DISSERTATION

# LAND USE RESTRICTIONS AND HOUSEHOLD TRANSPORTATION CHOICE

Submitted by

Andrew G. Mueller

Department of Economics

In partial fulfillment of the requirements

For the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Fall 2016

Doctoral Committee:

Advisor: Martin Shields
Co-Advisor: Stephan Weiler

David Mushinski
Stephen Liesz

ABSTRACT

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The primary objective of the dissertation is to further existing research on the link between the built environment and travel behavior. The dissertation proposes to make this advance in two distinct ways. First, by testing the impact of land use regulation on travel behavior by incorporating zoning restrictions as an exogenous variable in the model. Second, by explicitly modeling spatial variation in the discrete choice of mode of transportation. The dissertation is organized into three chapters. The first develops a multinomial discrete choice model that addresses unobserved travel preferences by incorporating sociodemographic, built environment, and land use restriction variables. The second builds upon the first by explicitly modeling spatial dependence of travel mode choice in a and compares the results of models from the first and second chapters to address the effect of spatial dependence on travel behavior-built environment model estimates. The third reviews previous models and theories related to land use restrictions, and reviews the economic and policy implications of findings from the first two chapters.

ACKNOWLEDGMENTS

I would like to thank my parents, Glenn and Jan Mueller for their unending love and support throughout my academic career, and for instilling a sense of curiosity and wonder that led me in the direction of research as a career. I would also like to thank my advisors Martin Shields and Stephan Weiler for their support and guidance throughout the process of honing my research interests and brining this work to fruition. Finally, I'd like to thank my brothers, Starke and Graham for their love, friendship, and limitless encouragement.

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## 1.1 INTRODUCTION

Municipalities across the United States are changing existing land use regulations to balance economic, social, and environmental goals. Existing literature suggests that physical built environment characteristics of urban areas have an impact on consumer travel behavior (Cervero, 2002; Handy et al., 2005; Tobergte and Curtis, 2013; Ewing and Cervero, 2010; Boarnet, 2011). Zoning laws adopted by municipalities dictate the form, density, use, and infrastructure required for approval of new development or redevelopment of private land. Distortions in the land market can occur when optimal use type or density are precluded from being built by zoning laws. This study develops a model to test the impact of different zoning restrictions on travel behavior and finds that some zoning classes within close proximity to residences are associated with reduced non-auto travel, while others are statistically insignificant.

Previous research has modeled many built environment characteristics as predictors of travel mode choice or overall travel distances for commuting to work, but none have attempted to test the impact of land use restrictions encompassed by municipal zoning codes on mode choice (Ewing and Cervero, 2010). Zoning codes are the result of a political process involving city planning professionals and input from municipal stakeholders. By analyzing the effects of zoning laws on travel behavior, results of the current study can inform decision makers about the expected effects that changes to zoning laws will have on stated municipal goals such as higher shares of non-auto travel and lower pollution and traffic congestion. These expected consequences can then be balanced with other municipal objectives such as historic preservation, improved infrastructure and economic vitality when determining optimal adjustments to land use regulations codified in zoning code statutes.

Using transportation survey data and zoning code statutes and maps, this study characterizes the existing built environment, including land use restrictions surrounding survey respondents' primary residences, to determine whether land use restrictions are associated with transportation behavior of households within the City and County of Denver, Colorado. Geocoded data of survey respondents' travel behavior and built environment characteristics of the City and County of Denver are combined in a geographical information system (GIS) to obtain data relevant to travel behavior of respondents. An alternative specific multinomial logit model of transportation mode choice (McFadden, 1974) for both commuting and other activities is developed and shows that previously studied built environment characteristics as well as some zoning restrictions are associated with consumer transportation mode choice.

## 1.2 REVIEW OF EXISTING LITERATURE

The transportation literature has recently seen an increase in attempts to model consumer travel behavior, and in particular, efforts to establish a causal link between the built environment and travel behavior (Ewing and Cervero, 2010). Studies apply consumer choice theory to a variety of travel decisions, including mode choice, commuting distance, and residential location. "Travelers are said to weigh the comparative travel times, costs, and other attributes of modes when deciding how to get between point A and point B. Characteristics of the traveler, like the availability of a car, theory holds, also influence the selection" (Cervero, 2002, p.266). These models follow canonical discrete choice theory, where a choice is made from an exhaustive choice set, and unobserved utility is assumed to be highest for the observed choice (Train, 2009).

In additional to individual and transportation mode characteristics, interest in the benefits of “new urbanism” and “walkability” have led to a vast amount of modeling efforts directed towards built environment impacts on mode choice and total automobile usage. Badoe and Miller (2000) outline the various attempts researchers have made to study the impacts on vehicle miles traveled (VMT) of several broad categories: 1) residential density 2) employment density 3) accessibility 4) neighborhood design. Most models eventually adopted the framework of Cervero and Kockelman (1997), addressing travel demand and the “3Ds”, density, diversity, and design, later adding destination accessibility and distance to transit. Ewing and Cervero (2010) conduct an extensive meta analysis to compare different model constructs and estimated coefficients over the past four decades, deriving travel demand elasticities from over 50 studies. The studies included in Ewing and Cervero (2010) measure a travel outcome (vehicle miles traveled, walking, and transit use) against a built environment characteristic (density, diversity, design, destination accessibility, distance to transit, and neighborhood type). An example for walking behavior and built environment variables studied is given below in Figure 1.1(Ewing and Cervero, 2010, p.274). The authors made an attempt to transform reported coefficients into elasticities that give a unit free measurement of sensitivity of travel behavior to the built environment characteristics. They find that the majority of the built environment characteristics have elasticities below 1, indicating that built environment factors affect transportation, but only explain part of the transportation decision to walk. The three density measures studied in Ewing and Cervero (2010) have elasticities below 0.08, indicating highly inelastic responses to these variables for walking. Diversity variables land use mix, jobs-housing balance, and distance to a store have weighted average elasticities of 0.15, 0.19, and 0.25, respectively, indicating a slightly more elastic effect on propensity to walk, but still highly inelastic. The design variable intersection/street density has the highest elasticity studied with a weighted average of 0.39 across 7 studies, but still remains inelastic. Destination accessibility and distance to transit both have weighted average elasticities of 0.15. The highly inelastic results across many studies reviewed and averaged in Ewing and Cervero (2010) show that built environment variables provide only some explanation for what drives consumer preferences to walk over other modes of transportation. Travel mode choice may be largely determined by other factors such as preference for a specific mode, habit, and necessity, with the built environment playing a subdued role in the travel mode decision.

Figure 1.1 highlights one of the major findings in the literature, particularly that built environment characteristics tend to be significant, but have a small effect. The work of Ewing and Cervero (2010) and Boarnet (2011) highlight the lack of consistency across studies. Lack of sufficient data and consensus on how to model travel behavior with built environment variables has led to difficulty in ascertaining consistent underlying themes in the literature. To date, the vast majority of studies are confined by regional or transportation analysis zone level data, an arbitrarily sized area approximately the size of a census tract that subsumes much of the variation across individuals into broader regional aggregates (e.g., Pinjari et al., 2011). Although the broad characterization of the built environment can be managed at this level of detail, individuals may actually face higher levels of variation in built environment characteristics when making transportation mode choice decisions at a more localized level. Transportation analysis zones with highly segregated uses but an overall balanced mix of land usage could be incorrectly characterized as equivalent to land use mix in a zone with true integration of diverse land uses. Additionally, only commuting data is typically available, leaving non-work travel behavior underrepresented. When higher resolution data is available, it is often incomplete, and only specific types of models can be developed. Iacono et al. (2010) offer an extensive review of these issues and other problems associated with travel behavior models.

As an example of the wide disparity in findings across models in this area of the literature, Crane and Crepeau (1998), using a travel survey and GIS data from San Diego, find that land use (residential, commercial) does not play a significant role in explaining travel behavior, refuting previous work on the connection between land use and travel behavior. Leck (2006) compares 17 studies and finds that residential density and land use mix are inversely related to vehicle miles traveled, but that street pattern design (gridded vs. cul-de-sac street connections) cannot be shown to affect travel behavior.

Several recent studies using various methodologies have found impacts of built environment characteristics on travel behavior. Using propensity scores, Boer et al. (2007) find higher levels of business diversity (number of different businesses) and higher levels of four-way intersections to be associated with higher frequencies of walking. Boarnet et al. (2010) find that higher concentrations of commercial land use lead to increased frequency of walking trips for those living within suburban commercial corridors, but also lead to more vehicle traffic by drawing from surrounding non-commercial suburban areas.

The existing literature indicates that travel behavior models with data at the individual level, typically gathered from travel surveys, are superior to studies using aggregated data, typically gathered from census block groups, census tracts, or transportation analysis zones (Boarnet et al., 2010). In the current study, access to high resolution survey data allows modeling of both work and non-work travel, as well as more accurately characterizing the built environment that individuals face. Location of survey respondent households are known at the census block level, roughly several hundred feet in diameter in most locations in the study area.

Coupled with exact locations of built environment characteristics, the highly spatial nature of transportation behavior can be more accurately measured in this study.

## 1.3 MODELING METHODOLOGY

In the context of city planning, models of travel volume (such as vehicle miles traveled) are important for understanding overall demand for travel infrastructure. Models of mode choice are also important, but serve a different purpose. Determining factors that influence the type of transportation used by individuals helps policymakers determine built environment characteristics that promote increased use of one mode of travel over another, such as access to transit or land use mix. Due to the relative convenience and shorter travel times of automobile travel in the United States, cars have become the dominant form of transportation for most activities. Increased convenience and reduced travel times are therefore paramount to increasing use of non-auto transportation alternatives. Since the relative attractiveness of a mode is directly or indirectly determined by proximity of non-residential uses to residential home location throughout a given area, land use is a primary concern when promoting non-auto travel.

The economic model used in this study is commonly referred to as the random utility 16 model and is often specified econometrically as a multinomial logit model (McFadden, 1973). The utility that each respondent *n* receives from choosing mode *j* is $U_{nj}, j = \{Auto, Transit, Bike, Walk\}$. Assuming utility maximization, the respondent chooses mode $i$ to satisfy the equation $U_{ni} > U_{nj}\ \forall j \neq i$. Representative utility is specified as $U_{nj} = V_{nj} + \varepsilon_{nj}$ where $V_{nj}$ is the observable portion of utility. Socioeconomic characteristics of individuals, mode specific transportation attributes, and built environment characteristics are expected to influence travel behavior. Many of these exogenous variables associate with travel behavior through the opportunity cost of time spent traveling. Better access to transit, shops, recreation, and employment decrease travel time between various activities for non-auto modes of transportation. The representative utility takes the form:

$$(1.1) \quad V_{nj} = \kappa_j + \alpha_j A_{nj} + \beta_j S_n + \gamma_j BE_n + \varepsilon_{nj}$$

Where $\kappa_j$ are mode specific constants, *A* is a vector of mode alternative characteristics with mode specific coefficients, *S* is a vector of socio demographic characteristics that varies across individuals with mode specific coefficients, and *BE* is a vector of built environment characteristics, including zoning restrictions, that vary by individual and have mode specific coefficients. Using the assumption that the error terms are general extreme value distributed, the alternative specific multinomial logit function can be specified as the probability of mode choice *i* being chosen by individual *n* such that:

$$(1.2) \quad P_{ni} = \frac{e^{V_{ni}}}{\sum_j e^{V_{nj}}}$$

$$= \frac{\exp\left(\kappa_i + \alpha_i A_{ni} + \beta_i S_n + \gamma_i BE_n + \varepsilon_{ni}\right)}{\sum_j \exp\left(\kappa_j + \alpha_j A_{nj} + \beta_j S_n + \gamma_j BE_n + \varepsilon_{nj}\right)}$$

The term multinomial logit is used inconsistently throughout the literature to mean a variety of different logit specifications. In an attempt to distinguish the current model from other forms of the multinomial logit, I use the term alternative specific multinomial logit, also referred to as the conditional logit model (Greene, 2007). The distinction to be made is that in the current model, each vector of independent regressors is multiplied by a mode dummy variable. To be fully specified, one mode must be set to zero, which can be thought of as the base alternative. In the current specification, I choose the auto mode of transportation as the base alternative. The current specification also allows for including regressors that only apply to one mode, by interacting the terms with a specific mode dummy variable prior to inclusion in the model matrix. For example, number of bus stops within 1/2 mile of residences is only interacted with the transit mode, and set to zero for all other modes, allowing the estimation of the bus stops coefficient only for the transit mode. Individual level regressors are interacted with all modes other than auto and coefficients are obtained for built environment and socioeconomic characteristics. Travel time varies across all alternatives and each tour taken by each respondent, which allows for the estimation of coefficients on all four travel modes. It is important to note the shortcomings of the alternative specific multinomial logit. The coefficients cannot be interpreted as one directional causal links between regressor and mode choice. Instead, they give an estimate of the decision maker's change in probability for a given increase in the regressor of interest. Also, when forecasting, the multinomial logit produces proportional share increase. This means that forecasting a change in one variable necessarily leads to proportionate increase or decrease in the other three modes. Marginal effects can be calculated by dividing coefficients, giving an estimate of the elasticity of substitution between two variables of interest.

## 1.4 DATA

1.4.1 Front Range Travel Count Data. Data for this study consists of several sources that have been merged together using GIS software. From the Denver Regional Council of Governments (DRCOG), a micro-level data set was obtained from the Front Range Travel Counts (FRTC) household survey conducted from October 2009 to December 2010. The data was collected by DRCOG using a travel diary survey of 7,302 households within the DRCOG member counties. Each person within the household kept a travel diary of all physical locations visited during a 24 hour period starting at 3:00 a.m. on randomly selected dates throughout the survey period. Within the data set are detailed household and individual characteristics, location of primary residences (geocoded to the census block for privacy reasons), travel mode, trip duration, departure and arrival times, and purpose of the trip. The dataset was truncated to include only individuals residing within the City and County of Denver who were are least 16 years of age. The final dataset for the City and County of Denver consists of 3,308 respondents from 2,096 households. Destinations visited by each respondent are summarized into “tours” defined as departure and return from primary residence. Information is aggregated and associated with each tour, such as total tour distance, total travel time, and number of stops made on the tour for work, social, health, or shopping purposes. The geographic distribution of respondents is shown in Figure 1.2.Income, which was reported categorically, was transformed by assigning each survey respondent’s income response to the midpoint within the income range they specified. The only exception was those who reported household income of greater than $150,000, who were assigned an income value of $160,000. The income category ranges from the survey instrument are $0 to $14,999, $15,000 to $19,999, $20,000 to $29,000, $30,000 to $39,000, $40,000 to $49,000, $50,000 to $59,000, $60,000 to $74,999, $75,000 to $99,000, $100,000 to $134,000, $135,000 to $149,999, and $150,000 or greater.

1.4.2 Quarterly Census of Employment and Wages. Micro level data from the Quarterly Census of Employment and Wages (QCEW) was also obtained, giving detailed employment data by location for each business within the City and County of Denver. This data was geocoded and used to provide the exact number and location of jobs across the study area. The number of jobs at each location were aggregated to provide employment density for each census block group in jobs per square mile.

1.4.3 Built Environment Geographic Data. Built environment data from the Denver GIS department includes geocoded assessor data for each parcel within Denver county, zoning boundaries, streets, bus routes, census data, and various other physical environment characteristics. Using GIS software, built environment and transportation related characteristics are calculated within distance bands of 0 to 1/4 mile, 1/4 to 1/2 mile, 1/2 to 3/4 mile, and 3/4 to 1 mile surrounding each FRTC respondent's residential location. Built environment variables used in the dataset include miles of bike lanes within 1 mile, miles of bus routes within half a mile, miles of rail lines within 1 mile, number of intersections within half a mile, census block group population per square mile, and census block group population per square mile. An example of the distance bands is shown in Figure 1.3. Due to the one mile radius of the zoning bands used to measure spatial built environment characteristics, there are many instances in which the zoning bands protrude outside the sample area for built environment characteristics. To test for edge effects for household observations in which the built environment measures are truncated, I also run a probit model on a truncated sample consisting of observations that only occur greater than one mile inside the border of the City and County of Denver's border as a robustness check on the results of all other models. The truncated sample area is depicted in Figure 1.4. Zoning restrictions were characterized into 7 categories based on density and allowed uses. Residential zoning was classified into either low, medium, or high density, with medium density residential allowing specific tenant related business use and high density allowing some forms of restaurants. Business zoning was grouped into low and high density, with low density business zoning restricting uses to those appealing to neighborhood residents and high density business allowing most business uses. Finally, industrial zoning and flexible zoning were specified as separate zoning types without a density grouping. A list of the zoning categories appears in Table 1.1. The range of uses for flexible zoning is dependent on city approval of master plans for each project, and was used as the base category for identification purposes by excluding it from the model. Zoning area within 1/4 mile, 1/4 to 1/2 mile, 1/2 to 3/4, and 3/4 to 1 mile bands from each survey respondent's home was used for the zoning indicators in the econometric specification.

Each zoning type was normalized to a percentage of total land area in each band. Units are stated as percentages ranging from 0 to 100%. The geographic distribution of the zoning classifications is presented in Figure 1.5. The average of all three residential zoning densities within a 1/4 mile radius of a survey respondent's residence is 84% while business makes up 10.9% and industrial makes up 1.9%. The remaining land area is made up of flexible zoning, which has a wide variation in possible uses. Because zoning is a categorical variable, it is necessary to drop one category of zoning from the analysis to make the model equation fully specified. I chose the flexible zoning type, as it makes up only a small portion of the overall land area and is the least consistent in its permitted uses across the study area. Table 1.2 shows zoning descriptive statistics for the entire dataset.

