Network Structure and Travel Behavior

David Levinson and Pavithra Parthasarathi
Design of urban form is commonly suggested to affect travel behavior.

These studies miss the explicit consideration of the underlying network structure.
What is Network Structure?

The layout of the network and the characteristics of the individual elements (Kissling 1969).

The arrangement and connectivity of the network (Xie 2005).
Travel Behavior

Urban Form Factors

Non Urban Form Factors

Source: Frank & Pivo (1994)
Travel Behavior

Urban Form Factors

Non Urban Form Factors

Source: Frank & Pivo (1994)
Travel Behavior

Urban Form Factors

Non Urban Form Factors

Source: Frank & Pivo (1994)
Travel Behavior

Non Urban Form Factors

Urban Form Factors

Source: Frank & Pivo (1994)
Network Structure Factors

Transportation System Performance

Perceived Travel

Actual Travel

Transportation System Performance
Network Structure Factors

Transportation System Performance

Perceived Travel Time

Actual Travel

Transportation System Performance
Network Structure Factors

Perceived Travel Time

Transportation System Performance

Actual Travel

-
Network Structure Factors

- Transportation System Performance
- Perceived Travel Time
- Actual Travel
- Congestion

Relationships:
- Positive impact from Network Structure Factors to Perceived Travel Time
- Positive impact from Perceived Travel Time to Actual Travel
- Positive impact from Actual Travel to Congestion
- Negative impact from Network Structure Factors to Actual Travel
Levels of analysis

Trip Level

Trip buffer
Household Level

Activity space polygon
Metropolitan Level
Network Measures
<table>
<thead>
<tr>
<th>Category</th>
<th>Network Measures</th>
<th>Trip</th>
<th>Household</th>
<th>Metropolitan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hierarchy</strong></td>
<td>Relative discontinuity</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Proportion of limited access roads</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>Topology</strong></td>
<td>Treeness</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Completeness</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Proportion of nodal degrees</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Circuity</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td><strong>Morphology</strong></td>
<td>P2A ratio</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td><strong>Scale</strong></td>
<td>Street density</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Intersection density</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Relative discontinuity

A

B

50 km/h

k=1

75 km/h

k=2

100 km/h

k=3

75 km/h

k=2

50 km/h

k=1

A

B
Change in hierarchy, \( y_a = |k_1 - k_2| \)

\( k = \text{Hierarchy level} \)

Trip discontinuity, \( Y_P = \sum_{a \in P} y_a \)

\( P = \text{Identified shortest path} \)

Relative discontinuity, \( Y'_P = Y_P / l_P \)

\( l_P = \text{Length (km) of the shortest path} \)
Proportion of limited access roads
Proportion of limited access roads = \frac{L_{lb}}{L_{sb}}

L_{lb} = \text{Length of limited access roads within the trip buffer}
L_{sb} = \text{Length of street network within the trip buffer}

Proportion of limited access roads = \frac{L_{la}}{L_{sa}}

L_{la} = \text{Length of limited access roads within the activity space polygon}
L_{sa} = \text{Length of street network within the activity space polygon}

Percentage of freeways \%F = \frac{L_{fm}}{L_{rm}} * 100

L_{fm} = \text{Freeway kilometers in the area}
L_{rm} = \text{Roadway kilometers in the area}
Circuit (Tree) Networks

Circuit - A closed path, with no less than three links that begin and end at the same vertex

Tree - Set of connected links without any complete circuits
Treeness, $\phi_{\text{tree}} = \frac{L_{tb}}{L_{sb}}$

$L_{tb} = \text{Length of street segments belonging to a tree network within the buffer}$

$L_{sb} = \text{Length of street network within the buffer}$

Treeness, $\phi_{\text{tree}} = \frac{L_{ta}}{L_{sa}}$

$L_{ta} = \text{Length of street segments belonging to a tree network within the activity space polygon}$

$L_{sa} = \text{Length of street network within the activity space polygon}$

Treeness, $\phi_{\text{tree}} = \frac{L_{tm}}{L_{sm}}$

$L_{tm} = \text{Length of street segments belonging to a tree network in the area}$

