} \ln|\Omega| - \frac{1}{2} \left( \mathbf{X} - XB \right) \hat{\Omega}^{-1} \left( \mathbf{X} - XB \right) \]
Data for Analysis

- 2001 National Household Travel Survey
- Population Census
- Weather – precipitation & temperature (NCDC)
- Land use data
- Employment data
- Bicycle, pedestrian facilities
- Roadway network
Exogenous Variables

- Trip-Maker Characteristics
- Trip Day Characteristics: temperature, snowfall, weekend, weekday trips
- Built Environment Characteristics
  - **Regional level:** retail, recreation, and employment accessibility measures
  - **Neighborhood level:** 0.25 and 1 mile network buffers around sampled households. Include:
    - Socio-demographic distribution
    - Land use mix
    - Multimodal transportation facilities
## Sample Characteristics

- **50% of 4974 persons in the final sample**

<table>
<thead>
<tr>
<th></th>
<th>Sample %</th>
<th>Average Miles Walked/Biked (MWB) per person</th>
<th>Average Vehicle Miles Traveled (VMT) per person</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Entire Sample</strong></td>
<td>100</td>
<td>0.512 (1.90)</td>
<td>18.269 (22.24)</td>
</tr>
<tr>
<td><strong>Age</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17 to 30 years</td>
<td>16.5</td>
<td>0.761 (2.39)</td>
<td>18.624 (22.39)</td>
</tr>
<tr>
<td>31 to 45 years</td>
<td>42.1</td>
<td>0.484 (1.95)</td>
<td>17.239 (22.89)</td>
</tr>
<tr>
<td>46 to 60 years</td>
<td>27.6</td>
<td>0.499 (1.82)</td>
<td>20.109 (21.05)</td>
</tr>
<tr>
<td>Above 60 years</td>
<td>13.8</td>
<td>0.323 (1.03)</td>
<td>17.312 (22.16)</td>
</tr>
<tr>
<td><strong>Gender</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>42.6</td>
<td>0.564 (1.90)</td>
<td>18.409 (22.18)</td>
</tr>
<tr>
<td>Female</td>
<td>57.4</td>
<td>0.473 (1.89)</td>
<td>18.166 (22.28)</td>
</tr>
<tr>
<td><strong>Household Income per Annum</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low (less than $25K)</td>
<td>9.5</td>
<td>0.685 (1.95)</td>
<td>13.104 (19.63)</td>
</tr>
<tr>
<td>Medium (&gt; $25K to $50K)</td>
<td>25</td>
<td>0.501 (1.72)</td>
<td>17.111 (20.15)</td>
</tr>
<tr>
<td>High (&gt; $50K to $75K)</td>
<td>23.7</td>
<td>0.501 (1.85)</td>
<td>19.666 (22.23)</td>
</tr>
<tr>
<td>Very High (more than $75K)</td>
<td>35.8</td>
<td>0.512 (2.11)</td>
<td>20.031 (24.69)</td>
</tr>
<tr>
<td><strong>Ethnicity</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>White</td>
<td>92</td>
<td>0.528 (1.95)</td>
<td>18.761 (22.49)</td>
</tr>
<tr>
<td>African American</td>
<td>1.8</td>
<td>0.245 (0.83)</td>
<td>12.733 (19.53)</td>
</tr>
<tr>
<td>Asian</td>
<td>2.2</td>
<td>0.633 (1.81)</td>
<td>10.103 (14.72)</td>
</tr>
</tbody>
</table>
## Sample Characteristics

<table>
<thead>
<tr>
<th></th>
<th>Quartile 1</th>
<th>Quartile 2</th>
<th>Quartile 3</th>
<th>Quartile 4</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Retail Accessibility</strong></td>
<td>25</td>
<td>0.344 (1.59)</td>
<td>23.838 (25.35)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.328 (1.31)</td>
<td>19.325 (21.77)</td>
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<tr>
<td></td>
<td>25</td>
<td>0.426 (1.56)</td>
<td>16.997 (21.80)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.952 (2.75)</td>
<td>12.864 (17.97)</td>
<td></td>
</tr>
<tr>
<td><strong>Population Density - 1 mi buffer</strong></td>
<td>25</td>
<td>0.351 (1.49)</td>
<td>21.754 (22.32)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.375 (1.47)</td>
<td>19.932 (22.36)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.433 (1.67)</td>
<td>17.390 (23.45)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.893 (2.67)</td>
<td>13.951 (19.90)</td>
<td></td>
</tr>
<tr>
<td><strong>Population Density – ¼ mi buffer</strong></td>
<td>25</td>
<td>0.364 (1.48)</td>
<td>22.113 (22.35)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.443 (1.75)</td>
<td>18.598 (23.64)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.483 (1.93)</td>
<td>17.093 (19.89)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.764 (2.34)</td>
<td>15.168 (22.37)</td>
<td></td>
</tr>
<tr>
<td><strong>Road length with bike lane - 1 mi buffer</strong></td>
<td>25</td>
<td>0.408 (1.65)</td>
<td>20.412 (24.52)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.436 (1.72)</td>
<td>18.106 (22.82)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.514 (1.76)</td>
<td>17.966 (20.70)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.696 (2.39)</td>
<td>16.230 (20.19)</td>
<td></td>
</tr>
<tr>
<td><strong>Road length with bike lane – ¼ mi buffer</strong></td>
<td>25</td>
<td>0.427 (1.66)</td>
<td>19.675 (21.66)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.411 (1.53)</td>
<td>18.314 (21.35)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.397 (1.57)</td>
<td>19.902 (26.11)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>0.800 (2.60)</td>
<td>14.889 (19.17)</td>
<td></td>
</tr>
</tbody>
</table>
### Estimation Results