1.4.4 Self Selection Bias. Many researchers believe endogeneity is a problem in built environment-travel mode modeling (Ewing and Cervero, 2010; Pinjari et al., 2011). Endogeneity, or self selection problems, can arise in these models when transportation mode preference and residential location are related. For example, people who prefer to walk may locate in areas where completing daily tasks on foot is more easily accomplished. An extensive review of self selection bias corrections applied to travel behavior-built environment models is given by Mokhtarian and Cao (2008). The study identifies seven approaches to control for self selection; direct questioning, statistical control, instrumental variables models, sample selection models, joint discrete choice models, structural equations models, and longitudinal designs. Mokhtarian and Cao (2008) identifies two main sources of residential self selection in relation to travel behavior: socioeconomic traits and attitudes toward travel. Economic traits can effect travel behavior when low income households locate in areas that have higher levels of transit service because they either prefer to use transit more or do not own an automobile. Attitudes affect residential self selection when households locate in areas that align with their travel preferences, for example, a household who prefers to walk to work locating within walking distance of their place of employment. Of the seven approaches to dealing with residential self selection in built environment- travel behavior models, Mokhtarian and Cao (2008) recommends longitudinal structural equations modeling with control groups as the best method for establishing causality of built environment characteristics influencing travel behavior.

Unfortunately, due to the dataset used in the current study, a longitudinal structural equation model with control groups is not available as a longitudinal study was not performed in the survey used. Several of the other models are also not available as they can only be implemented in binomial choice context. While the goal of establishing causal direction between built environment and travel behavior is a useful goal, the implementation and direction of causality can be difficult to implement and hard to quantify in practice Cao et al. (2009a). Furthermore, self selection bias only causes problems in validity of model results when the error term of the travel behavior equation is highly correlated with built environment characteristics used in the model (Cao et al., 2009a; Mokhtarian and Cao, 2008). Controlling for residential self selection has had mixed results in the literature, with some built environment characteristics becoming significant only after control, some becoming less or insignificant, and some having little impact (Cao et al., 2009a). Most previous studies show that both residential self selection and built environment can impact travel behavior, but that both residential self selection and built environment characteristics have impacts on travel behavior. I present correlations between built environment measures and model residuals in Table 1.8, which shows that correlations are low between model residuals and built environment measures, and therefore self selection is not a major concern in the dataset, although it may have a small effect. Cao et al. (2009a) notes that small correlations between built environment variables and travel behavior are accepted frequently in previous research, and in some cases can be a better alternative to other approaches that may confound issues relating to self selection bias. Furthermore, self selection bias is useful in establishing direction of causality, while in the present study association between different zoning regimes and non-auto based modes of transportation may be all that is necessary to guide policy since direction of causality from built environment to travel behavior may not be as important as encouraging non-auto transportation through zoning changes. Cao et al. (2009a) and Mokhtarian and Cao (2008) outline several possibilities for interactions between travel attitudes, travel behavior, and the built environment, including the case where the built environment, travel behavior, and attitudes are all simultaneously determined. Thus, cases where preferences for non-auto travel behavior are increased by residential location in more pedestrian friendly built environments may be a legitimate policy objective, and in these cases, direction of causality is less important than association between built environment and travel behavior. This study jointly uses a statistical control and sample selection approach, in which attitudes and socioeconomic characteristics are controlled for by incorporating socioeconomic characteristics of households, and attributes of households that are associated with attitudes toward travel such as number of automobiles and bicycles in the household. As a test for robustness against self selection bias, the dataset split into an urban and suburban dataset defined by proximity to the central business district. This approach to self selection does not do well in establishing causality, but is strong in establishing association (Mokhtarian and Cao, 2008). Urban households are defined as respondents whose residential census block intersects a 2 mile radius from the center of downtown Denver, which I define as the corner of 16th Avenue and Broadway. A map showing the location of urban and suburban census blocks is shown in Figure 1.6.

Table 1.3 shows the zoning makeup of households within 2 miles of downtown (urban) and Table 1.4 shows the zoning makeup of households living more than 2 miles from downtown (suburban). The higher percentage of high density residential, business, and industrial zoning of the urban dataset contrasts the suburban dataset, which has higher levels of low density residential. The contrast between the urban and suburban subsets helps address the problem of endogeneity by separating households into those who choose to live in more urban settings with higher levels of transportation and employment access within distances that are convenient for non-auto travel. While some of the travel preferences of respondents still remain unobservable in this study, modeling the two populations separately helps to address the self selection bias that may be present in the unobserved portion of travel behavior, and comparative analysis of the model on the urban and suburban populations helps to further characterize the sensitivity to built environment characteristics across the two populations.

Table 1.5 shows individual survey respondent summary statistics for the entire dataset, the urban subset, and the suburban subset. On average, the respondent choosing to live in the urban portion of Denver has fewer vehicles in the household, is more likely to have a transit pass, and has fewer bicycles in the household. This agrees with the notion that individuals choosing to live closer to the city center may have a higher preference for a pedestrian lifestyle than those who choose to live further from city center. Urban households also have better access to transit and bicycle facilities, and a more connected street network evidenced by a higher number of intersections close to their residences. Surprisingly, those in the urban population have a slightly lower average income, which, coupled with higher rent closer to downtown, indicates that these individuals may be willing to pay for the amenities that are unique to the urban area of Denver, including better transit, shopping, and employment access. Average household size of urban respondents is also smaller, indicating that families may be more likely to move further away from the urban center to gain access to larger homes at lower prices. Population and employment density at the census block group (CBG) level are approximately 2 and 8 times greater for urban survey respondents, respectively. This is indication that convenient access to employment may be a factor in urban respondents' willingness to pay rent premiums even though they have slightly lower incomes on average than suburban residents.

1.4.5 Travel Time. Travel time is observed for each tour for the mode alternative chosen, but must be estimated for all other alternatives. To estimate coefficients on alternative modes not chosen by respondents in the proposed mode specific multinomial logit mode, travel times must be estimated for all modes of transportation. This allows for effects of travel time to be estimated for all latent utilities in the model, and would otherwise cause a missing data problem. For estimation of these travel times, I turn to previous studies that estimate speeds for different modes of transportation. Rodrguez and Joo (2004) assume 27, 4.94, and 19.3 kph for auto, walk, and bike modes to estimate a similar mode choice model. I take a different approach, estimating a linear model of travel time for each mode based on average speeds reported in the dataset used for this study. Using mile per hour and distance, I estimate a linear function for each mode and use a cap on maximum speed for each mode. These speeds are then used to determine total travel time for modes not chosen by the survey respondent. Actual travel times are used for the mode that was chosen in the model estimation.

(1.3) Auto:min(mph=7+0.435805*tourdistance,75)

Bike:min(mph=3.776+0.40386*tourdistance,20)

Transit:min(mph=3.887+0.36673*tourdistance,50)

Walk:min(mph=1.584+0.45931*tourdistance,4)

1.4.6 Tour Characteristics. Travel diary records from each survey respondent are in the form of trips between locations. Following suggestions in the literature (Pinjari et al., 2011), I chain trips together into tours, which are defined as trip chains that start when the respondent leaves their home and ends when they return home. I aggregate travel time for each tour. Survey respondents also report the purpose of each location they visited, either work, shopping, health care, or social. I aggregate number of stops for each reported purpose for each tour. Travel times in the urban population are slightly less than that of the suburban population. Tour distances are also just under 2 miles shorter for the urban population, reflecting better access to goods and services near the urban core. With an average tour distance of 9.3 miles for urban respondents and 11.13 miles for suburban respondents, it is clear why the auto mode of transportation was chosen for 83.4% of tours, while biking, transit, and walking made up 1.5%, 7.71%, and 7.42%, respectively. A total of 5,123 tours were observed in the dataset. Descriptive statistics for each of the tour characteristic variables is listed in Table 1.6 and also reported for the urban and suburban subsets.

## 1.5 RESULTS

Table 1.7 shows the coefficients for the base model (excluding zoning variables), the full model, and the full model using the truncated dataset for the alternative specific multinomial logit model, separated by mode type. Auto tour was chosen as the base alternative. The overall model fits the data relatively well, with a log likelihood of the model equal to -590.969 and chi square test over the intercept only model of 5,019.697, which is statistically significant at the 1% level for the overall model. Table 1.8 shows correlations between the full model residuals for each of the four mode choices and built environment variables, demonstrating a low correlation and therefore low presence of residential self selection problems with the model. The urban and suburban subset models listed in Table 1.9 also fit the data relatively well and are statistically significant at the 1% level.

For the bicycle mode, low and high density residential zoning within 1/4 mile of home is associated with increased likelihood of biking. For the urban subset, industrial zoning within 1/4 mile of home is associated with decreased propensity to bike, while the opposite effect occurs for industrial zoning in the 1/4 to 1/2 mile band. High density residential and low density business in the 1/2 to 3/4 mile zoning band decrease the likelihood of biking. Finally, low density business within the 3/4 to 1 mile zoning band increases the likelihood of biking for the urban subset. All zoning measures in the suburban subset model are insignificant.

For the transit mode, only medium density residential zoning at the 1/2-3/4 mile zoning band is significant and decreases the likelihood of transit usage. For the urban subset, low density residential zoning coefficient in the 1/2 to 3/4 mile band (negative) and 3/4 to 1 mile band (positive), and industrial in the 3/4 to 1 mile band has increases the probability of the transit mode. For the suburban population, high density residential zoning in the 0 to 1/4 mile band increases the likelihood of taking transit, while in the 1/4 to 1/2 mile band this variable has the opposite effect.

For the walk mode, low and high density residential zoning within 1/4 to 1/2 mile of residences are associated with increased walking, high density business zoning in the 1/2 to 3/4 mile band is associated with decreased walking, and residential medium density in the 3/4 to 1 mile band is associated with increased walking. For the urban subset, industrial zoning in the 0 to 1/4 mile band is associated with decreased walking, low density residential and industrial zoning in the 1/4 to 1/2 mile band are associated with increased walking, high density residential and low density business zoning in the 1/2 to 3/4 mile band are associated with decreased walking, and low density business zoning in the 3/4 to 1 mile band is associated with increased walking. For the suburban dataset, residential high density and low density business zoning is associated with increased walking. There are at least two probable causes of the majority of results being insignificant in the present model. The first is the high percentage of survey responses where the auto mode was chosen. While this reflects the auto centric transportation behavior of the average American, lower amounts of information on all other mode alternatives may be leading to less significant statistical tests. The other possibility is that much of variation in built environment that characterizes a specific zoning type is being subsumed in the coefficients of other variables that are correlated with specific zoning types such as intersection density, bus routes, population and employment density. Many of these variables confirm existing academic and non-academic literature on non-auto transportation, primarily that access to businesses, street connectivity (measured by intersection density), and access to transit are associated with higher proportions of people using non-auto forms of transportation.

The remaining variables in the model are those typically included in other studies of the link between travel behavior and the built environment. In the urban model, CBG population and employment density was dropped from the model because of singularity issues during estimation, but is insignificant across the other models, contradicting some other studies that find these measures of the built environment to be significant (Ewing and Cervero, 2010). Consistent with other studies, access to transportation networks, estimated by miles of bike, bus, and rail lines, are associated with higher usage of those mode types, as are level of ownership of bikes and autos. Males are more likely to use non-auto modes of transportation, while respondents over 65 years old are less likely to use non-auto travel modes. Respondents were less likely to travel by bicycle at night, and more likely to travel by transit at night. For respondent reported tour purposes, biking is negatively associated with shopping. Increased number of stops for any purpose had a negative association with most travel modes or was insignificant.

## 1.6 CONCLUSION

This study analyzes the effects of physical built environment and land use restriction on the travel mode choices of survey respondents within the City and County of Denver. I find evidence that built environment characteristics and some land use restrictions are associated with increased use of non-auto transportation in the sample dataset. This study provides further evidence that good urban design characterized by easy access to transportation networks and businesses is associated with increased non-auto transportation. Many cities seek to reduce usage of automobiles through better city planning to gain the benefits associated with lower traffic volumes, decreased air pollution, and more enjoyable urban spaces. This study furthers the investigation into the relationship between the built environment and travel behavior by incorporating land use restrictions into the exogenous variables affecting travel mode choice. Model results indicate associations between non-auto travel behavior and certain zoning types at specific distances from residential dwellings. These results provide useful distance thresholds for city planners when considering specific changes to permitted land uses if their goal is to increase non-auto travel. Model results do not provide definitive results that can suggest whether business zoning closer to households would increase non-auto transportation. However, results do confirm previous literature that suggests access to transit and bike infrastructure increases usage. While somewhat inconclusive, the results from this model provide some support for the assertions of new urbanism that mixed land use promotes non-auto transportation (Urban Land Institute, 2016).

This study attempts to address endogeneity of the residential location choice in travel behavior by splitting the dataset into urban and suburban populations. Some evidence that sensitivity to built environment characteristics differs across these populations was found. Others have attempted to address the issue of endogeneity by simultaneously estimating the residential and travel choices (Pinjari et al., 2011). While these approaches provide a rigorous treatment of self selection, the current study benefits from the availability of comparison between the urban and suburban populations. Further research on the role of zoning in travel behavior would benefit from incorporating such techniques, as well as incorporating more rigorous spatial modeling techniques that address the variation of travel behavior and built environment characteristics over physical space as well as over different populations.

## 1.7 FIGURES

Table 4. Weighted average elasticities of walking with respect to built environment variables.

| | | Total number of studies | Number of studies with controls for self-selection | Weighted average elasticity of walking (*e*) |
|---|---|---|---|---|
| Density | Household/population density | 10 | 0 | 0.07 |
| | Job density | 6 | 0 | 0.04 |
| | Commercial floor area ratio | 3 | 0 | 0.07 |
| Diversity | Land use mix (entropy index) | 8 | 1 | 0.15 |
| | Jobs-housing balance | 4 | 0 | 0.19 |
| | Distance to a store | 5 | 3 | 0.25 |
| Design | Intersection/street density | 7 | 2 | 0.39 |
| | % 4-way intersections | 5 | 1 | −0.06 |
| Destination accessibility | Job within one mile | 3 | 0 | 0.15 |
| Distance to transit | Distance to nearest transit stop | 3 | 2 | 0.15 |

Figure 1.1 Excerpt: Weighted Average Elasticities of Walking with Respect to Built Environment Variables (Ewing and Cervero, 2010, p. 274)

