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

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Spatial Dependency

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- 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

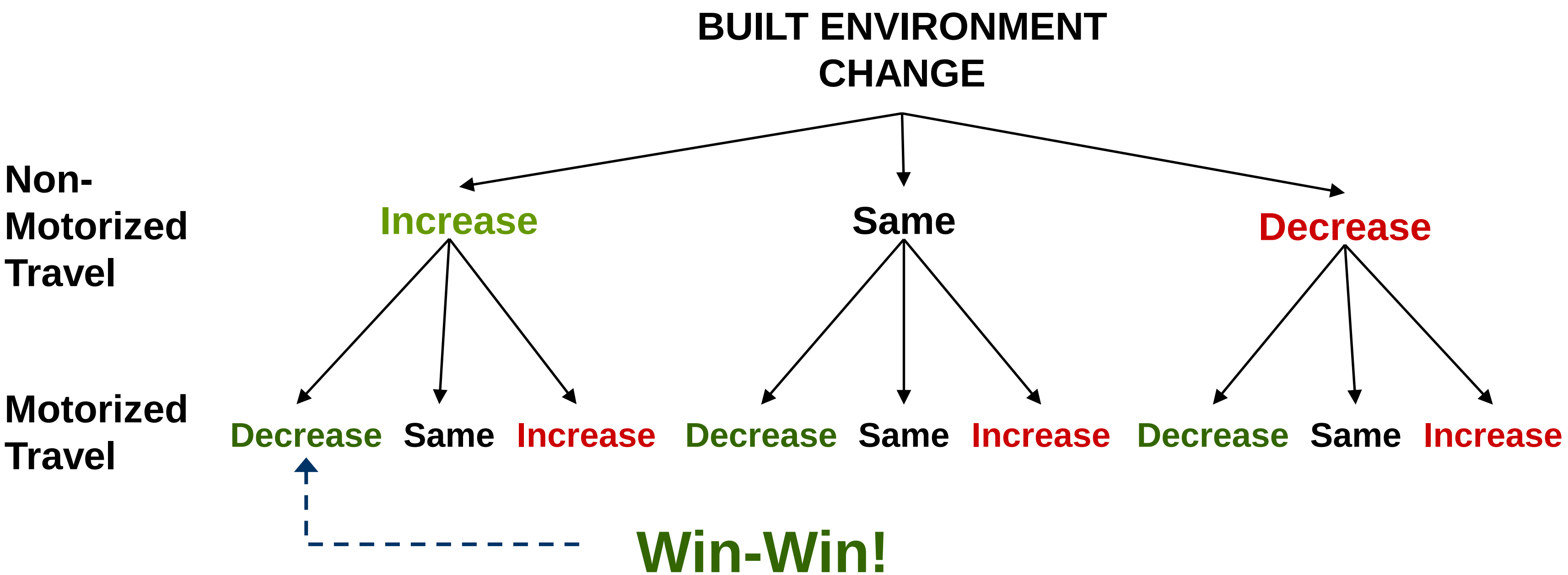
- Implications on travel modeling

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 ?



Existing Literature

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- 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

Built Env. → **Amount of Driving** *and* **Amount of Biking/Walking**

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

Independent Regression

$$\text{VMT}: \quad y_1 = \mathbf{X}_1\beta_1 + \varepsilon_1$$

$$\text{MWB}: \quad y_2 = \mathbf{X}_2\beta_2 + \varepsilon_2$$

$$\varepsilon_1 \sim N\left(0, \sigma_1^2\right)$$

$$\varepsilon_2 \sim N\left(0, \sigma_2^2\right)$$

$$\text{COV}\left(\varepsilon_1, \varepsilon_2\right) = 0$$

Independent Regression

$$\text{VMT}: \quad y_1 = \mathbf{X}_1\beta_1 + \varepsilon_1$$

$$\text{MWB}: \quad y_2 = \mathbf{X}_2\beta_2 + \varepsilon_2$$

Model Estimation

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

$$\hat{\beta}_{2,OLS} = \left(X_2{}' X_2 \right)^{-1} X_2{}' y_2$$

Seemingly Unrelated Regression

$$\text{VMT}: \quad y_1 = \mathbf{X}_1\beta_1 + \varepsilon_1$$

$$\text{MWB}: \quad y_2 = \mathbf{X}_2\beta_2 + \varepsilon_2$$

Inter-equation correlation

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

$$\Leftrightarrow \quad Y = \mathbf{X}\beta + \varepsilon$$

Stacked Form

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

Seemingly Unrelated Regression

$$Y = \mathbf{X}\beta + \varepsilon$$

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Model Estimation

$$\hat{\beta}_{GLS} = \left[X'\left(\Sigma^{-1} \otimes I\right)X\right]^{-1} X'\left(\Sigma^{-1} \otimes I\right)Y$$