$L_{sm} = \text{Length of street network in the area}$
### Completeness

<table>
<thead>
<tr>
<th>Network</th>
<th>Nodes, v</th>
<th>Maximum number of 2-way links, e</th>
<th>Completeness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>6</td>
<td>100%</td>
</tr>
<tr>
<td>C</td>
<td>4</td>
<td>12</td>
<td></td>
</tr>
</tbody>
</table>
\[
\rho_e = \frac{E}{E_{max}} = \frac{E}{V^2 - V}
\]

\(E_{max}\) = Maximum number of links or street segments in the network

\(E\) = Number of links or street segments in the network

\(V\) = Number of nodes or intersections in the network
Proportion of nodal degrees

Nodal degree

i
Proportion of $i$-degree nodes $= \frac{V_{ib}}{V_b}$

$V_{ib} =$ Number of nodes with $i$-degrees within the trip buffer

$V_b =$ Number of intersection nodes within the trip buffer

$i =$ 1,2,...... maximum degree

Proportion of $i$-degree nodes $= \frac{V_{ia}}{V_a}$

$V_{ia} =$ Number of nodes with $i$-degrees within the activity space polygon

$V_a =$ Number of intersection nodes within the activity space polygon

$i =$ 1,2,...... maximum degree
Circuity

Euclidean Distance

Network Distance
Trip Circuity, $C_t = \frac{D_{tn}}{D_{te}}$

$D_{tn}$ = Network distance between trip origin and destination
$D_{te}$ = Euclidean distance between trip origin and destination

Metropolitan Circuity, $C_m = \frac{D_n}{D_e}$

$D_n$ = Sum of network distance between OD pairs
$D_e$ = Sum of euclidean distance between OD pairs
P2A = \frac{P_p^2}{A_p}

Squared perimeter of the polygon enclosed by the street network

A_p = Area of of the polygon enclosed by the street network
Street density

Intersection density

\[ \rho_{lx} = \frac{L_{sx}}{A_x} ; \quad \rho_{vx} = \frac{V_x}{A_x} \]

\( L_{sx} \) = Length of street network

\( V_{sx} \) = Number of street intersections

\( A_x \) = Area, defined as trip buffer, activity space polygon or metropolitan area
Network Structure Factors

Perceived Travel

Transportation System Performance

Actual Travel
Questions

Do travelers perceive travel time differently?

Can this difference be related to network structure?
Dataset 1 -

Travel Behavior Inventory (TBI).

Conducted by the Twin Cities Metropolitan Council and MnDOT in 2000.

One day household travel survey.
Dataset II -

I-35 W travel surveys

Conducted by the University of Minnesota in 2007-2008.

Combination of computer-based (W-2007), paper (P-2008) and GPS surveys.
I. Estimate measures of network structure along the route.

Actual route either obtained directly from GPS data or identified using shortest travel time path algorithms.
2. Estimate ratio of travel time.

\[ \tau = \frac{T_r}{T_m} \]

\( \tau \) = Ratio of travel time,

\( T_r \) = Perceived (reported) commute travel time,

\( T_m \) = Measured commute travel time.
3. Stratify travelers into two groups.

Overestimating group, \( G_o : \tau > 1.0 \)

Underestimating group, \( G_u : \tau < 1.0 \)
4. Conduct t-tests to compare means.

\[ \bar{N}_{iGo} = \bar{N}_{iGu} \]

- \( \bar{N}_{iGo} \) = Network measure, \( i \), in the over group, \( G_o \)
- \( \bar{N}_{iGu} \) = Network measure, \( i \), in the under group, \( G_u \)
5. Develop regression models to predict the ratio ($\tau_{tt}$) of travel time.

$$\tau = \frac{Tr}{Tm} = f(N_b, X_{sd}, Acc_d)$$

- $N_b$ = Measures of network structure within the trip buffer,
- $X_{sd}$ = Socio-demographic characteristics,
- $Acc_d$ = Distance based measure of accessibility
Hypothesis A-1

Aspects of network structure that increase travel complexity will increase the perceived travel time.

For travelers in the over group ($G_o$) compared to travelers in the under group ($G_u$).

The mean of relative discontinuity is higher.
Hypothesis A-2

Aspects of network structure that decrease network speed will increase the perceived travel time.

For travelers in the over group \( (G_o) \) compared to travelers in the under group \( (G_u) \).

The mean of the proportion of non-limited access roadways is *higher*.

The mean of street density is *higher*.