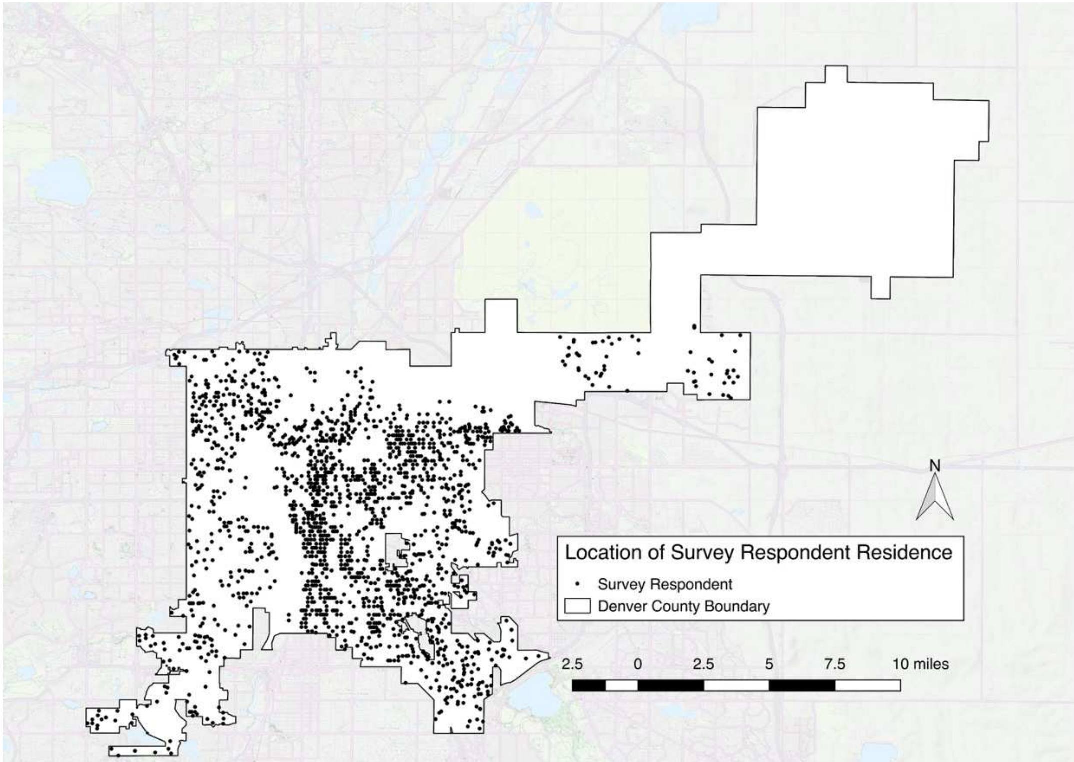

Figure 1.2 Location of Survey Respondents' Residences

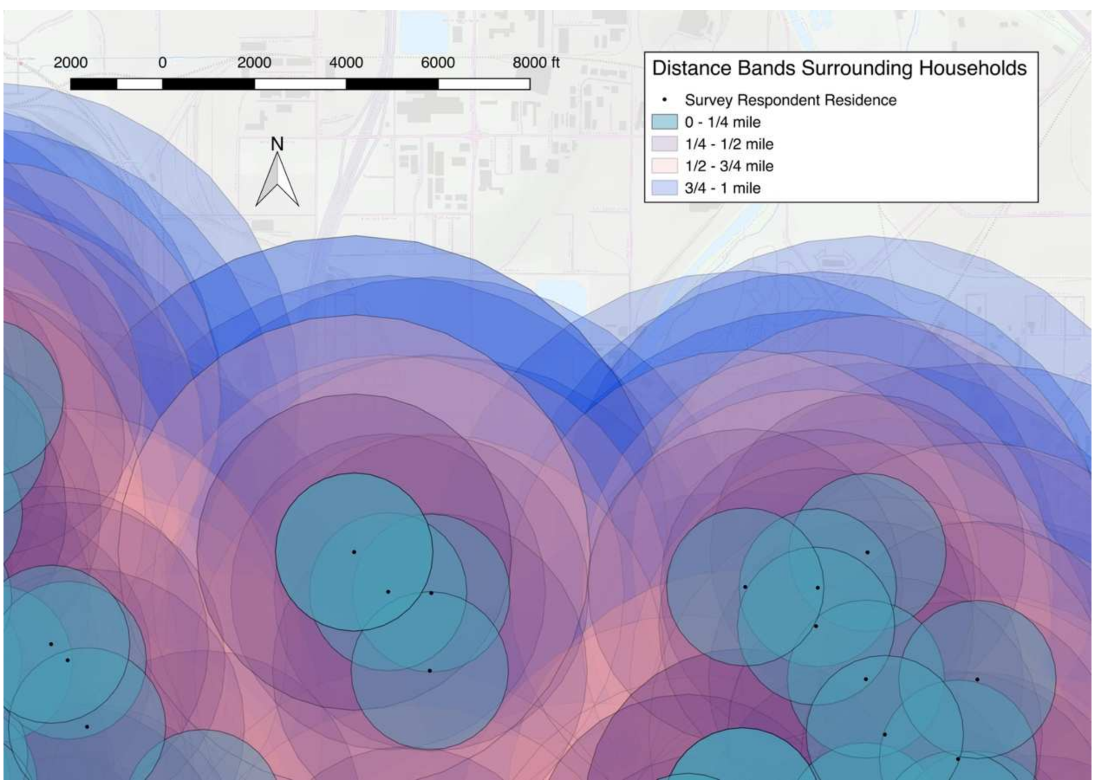

Figure 1.3 Distance Bands Surrounding Survey Respondents' Residences

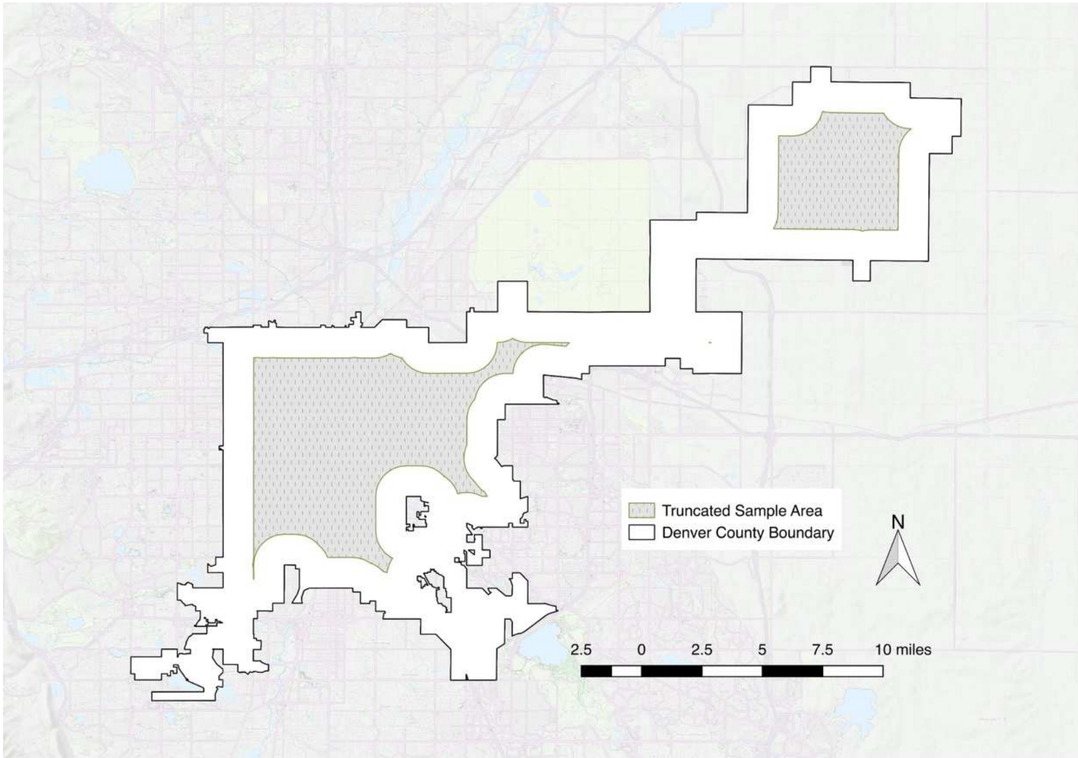

Figure 1.4 Truncated Sample Area

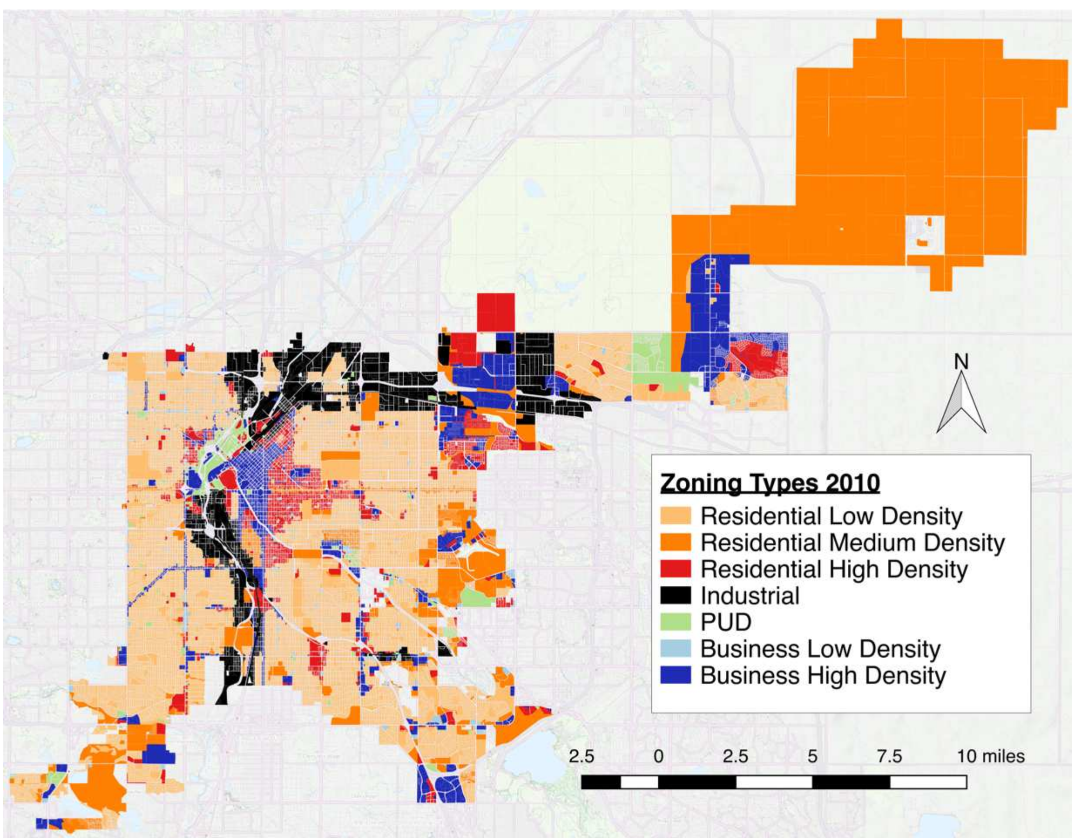

Figure 1.5 Denver Zoning Classifications

## 1.8 TABLES

Table 1.1 Zoning Classification

| Zoning Classification | Zoning Code |
|---|---|
| Residential, Low Density | R0, R1, R2 |
| Residential, Medium Density | O1, O2, OS1, R2A, R3X, RX |
| Residential, High Density | R3, R4, R5, RMU20, RMU30, TMU30 |
| Business, Low Density | B1, B1A, B2 ,B2A |
| Business, High Density | B3-B8, C10, C20, C30, CMU10-30, CCN, H1,H2 |
| Industrial | I1, I2 |
| Flexible | PUD, PRV, P1 |

R: Residential, RMU: Residential Mixed Use, O & OS: Open Space, B: Business, C: Commercial, CCN: Cherry Creek North, I: Industrial, PUD: Planned Unit Development, P1: Parking, PRV: Platte River Valley, TMU: Transit Mixed Use, H: Hospital

Source: City and County of Denver Community Planning Department (2014)

Table 1.2 Descriptive Statistics, Zoning

| Statistic | Households | Mean | St. Dev. | Min | Max |
|---|---|---|---|---|---|
| Res. Low Density, 0-1/4 mile | 2,096 | 60.1 | 37.4 | 0.0 | 100.0 |
| Res. Medium Density, 0-1/4 mile | 2,096 | 10.0 | 18.9 | 0.0 | 100.0 |
| Res. High Density 0-1/4 mile | 2,096 | 13.9 | 24.0 | 0.0 | 100.0 |
| Bus. Low Density 0-1/4 mile | 2,096 | 2.1 | 3.9 | 0.0 | 29.6 |
| Bus. High Density 0-1/4 mile | 2,096 | 8.8 | 18.3 | 0.0 | 100.0 |
| Ind. 0-1/4 mile | 2,096 | 1.9 | 8.4 | 0.0 | 73.7 |
| Res. Low Density, 1/4-1/2 mile | 2,096 | 57.2 | 30.9 | 0.0 | 100.0 |
| Res. Medium Density, 1/4-1/2 mile | 2,096 | 11.0 | 15.2 | 0.0 | 98.1 |
| Res. High Density 1/4-1/2 mile | 2,096 | 12.9 | 16.8 | 0.0 | 76.6 |
| Bus. Low Density 1/4-1/2 mile | 2,096 | 2.0 | 2.3 | 0.0 | 14.6 |
| Bus. High Density 1/4-1/2 mile | 2,096 | 10.3 | 14.3 | 0.0 | 100.0 |
| Ind. 1/4-1/2 mile | 2,096 | 3.4 | 9.8 | 0.0 | 76.2 |
| Res. Low Density, 1/2-3/4 mile | 2,096 | 15.3 | 26.3 | 0.0 | 94.2 |
| Res. Medium Density, 1/2-3/4 mile | 2,096 | 2.4 | 5.7 | 0.0 | 44.4 |
| Res. High Density 1/2-3/4 mile | 2,096 | 3.6 | 7.8 | 0.0 | 40.1 |
| Bus. Low Density 1/2-3/4 mile | 2,096 | 0.6 | 1.3 | 0.0 | 8.5 |
| Bus. High Density 1/2-3/4 mile | 2,096 | 3.3 | 7.5 | 0.0 | 57.3 |
| Ind. 1/2-3/4 mile | 2,096 | 3.9 | 9.2 | 0.0 | 88.0 |
| Res. Low Density, 3/4-1 mile | 2,096 | 14.6 | 24.6 | 0.0 | 91.7 |
| Res. Medium Density, 3/4-1 mile | 2,096 | 2.7 | 5.8 | 0.0 | 41.6 |
| Res. High Density 3/4-1 mile | 2,096 | 3.6 | 7.3 | 0.0 | 47.4 |
| Bus. Low Density 3/4-1 mile | 2,096 | 0.6 | 1.2 | 0.0 | 9.1 |
| Bus. High Density 3/4-1 mile | 2,096 | 2.7 | 5.8 | 0.0 | 39.1 |
| Ind. 3/4-1 mile | 2,096 | 5.0 | 10.1 | 0.0 | 77.8 |

Table 1.3 Descriptive Statistics, Zoning, Urban Subsample

| Statistic | Households | Mean | St. Dev. | Min | Max |
|---|---|---|---|---|---|
| Res. Low Density, 0-1/4 mile | 410 | 21.9 | 32.0 | 0.0 | 99.6 |
| Res. Medium Density, 0-1/4 mile | 410 | 7.7 | 15.2 | 0.0 | 94.5 |
| Res. High Density 0-1/4 mile | 410 | 38.9 | 31.8 | 0.0 | 98.1 |
| Bus. Low Density 0-1/4 mile | 410 | 1.6 | 2.3 | 0.0 | 9.5 |
| Bus. High Density 0-1/4 mile | 410 | 20.5 | 29.2 | 0.0 | 100.0 |
| Ind. 0-1/4 mile | 410 | 3.2 | 11.3 | 0.0 | 70.1 |
| Res. Low Density, 1/4-1/2 mile | 410 | 23.8 | 25.3 | 0.0 | 96.3 |
| Res. Medium Density, 1/4-1/2 mile | 410 | 7.3 | 8.3 | 0.0 | 34.8 |
| Res. High Density 1/4-1/2 mile | 410 | 33.8 | 19.2 | 0.0 | 76.6 |
| Bus. Low Density 1/4-1/2 mile | 410 | 1.5 | 1.5 | 0.0 | 6.2 |
| Bus. High Density 1/4-1/2 mile | 410 | 21.8 | 19.8 | 0.0 | 84.9 |
| Ind. 1/4-1/2 mile | 410 | 5.1 | 12.0 | 0.0 | 68.7 |
| Res. Low Density, 1/2-3/4 mile | 410 | 8.3 | 14.7 | 0.0 | 71.2 |
| Res. Medium Density, 1/2-3/4 mile | 410 | 2.7 | 6.2 | 0.0 | 30.6 |
| Res. High Density 1/2-3/4 mile | 410 | 8.6 | 12.3 | 0.0 | 40.1 |
| Bus. Low Density 1/2-3/4 mile | 410 | 0.5 | 0.9 | 0.0 | 4.4 |
| Bus. High Density 1/2-3/4 mile | 410 | 8.6 | 13.5 | 0.0 | 57.3 |
| Ind. 1/2-3/4 mile | 410 | 7.0 | 13.0 | 0.0 | 55.7 |
| Res. Low Density, 3/4-1 mile | 410 | 8.9 | 13.8 | 0.0 | 46.8 |
| Res. Medium Density, 3/4-1 mile | 410 | 2.0 | 3.9 | 0.0 | 17.2 |
| Res. High Density 3/4-1 mile | 410 | 8.4 | 11.7 | 0.0 | 47.4 |
| Bus. Low Density 3/4-1 mile | 410 | 0.5 | 0.8 | 0.0 | 4.5 |
| Bus. High Density 3/4-1 mile | 410 | 7.0 | 10.0 | 0.0 | 39.1 |
| Ind. 3/4-1 mile | 410 | 9.4 | 13.5 | 0.0 | 54.6 |

Table 1.4 Descriptive Statistics, Zoning, Suburban Subsample

| Statistic | Households | Mean | St. Dev. | Min | Max |
|---|---|---|---|---|---|
| Res. Low Density, 0-1/4 mile | 1,686 | 69.4 | 32.4 | 0.0 | 100.0 |
| Res. Medium Density, 0-1/4 mile | 1,686 | 10.6 | 19.7 | 0.0 | 100.0 |
| Res. High Density 0-1/4 mile | 1,686 | 7.9 | 16.9 | 0.0 | 100.0 |
| Bus. Low Density 0-1/4 mile | 1,686 | 2.2 | 4.2 | 0.0 | 29.6 |
| Bus. High Density 0-1/4 mile | 1,686 | 6.0 | 13.0 | 0.0 | 100.0 |
| Ind. 0-1/4 mile | 1,686 | 1.6 | 7.6 | 0.0 | 73.7 |
| Res. Low Density, 1/4-1/2 mile | 1,686 | 65.3 | 26.4 | 0.0 | 100.0 |
| Res. Medium Density, 1/4-1/2 mile | 1,686 | 11.9 | 16.3 | 0.0 | 98.1 |
| Res. High Density 1/4-1/2 mile | 1,686 | 7.8 | 11.4 | 0.0 | 66.7 |
| Bus. Low Density 1/4-1/2 mile | 1,686 | 2.1 | 2.4 | 0.0 | 14.6 |
| Bus. High Density 1/4-1/2 mile | 1,686 | 7.5 | 10.8 | 0.0 | 100.0 |
| Ind. 1/4-1/2 mile | 1,686 | 3.0 | 9.1 | 0.0 | 76.2 |
| Res. Low Density, 1/2-3/4 mile | 1,686 | 17.0 | 28.1 | 0.0 | 94.2 |
| Res. Medium Density, 1/2-3/4 mile | 1,686 | 2.3 | 5.5 | 0.0 | 44.4 |
| Res. High Density 1/2-3/4 mile | 1,686 | 2.4 | 5.6 | 0.0 | 32.1 |
| Bus. Low Density 1/2-3/4 mile | 1,686 | 0.7 | 1.4 | 0.0 | 8.5 |
| Bus. High Density 1/2-3/4 mile | 1,686 | 2.1 | 4.2 | 0.0 | 27.4 |
| Ind. 1/2-3/4 mile | 1,686 | 3.1 | 7.8 | 0.0 | 88.0 |
| Res. Low Density, 3/4-1 mile | 1,686 | 16.0 | 26.4 | 0.0 | 91.7 |
| Res. Medium Density, 3/4-1 mile | 1,686 | 2.8 | 6.2 | 0.0 | 41.6 |
| Res. High Density 3/4-1 mile | 1,686 | 2.4 | 5.1 | 0.0 | 25.6 |
| Bus. Low Density 3/4-1 mile | 1,686 | 0.6 | 1.3 | 0.0 | 9.1 |
| Bus. High Density 3/4-1 mile | 1,686 | 1.7 | 3.5 | 0.0 | 22.8 |
| Ind. 3/4-1 mile | 1,686 | 3.9 | 8.8 | 0.0 | 77.8 |