Spatial Seemingly Unrelated Regression

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$$\text{VMT}: \quad y_1 = \mathbf{X}_1\beta_1 + \varepsilon_1, \qquad \varepsilon_1 = \lambda_1 W_1 \varepsilon_1 + \mu_1$$

$$\text{MWB}: \quad y_2 = \mathbf{X}_2\beta_2 + \varepsilon_2, \qquad \varepsilon_2 = \lambda_2 W_2 \varepsilon_2 + \mu_2$$

Inter-person correlation due to spatial dependence

Rewrite

$$\varepsilon_1 = (I_N - \lambda_1 W_1)^{-1} \mu_1 = B_1^{-1} \mu_1$$

$$\varepsilon_2 = (I_N - \lambda_2 W_2)^{-1} \mu_2 = B_2^{-1} \mu_2$$

$$\Leftrightarrow \quad Y = \mathbf{X}\beta + \varepsilon$$

Stacked Form

$$E[\varepsilon\varepsilon'] = \Omega = B^{-1}(\Sigma \otimes I_N) B^{-1\prime}, \; B = \begin{bmatrix} B_1 & 0 \\ 0 & B_2 \end{bmatrix}$$

Spatial Seemingly Unrelated Regression

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$$Y = \mathbf{X}\beta + \varepsilon$$

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

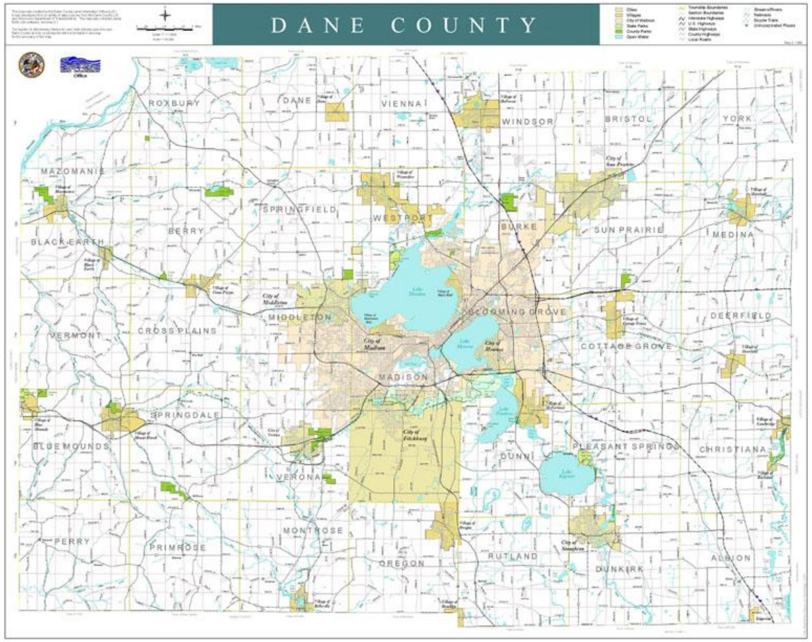
Model Estimation

Iterative procedure to optimize the following log-likelihood function:

$$L = -\frac{1}{2}\ln|\Omega| - \frac{1}{2}\left(Y - XB\right)'\Omega^{-1}\left(Y - XB\right)$$

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

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- 50% of 4974 persons in the final sample

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

Sample Characteristics

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

Estimation Results

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	SUR MODEL				SPATIAL SUR MODEL			
	MWB		VMT		MWB		VMT	
Explanatory Variables	Coeff.	z-stat	Coeff.	z-stat	Coeff.	z-stat	Coeff.	z-stat
Person/Household/Trip Day Characteristics								
Person is employed	0.1663	2.976***	14.4811	9.583***	0.0610	0.894	16.9346	7.994***
Person is young (17 to 30 years old)	0.2255	2.929***	--	--	0.1271	1.36741		
Person is Caucasian	0.2729	2.761***	--	--	0.2582	2.172**		
Person holds a driving license	--	--	11.6439	12.446***			10.5879	8.136***
Person has a degree (Bachelor's or higher)	--	--	2.3258	3.570***			2.0657	2.281**
Number of bicycles owned by household	0.1480	8.309***	--	--	0.1452	6.524***		
Household has no car	0.3548	1.803*	--	--	0.0439	0.186		
Family income per year (in $10,000)	--	--	0.2956	2.266**			-0.1229	-0.661
Number of cell phones in household	--	--	0.8638	2.806***			1.5234	3.480***
Housing type is either an apartment or a dormitory	0.1704	1.985**	2.2296	2.495**	0.1968	1.800*	2.1285	1.578
Lowest temperature on travel day	0.0073	4.805***	--	--	0.0066	3.609***		
Travel day is on a weekend	--	--	-6.8482	-2.343**			-13.1987	-3.397***