The mean of intersection density is *higher*.
Hypothesis A-3

Aspects of network structure that increase network travel distance between fixed origin and destinations will increase perceived travel time.

For travelers in the over group ($G_o$) compared to travelers in the under group ($G_u$).

- The mean of arterial treeness is higher
- The mean of P2A ratio is higher
- The mean of circuity is higher
<table>
<thead>
<tr>
<th>Network variables</th>
<th>Over group</th>
<th>Under group</th>
<th>t</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative discontinuity</td>
<td>0.304</td>
<td>0.199</td>
<td>5.493</td>
<td>***</td>
</tr>
<tr>
<td>Proportion of limited access roads</td>
<td>0.055</td>
<td>0.054</td>
<td>0.732</td>
<td></td>
</tr>
<tr>
<td>Street density</td>
<td>18.296</td>
<td>15.164</td>
<td>12.643</td>
<td>***</td>
</tr>
<tr>
<td>Intersection density</td>
<td>28.936</td>
<td>22.374</td>
<td>11.853</td>
<td>***</td>
</tr>
<tr>
<td>Arterial treeness</td>
<td>0.009</td>
<td>0.011</td>
<td>-1.672</td>
<td>*</td>
</tr>
<tr>
<td>P2A ratio</td>
<td>24.505</td>
<td>24.906</td>
<td>-2.657</td>
<td>***</td>
</tr>
<tr>
<td>Trip circuity</td>
<td>1.344</td>
<td>1.365</td>
<td>-0.751</td>
<td></td>
</tr>
<tr>
<td>No. of observations</td>
<td>3,655</td>
<td>450</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* p<.10, ** p<0.05, *** p<.01
T-test comparisons - I-35 W Travel Surveys, Commute Trips

Ho: Difference between means is not zero

<table>
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<th>Over group</th>
<th>Under group</th>
<th>t</th>
<th>Sig</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative discontinuity</td>
<td>0.331</td>
<td>0.251</td>
<td>1.917</td>
<td>*</td>
</tr>
<tr>
<td>Proportion of limited access roads</td>
<td>0.082</td>
<td>0.105</td>
<td>-2.767</td>
<td>***</td>
</tr>
<tr>
<td>Street density</td>
<td>18.936</td>
<td>15.373</td>
<td>4.137</td>
<td>***</td>
</tr>
<tr>
<td>Intersection density</td>
<td>37.926</td>
<td>34.989</td>
<td>1.679</td>
<td>*</td>
</tr>
<tr>
<td>Arterial treeness</td>
<td>0.012</td>
<td>0.012</td>
<td>0.054</td>
<td></td>
</tr>
<tr>
<td>P2A ratio</td>
<td>23.292</td>
<td>22.925</td>
<td>0.315</td>
<td></td>
</tr>
<tr>
<td>Trip circuity</td>
<td>1.333</td>
<td>1.362</td>
<td>-0.856</td>
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<tr>
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<td>213</td>
<td>45</td>
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<td></td>
</tr>
</tbody>
</table>

* p<.10, ** p<0.05, *** p<.01
Predicting ratio (Tau) of travel time - TBI, commute trips

<table>
<thead>
<tr>
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<th>Hypothesis</th>
<th>Coef.</th>
<th>Sig.</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative discontinuity</td>
<td>+S</td>
<td>-0.323</td>
<td></td>
<td>-0.554</td>
</tr>
<tr>
<td>Proportion of limited access roads</td>
<td>-S</td>
<td>-4.722</td>
<td>*</td>
<td>-1.876</td>
</tr>
<tr>
<td>Street density</td>
<td>+S</td>
<td>0.086</td>
<td>***</td>
<td>3.113</td>
</tr>
<tr>
<td>Arterial treeness</td>
<td>+S</td>
<td>8.115</td>
<td>**</td>
<td>2.354</td>
</tr>
<tr>
<td>P2A ratio</td>
<td>+S</td>
<td>-0.102</td>
<td>**</td>
<td>-2.031</td>
</tr>
<tr>
<td>OD trip circuity</td>
<td>+S</td>
<td>8.801</td>
<td>***</td>
<td>6.509</td>
</tr>
<tr>
<td>Constant</td>
<td></td>
<td>-8.315</td>
<td>***</td>
<td>-3.451</td>
</tr>
<tr>
<td>No. of observations</td>
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<td></td>
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<td>3,655</td>
</tr>
<tr>
<td>R-squared</td>
<td></td>
<td></td>
<td></td>
<td>0.623</td>
</tr>
</tbody>
</table>

* p<.10, ** p<0.05, *** p<.01
Do travelers perceive travel time differently?