Table 1.5 Descriptive Statistics, Survey Respondents

| Statistic | Individuals | Mean | St. Dev. | Min | Max |
|---|---|---|---|---|---|
| HH vehicles | 3,308 | 1.87 | 0.92 | 0 | 6 |
| Drivers license | 3,308 | 0.93 | 0.25 | 0 | 1 |
| Transit pass | 3,308 | 0.15 | 0.36 | 0 | 1 |
| HH bicycles | 3,308 | 1.53 | 1.78 | 0 | 30 |
| Miles bike lanes < 1 M. | 3,308 | 11.66 | 5.58 | 0.00 | 33.05 |
| Miles of bus routes < 0.5 M. | 3,308 | 8.65 | 12.20 | 0.00 | 90.31 |
| Miles of rail lines < 1 M. | 3,308 | 2.17 | 3.17 | 0.00 | 14.35 |
| Intersections < 0.5 M. | 3,308 | 125.48 | 28.13 | 9 | 255 |
| HH size | 3,308 | 2.34 | 1.16 | 1 | 7 |
| Male | 3,308 | 0.47 | 0.50 | 0 | 1 |
| Age | 3,308 | 52.28 | 15.88 | 16 | 93 |
| Income (000s) | 3,308 | 78.25 | 50.98 | 0.00 | 160.00 |
| College education | 3,308 | 0.36 | 0.48 | 0 | 1 |
| Employed | 3,308 | 0.67 | 0.47 | 0 | 1 |
| CBG population/sq. mile | 3,308 | 7,310.65 | 4,661.55 | 27.72 | 33,611.99 |
| CBG jobs/sq. mile | 3,308 | 4,742.56 | 20,052.30 | 0.00 | 278,470.50 |
| Urban | | | | | |
| HH vehicles | 595 | 1.50 | 0.93 | 0 | 6 |
| Drivers license | 595 | 0.90 | 0.30 | 0 | 1 |
| Transit pass | 595 | 0.19 | 0.40 | 0 | 1 |
| HH bicycles | 595 | 1.39 | 1.49 | 0 | 8 |
| Miles bike lanes < 1 M. | 595 | 20.22 | 5.71 | 10.70 | 33.05 |
| Miles of bus routes < 0.5 M. | 595 | 23.39 | 22.30 | 2.81 | 90.31 |
| Miles of rail lines < 1 M. | 595 | 4.27 | 4.09 | 0.00 | 14.35 |
| Intersections < 0.5 M. | 595 | 138.63 | 17.30 | 95 | 178 |
| HH size | 595 | 1.99 | 1.02 | 1 | 6 |
| Male | 595 | 0.51 | 0.50 | 0 | 1 |
| Age | 595 | 51.61 | 15.41 | 16 | 88 |
| Income (000s) | 595 | 72.11 | 50.73 | 0.00 | 160.00 |
| College education | 595 | 0.43 | 0.49 | 0 | 1 |
| Employed | 595 | 0.69 | 0.46 | 0 | 1 |
| CBG population/sq. mile | 595 | 12,376.04 | 7,175.99 | 642.32 | 33,611.99 |
| CBG jobs/sq. mile | 595 | 16,811.90 | 43,340.44 | 0.00 | 278,470.50 |
| Suburban | | | | | |
| HH vehicles | 2,713 | 1.94 | 0.90 | 0 | 6 |
| Drivers license | 2,713 | 0.94 | 0.24 | 0 | 1 |
| Transit pass | 2,713 | 0.14 | 0.35 | 0 | 1 |
| HH bicycles | 2,713 | 1.56 | 1.84 | 0 | 30 |
| Miles bike lanes < 1 M. | 2,713 | 9.78 | 3.34 | 0.00 | 18.17 |
| Miles of bus routes < 0.5 M. | 2,713 | 5.41 | 3.80 | 0.00 | 24.63 |
| Miles of rail lines < 1 M. | 2,713 | 1.72 | 2.73 | 0.00 | 10.13 |
| Intersections < 0.5 M. | 2,713 | 122.59 | 29.20 | 9 | 255 |
| HH size | 2,713 | 2.42 | 1.18 | 1 | 7 |
| Male | 2,713 | 0.46 | 0.50 | 0 | 1 |
| Age | 2,713 | 52.43 | 15.98 | 16 | 93 |
| Income (000s) | 2,713 | 79.60 | 50.94 | 0.00 | 160.00 |
| College education | 2,713 | 0.34 | 0.47 | 0 | 1 |
| Employed | 2,713 | 0.67 | 0.47 | 0 | 1 |
| CBG population/sq. mile | 2,713 | 6,199.74 | 2,890.49 | 27.72 | 30,092.68 |
| CBG jobs/sq. mile | 2,713 | 2,095.58 | 6,318.71 | 0.00 | 138,294.70 |

Table 1.6 Descriptive Statistics, Tour Characteristics

| Statistic | Tours | Mean | St. Dev. | Min | Max |
|---|---|---|---|---|---|
| Tour distance | 5,123 | 10.82 | 12.27 | 0.01 | 135.42 |
| Tour duration (min) | 5,123 | 49.94 | 37.06 | 2 | 452 |
| Tour crosses highway | 5,123 | 0.75 | 0.44 | 0 | 1 |
| Departure hour | 5,123 | 11.21 | 4.26 | 0 | 23 |
| Tour time, auto | 5,123 | 44.98 | 34.96 | 0.09 | 452.00 |
| Tour time, bike | 5,123 | 63.87 | 38.22 | 0.20 | 406.25 |
| Tour time, transit | 5,123 | 65.46 | 37.75 | 0.19 | 232.00 |
| Tour time, walk | 5,123 | 168.01 | 180.11 | 0.56 | 2,031.23 |
| Work stops | 5,123 | 0.57 | 1.10 | 0 | 30 |
| Shopping stops | 5,123 | 0.71 | 0.98 | 0 | 10 |
| Healthcare stops | 5,123 | 0.07 | 0.26 | 0 | 3 |
| Social stops | 5,123 | 0.25 | 0.50 | 0 | 4 |
| Urban | | | | | |
| Tour distance | 887 | 9.30 | 11.60 | 0.01 | 77.63 |
| Tour duration (min) | 887 | 51.50 | 35.76 | 2 | 232 |
| Tour crosses highway | 887 | 0.78 | 0.42 | 0 | 1 |
| Departure hour | 887 | 11.32 | 4.24 | 4 | 23 |
| Tour time, auto | 887 | 40.57 | 32.06 | 0.09 | 190.00 |
| Tour time, bike | 887 | 56.11 | 37.61 | 0.20 | 232.88 |
| Tour time, transit | 887 | 59.48 | 40.14 | 0.19 | 232.00 |
| Tour time, walk | 887 | 147.60 | 169.13 | 0.56 | 1,164.38 |
| Work stops | 887 | 0.56 | 0.84 | 0 | 6 |
| Shopping stops | 887 | 0.71 | 0.93 | 0 | 6 |
| Healthcare stops | 887 | 0.06 | 0.27 | 0 | 3 |
| Social stops | 887 | 0.25 | 0.49 | 0 | 4 |
| Suburban | | | | | |
| Tour distance | 4,236 | 11.13 | 12.38 | 0.03 | 135.42 |
| Tour duration (min) | 4,236 | 49.61 | 37.32 | 2 | 452 |
| Tour crosses highway | 4,236 | 0.74 | 0.44 | 0 | 1 |
| Departure hour | 4,236 | 11.18 | 4.26 | 0 | 23 |
| Tour time, auto | 4,236 | 45.90 | 35.47 | 0.18 | 452.00 |
| Tour time, bike | 4,236 | 65.50 | 38.15 | 0.40 | 406.25 |
| Tour time, transit | 4,236 | 66.71 | 37.11 | 0.39 | 215.00 |
| Tour time, walk | 4,236 | 172.29 | 182.06 | 2.00 | 2,031.23 |
| Work stops | 4,236 | 0.57 | 1.14 | 0 | 30 |
| Shopping stops | 4,236 | 0.71 | 1.00 | 0 | 10 |
| Healthcare stops | 4,236 | 0.07 | 0.26 | 0 | 2 |
| Social stops | 4,236 | 0.25 | 0.51 | 0 | 4 |

Table 1.7 MNL: Base, Full, Truncated

| Variable | Base | Full | Truncated |
|---|---|---|---|
| **Auto** | | | |
| HH Vehicles | 0.281* | 0.309* | 0.555* |
| Driver License | 1.524*** | 1.605*** | 1.221 |
| Tour Duration | −0.671*** | −0.664*** | −0.907*** |
| Time | 0.673*** | 0.665*** | 0.919*** |
| **Bicycle** | | | |
| Intercept | −5.925*** | −10.454*** | −12.782** |
| HH bicycles | 0.243*** | 0.241*** | 0.318*** |
| Tour crosses highway | 0.517 | 0.506 | 0.965** |
| Miles bike lanes < 1 M. | 0.010 | 0.021 | 0.042 |
| HH size | 0.071 | 0.070 | 0.230 |
| Male | 1.030*** | 1.235*** | 1.490*** |
| Age > 65 | −1.389* | −0.922 | −0.497 |
| Income | 0.000 | −0.000 | −0.009 |
| Employed | 0.576 | 0.555 | 0.772 |
| College Degree | 0.069 | 0.097 | 0.176 |
| CBG population/sq. mile | −0.000 | −0.000 | |
| CBG jobs/sq. mile | −0.000 | −0.000 | |
| Departure hour | 0.029 | 0.027 | 0.031 |
| Daytime departure | 0.580 | 0.635 | 0.968* |
| Work stops | −0.010 | −0.112 | 0.223 |
| Shopping stops | −0.975*** | −1.048*** | −0.975** |
| Healthcare stops | −1.076 | −0.899 | −16.496 |
| Social stops | 0.099 | 0.185 | 0.085 |
| Tour distance | −0.360*** | −0.364*** | −0.452** |
| Res. Low Density, 0-1/4 mile | | 0.073* | 0.001 |
| Res. Medium Density, 0-1/4 mile | | −0.017 | −0.093 |
| Res. High Density 0-1/4 mile | | 0.076** | −0.002 |
| Bus. Low Density 0-1/4 mile | | 0.113 | 0.071 |
| Bus. High Density 0-1/4 mile | | 0.025 | −0.035 |
| Ind. 0-1/4 mile | | 0.022 | −0.026 |
| Res. Low Density, 1/4-1/2 mile | | −0.026 | 0.060 |
| Res. Medium Density, 1/4-1/2 mile | | 0.014 | 0.090 |
| Res. High Density 1/4-1/2 mile | | −0.016 | 0.079 |
| Bus. Low Density 1/4-1/2 mile | | −0.116 | −0.297 |
| Bus. High Density 1/4-1/2 mile | | −0.027 | 0.055 |
| Ind. 1/4-1/2 mile | | −0.054 | −0.010 |
| Res. Low Density, 1/2-3/4 mile | | −0.059 | 0.039 |
| Res. Medium Density, 1/2-3/4 mile | | −0.182 | −0.125 |
| Res. High Density 1/2-3/4 mile | | −0.022 | 0.024 |
| Bus. Low Density 1/2-3/4 mile | | 0.007 | 0.395 |
| Bus. High Density 1/2-3/4 mile | | −0.019 | 0.050 |
| Ind. 1/2-3/4 mile | | −0.029 | 0.053 |
| Res. Low Density, 3/4-1 mile | | 0.063 | −0.055 |
| Res. Medium Density, 3/4-1 mile | | 0.177 | 0.252 |
| Res. High Density 3/4-1 mile | | −0.031 | −0.151 |
| Bus. Low Density 3/4-1 mile | | −0.255 | 0.394 |
| Bus. High Density 3/4-1 mile | | 0.140 | 0.060 |
| Ind. 3/4-1 mile | | 0.056 | −0.045 |
| Time | 0.034** | 0.032* | 0.025 |

| Variable | Base | Full | Truncated |
|---|---|---|---|
| Transit | | | |
| Intercept | $-3.094^{***}$ | $-3.211^{*}$ | $-5.317$ |
| Transit pass | $2.051^{***}$ | $2.260^{***}$ | $2.539^{***}$ |
| Miles bus routes < 1/2 M. | 0.020 | 0.025 | 0.003 |
| Bus stops < 1/2 M. | −0.003 | −0.010 | 0.014 |
| Miles rail lines < 1 M. | 0.058 | $0.131^{**}$ | $0.218^{***}$ |
| Rail stops < 1 M. | 0.054 | 0.265 | 0.258 |
| HH size | −0.014 | −0.033 | 0.180 |
| Male | −0.201 | −0.187 | −0.284 |
| Age > 65 | $-0.875^{*}$ | $-0.890^{*}$ | −1.007 |
| Income | −0.005 | −0.004 | $-0.013^{**}$ |
| Employed | −0.363 | −0.442 | 0.015 |
| College Degree | −0.289 | −0.405 | −0.413 |
| CBG population/sq. mile | 0.000 | 0.000 | |
| CBG jobs/sq. mile | −0.000 | 0.000 | |
| Departure hour | −0.023 | −0.024 | −0.016 |
| Daytime departure | $-0.647^{**}$ | $-0.692^{**}$ | −0.197 |
| Work stops | −0.044 | −0.069 | 0.018 |
| Shopping stops | $-0.544^{**}$ | $-0.507^{**}$ | −0.057 |
| Healthcare stops | −0.451 | −0.435 | −0.256 |
| Social stops | $-0.627^{*}$ | $-0.552^{*}$ | −0.181 |
| Tour distance | $0.039^{**}$ | $0.043^{***}$ | 0.049 |
| Res. Low Density, 0-1/4 mile | | 0.021 | −0.004 |
| Res. Medium Density, 0-1/4 mile | | 0.020 | −0.027 |
| Res. High Density 0-1/4 mile | | 0.029 | −0.008 |
| Bus. Low Density 0-1/4 mile | | 0.026 | 0.093 |
| Bus. High Density 0-1/4 mile | | 0.012 | −0.025 |
| Ind. 0-1/4 mile | | −0.003 | 0.003 |
| Res. Low Density, 1/4-1/2 mile | | −0.014 | −0.002 |
| Res. Medium Density, 1/4-1/2 mile | | −0.013 | −0.014 |
| Res. High Density 1/4-1/2 mile | | −0.013 | 0.031 |
| Bus. Low Density 1/4-1/2 mile | | −0.119 | −0.246 |
| Bus. High Density 1/4-1/2 mile | | −0.048 | −0.027 |
| Ind. 1/4-1/2 mile | | −0.007 | −0.020 |
| Res. Low Density, 1/2-3/4 mile | | −0.109 | −0.058 |
| Res. Medium Density, 1/2-3/4 mile | | $-0.133^{*}$ | −0.054 |
| Res. High Density 1/2-3/4 mile | | −0.074 | −0.049 |
| Bus. Low Density 1/2-3/4 mile | | −0.118 | −0.249 |
| Bus. High Density 1/2-3/4 mile | | −0.101 | −0.084 |
| Ind. 1/2-3/4 mile | | −0.091 | −0.079 |
| Res. Low Density, 3/4-1 mile | | 0.114 | 0.055 |
| Res. Medium Density, 3/4-1 mile | | 0.121 | 0.104 |
| Res. High Density 3/4-1 mile | | 0.029 | −0.013 |
| Bus. Low Density 3/4-1 mile | | 0.105 | 0.585 |
| Bus. High Density 3/4-1 mile | | 0.125 | 0.045 |
| Ind. 3/4-1 mile | | 0.091 | 0.082 |
| Time | 0.007 | 0.006 | $0.024^{***}$ |

| Variable | Base | Full | Truncated |
|---|---|---|---|
| Walk | | | |
| Intercept | 0.855 | −2.098 | −2.668 |
| Tour crosses highway | 0.168 | 0.049 | 0.523 |
| Intersections < 1/2 M. | −0.005 | −0.006 | −0.012 |
| HH size | −0.230* | −0.228* | −0.119 |
| Male | 0.283 | 0.269 | 0.758* |
| Age > 65 | −0.259 | −0.192 | −0.331 |
| Income | −0.001 | −0.001 | −0.009* |
| Employed | 0.797** | 0.683** | 0.776 |
| College Degree | 0.381 | 0.354 | 0.421 |
| CBG population/sq. mile | 0.000 | 0.000 | |
| CBG jobs/sq. mile | 0.000 | 0.000 | |
| Departure hour | 0.023 | 0.021 | 0.034 |
| Daytime departure | −0.046 | −0.117 | 0.004 |
| Work stops | −0.543** | −0.562** | −0.181 |
| Shopping stops | −1.059*** | −1.052*** | −1.087*** |
| Healthcare stops | −0.851 | −0.923 | −1.323 |
| Social stops | −0.687** | −0.719** | −0.773 |
| Tour distance | −2.074*** | −2.186*** | −2.903*** |
| Res. Low Density, 0-1/4 mile | | −0.033 | −0.054 |
| Res. Medium Density, 0-1/4 mile | | −0.022 | −0.051 |
| Res. High Density 0-1/4 mile | | −0.021 | −0.029 |
| Bus. Low Density 0-1/4 mile | | −0.041 | −0.035 |
| Bus. High Density 0-1/4 mile | | −0.017 | −0.026 |
| Ind. 0-1/4 mile | | −0.017 | −0.030 |
| Res. Low Density, 1/4-1/2 mile | | 0.071** | 0.102 |
| Res. Medium Density, 1/4-1/2 mile | | 0.052 | 0.095 |
| Res. High Density 1/4-1/2 mile | | 0.067* | 0.101 |
| Bus. Low Density 1/4-1/2 mile | | 0.015 | −0.237 |
| Bus. High Density 1/4-1/2 mile | | 0.056 | 0.073 |
| Ind. 1/4-1/2 mile | | 0.065 | 0.076 |
| Res. Low Density, 1/2-3/4 mile | | −0.088 | −0.073 |
| Res. Medium Density, 1/2-3/4 mile | | −0.102 | −0.190 |
| Res. High Density 1/2-3/4 mile | | −0.029 | −0.023 |
| Bus. Low Density 1/2-3/4 mile | | −0.148 | 0.189 |
| Bus. High Density 1/2-3/4 mile | | −0.138* | −0.170 |
| Ind. 1/2-3/4 mile | | −0.106 | −0.139 |
| Res. Low Density, 3/4-1 mile | | 0.086 | 0.044 |
| Res. Medium Density, 3/4-1 mile | | 0.152* | 0.319** |
| Res. High Density 3/4-1 mile | | 0.020 | −0.015 |
| Bus. Low Density 3/4-1 mile | | 0.033 | 0.225 |
| Bus. High Density 3/4-1 mile | | 0.134 | 0.154 |
| Ind. 3/4-1 mile | | 0.090 | 0.115 |
| Time | 0.043*** | 0.042*** | 0.066*** |
| Observations | 5,123 | 5,123 | 2,463 |
| McFadden $R^2$ | 0.796 | 0.810 | 0.840 |
| Log Likelihood | -632.281 | -589.834 | -291.433 |
| LR Test | 4,937.074*** (df = 65) | 5,021.968*** (df = 137) | 3,054.118*** (df = 131) |