Estimation Results

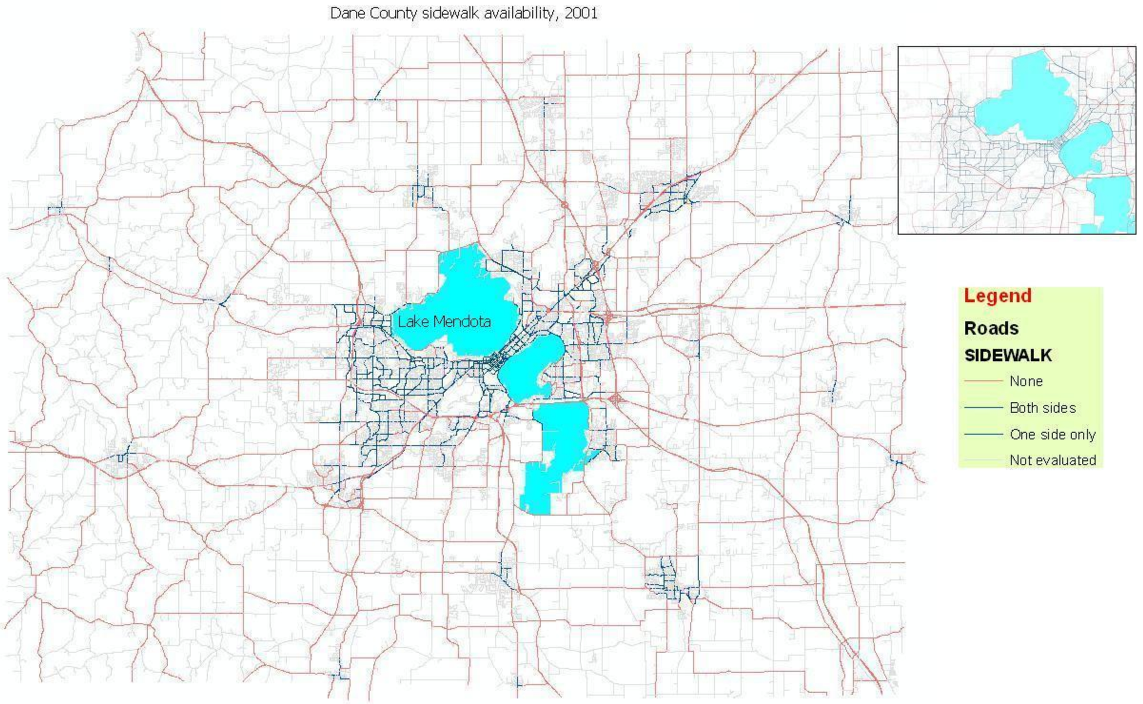
Explanatory Variables	SUR MODEL MWB Coeff.	SUR MODEL MWB z-stat	SUR MODEL VMT Coeff.	SUR MODEL VMT z-stat	SPATIAL SUR MODEL MWB Coeff.	SPATIAL SUR MODEL MWB z-stat	SPATIAL SUR MODEL VMT Coeff.	SPATIAL SUR MODEL VMT z-stat
Built Environment Characteristics								
Regional factors								
Rural setting	--	--	1.3241	1.553			0.9449	0.721
Retail accessibility	0.0399	3.341***	-0.5785	-3.438***	0.0437	2.693***	-0.0145	-0.053
interacted with individual's work status	--	--	-1.2072	-5.624***			-1.7220	-5.601***
Neighborhood socio-demographic composition								
% high income households in neighborhood – 1 mile buffer	-0.9233	-3.846***	9.7954	3.561***	-0.8449	-2.767***	15.9405	3.782***
Household density (per acre) – ¼ mile buffer	--	--	0.2823	2.833***			0.2084	1.167
Neighborhood land use characteristics								
Land use mix – 1 mile buffer	-0.5786	-3.466***	-6.0547	-2.874***	-0.3574	-1.684*	-10.0319	-3.207***
interacted with vehicles per person in household	--	--	4.7199	4.334***			4.5087	2.889***
interacted with travel day being on a weekend	--	--	8.1199	1.786*			17.1592	2.816***
Neighborhood transportation network characteristics								
Length of roadway with no sidewalk – 1 mile buffer	-0.0483	3.288***	0.3397	2.128**	-0.0554	2.784***	0.6447	2.399**
Length of roadway with bike lane – ¼ mile buffer	0.2140	2.265**	--	--	0.1005	0.801		
Number of intersections (per acre) – ¼ mile buffer	0.0503	2.261**	--	--	0.0160	0.550		
r-squared	0.0511		0.1898		0.0429		0.236	
system r-square	0.1261				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