Can this difference be related to network structure?

Response:

Network structure variables influence the perception of travel time.

Statistically significant differences in network structure can be seen between the traveler groups.
Network Structure Factors

Transportation System Performance

Perceived Travel

Actual Travel

Transportation System Performance
**Question**

*Do travelers respond to perceived travel time by increasing or decreasing actual travel?*

Focus is to understand the affect on travel behavior of the underlying street network structure.

- Individual travel
- Household travel
<table>
<thead>
<tr>
<th>Data</th>
<th>Twin Cities</th>
<th>South Florida</th>
</tr>
</thead>
<tbody>
<tr>
<td>Travel Behavior</td>
<td>Travel Behavior Inventory (2000)</td>
<td>Southeast Florida Travel Survey (1999)</td>
</tr>
</tbody>
</table>

- Data
- Twin Cities
- South Florida

- Travel Behavior Inventory (2000)
- Southeast Florida Travel Survey (1999)
- Census TIGER/line files (2000)
Individual Travel Analysis

Two types of regression analyses:

*Trip distance between origin & destination*

- Work trips
- Non-work trips

*Vehicle Kilometers Traveled (VKT) per individual commuter*
Modeling Methodology

\[ T = f(N_b, X_{sd}, Acc_d) \]

- \(T\) = Travel behavior (i.e. trip length),
- \(N_b\) = Measures of network structure within the trip buffer,
- \(X_{sd}\) = Socio-demographic characteristics (ex. age, household size etc.),
- \(Acc_d\) = Distance based accessibility measure.
<table>
<thead>
<tr>
<th>Independent variables</th>
<th>Hypothesis</th>
<th>Twin Cities</th>
<th>Florida</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative discontinuity</td>
<td>-S</td>
<td>-8.80 ***</td>
<td>-7.25 ***</td>
</tr>
<tr>
<td>Proportion of limited access roads</td>
<td>+S</td>
<td>94.41 ***</td>
<td>80.77 ***</td>
</tr>
<tr>
<td>Street density</td>
<td>-S</td>
<td>-0.41 ***</td>
<td>-0.55 ***</td>
</tr>
<tr>
<td>Arterial treeness</td>
<td>-S</td>
<td>-35.90 ***</td>
<td>-7.06</td>
</tr>
<tr>
<td>OD trip circuity</td>
<td>-S</td>
<td>-1.98 ***</td>
<td>-0.24</td>
</tr>
<tr>
<td>P2A</td>
<td>-S</td>
<td>-0.46 ***</td>
<td>-0.63 ***</td>
</tr>
<tr>
<td>Distance to downtown Minneapolis</td>
<td></td>
<td>0.22 ***</td>
<td></td>
</tr>
<tr>
<td>Distance to downtown St. Paul</td>
<td></td>
<td>0.10 ***</td>
<td></td>
</tr>
<tr>
<td>Distance to downtown Fort Lauderdale</td>
<td></td>
<td></td>
<td>0.19 ***</td>
</tr>
<tr>
<td>Distance to downtown Miami</td>
<td></td>
<td></td>
<td>0.15 ***</td>
</tr>
<tr>
<td>Constant</td>
<td></td>
<td>32.13 ***</td>
<td>24.76 ***</td>
</tr>
<tr>
<td>No. of observations</td>
<td></td>
<td>4,105</td>
<td>1,492</td>
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<tr>
<td>R-squared</td>
<td></td>
<td>0.301</td>
<td>0.429</td>
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<table>
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<th>Independent network variables</th>
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<th>Florida</th>
<th>Twin Cities</th>
<th>Florida</th>
<th>Twin Cities</th>
<th>Florida</th>
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</thead>
<tbody>
<tr>
<td>Relative discontinuity</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
</tr>
<tr>
<td>Proportion of limited access highways</td>
<td>+S</td>
<td>+S</td>
<td>+S</td>
<td>+S</td>
<td>+S</td>
<td>+S</td>
<td>+S</td>
</tr>
<tr>
<td>Street density</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>NS</td>
<td>-S</td>
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<tr>
<td>Arterial Treeness</td>
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<td>-S</td>
<td>NS</td>
<td>-S</td>
<td>NS</td>
<td>-S</td>
<td>NS</td>
</tr>
<tr>
<td>OD trip circuity</td>
<td>-S</td>
<td>-S</td>
<td>NS</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>NS</td>
</tr>
<tr>
<td>P2A ratio</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>-S</td>
<td>NS</td>
<td>-S</td>
</tr>
<tr>
<td>No. of observations</td>
<td>4,105</td>
<td>1,492</td>
<td>15,274</td>
<td>3,228</td>
<td>2,296</td>
<td>1,122</td>
<td></td>
</tr>
</tbody>
</table>
Relation exists between network structure and actual individual travel, after controlling for other independent variables.