*Notes: Significance at the 1, 5, and 10% levels shown by ***, **, and *, respectively.*

Table 1.8 Correlation Matrix: MNL Residuals

| Variable | Auto | Bike | Transit | Walk |
|---|---|---|---|---|
| Miles bike lanes <1 M. | −0.164 | 0.109 | 0.134 | 0.189 |
| Miles bus routes <0.5 M. | −0.200 | 0.090 | 0.167 | 0.192 |
| Bus stops <0.5 M. | −0.214 | 0.103 | 0.185 | 0.207 |
| Rail stops <0.5 M. | −0.121 | 0.080 | 0.126 | 0.154 |
| Miles rail lines <1 M. | −0.130 | 0.108 | 0.127 | 0.145 |
| Intersections <0.5 M. | −0.036 | 0.012 | 0.016 | 0.043 |
| CBG population/sq. mile | −0.150 | 0.055 | 0.128 | 0.111 |
| CBG jobs/sq. mile | −0.141 | 0.054 | 0.131 | 0.120 |
| Res. Low Density, 0-1/4 mile | 0.157 | −0.018 | −0.094 | −0.129 |
| Res. Medium Density, 0-1/4 mile | −0.001 | −0.070 | −0.029 | −0.041 |
| Res. High Density 0-1/4 mile | −0.088 | 0.056 | 0.073 | 0.097 |
| Bus. Low Density 0-1/4 mile | −0.043 | 0.024 | 0.014 | 0.041 |
| Bus. High Density 0-1/4 mile | −0.143 | 0.019 | 0.088 | 0.126 |
| Ind. 0-1/4 mile | −0.044 | −0.002 | 0.015 | 0.024 |
| Res. Low Density, 1/4-1/2 mile | 0.132 | −0.028 | −0.086 | −0.119 |
| Res. Medium Density, 1/4-1/2 mile | 0.042 | −0.066 | −0.055 | −0.070 |
| Res. High Density 1/4-1/2 mile | −0.131 | 0.069 | 0.097 | 0.135 |
| Bus. Low Density 1/4-1/2 mile | 0.018 | −0.013 | −0.027 | −0.022 |
| Bus. High Density 1/4-1/2 mile | −0.127 | 0.037 | 0.087 | 0.128 |
| Ind. 1/4-1/2 mile | −0.048 | 0.002 | 0.028 | 0.028 |
| Res. Low Density, 1/2-3/4 mile | 0.014 | 0.032 | 0.027 | −0.008 |
| Res. Medium Density, 1/2-3/4 mile | −0.021 | 0.021 | 0.021 | 0.017 |
| Res. High Density 1/2-3/4 mile | −0.069 | 0.063 | 0.072 | 0.077 |
| Bus. Low Density 1/2-3/4 mile | 0.006 | 0.004 | 0.011 | −0.007 |
| Bus. High Density 1/2-3/4 mile | −0.083 | 0.069 | 0.098 | 0.087 |
| Ind. 1/2-3/4 mile | −0.036 | 0.050 | 0.059 | 0.031 |
| Res. Low Density, 3/4-1 mile | 0.003 | 0.031 | 0.032 | 0.003 |
| Res. Medium Density, 3/4-1 mile | −0.007 | 0.051 | 0.031 | 0.028 |
| Res. High Density 3/4-1 mile | −0.066 | 0.059 | 0.078 | 0.069 |
| Bus. Low Density 3/4-1 mile | 0.005 | 0.009 | 0.015 | −0.001 |
| Bus. High Density 3/4-1 mile | −0.076 | 0.069 | 0.091 | 0.089 |
| Ind. 3/4-1 mile | −0.037 | 0.057 | 0.067 | 0.023 |

Table 1.9 MNL: Urban and Suburban

| Variable | Urban | Suburban |
|---|---|---|
| Auto | | |
| HH Vehicles | −1.769* | 0.397** |
| Driver License | 6.091 | 1.990*** |
| Tour Duration | −2.456*** | −0.587*** |
| Time | 2.514*** | 0.576*** |
| Bicycle | | |
| Intercept | −71.455*** | −42.547** |
| HH bicycles | 4.227*** | 0.250*** |
| Tour crosses highway | 6.021* | −0.238 |
| Miles bike lanes < 1 M. | 1.041 | 0.086 |
| HH size | −4.717* | 0.156 |
| Male | 7.899** | 1.020** |
| Age > 65 | −14.592** | −1.275 |
| Income | −0.023 | −0.001 |
| Employed | −5.084 | 0.956* |
| College Degree | 2.117 | 0.368 |
| CBG population/sq. mile | | −0.000 |
| CBG jobs/sq. mile | | −0.000 |
| Departure hour | 0.450** | 0.028 |
| Daytime departure | −3.251 | 1.360*** |
| Work stops | 1.674 | −0.379 |
| Shopping stops | −6.308** | −1.332*** |
| Healthcare stops | −24.741 | −0.513 |
| Social stops | 2.554 | 0.071 |
| Tour distance | −3.739*** | −0.376*** |
| Res. Low Density, 0-1/4 mile | −0.122 | 0.271* |
| Res. Medium Density, 0-1/4 mile | −0.225 | 0.126 |
| Res. High Density 0-1/4 mile | 0.014 | 0.249 |
| Bus. Low Density 0-1/4 mile | 0.937 | 0.391** |
| Bus. High Density 0-1/4 mile | 0.015 | 0.175 |
| Ind. 0-1/4 mile | −1.150** | 0.214 |
| Res. Low Density, 1/4-1/2 mile | 0.471* | 0.094 |
| Res. Medium Density, 1/4-1/2 mile | 0.419 | 0.157 |
| Res. High Density 1/4-1/2 mile | 0.333 | 0.124 |
| Bus. Low Density 1/4-1/2 mile | 0.362 | 0.111 |
| Bus. High Density 1/4-1/2 mile | 0.254 | 0.130 |
| Ind. 1/4-1/2 mile | 1.340** | 0.111 |
| Res. Low Density, 1/2-3/4 mile | −1.465 | −0.123 |
| Res. Medium Density, 1/2-3/4 mile | −0.471 | −0.381 |
| Res. High Density 1/2-3/4 mile | −2.444* | 0.013 |
| Bus. Low Density 1/2-3/4 mile | −15.512 | −0.062 |
| Bus. High Density 1/2-3/4 mile | −1.195 | 0.075 |
| Ind. 1/2-3/4 mile | −0.236 | −0.117 |
| Res. Low Density, 3/4-1 mile | 1.627 | 0.105 |
| Res. Medium Density, 3/4-1 mile | 1.753 | 0.238 |
| Res. High Density 3/4-1 mile | 2.779 | −0.049 |
| Bus. Low Density 3/4-1 mile | 13.665* | −0.255 |
| Bus. High Density 3/4-1 mile | −0.125 | 0.302 |
| Ind. 3/4-1 mile | −0.121 | 0.103 |
| Time | 0.364** | 0.033* |

| Variable | Urban | Suburban |
|---|---|---|
| Transit | | |
| Intercept | −11.175 | −5.445 |
| Transit pass | 5.693*** | 2.619*** |
| Miles bus routes < 1/2 M. | 0.259* | −0.027 |
| Bus stops < 1/2 M. | 0.071 | −0.002 |
| Miles rail lines < 1 M. | 0.355 | 0.141* |
| Rail stops < 1 M. | 0.187 | 0.397 |
| HH size | −4.097** | 0.023 |
| Male | −0.920 | −0.160 |
| Age > 65 | −5.028** | −0.826 |
| Income | −0.024 | −0.005 |
| Employed | −4.967** | −0.437 |
| College Degree | −0.708 | −0.321 |
| CBG population/sq. mile | | 0.000 |
| CBG jobs/sq. mile | | −0.000 |
| Departure hour | −0.055 | −0.034 |
| Daytime departure | −3.293* | −0.874** |
| Work stops | −2.021 | −0.139 |
| Shopping stops | −2.277 | −0.898*** |
| Healthcare stops | −7.052 | −0.031 |
| Social stops | −2.856 | −1.227*** |
| Tour distance | 0.167 | 0.046** |
| Res. Low Density, 0-1/4 mile | −0.001 | 0.058 |
| Res. Medium Density, 0-1/4 mile | −0.109 | 0.062 |
| Res. High Density 0-1/4 mile | 0.026 | 0.082** |
| Bus. Low Density 0-1/4 mile | −0.235 | 0.030 |
| Bus. High Density 0-1/4 mile | −0.014 | 0.063 |
| Ind. 0-1/4 mile | −0.242 | 0.042 |
| Res. Low Density, 1/4-1/2 mile | 0.196 | −0.015 |
| Res. Medium Density, 1/4-1/2 mile | −0.442 | −0.016 |
| Res. High Density 1/4-1/2 mile | 0.206 | −0.068* |
| Bus. Low Density 1/4-1/2 mile | −0.523 | −0.105 |
| Bus. High Density 1/4-1/2 mile | −0.167 | −0.048 |
| Ind. 1/4-1/2 mile | −0.559 | −0.012 |
| Res. Low Density, 1/2-3/4 mile | −2.313** | −0.095 |
| Res. Medium Density, 1/2-3/4 mile | −0.535 | −0.163 |
| Res. High Density 1/2-3/4 mile | −1.231 | 0.039 |
| Bus. Low Density 1/2-3/4 mile | −6.697 | −0.017 |
| Bus. High Density 1/2-3/4 mile | −0.115 | −0.113 |
| Ind. 1/2-3/4 mile | −0.989 | −0.113 |
| Res. Low Density, 3/4-1 mile | 2.475** | 0.086 |
| Res. Medium Density, 3/4-1 mile | 0.834 | 0.126 |
| Res. High Density 3/4-1 mile | 0.378 | −0.072 |
| Bus. Low Density 3/4-1 mile | −3.713 | −0.051 |
| Bus. High Density 3/4-1 mile | 0.034 | 0.240 |
| Ind. 3/4-1 mile | 1.915** | 0.116 |
| Time | 0.055* | −0.011 |

| Variable | Urban | Suburban |
| --- | --- | --- |
| Walk | | |
| Intercept | 2.966 | −0.429 |
| Tour crosses highway | 0.923 | −0.054 |
| Intersections < 1/2 M. | 0.036 | −0.005 |
| HH size | −3.307** | −0.196 |
| Male | 0.086 | −0.029 |
| Age > 65 | −3.126 | −0.432 |
| Income | −0.027 | 0.003 |
| Employed | −0.521 | 0.604 |
| College Degree | 1.448 | 0.365 |
| CBG population/sq. mile | | −0.000 |
| CBG jobs/sq. mile | | −0.000 |
| Departure hour | 0.024 | 0.027 |
| Daytime departure | −1.425 | 0.099 |
| Work stops | −2.084 | −1.059** |
| Shopping stops | −4.493** | −1.062*** |
| Healthcare stops | −10.572 | −0.465 |
| Social stops | −4.429** | −0.168 |
| Tour distance | −10.704*** | −1.697*** |
| Res. Low Density, 0-1/4 mile | −0.355* | −0.040 |
| Res. Medium Density, 0-1/4 mile | −0.189 | −0.028 |
| Res. High Density 0-1/4 mile | −0.216 | −0.033 |
| Bus. Low Density 0-1/4 mile | −0.924* | −0.032 |
| Bus. High Density 0-1/4 mile | −0.176 | −0.037 |
| Ind. 0-1/4 mile | −0.458 | −0.009 |
| Res. Low Density, 1/4-1/2 mile | 0.444** | 0.072 |
| Res. Medium Density, 1/4-1/2 mile | 0.145 | 0.052 |
| Res. High Density 1/4-1/2 mile | 0.314* | 0.060 |
| Bus. Low Density 1/4-1/2 mile | −0.120 | 0.001 |
| Bus. High Density 1/4-1/2 mile | 0.240 | 0.056 |
| Ind. 1/4-1/2 mile | 0.274 | 0.046 |
| Res. Low Density, 1/2-3/4 mile | −1.779 | −0.140 |
| Res. Medium Density, 1/2-3/4 mile | −1.171 | −0.146 |
| Res. High Density 1/2-3/4 mile | −0.755 | −0.079 |
| Bus. Low Density 1/2-3/4 mile | −6.089 | −0.235 |
| Bus. High Density 1/2-3/4 mile | −0.815 | −0.200 |
| Ind. 1/2-3/4 mile | −1.660 | −0.119 |
| Res. Low Density, 3/4-1 mile | 1.665 | 0.141 |
| Res. Medium Density, 3/4-1 mile | 2.543 | 0.170 |
| Res. High Density 3/4-1 mile | 0.549 | 0.103 |
| Bus. Low Density 3/4-1 mile | −5.992 | 0.185 |
| Bus. High Density 3/4-1 mile | 0.479 | 0.133 |
| Ind. 3/4-1 mile | 1.889 | 0.130 |
| Time | 0.351*** | 0.006 |
| Observations | 887 | 4,236 |
| McFadden $R^2$ | 0.924 | 0.810 |
| Log Likelihood | -62.225 | -415.978 |
| LR Test | 1,514.070*** (df = 131) | 3,546.944*** (df = 137) |

*Notes: Significance at the 1, 5, and 10% levels shown by ***, **, and *, respectively.*

# CHAPTER 2: SPATIAL MODELS OF TRAVEL BEHAVIOR AND LAND USE RESTRICTION

## 2.1 INTRODUCTION

Location of economic activity has always been an important aspect of regional economics. Spatial proximity plays a key role in many decisions made by individuals when it comes to weighing the benefits and costs of purchase decisions, allocation of resources, and other economic behavior in general. Transportation choices are particularly affected by location, and distances between origins and destinations undoubtedly influence travel decisions among individuals.

While the study of regional economics and regional science in general has been around for a long time, the development of formal econometric techniques to address location is a more recent development in the field. Of particular importance to the field of spatial econometrics is the treatment of spatial dependence (spatial autocorrelation) and spatial heterogeneity (spatial structure). Spatial dependence and spatial heterogeneity are important in applied economic models because the presence of these phenomena may invalidate or bias mainstream results. In addition, these issues have been largely ignored in the mainstream literature (Anselin, 1988). This chapter focuses on consumer transportation mode choice in a spatial context. Behavioral models of transportation choice employ the random utility model addressed in the previous chapter. In this chapter, the travel mode behavior model is adapted from the preceding chapter to incorporate spatial dependence and spatial heterogeneity to test whether the results are significantly different from the standard econometric model of transportation mode choice where space is dealt with informally. It is particularly important to investigate the presence of spatial dependence and heterogeneity in regards to land use restrictions because each individual faces a unique set of transportation choices based on their residential location and the proximity of this residential location to available goods, services, recreation, transportation, and employment opportunities.

The previous chapter used a choice specific multinomial logit model to estimate the effect of built environment, socioeconomic, and land restriction measures on the propensity of survey respondents to use four mode choice alternatives; auto, transit, bike, and walk. Due to the lack of understanding of spatial multinomial logit models, I condense the dependent variable choice set in this chapter to a binary choice between auto and non-auto transportation. The unit of observation continues to be a tour taken by individuals, as in the previous chapter. The key independent variables of interest in this study are the land use restriction variables encompassed in percentages of different zoning types within a 1/4, 1/4 to 1/2, 1/2 to 3/4 and 3/4 to 1 mile radius surrounding each survey respondents home. While these measures are spatially derived using GIS and measure a spatial component of mode choice decision, they rely on the canonical econometric approaches to model choice preference under the assumption of a random utility model. This chapter formally implements econometric techniques that explicitly deal with bias and inefficiency in the estimation of effects that may be introduced if spatial autocorrelation or spatial heterogeneity is present in the underlying data generating process.

In this chapter, I formally test for spatial autocorrelation and spatial heterogeneity in the data, and apply spatial econometric methods to correct for spatial components in the data generating process. The chapter covers the relevant spatial econometric theory, and applies the Moran's I and Geary's C tests for spatial processes at work in the data generating process. I then explore several models that address spatial autocorrelation, spatial heterogeneity, and both spatial autocorrelation and spatial heterogeneity jointly. Estimates of each model are performed with the two most commonly used spatial weights matrices in the literature, the row standardized binary weights matrix and the row standardized inverse distance matrix. The results from each model show that there is a high likelihood of the presence of spatial processes in the data generating process and that these models are preferable to canonical approaches to estimating travel mode choice behavior in this travel survey sample.

## 2.2 METHODOLOGY: THE SPATIAL ECONOMETRIC APPROACH

Spatial econometrics differentiates itself from mainstream econometric approaches by applying formal spatial modeling best summarized in Luc Anselin's pioneering work on the topic:

"I will consider the field of spatial econometrics to consist of those methods and techniques that, based on formal representation of the structure of spatial dependence and spatial heterogeneity, provide the means to carry out the proper specification, estimation, hypothesis testing, and prediction for models in regional science." (Anselin, 1988, p. 10)

2.2.1 Spatial Effects. Regional science and regional economics inherently deal with issues related to human behavior across space, cities, and regions. The term *spatial econometrics* and its designation as a distinct branch of econometrics dates back to the seminal work of Paelinck and Klaassen (1979) that collected a growing body of literature in the regional sciences that attempted to formally deal with the problems inherent in modeling spatial data in the context of regional econometric models. The primary characteristics that delineate the field according to Paelinck and Klaassen (1979) and summarized by Anselin (1988, p. 7) are: 1) the role of spatial interdependence in spatial models, 2) the asymmetry in spatial relations, 3) the importance of explanatory factors located in other spaces, 4) differentiation between ex post and ex ante interaction, and 5) explicit modeling of space. While it is possible to measure and model spatial data using standard econometric techniques by including variables in the model that have a spatial nature to their measurement (as I have done in the previous chapter, i.e. the percentage of zoning types within a distance from a respondent's residence), the distinction to be made here is that spatial econometrics formally deals with specific spatial aspects of the data at hand that preclude the use of traditional econometric techniques, and more particularly, address spatial dependence and spatial heterogeneity formally (Anselin, 1988; LeSage and Pace, 2009).