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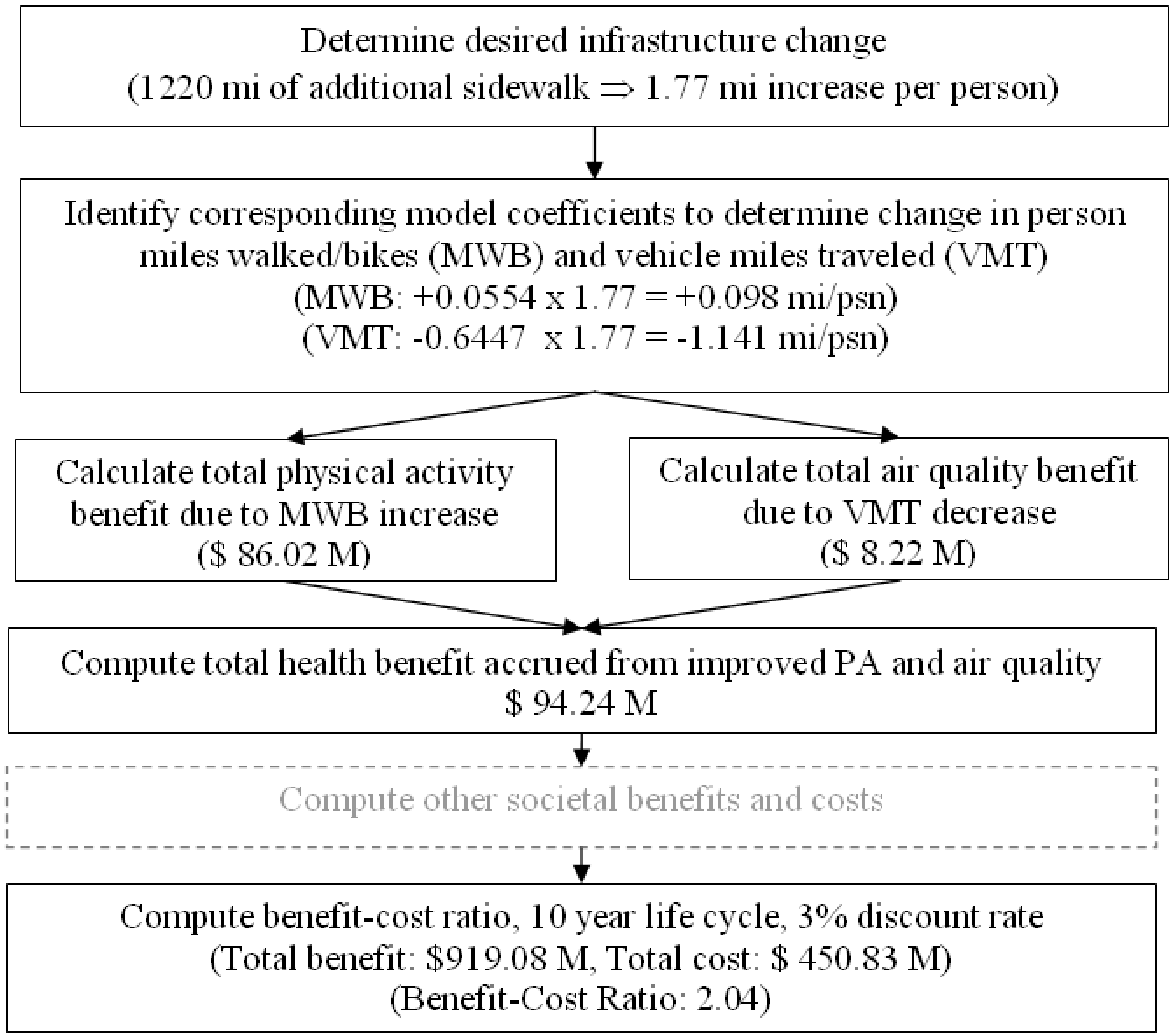
- Construction Cost
  - Cost for concrete curbs is approximately $15 per linear foot and $11 per ft^2 for walkways
  - FHWA and ITE recommended minimum width of 5 ft is estimated at $70 per linear foot
  - Total cost estimated at $450.83M

Scenario Analysis



Sensitivity to Model Structure

	SSUR	SUR
Parameter on sidewalk for MWB	0.0554	0.0483
Parameter on sidewalk for VMT	-0.6447	-3.288
BCR	2.04	1.77

Conclusions

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- 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…