Stratification by trip purpose across two study areas show similarities in the patterns of influence.

Minor differences exist in the magnitude of influence.
Household Travel

Use travel data from the same two study areas (Twin Cities, South Florida) to understand household travel.
Activity Spaces

Newsome et al. (1998)

“Graphical representation of the space within which a group of activities are carried out by the individual or the household subject to time constraints imposed by or on the traveler.”
Identification of household activity space polygon

Individual travel survey data aggregated to household level.

Origin and destinations reached by household members on travel day identified.

GIS used to link the origin and destinations creating a household activity space polygon.
Identified Activity Space for a household - Twin Cities
Modeling Methodology

\[ A_a = f(N_a, X_{sd}, Acc_d) \]

- \( A_a \): Area of the activity space polygon,
- \( N_a \): Measures of network structure within the activity space polygon,
- \( X_{sd} \): Socio-demographic characteristics (e.g., household size, household income, etc.),
- \( Acc_d \): Distance based accessibility measure.
### Dependent variable: ln (Area of the household activity space)

<table>
<thead>
<tr>
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<th>Hypothesis</th>
<th>Coef.</th>
<th>Sig</th>
<th>t</th>
<th>Coef.</th>
<th>Sig</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportion of limited access roads</td>
<td>+S</td>
<td>7.48</td>
<td>9.98</td>
<td>***</td>
<td>3.22</td>
<td>1.99</td>
<td>**</td>
</tr>
<tr>
<td>Street density</td>
<td>-S</td>
<td>-0.19</td>
<td>-7.16</td>
<td>***</td>
<td>-0.04</td>
<td>-2.92</td>
<td>***</td>
</tr>
<tr>
<td>Arterial treeness</td>
<td>-S</td>
<td>-4.41</td>
<td>-2.16</td>
<td>**</td>
<td>-1.46</td>
<td>-1.05</td>
<td></td>
</tr>
<tr>
<td>P2A</td>
<td>-S</td>
<td>-0.18</td>
<td>-10.33</td>
<td>***</td>
<td>-0.20</td>
<td>-10.36</td>
<td>***</td>
</tr>
<tr>
<td>Proportion of 1-degree nodes</td>
<td>-S</td>
<td>-4.22</td>
<td>-5.05</td>
<td>***</td>
<td>5.31</td>
<td>3.52</td>
<td>***</td>
</tr>
<tr>
<td>Proportion of 3-degree nodes</td>
<td>-S</td>
<td>0.89</td>
<td>1.81</td>
<td>*</td>
<td>4.53</td>
<td>3.40</td>
<td>***</td>
</tr>
<tr>
<td>Distance to downtown Minneapolis</td>
<td></td>
<td>0.00</td>
<td>2.35</td>
<td>**</td>
<td>0.00</td>
<td>1.50</td>
<td></td>
</tr>
<tr>
<td>Distance to downtown St. Paul</td>
<td></td>
<td>0.00</td>
<td>6.13</td>
<td>***</td>
<td>0.00</td>
<td>1.99</td>
<td>**</td>
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<td>Distance to downtown Fort Lauderdale</td>
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<td>Distance to downtown Miami</td>
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<td>0.00</td>
<td>1.99</td>
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<tr>
<td>Constant</td>
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<td>8.10</td>
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<td>3.67</td>
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</tbody>
</table>

* Proportion of 4+ degree nodes is the base category

* p<.10, ** p<0.05, *** p<.01
The size of the activity space is influenced by network measures within the polygon, after controlling for other independent variables.
Do travelers respond to perceived travel time by increasing or decreasing actual travel?