Spatial dependence addresses the lack of mutual independence across observations in cross-sectional data-sets and is often referred to as spatial autocorrelation following the path-breaking work of Cliff and Ord (1969, 1973). In essence, addressing spatial dependence is the development of formal statistical specifications of economic models that address Tobler's first law of geography, that "everything is related to everything else, but near things are more related than distant things"(Tobler, 1970, p.236). Spatial dependence is estimated by the relative location of one observation in the dataset to another, with an emphasis on the effect of distance between observations. Spatial dependence is caused by a variety of measurement errors, by spatial spill-over effects, or spatial externalities (Anselin, 1988), by spatially autocorrelated variables (Fingleton and Lopez-Bazo, 2006), or any situation in which the covariance of observations across geographical space is not equal to zero (Anselin, 2001). For example, spatial autocorrelation is often found in hedonic pricing models of residential real estate, where the sale price of one residential property is influenced by housing prices in surrounding neighborhoods.

Spatial heterogeneity is the "lack of stability over space of the behavioral or other relationship under study. More precisely, this implies that functional forms and parameters vary with location and are not homogeneous throughout the data set" (Anselin, 1988, p. 9). This type of econometric model addresses these issues by formally modeling the variation in parameters across space to address the heterogeneous effect an independent variable may have in different locations. More importantly, when spatial dependence and spatial heterogeneity are present in the data generating process and not explicitly modeled, the results of mainstream econometric techniques may be biased, inefficient, or both (Anselin, 1988; LeSage and Pace, 2009). Spatial econometric techniques address spatial processes within the data generating process and are generally preferred when spatial processes are at work in the data. An example of spatial heterogeneity is the variation in the effect income may have on travel mode preferences across the urban landscape. Income may have the opposite effect on preferences to drive in suburban locations than it does in central business districts because higher incomes allow suburban dwellers greater access to automobiles, while in urban locations higher income may allow individuals to live in areas with better access to goods and services, thus increasing reliance on alternative forms of transportation.

2.2.2 Formally Modeling Spatial Interaction. At the center of spatial econometrics is defining spatial association amongst observations (Anselin, 1988; Arbia, 2006; Anselin, 2010). To formally address the spatial connectedness of observations across space, an approach has been developed which uses a decision rule that determines whether two observations are spatial neighbors and thus close enough to exert influence on each other. The typical convention is to formally define spatial connectedness through the use of a symmetric matrix $W$ of dimensions equal to the number of observations $n$, whose strictly non-negative elements $w_{ij}$ indicate the spatial connectedness between units $i$ and $j \neq i$. With the spatial neighbor matrix constructed, spatial modeling proceeds by re-weighting each row to develop a spatial weights matrix, then pre-multiplying either the dependent or independent variables by the spatial weights matrix and estimating a vector of coefficients that includes a spatial dependence parameter. This modeling approach formally connects variables of neighboring observations through the spatial weights matrix W and produces an estimate of spatial association in the data generating process through the spatial dependence parameter(s). To demonstrate the use of the spatial weights matrix, the spatial autoregressive model equation is illuminating. In its simplest form with no independent regressors, the spatial autoregressive model equation is:

(2.1) $y_i = \rho \sum_j w_{ij} y_i + \varepsilon_i$

The term $\sum_j w_{ij} y_i + \varepsilon_i$ gives a weighted sum of each neighboring observation $j$'s dependent variable $y_j, j \neq i$. The estimated spatial dependence parameter ρ gives a measure of the influence those neighboring observations have on each $y_i$ observation. High values of ρ indicate strong spatial autocorrelation between observations, while a value of 0 indicates no spatial autocorrelation. In addition to measuring the direct influence of neighbors $j$ on observation $i$, the parameter ρ is sometimes referred to as the spatial decay parameter, because it also indicates how fast the effect of neighboring observations declines with higher order neighbors, i.e. neighbors of neighbors (Anselin, 1988; LeSage and Pace, 2009). For example, second order neighbors of $y_i$ are first order or first order neighbors of $y_i$'s first order neighbors and have an influence on $y_i$ equal to $\rho^2$, their influence on $y_i$ being exerted indirectly through $y_i$'s direct neighbors. Influence dissipates as observations become further removed from $y_i$, and $k$ order neighbors have and influence equal to $\rho^k$. Thus, values of $\rho$ closer to 1 indicate a slowly dissipating influence, while values close to 0 indicate an effect that quickly dissipates with higher order neighbors.

The literature has yet to determine a formal approach to developing the spatial weights matrix, although several approaches have widespread adoption. The pioneering work of Moran (1950) and Geary (1954) developed the notion of a binary weights matrix $W$, where each element $w_{ij}$ was assigned a value of 1 if two observational units were neighbors and assumed to exhibit influence on each other, and 0 otherwise. The spatial weights matrix was originally developed in the context of areal units and neighbors were defined as two observational units that shared a common border (Cliff and Ord, 1973). When observational units are points in space rather than areal units (as the data in this study is), neighbors are identified on the basis of distance. Two spatial point observations $i$ and $j$ are considered neighbors if $0 \leq d_{ij} \leq D$, where $d_{ij}$ is the distance between points $i$ and $j$ and $D$ is the bandwidth after which interaction between observations is considered non-existent and $w_{ij}$ is assigned a 0 weight (Anselin, 1988). Assignment of a zero weight does not preclude spatial effects occurring between more distant neighbors, however. Instead, influence is modeled as a higher order recursive effect through the estimated spatial dependence parameter as discussed above. Thus, observations that are not direct neighbors can influence each other indirectly through intermediary neighbors that connect them. Once a binary spatial weights matrix is constructed which determines which observations are neighbors of each other, the spatial weight matrix is often row standardized so that each row sums to 1. Row standardization normalizes spatial effects across a dataset, preventing observations that have many spatial neighbors from dominating coefficient estimates (Anselin, 1988).

Additional weighting schemes have also been applied to the binary weights matrix, and it is currently convention to row standardize the spatial weight matrices after applying alternative weighting schemes. If an alternative weighting scheme is applied, the construction of the spatial weights matrix becomes a two step process, first constructing a binary spatial neighbor matrix as above, then multiplying this matrix by another measure of spatial association. Cliff and Ord (1973, 1981) pioneered this concept by multiplying the binary spatial neighbor matrix by the inverse of distance between observations. This approach places higher weights on neighboring observations that are closer, while still placing zero weights on neighbors that are further apart than distance *D*. In this study, I test the sensitivity of results of all models to the choice of spatial weights matrix by estimating models with both a binary row standardized spatial weights matrix and an inverse distance row standardized weights matrix.

The decision to standardize the spatial weights matrix is not at all clear from the literature, and decisions on how to form the spatial weights matrix are generally determined by *a priori* assumptions made by the researcher in the context of each study. Anselin (1988) argues that in certain cases, such as inverse distance, the standardization of the spatial weights matrix may eliminate the economic interpretation of the results. However, the consensus is that the standardization of the spatial weights matrix is the preferable approach to avoid magnitude complications amongst variables and avoid certain spatially weighted variables dominating the results of spatial models (LeSage and Pace, 2009).

Formally, each element of a binary spatial weights matrix (spatial neighbor matrix) is calculated based on a decision rule. For contiguity neighbors, each element $w_{ij} = 1$ if the two areal units represented as polygons share a common boundary, and 0 otherwise. For distance based neighbors, $w_{ij} = 1 \; if \; d \leq D$ and 0 otherwise, where *d* is the distance between observation *i* and *j*, and *D* is a pre-determined distance threshold above which observations are said to exhibit no direct influence on each other. The choice of the distance threshold *D* is not well developed in the literature, and is typically based on domain knowledge or correspondence to other distance measurements in the dataset. Each element of a row standardized spatial weights matrix $W^{S}$ is calculated as:

(2.2) $$w_{ij}^{s} = \frac{w_{ij}}{\sum_j w_{ij}}$$

with each element of $W^S$ equal to 0 or 1 in a binary specification, and $1/d$ in an inverse distance specification if the two observations are neighbors. Matrix $W^S$ is used to link neighboring observations in spatial regression models, which produces estimates of coefficients on the resulting spatially weighted variables.

2.2.3 Measuring Spatial Dependence. Constructing a spatial weights matrix allows for formal testing of spatial dependence in the data generating process. The canonical measure of spatial dependence was developed by Moran (1950), and is widely used across many fields of study. Moran's I is a global test of spatial dependence. Shortly after Moran's I, Geary (1954) developed a formal test of localized autocorrelation, known as Geary's C. Moran's I indicates the level of global spatial autocorrelation, while Geary's C indicates localized spatial autocorrelation and therefore the possibility that spatial heterogeneity is also present in the data generating process.

Moran's I ranges between 0 and 1, with values near 1 indicating the absence of spatial autocorrelation, and values near 0 indicating strong spatial dependence of the observed variables (Moran, 1950). Geary's C ranges between 0 and 2, with values less than 1 demonstrating increasing positive spatial autocorrelation and values greater than 1 indicating increasing negative spatial autocorrelation Geary (1954). Formally, Moran's I is calculated as:

$$(2.3) \quad I = \frac{n}{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i-\bar{x})(x_j-\bar{x})}{\sum_{i=1}^{n}(x_i-\bar{x})^2}$$

and Geary's C is calculated as:

$$(2.4) \quad C = \frac{(n-1)}{2\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}} \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} w_{ij}(x_i-x_j)^2}{\sum_{i=1}^{n}(x_i-\bar{x})^2}$$

Using the equations above, it is possible to test Moran's I and Geary's C statistics against their theoretical values under different distributional assumptions. I test these two statistics against their theoretical values under a normal Gaussian distribution and the results are shown as significance stars in Table 2.1. Standard deviates for the Moran's I and Geary's C test statistics for normal variance following the method proposed in Cliff and Ord (1969) are relegated to Table B.1 of the appendix. As can be seen from the equations above, both statistics I and C are measurements of the covariance of deviation from the mean of observations of a single variable x across a dataset, linked through the spatial weights matrix $W$. Thus, one can think of the measures as clustering of deviations from the mean. If neighboring observations defined through W deviate from the mean in the same direction, high spatial clustering (autocorrelation) is present.

Moran's I and Geary's C for most variables in the current dataset are statistically significant at the 1 percent level and below 1, indicating the presence of spatial dependence (autocorrelation). Table 2.1 shows that Moran's I is close to 0 for many of the variables under study using the binary row standardized spatial weights matrix, indicating global autocorrelation, with weaker autocorrelation indicated using the inverse distance row standardized spatial weights matrix. Geary's C statistics also show local positive auto- correlation under both spatial weights matrices. This result is an indication that spatial dependence may be present both globally (spatial autocorrelation) and locally (spatial heterogeneity) in the underlying data generating processes. The dataset may include clustering that results from socioeconomic traits, political zoning boundary determination, and transit network design among other spatial phenomena, which is not surprising, considering that spatial segregation of land use is one of the objectives of zoning laws, and socioeconomic segregation is a widely accepted phenomenon.

The test results from Table 2.1 justify using spatial econometric modeling techniques to address the spatial dependence and heterogeneity that may be present in the data. I focus on three specifications of spatial models to correct for these spatial processes; the spatial autoregressive model (SAR) which addresses spatial dependence, the spatial error model (SEM) which addresses spatial heterogeneity, and the spatial Durbin model (SDM) which simultaneously addresses spatial dependence and spatial heterogeneity. As suggested by LeSage and Pace (2009), I estimate each of the models using the two most common row standardized spatial weights matrices and use a Lagrange multiplier test to determine which spatial weight matrix best fits the data. The two spatial weighting schemes employed in the spatial weights matrix before row standardization are the two most common in the literature, binary and inverse distance. Both spatial weight matrices are then row standardized before estimating each model.

2.2.4 The Spatial Autoregressive Model. The spatial autoregressive model (SAR) formally estimates the presence of spatial dependence by incorporating a spatially lagged dependent variable on the right hand side of the regression equation (Cliff and Ord, 1973). Thus, observations of the dependent variable are influenced by other observations of the dependent variable nearby. In the context of the present study, the SAR model is a way of controlling for the influence of neighboring survey respondents' transportation mode choices on the observational unit under study which represents a spatial clustering effect. In the binomial context, the choice variable observed (transportation mode = auto or non-auto) depends on the underlying utility of the choice indicator observed. The underlying latent variable $y_i = U_{1i} - U_{0i}$ is assumed to follow a normal distribution in the probit model estimation. The general spatial autoregressive model in a binomial context can be formally stated in the system of equations as:

(2.5) $y_i^* = \rho W y + X \beta + \varepsilon$

$\varepsilon \sim N(0, \sigma^2 I_n)$

$y_i = 1, if \ y_i \geq 0$

$y_i = 0, if \ y_i < 0$

where $y_i = 1$ if the binomial choice is observed, and 0 otherwise, W is the spatial weights matrix, y is a binomial vector of all dependent variables for the data set, ρ is an estimated spatial dependence parameter of spatial autocorrelation between observations, *X* is a matrix of independent variables, and β is a vector of estimated coefficients. The latent utility construct implies that $Pr(y_i = 1) = Pr(U_{1i} \geq U_{0i}) = Pr(y_i \geq 0)$ (LeSage and Pace, 2009). Typically, the SAR model is used to adjust for dependent variables that have a direct effect on the realization of the dependent variable in close proximity. The classic example is SAR hedonic pricing models of residential home values (e.g., Pace and Barry, 2004). This model says that the value of a house sold has a direct impact on other residential home prices in the area, and has been shown to be a valuable addition to traditional home price models (Anselin and Lozano-Gracia, 2007). Conceptually, the SAR would be the correct model for the underlying data generating process if a survey respondent's choice to use auto or non-auto transportation depended upon neighboring survey respondents' transportation mode choices, i.e. a clustering effect of mode choice. While theoretically the model has justifiable merit in controlling for spatial dependence, it is important to note that this model does not distinguish the direction of causality. It is quite possible that people who enjoy non-auto forms of transportation tend to live in the same locations because these locations provide employment, leisure, and shopping in close enough proximity to make non-auto trips more convenient. However, this model does identify if there is spatially clustered transportation behavior, and how fast this clustering effect deteriorates with distance. If the spatial dependence parameter ρ is significant, explicitly modeling spatial dependence is justified and therefore relevant to the study of spatial effects of zoning laws on transportation mode choice. While this model cannot determine the underlying cause of clustering in mode choice, it does control for the spatial phenomenon, and therefore is preferable to a non-spatial model that would otherwise suffer from missing variable bias, which in this case would be spatial autocorrelation of the dependent variable. It is also important to note that in the SAR model, the spatial dependence parameter ρ incorporates a feedback loop in the effect of neighboring observations on the dependent variable. There is a direct effect of independent variables on transportation choice, and this transportation choice then indirectly effects transportation mode choices of neighboring observations, which in turn affect the observation under study, creating a feedback loop effect. Thus, direct, indirect, and total effects of independent variables on the dependent variable are estimated.

2.2.5 The Spatial Error Model. In contrast to the spatial autoregressive model, the spatial error model (SEM) allows for heterogeneous effects of independent regressors across space. This adaptation of the traditional OLS model allows for both global coefficients (β) and local variation across space of coefficients to be modeled. In the binomial choice context, the latent variable approach of unobserved utility of the resulting choice indicator is used for the probit estimator similar to the process described for the SAR model. The SEM binomial choice model can be formally stated as:

(2.6) $y_i^* = X\beta + u$

$u = \lambda W u + e$

$e \sim N(0, \sigma^2 I_n)$

$y_i = 1, if\ y_i \geq 0$

$y_i = 0, if\ y_i < 0$

where $W$ is the spatial weights matrix. The SEM model allows for spatial variance of the error term and the estimation of its spatial lag parameter λ. Unlike the SAR model, indirect and direct effects cannot be estimated because there is no feedback loop of changes in the dependent regressors of neighboring observations on the dependent variable since the there is no autocorrelation parameter present. The parameter λ represents the extent to which heterogeneous independent coefficient estimates vary across space. This is the correct model to use if neighboring respondents' transportation mode choices observations do not affect an individual's mode choice, but the effect of independent variables have varying effects across space, such as the variation in the effect of income described earlier.

2.2.6 Spatial Durbin Model. The spatial Durbin model (SDM) allows for the estimation of both spatial autocorrelation and spatial dependence, simultaneously including a spatially lagged dependent variable as well as spatially lagged independent variables in a single model. The advantages of this model are the simultaneous control of both spatial dependence and spatial heterogeneity, but in practice can suffer from the curse of dimensionality. One advantage of the Bayesian approach to model estimation employed in this chapter and described below is the ability to estimate such models without running into non-convergence problems. These problems can be a significant challenge with the maximization procedures employed in maximum likelihood and generalized method of moments estimation, and often lead to severe computational challenges. The binomial probit SDM model can be formally stated as:

(2.7) $y_i^* = \rho W y + X \beta + WX\theta + \varepsilon$

$\varepsilon \sim N(0, \sigma^2 I_n$

$y_i = 1, if \; y_i \geq 0$

$y_i = 0, if \; y_i < 0$

where ρ is the estimated parameter of spatial autocorrelation of the dependent variable, β is the estimated vector of parameters on the independent variables, and θ is the vector of estimated parameters on the spatially lagged independent variables. The estimation of the SDM is similar to that of the SAR model with the independent variables multiplied by the spatial weights matrix added as additional independent variables. The resulting model then produces a vector of global effects of the independent variables β and a vector of local effects of the independent variables θ. LeSage and Pace (2009) detail the advantages of each spatial modeling approach, and determine that when the correct model is unknown and not dictated by theory, only the SDM gives unbiased results even if the true model is SAR or SEM. More particularly, when the true data generating process is the SEM model, SAR and SDM will produce unbiased but inefficient estimates. When the true data generating process is the SAR model, the SEM model produces biased estimates, while the SDM does not. If the true data generating process is the SDM model, the other models will have omitted variable bias. The SAR, SEM, and SDM versions of the travel behavior - built environment models are estimated below using both a binary and inverse distance weighted row standardized spatial weights matrix. General measures of spatial dependence and model validity are also estimated.