<table>
<thead>
<tr>
<th>Explanatory Variables</th>
<th>SUR MODEL</th>
<th>SPATIAL SUR MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MWB</td>
<td>VMT</td>
</tr>
<tr>
<td></td>
<td>Coeff.</td>
<td>z-stat</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Person/Household/Trip Day Characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Person is employed</td>
<td>0.1663</td>
<td>2.976***</td>
</tr>
<tr>
<td>Person is young (17 to 30 years old)</td>
<td>0.2255</td>
<td>2.929***</td>
</tr>
<tr>
<td>Person is Caucasian</td>
<td>0.2729</td>
<td>2.761***</td>
</tr>
<tr>
<td>Person holds a driving license</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Person has a degree (Bachelor’s or higher)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Number of bicycles owned by household</td>
<td>0.1480</td>
<td>8.309***</td>
</tr>
<tr>
<td>Household has no car</td>
<td>0.3548</td>
<td>1.803*</td>
</tr>
<tr>
<td>Family income per year (in $10,000)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Number of cell phones in household</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Housing type is either an apartment or a dormitory</td>
<td>0.1704</td>
<td>1.985**</td>
</tr>
<tr>
<td>Lowest temperature on travel day</td>
<td>0.0073</td>
<td>4.805***</td>
</tr>
<tr>
<td>Travel day is on a weekend</td>
<td>--</td>
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</tr>
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<td></td>
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## Estimation Results

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<td>Coeff.</td>
<td>z-stat</td>
<td>Coeff.</td>
<td>z-stat</td>
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</tbody>
</table>

### Built Environment Characteristics

#### Regional factors
- Rural setting
- Retail accessibility

#### Neighborhood socio-demographic composition
- % high income households in neighborhood – 1 mile buffer
- Household density (per acre) – ¾ mile buffer

#### Neighborhood land use characteristics
- Land use mix – 1 mile buffer
- Interacted with vehicles per person in household
- Interacted with travel day being on a weekend

#### Neighborhood transportation network characteristics
- Length of roadway with no sidewalk – 1 mile buffer
- Length of roadway with bike lane – ¾ mile buffer
- Number of intersections (per acre) – ¾ mile buffer

---

**Coefficients and z-statistics for MWB and VMT in both SUR and spatial SUR models**

- Retail accessibility: MWB = 0.0399, z-stat = 3.341***; VMT = -0.5785, z-stat = -3.438***
- Household density: MWB = 0.2823, z-stat = 2.833***; VMT = 0.2084, z-stat = 1.167
- Land use mix: MWB = -0.5786, z-stat = -3.466***; VMT = -6.0547, z-stat = -2.874***
- Length of roadway with no sidewalk: MWB = 0.0483, z-stat = 3.288***; VMT = 0.5397, z-stat = 2.128**
- Number of intersections: MWB = 0.0503, z-stat = 2.261**; VMT = 0.0160, z-stat = 0.550

**R-squared and system R-square**

- SUR Model: MWB = 0.0511, VMT = 0.1898; Spatial SUR Model: MWB = 0.0429, VMT = 0.236
- System R-square: SUR Model = 0.1261; Spatial SUR Model = 0.1507
Model Goodness-of-Fit

- Inter-equation correlation (-0.08) is statistically significant
- Spatial autocorrelation is statistically significant
- SSUR has a higher overall r-square (0.1507 vs. 0.1261)
Scenario Analysis

- What if all roadways in Dane County were fitted with sidewalks at least on one side?
  - 1220 mi of 4509 mi did not have sidewalk on either side of the road
Scenario Analysis

- **Construction Cost**
  - Cost for concrete curbs is approximately $15 per linear foot and $11 per ft$^2$ for walkways.
  - FHWA and ITE recommended minimum width of 5 ft is estimated at $70 per linear foot.
  - Total cost estimated at $450.83M.
Scenario Analysis

Determine desired infrastructure change
(1220 mi of additional sidewalk ⇒ 1.77 mi increase per person)

Identify corresponding model coefficients to determine change in person miles walked/bikes (MWB) and vehicle miles traveled (VMT)
(MWB: +0.0554 x 1.77 = +0.098 mi/psn)
(VMT: -0.6447 x 1.77 = -1.141 mi/psn)

Calculate total physical activity benefit due to MWB increase
($ 86.02 M)

Calculate total air quality benefit due to VMT decrease
($ 8.22 M)

Compute total health benefit accrued from improved PA and air quality
$ 94.24 M

Compute other societal benefits and costs

Compute benefit-cost ratio, 10 year life cycle, 3% discount rate
(Total benefit: $919.08 M, Total cost: $ 450.83 M)
(Benefit-Cost Ratio: 2.04)
## Sensitivity to Model Structure

<table>
<thead>
<tr>
<th>Parameter on sidewalk</th>
<th>SSUR</th>
<th>SUR</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWB</td>
<td>0.0554</td>
<td>0.0483</td>
</tr>
<tr>
<td>VMT</td>
<td>-0.6447</td>
<td>-3.288</td>
</tr>
<tr>
<td>BCR</td>
<td>2.04</td>
<td>1.77</td>
</tr>
</tbody>
</table>
Conclusions

- SSUR model is statistically superior to the SUR mode – at least in this empirical context – but more difficult to estimate
- Estimate of return on investment can differ significantly when different model structures are used
- Need to account for the possibility of inter-modal correlation and spatial dependency
- Other applications of the SSUR in travel modeling...