Response:

Analyses confirms that travelers respond to perceived travel time by adjusting actual travel both at the individual level and household level.
Network Structure Factors

Perceived Travel

Transportation System Performance

Actual Travel

Dashed arrows indicate the relationships between the factors.
Does network structure affect transportation system performance?
<table>
<thead>
<tr>
<th>Data</th>
<th>Source</th>
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</thead>
<tbody>
<tr>
<td>Street Network</td>
<td>Census TIGER/Line files (2000)</td>
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<tr>
<td>Travel</td>
<td>Texas Transportation Institute (TTI) Urban Mobility Data</td>
</tr>
<tr>
<td>Socio-demographics</td>
<td>U.S Census Bureau (2000)</td>
</tr>
</tbody>
</table>
Model I - Congestion

Congestion,  \( Q_m = \frac{Demand}{Supply} \)

\( Q_m = \) Price of highway travel, measured here as congestion, using TTI

Demand = \( f(p) \)

\( p = \) Population of the area

Supply = \( f(L_{rm}, N_m) \)

\( L_{rm} = \) Total roadway kilometers in the area

\( N_m = \) Measures of network structure within the area
### Dependent variable (ln): Congestion (TTI)

TTI = Congested time / Free flow time

<table>
<thead>
<tr>
<th>Independent Variables (ln)</th>
<th>Hypothesis</th>
<th>Coef.</th>
<th>t</th>
<th>Sig.</th>
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<tbody>
<tr>
<td>Population</td>
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<td>0.13</td>
<td>6.19</td>
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<td>Total length of local roads</td>
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<td>-0.57</td>
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<td>Total length of non-local roads</td>
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<tr>
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<td>+S</td>
<td>0.05</td>
<td>2.10</td>
<td>**</td>
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<tr>
<td>Constant</td>
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<tr>
<td>Adj. R-squared</td>
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<td>0.5891</td>
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</tr>
</tbody>
</table>

Natural log of variables considered in the analysis

* p<0.10, ** p<0.05, *** p<0.01
Model II - System Usage

System Usage, $U_m = f(Q_m, N_m, Acc_m)$

- $U_m = \text{DVKT per capita on all roadways in the area}$
- $Q_m = \text{Price of highway travel, measured by congestion}$
- $N_m = \text{Measures of network structure}$
- $Acc_m = \text{Accessibility in the area}$
**Accessibility**

\[ A_{cm} = A_t \times \rho_{pm} \]

- \( A_t \): Area (km\(^2\)) covered in \( t \) minutes
- \( t \): Time contour, defined as 30 mins
- \( \rho_{pm} \): Population density (persons/km\(^2\))

\[ A_t = \pi \times R_e^2 \]

\[ R_e^2 = \text{Euclidean radius (km)} \]

\[ R_e = S_e \times t \]

\[ S_e = \frac{S_n}{C_m} \]

- \( S_n \): Average network speed (km/h)
- \( C_m \): Average metropolitan circuity
### Dependent variable (ln): System usage (DVKT) per capita

<table>
<thead>
<tr>
<th>Independent Variables (ln)</th>
<th>Model A</th>
<th></th>
<th></th>
<th>Model B</th>
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<td>Coef.</td>
<td>t</td>
<td>Sig.</td>
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<td>2.12</td>
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<td>Median household income</td>
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<td>Auto mode share</td>
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</tbody>
</table>

Natural log of variables considered in the analysis

* p<0.10, ** p<0.05, *** p<0.01
Statistical models show a relation between quantitative measures of network structure and system performance. Influence varies with the aspect of performance that is being analyzed.
Does network structure affect transportation system performance?

Response:

The design of a transportation network affects the system performance.
Conclusions

The analyses show that the design of a transportation network affects travel.

A combination of network measures can be used to bring about changes in the system.
It is important to consider these results in the context of traditional measures of urban form.

Results provide an additional tool to analyze travel in a region and are not meant to replace the traditional measures of urban form.
Future Extensions

Develop additional measures to capture other aspects of network structure.

Quantify the structure of multi-modal networks (ex. transit) to see how it influences performance (ex. mode share).

Extend the cross-sectional comparison to include temporal aspects.
Questions?