2.2.7 Estimation Techniques. McMillen (1992) was the first to propose techniques for estimating the SAR and SEM probit models. Due to the complicated error structure of the SAR and SEM probit models, direct maximum-likelihood estimation is not possible; however, in McMillen's procedure, the discrete variable is replaced by the expected value of the underlying latent variable, and the expectation is calculated iteratively until convergence. McMillen (1992), among others, deem this procedure impractical for large datasets, however. LeSage (2000) outlines several other drawbacks to the procedure. First, the estimation procedure requires the estimation of the likelihood function, which prohibits use of the information matrix for calculating the precision of the parameter estimates. Attempts to circumvent this problem produces biased estimates of the covariance matrix. Second, McMillen's approach requires the researcher to specify a functional form of the heteroskedastic spatial variance, and leads to varying inferences across alternative specifications. Alternatively, Bayesian estimation techniques do not require these assumptions about the functional form of the error process. I therefore implement a spatial Bayesian technique to estimate the spatial probit models in this chapter.

Following the work of Chib (1992) and Albert and Chib (1993), which detail the estimation of probit and logit models for discrete choices using Markov Chain Monte Carlo estimation in a Bayesian context, LeSage (2000) proposes a Bayesian estimation technique based on the Gibbs sampling approach (Albert and Chib, 1993). The estimation technique specifies a complete set of prior distributions for all parameters in the model and then samples from these distributions until a large number of parameter draws are obtained that converge to the true join posterior distribution of the parameters. This approach overcomes the drawbacks of the approach proposed by McMillen (1992) because the posterior distributions are available to calculate valid inference measures of the parameter estimates, thus escaping the bias inherent in McMillen's algorithm and the necessity to specify the functional form of model variance over space *a priori*. The likelihood function for the SAR, SDM, and SEM models is:

(2.8) $L(y, W|\rho, \beta, \sigma) = \frac{1}{2\pi\sigma^{2\left(\frac{n}{2}\right)}} |I_n - \rho W| \exp\left\{-\frac{1}{2\sigma^2}(\varepsilon'\varepsilon\right\}$

$\varepsilon = (I_n - \rho W)y - X\beta$ for the SAR model,

$\varepsilon = (I_n - \rho W)(y - X\theta) - X\beta$ for the SDM model,

$\varepsilon = (I_n - \lambda W)(y - X\beta)$ for the SEM model. (LeSage, 2000, p.23)

It is important to note that the Bayesian approach to modeling is fundamentally different from that the of the frequentist approach employed in OLS and other canonical statistical models. The results of Bayesian estimation produce full distributions of parameter estimates, and convention is to report the mean of each parameter distribution. Significance tests are then the probability of the parameter estimate containing zero calculated directly from the parameter distribution. This approach is fundamentally different from the frequentist approach, which calculates the probability of the parameter estimate being zero from the standard errors of each estimate and the underlying distributional assumption (often Gaussian) of the errors (Albert and Chib, 1993; LeSage, 2000; Albert, 2007).

## 2.3 ECONOMETRIC MODELS AND RESULTS

2.3.1 Econometric Model. Three econometric models are specified following the theoretical specifications for the SAR, SEM, and SDM above. The binary choice indicator variable y is set to 1 if the survey respondent used non-auto transportation for an observed tour, and 0 otherwise. The spatial probit model for the SAR, SEM, and SDM is comprised of the travel choice indicator variable and the independent regressors which are the same as the previous chapter. The independent regressor matrix X = [I S BE] where I is an $n \times 1$ vector of ones, S is a matrix of sociodemographic characteristics, and BE is a matrix of built environment characteristics including zoning variable used in the previous chapter. The formal equation to be estimated for the SDM is then:

(2.9) $$y_i = \rho W y + [I\ S\ BE]\beta + W\,[I\ S\ BE]\theta + \varepsilon$$

$$\varepsilon \sim N(0, \sigma^2 I_n)$$

$$y_i = 1, if\ y_i \geq 0$$

$$y_i = 0, if\ y_i < 0$$

where $X = [I\ S\ BE]$ and follows the same substitution for the SAR and SEM. In the SEM model, both ρ and θ are set to 0 and λ enters the distribution of ε as described in Equation 2.6. In the SAR θ is set to 0.

2.3.2 Determination of the Spatial Weights Matrix. The spatial weight matrix, $W$, in the equations above is developed by a two step process. In the first step, observations are determined to be spatial neighbors if they are within a distance *D* from one another. The bandwidth used to create the neighbor matrix was the minimum distance necessary so that each observation included at least one neighbor, *D* =1.076 miles. This distance corresponds closely with the distance bands used to calculate the zoning percentages surrounding survey respondents' residences, and therefore is an ideal choice for *D*. While it is possible to estimate spatial models with some observations having no neighbors, in practice this also causes far more problems than the benefits of having more restrictive definitions of spatial neighbors, as outlined by Bivand and Portnov (2004). Using this distance based neighbor rule, the neighbor binary matrix is constructed, with observations within *D* distance of each other assigned a 1, and observations further apart than *D* assigned a 0.

In the second step, the neighbor matrix is transformed into a spatial weight matrix W by either row standardizing the binary neighbor matrix so that all rows sum to 1, or applying a function based on distance and then row standardizing the matrix. While there are no generally accepted procedures for determining the correct weighting structure to use for W , I apply the two most commonly used weighting schemes, the binary neighbor matrix, and a weight that declines with distance where the weight of each neighboring observation is set to the inverse of distance, $w_{ij} = 1/d_{ij}$, where *d* is the distance between observations *i* and *j* in miles. I estimate the SAR and SEM models using each spatial weight matrix and compare the results below.

2.3.3 Estimation. The SAR and SEM have been estimated in the past using maximum likelihood techniques, as well as more recently with Bayesian techniques. The estimation of the model using Bayesian techniques has some advantages over maximum likelihood, the most important being the recovery of the posterior coefficient distributions which can be used for statistical inference tests (LeSage, 2000).

The SAR and SEM models are estimated with a Bayesian model that takes 1,000 draws with a burn-in of 100 draws. Model results are listed in Table 2.2 and Table 2.3. All estimations are implemented in the software system R (R Core Team, 2014). The spatial weights matrix was constructed and standardized using the R add-on package *spdep* (Bivand et al., 2013; Bivand and Piras, 2015). The spatial probit SAR, SEM, and SDM models are estimated using the Bayesian approach implemented in the R package *spatialprobit* (Wilhelm and de Matos, 2013).

2.3.4 Spatial Dependence Parameters. The model results for both the SAR and SEM models without zoning variables included using both a binary neighbor row standardized and inverse distance row standardized spatial weights matrix show that there is spatial dependence, with the spatial parameters $\rho$ and $\lambda$ statistically significant at the 5 percent level in the SAR and 10 percent level in the SEM model using the inverse distance weight matrix, and $\rho$ and $\lambda$ statistically significant at the 5 percent and 10 percent level in the SAR and SEM models using the row standardized binary spatial weights matrix. The value of $\rho$ in the SAR using a binary $W$ and inverse distance $W$ are 0.235 and 0.159, respectively. The lower coefficient on $\rho$ in the SAR model using the inverse distance spatial weights matrix implies that the effect of neighboring observations is greater when all neighbors within one mile are weighted equally, rather than closer neighbors being weighted more heavily, indicating a slightly larger regional effect than local effect. In the model using binary $W$ , $\rho$ is the estimated parameter on the $n \times 1$ vector $Wy$, where $y$ is a vector of 1's and 0's indicating non-auto transportation, and thus $Wy$ can be understood as the percentage of non-auto trips of all neighboring observations. Therefore, a value of ρ equal to 0.235 tells us that an increase in the percentage of non-auto trips of neighbors by 0.01 (1%) increases the probability of a non-auto trip by 0.01 $*$ 0.235 = 0.00235 (0.235%) on average. This value of ρ also indicates that the dissipation of the effect is quite rapid, as second order neighboring observations exhibit an effect of $0.271^2$ = 0.055225 and an effect of a 1 percent increase is equal to 0.01 $*$ 0.05225 = 0.00055225 (0.055225%). This is further evidence that the choice between auto and non-auto transportation is somewhat localized to a one mile radius surrounding place of residence. Using the inverse distance $W$ which places higher weights on closer neighbors, ρ is 0.159. The fact that ρ is a lower in this weighting scheme gives further evidence that the effect of neighboring observations is weaker at closer distances than 1 mile. In this model, the coefficient has a slightly different interpretation, as the vector $Wy$ is not a simple percentage, but rather a spatially weighted percentage of non-auto trips based on distance.

The value of λ in the SEM model using binary and inverse distance $W$ is 0.333 and 0.069, respectively. The coefficient λ is estimated using Equation 2.6, where $u = \lambda W u + e, u$ are the errors from the normal probit equation, W is the spatial weights matrix, and e are the residuals after spatial correction. The SEM model only addresses the spatial autocorrelation of errors across space, and therefore only corrects for spatial heteroskedasticity. The positive and significant values of λ indicate correlation between error terms that are neighbors. However, since the SAR model also demonstrates spatial autocorrelation, part of the error term spatial correlation may be due to missing variable bias since the spatially lagged dependent variable is absent from this model. The general conclusion from the significant values of ρ and λ indicate that a model that jointly addresses both spatial dependence and spatial heteroskedasticity may be the correct model. I estimate this model, known as the spatial Durbin model, in the next section.

2.3.5 Zoning Parameters. The most notable result of the SAR models is that the coefficients on all three residential zoning density levels are negative and statistically significant in the 0 to 1/4 mile distance band. This indicates that higher levels of residential zoning surrounding respondents' residences decreases the likelihood of observing non-auto transportation. The other result that indicates potential zoning impacts on travel behavior is the significant positive coefficients in the 1/2 to 1 mile band for industrial zoning. This indicates that increased industrial zoning from 1/2 to 1 mile from homes increases the likelihood of observing non-auto transportation. Coupled with the findings on the coefficients on the closest band to residential location, this implies that business zoning within one mile but more than a half mile leads to more respondents choosing non-auto. This indicates that residential locations surrounded by a band of residential zoning up to one half mile may prefer to drive to shopping, employment, and recreation, and that zoning that precludes much closer businesses may lead to more non-auto travel behavior. The coefficients on the SEM model are all statistically insignificant so no interpretation can be made for this model.

While the sign of the coefficients on the explanatory variables indicate the direction of effect on the conditional probability of non-auto transportation behavior, their magnitude cannot be interpreted the same as in OLS or probit models. Due to the non-linearity of the model, and the presence of spatial dependence, the impact on a change of one explanatory variable has a spatial feedback loop effect on the dependent variable due to the presence of the spatially lagged dependent variable in the estimated equation. Therefore, it is necessary to estimate marginal effects of the change in each explanatory variable in the model to determine the direct, indirect, and total effects. The full list of direct, indirect, and total effects of the change in each independent variable are listed in Appendix B.

While the SAR and SEM models both show significance in some of the zoning variables in determining mode choice, the SDM shows significance in the low, medium, and high residential zoning types for the binary spatial weights matrix, significant negative impacts for all spatially weighted zoning variables in the 1/2 to 3/4 mile zoning band, and positive associations of spatially weighted high density business and industrial zoning in the 3/4 to 1 mile zoning band. However, the SAR with binary spatial weights matrix is indicated as the best model using both Akaike Information Criteria (AIC) (Akaike, 1974) and the standard probit model is indicated as the best model using the Bayesian Information Criteria (BIC) (LeSage and Pace, 2009). A summary of the log likelihood, AIC, and BIC of each of the models tested in this chapter is shown in Table 2.5.

Theoretically, modeling spatial neighbors as having an impact that declines with distance makes for the most intuitive interpretation of the results, as one would expect closer neighbors to exert more influence on each observation. However, the lack of statistical significance of the zoning variables in the spatial Durban model with an inverse distance spatial weights matrix calls into question the validity of the zoning variables that are statistically significant in the spatial Durban model using binary weights and the previous SAR and SEM models. It may be the case that the zoning variables are highly correlated with other variables that are a result of zoning restrictions, and therefore the effect of zoning restrictions are subsumed in these other variables that are the result of long standing zoning laws at the local level. Comparing the use of the two spatial weights matrices in each model, the binary row standardized spatial weights matrix leads to a better posterior distribution fit to the data, indicating that the binary matrix is preferred to the inverse distance matrix. This indicates that the spatial effects may be strong within the distance used to specify spatial neighbors, just over one mile. Interpretation of the coefficients using the SAR model with binary spatial weights also lends itself to the most straightforward interpretation of the results, as the spatial autoregressive parameter ρ represents the effect of the equally weighted share of non-auto trips of neighboring observations.

2.3.6 Marginal Effects and Elasticities. The Bayesian Markov Chain Monte Carlo (MCMC) estimation technique used to estimate the models above produces samples of the posterior distribution of the model parameters. These sample distributions of coefficients can be used to compute average marginal effects across observations of a change in an independent variable of the model on the probability of the independent variable, non-auto travel mode choice (LeSage and Pace, 2009). While the SEM model coefficients can be interpreted as marginal effects as in ordinary least squares because the spatial variation is only present in the error term, for the SAR and SDM models which include spatially lagged dependent or independent variables, the impacts of a change in an explanatory variable can have an impact on all other neighboring dependent variables, creating a feedback loop with several orders of magnitude. Thus, these spatial models exhibit direct, indirect, and total impacts. LeSage and Pace (2009) propose summary measures of the marginal effects of a change in an explanatory variable $x_r$ by using the average change in the expected value of the dependent variable $y_i$ and changing the multiplier matrix $S_r$ *(W)* based on the spatial model. The expected value of a change is listed in Equation 2.10, where *X* is an *n* × *p* matrix of *n* observations and *p* explanatory variables.

(2.10) $E(y) = \sum_{i-1}^{p} S_r(W)x_r + \alpha I$

$S_r\ (W)$ for the SAR and SDM model are given in Equation 2.11 and Equation 2.12.

The diagonal elements of the trace of the $S_r(W)$ matrix multiplied by the change in independent variable $x_{ir}$ give the direct impacts (Equation 2.13), while the trace of the entire $S_r(W)$ matrix multiplied by the change in independent variable $x_{ir}$ gives the total impacts (Equation 2.14). Indirect impacts are the difference between total and direct impacts (Equation 2.15). Marginal direct effects for individual observations are contained in the diagonal elements of $S_r(W)$ (Equation 2.16) and indirect marginal effects are contained in the off diagonal elements of $S_r(W)$ (Equation 2.17) (LeSage and Pace, 2009).

(2.11) $S_r\,(W) = (I_n - \rho W)^{-1}\beta_r$

(2.12) $S_r\,(W) = (I_n - \rho W)^{-1}(I_n\beta_r + W\theta_r)$

(2.13) $M(r)_{direct} = n^{-1}tr(S_r(W))$

(2.14) $M(r)_{total} = n^{-1}I_n^{-1}S_r(W)I_n$

(2.15) $M(r)indirect = M(r)total - M(r)direct$

(2.16) $\frac{\partial y_i}{\partial x_{ir}} = S_r W_{ii}$

(2.17) $\frac{\partial y_i}{\partial x_{jr}} = S_r W_{ij}$

To calculate the elasticities, the change of each variable is taken at the mean of the posterior distribution and the mean of the expected probability of the binary dependent variable, which is 16.63%. Marginal effects are reported for the direct, indirect, and total marginal effects of a change in each independent variable. Direct effects are the change in the probability of observing non-auto mode choice attributed to the change in the independent variable. Indirect effects represent the spatially lagged effect on the autocorrelated dependent variable of a change in one of the independent variables after the feedback loop from a change in an independent variable has affected the spatially lagged dependent variable of spatial neighbor observations. The sum of direct and indirect effects equals the total effect of a change in the independent variables after the feedback loop of the change has run its course. Dummy variable elasticities are not reported. For comparison purposes, results for the SAR and SDM model are reported for the binary spatial weights matrix, with the remaining models marginal effects relegated to Appendix B. Marginal effects for the SAR model using a binary spatial weights matrix are listed in Table 2.6, and the corresponding elasticities in Table 2.7. Marginal effects for the SDM model using a binary spatial weights matrix are listed in Table 2.8, and the corresponding elasticities in Table 2.9.

Several of the statistically significant variables in the SAR model have small marginal effects of the expected sign. The largest of these is the number of household vehicles, with a marginal effect of -9.123%. This is not surprising considering this variable indicates preference for owning an asset that encourages automobile transportation. Miles of bike lanes has an unexpected negative marginal effect, but is very small. One possible reason for the unexpected sign on this variable may be that areas that are more dense, such as the CBD, may have an overall lower mileage of bike lanes, while areas that lack access to goods and services within a non-auto distance have a high mileage of bike lanes that are intended for recreational use. Mileage of bus routes and number of bus stops both have the expected sign but the effects are also small. The estimated coefficient for number of rail stops is unexpectedly negative, while the coefficient for miles of rail lines has the expected sign but a small positive coefficient. The study area has a more mature bus system than rail system, and the rail stops are spread more evenly between dense urban locations near downtown and suburban locations. Perhaps the reason for the unexpected sign on the rail stops coefficient is capturing the propensity of most suburban residents to use auto transportation even when they live in close proximity to rail stops. This phenomenon may be due to the rail lines not going to locations that meet suburban household needs, since many of the rail lines were built to service commuting to downtown from the suburbs, but not to perform everyday shopping or recreational tasks close to home. Shopping and social stops along a tour are both negative and relatively large compared with many of the other variables in the regression. These are of the expected sign and indicate a propensity to drive when shopping for goods that may need to be carried home or to social gatherings that are located at recreational or residential areas. Residential zoning within a quarter mile from place of residence has the expected negative sign, although the effects are small. Given the value people place on their own time, it is not surprising that higher residential density, and therefore lower business density, may encourage people to drive to locations that are not in the immediate vicinity of their residence. Residential zoning in the quarter to half mile range has the opposite sign with similarly small marginal effects. It is uncertain what explains the positive marginal effect on non-auto transportation for higher residential zoning levels within this band. Finally, high density business within the three quarter to one mile band has a positive marginal effect on non-auto transportation. This may indicate that if a high level of businesses are located within this band, survey respondents are willing to travel by non-auto modes to reach these destinations even though they are slightly farther than other statistically significant variables would suggest for encouraging non-auto transportation.

Elasticities calculated from the marginal effects at the means of the coefficient distributions indicate that non-auto transportation mode preferences are highly inelastic. This in part captures the sample distribution which indicates that people use auto for their mode of transportation at a much higher frequency then all other modes combined. Elasticities for number of household vehicles and age are above one, signaling that these variable are a good indicator of transportation mode preference. The most interesting result is that low density residential zoning is more elastic than all other zoning types. This is the expected result for the zoning band within a quarter mile of place of residence, indicating that altering this zoning type may have the most potential of all possible zoning changes in promoting non-auto transportation.

Marginal effects in the SDM model with binary spatial weights are similar to those in the SAR model, with many of the same variables being statistically significant and thus leading to many of the same conclusions. The inclusion of the spatially weighted variables in the regression make some of the variables that were statistically significant in the SAR regression insignificant.

Elasticities in the SDM model are also similar to the SAR model. One interesting observation is that household vehicles has a negative direct marginal effect, but a pos- itive indirect impact, indicating that having many cars may encourage auto usage, but discourage neighboring respondents to use auto transportation. The effects are still small however, with the indirect elasticity being less than half of direct elasticity.

Elasticities of residential zoning variables are negative but very small, indicating that the response to residential zoning is highly inelastic. Although the marginal effects are non-linear, in general most of the estimates follow a normal distribution. Thus, when considering that the marginal effects are capturing a one percent increase in a specific zoning type, it may be more appropriate to consider that, for example, a ten percent increase in a zoning type would have roughly ten times the impact on the probability of non-auto transportation modes being chosen. For example, if residential low density zoning was to increase by 10% within a quarter mile of a survey respondents' residence, using this rough measure we would expect to see a 0.136% decrease in non-auto transportation mode choices. While still a small impact, this change is not insignificant when considering the magnitude of trips away from home taken by city resident across the United States each year. Even small percentage reductions in auto trips could add up to large overall reductions in vehicle miles driven, and therefore energy usage.

## 2.4 CONCLUSION

The evidence provided by the log likelihood test indicate that the Bayesian models of the impact of zoning on travel mode preference favor the Spatial Durban Model with a inverse distance spatial weights matrix indicated in Table 2.5. Residential low, medium, and high density within one quarter mile of residences are all statistically significant and associated with lower propensity for non-auto travel. Using both AIC and BIC to asses the models considered in this chapter, the SAR model with a spatial binary weights matrix was the best model overall. In this model, residential zoning variables of low, medium, and high density in the 0 to 1/4 mile zoning band all have statistically significant and negative impacts on survey respondents' probability of choosing non-auto transportation. One possible conclusion from these results is that zoning variables may in fact have a significant influence on travel preference, but that zoning variables may manifest themselves in other built environment variables in the model and therefore warrant further study, as zoning laws and the resulting manifestation of the built environment are determined and implemented by a political process. While the impacts represented by the marginal effects of zoning variables are small when considering minute increases in zoning types surrounding residential locations, more drastic changes to zoning mixes may have a more profound impact.

Automobile usage was the dominant mode of transportation across respondents in this study, and corresponds to patterns of heavy auto usage in the United States in general (Glaeser, 2004). Part of the dominance of the automobile in the transportation of citizens in the United States may be the result of long term path dependence that followed from an early preference for auto transportation in the development of transportation infrastructure. The widespread building of roads may have led to a long chain of city planning decisions that have shaped the built environment to accommodate automobile transportation to the detriment of alternative modes of transportation that use less energy and decrease congestion. Further research will be needed to determine if drastic changes in built environment design that focus on alternatives to automobile transportation can change society's preference for the automobile towards transportation usage that is more environmentally and culturally sustainable for the long-term future. The current dataset in this study precludes the testing of such relationships, but in cities where sweeping changes to more flexible zoning policies have been implemented, event studies could shed light on the causal relationships between zoning mix and transportation behavior. Future research is needed that incorporates a multinomial choice set for mode choice in a spatial context, but more theoretical work on multinomial spatial models is needed to bring this avenue of research to fruition for empirical work.

## 2.5 TABLES

Table 2.1 Moran's I and Geary's C Statistics

| Dependent Variable: Non-auto Transportation Mode = 1 | | | | |
|---|---|---|---|---|
| Variable | Moran's I | Moran's I ($d^{-1}$) | Geary's C | Geary's C ($d^{-1}$) |
| HH size | 0.084*** | 0.449*** | 0.915*** | 0.555*** |
| HH vehicles | 0.065*** | 0.427*** | 0.934*** | 0.569*** |
| HH bikes | 0.072*** | 0.477*** | 0.935*** | 0.527*** |
| Male | 0.000 | −0.228 | 1.000 | 1.229 |
| Age | 0.035*** | 0.277*** | 0.962*** | 0.734*** |
| Income (000s) | 0.083*** | 0.420*** | 0.918*** | 0.581*** |
| College education | 0.070*** | 0.175*** | 0.931*** | 0.829*** |
| Employed | 0.011*** | 0.088*** | 0.988*** | 0.902*** |
| Tour distance | 0.024*** | 0.081*** | 0.979*** | 0.935*** |
| Tour crosses highway | 0.039*** | 0.117*** | 0.963*** | 0.876*** |
| Miles bike lanes < 1 M. | 0.838*** | 0.953*** | 0.156*** | 0.048*** |
| Miles of bus routes < 0.5 M. | 0.639*** | 0.903*** | 0.354*** | 0.111*** |
| Bus stops < 0.5 M. | 0.654*** | 0.905*** | 0.344*** | 0.111*** |
| Rail stops < 0.5 M. | 0.473*** | 0.846*** | 0.530*** | 0.173*** |
| Miles of rail lines < 0.5 M. | 0.687*** | 0.899*** | 0.301*** | 0.101*** |
| Intersections with 0.5 M | 0.475*** | 0.836*** | 0.496*** | 0.150*** |
| CBG population/sq. mile | 0.423*** | 0.758*** | 0.590*** | 0.244*** |
| CBG jobs/sq. mile | 0.179*** | 0.629*** | 0.854*** | 0.361*** |
| Work stops | −0.000 | 0.029*** | 1.004 | 0.964*** |
| Shopping stops | 0.006*** | 0.083*** | 0.996* | 0.907*** |
| Social stops | 0.001 | 0.084*** | 1.006 | 0.912*** |
| Res. Low Density, 0-1/4 mile | 0.548*** | 0.847*** | 0.449*** | 0.154*** |
| Res. Medium Density, 0-1/4 mile | 0.392*** | 0.808*** | 0.580*** | 0.190*** |
| Res. High Density 0-1/4 mile | 0.520*** | 0.820*** | 0.486*** | 0.186*** |
| Bus. Low Density 0-1/4 mile | 0.175*** | 0.697*** | 0.819*** | 0.288*** |
| Bus. High Density 0-1/4 mile | 0.397*** | 0.815*** | 0.579*** | 0.187*** |
| Ind. 0-1/4 mile | 0.269*** | 0.698*** | 0.667*** | 0.253*** |
| Res. Low Density, 1/4-1/2 mile | 0.681*** | 0.899*** | 0.315*** | 0.103*** |
| Res. Medium Density, 1/4-1/2 mile | 0.649*** | 0.895*** | 0.326*** | 0.104*** |
| Res. High Density 1/4-1/2 mile | 0.658*** | 0.880*** | 0.360*** | 0.125*** |
| Bus. Low Density 1/4-1/2 mile | 0.355*** | 0.778*** | 0.667*** | 0.224*** |
| Bus. High Density 1/4-1/2 mile | 0.527*** | 0.848*** | 0.454*** | 0.148*** |
| Ind. 1/4-1/2 mile | 0.469*** | 0.797*** | 0.449*** | 0.167*** |
| Res. Low Density, 1/2-3/4 mile | 0.476*** | 0.566*** | 0.539*** | 0.444*** |
| Res. Medium Density, 1/2-3/4 mile | 0.356*** | 0.477*** | 0.611*** | 0.503*** |
| Res. High Density 1/2-3/4 mile | 0.362*** | 0.479*** | 0.654*** | 0.522*** |
| Bus. Low Density 1/2-3/4 mile | 0.440*** | 0.529*** | 0.586*** | 0.489*** |
| Bus. High Density 1/2-3/4 mile | 0.282*** | 0.388*** | 0.737*** | 0.591*** |
| Ind. 1/2-3/4 mile | 0.363*** | 0.475*** | 0.599*** | 0.476*** |
| Res. Low Density, 3/4-1 mile | 0.515*** | 0.599*** | 0.500*** | 0.406*** |
| Res. Medium Density, 3/4-1 mile | 0.402*** | 0.525*** | 0.570*** | 0.470*** |
| Res. High Density 3/4-1 mile | 0.333*** | 0.446*** | 0.681*** | 0.551*** |
| Bus. Low Density 3/4-1 mile | 0.420*** | 0.517*** | 0.589*** | 0.504*** |
| Bus. High Density 3/4-1 mile | 0.303*** | 0.430*** | 0.708*** | 0.557*** |
| Ind. 3/4-1 mile | 0.402*** | 0.518*** | 0.569*** | 0.448*** |

*Notes: Significance at the 1, 5, and 10% levels shown by ***, **, and *, respectively.*

Table 2.2 Spatial Probit Models: SAR

| Dependent Variable: Non-auto Transportation Mode = 1 | | | | |
|---|---|---|---|---|
| Variable | Base | Base ($d^{-1}$) | SAR | SAR ($d^{-1}$) |
| Intercept | 1.007*** | 0.868*** | 0.419 | 0.279 |
| HH size | −0.059** | −0.058** | −0.052** | −0.052** |
| HH vehicles | −0.361*** | −0.360*** | −0.368*** | −0.368*** |
| HH bicycles | 0.059*** | 0.058*** | 0.052*** | 0.053*** |
| Male | 0.191*** | 0.186*** | 0.186*** | 0.185*** |
| Age | −0.013*** | −0.013*** | −0.014*** | −0.014*** |
| Income | −0.000 | −0.000 | −0.000 | −0.000 |
| College Degree | 0.045 | 0.051 | 0.038 | 0.044 |
| Employed | −0.070 | −0.070 | −0.084 | −0.085 |
| Tour distance | −0.013*** | −0.013*** | −0.013*** | −0.013*** |
| Tour crosses highway | −0.745*** | −0.750*** | −0.776*** | −0.781*** |
| Miles bike lanes < 1 M. | −0.015** | −0.011* | −0.013 | −0.010 |
| Miles bus routes < 0.5 M. | 0.011*** | 0.011*** | 0.015*** | 0.015*** |
| Bus stops < 0.5 M. | 0.008*** | 0.008*** | 0.008*** | 0.009*** |
| Rail stops < 0.5 M. | −0.111*** | −0.110*** | −0.114*** | −0.117*** |
| Miles rail lines < 1 M. | 0.032*** | 0.033*** | 0.051*** | 0.053*** |
| Intersections < 0.5 M. | −0.000 | −0.000 | −0.000 | −0.000 |
| CBG population/sq. mile | 0.000*** | 0.000*** | 0.000** | 0.000** |
| CBG jobs/sq. mile | 0.000 | 0.000 | 0.000* | 0.000* |
| Work stops | 0.043* | 0.043* | 0.040 | 0.040 |
| Shopping stops | −0.182*** | −0.184*** | −0.184*** | −0.185*** |
| Social stops | −0.099** | −0.102** | −0.102** | −0.104** |
| Res. Low Density, 0-1/4 mile | | | −0.010** | −0.010** |
| Res. Medium Density, 0-1/4 mile | | | −0.010** | −0.009** |
| Res. High Density 0-1/4 mile | | | −0.011*** | −0.011*** |
| Bus. Low Density 0-1/4 mile | | | 0.006 | 0.006 |
| Bus. High Density 0-1/4 mile | | | −0.005 | −0.004 |
| Ind. 0-1/4 mile | | | −0.008 | −0.008 |
| Res. Low Density, 1/4-1/2 mile | | | 0.017*** | 0.015*** |
| Res. Medium Density, 1/4-1/2 mile | | | 0.016*** | 0.014** |
| Res. High Density 1/4-1/2 mile | | | 0.019*** | 0.018*** |
| Bus. Low Density 1/4-1/2 mile | | | −0.004 | −0.006 |
| Bus. High Density 1/4-1/2 mile | | | 0.004 | 0.003 |
| Ind. 1/4-1/2 mile | | | 0.013* | 0.012* |
| Res. Low Density, 1/2-3/4 mile | | | −0.018 | −0.017 |
| Res. Medium Density, 1/2-3/4 mile | | | −0.023* | −0.021* |
| Res. High Density 1/2-3/4 mile | | | −0.021 | −0.020 |
| Bus. Low Density 1/2-3/4 mile | | | −0.028 | −0.027 |
| Bus. High Density 1/2-3/4 mile | | | −0.016 | −0.015 |
| Ind. 1/2-3/4 mile | | | −0.019 | −0.018 |
| Res. Low Density, 3/4-1 mile | | | 0.017 | 0.015 |
| Res. Medium Density, 3/4-1 mile | | | 0.031** | 0.029* |
| Res. High Density 3/4-1 mile | | | 0.002 | 0.001 |
| Bus. Low Density 3/4-1 mile | | | −0.032 | −0.032 |
| Bus. High Density 3/4-1 mile | | | 0.036** | 0.034** |
| Ind. 3/4-1 mile | | | 0.021* | 0.020* |
| $\rho$ | 0.235** | 0.159** | 0.197 | 0.073 |

*Notes: Significance at the 1, 5, and 10% levels shown by ***, **, and *, respectively.*

Table 2.3 Spatial Probit Models: SEM

| Dependent Variable: Non-auto Transportation Mode = 1 | | | | |
|---|---|---|---|---|
| Variable | Base | Base ($d^{-1}$) | SEM | SEM ($d^{-1}$) |
| Intercept | 0.666 | 1.105** | 0.433 | 246.420 |
| HH size | −0.057 | −0.102* | −0.108 | −75.260 |
| HH vehicles | −0.368* | −0.672*** | −0.777 | −531.245 |
| HH bicycles | 0.059 | 0.111** | 0.116 | 79.002 |
| Male | 0.187* | 0.354** | 0.398 | 271.248 |
| Age | −0.013* | −0.024*** | −0.029 | −19.952 |
| Income | −0.000 | −0.000 | −0.000 | −0.238 |
| College Degree | 0.048 | 0.088 | 0.107 | 71.322 |
| Employed | −0.077 | −0.135 | −0.180 | −121.357 |
| Tour distance | −0.013* | −0.024*** | −0.027 | −19.104 |
| Tour crosses highway | −0.774* | −1.399*** | −1.690 | −1173.837 |
| Miles bike lanes < 1 M. | −0.010 | −0.016 | −0.022 | −13.591 |
| Miles bus routes < 0.5 M. | 0.011 | 0.021** | 0.031 | 21.952 |
| Bus stops < 0.5 M. | 0.010 | 0.018** | 0.022 | 14.258 |
| Rail stops < 0.5 M. | −0.119 | −0.217** | −0.263 | −177.916 |
| Miles rail lines < 1 M. | 0.035 | 0.071** | 0.117 | 82.396 |
| Intersections < 0.5 M. | −0.000 | −0.001 | −0.001 | −0.420 |
| CBG population/sq. mile | 0.000 | 0.000** | 0.000 | 0.023 |
| CBG jobs/sq. mile | 0.000 | 0.000 | 0.000 | 0.003 |
| Work stops | 0.043 | 0.081 | 0.087 | 61.508 |
| Shopping stops | −0.180* | −0.335*** | −0.393 | −271.386 |
| Social stops | −0.111 | −0.194* | −0.222 | −144.744 |
| Res. Low Density, 0-1/4 mile | | | −0.022 | −15.438 |
| Res. Medium Density, 0-1/4 mile | | | −0.020 | −13.922 |
| Res. High Density 0-1/4 mile | | | −0.024 | −17.233 |
| Bus. Low Density 0-1/4 mile | | | 0.012 | 7.865 |
| Bus. High Density 0-1/4 mile | | | −0.010 | −7.086 |
| Ind. 0-1/4 mile | | | −0.017 | −12.583 |
| Res. Low Density, 1/4-1/2 mile | | | 0.033 | 23.383 |
| Res. Medium Density, 1/4-1/2 mile | | | 0.030 | 21.090 |
| Res. High Density 1/4-1/2 mile | | | 0.040 | 28.343 |
| Bus. Low Density 1/4-1/2 mile | | | −0.014 | −6.699 |
| Bus. High Density 1/4-1/2 mile | | | 0.005 | 3.929 |
| Ind. 1/4-1/2 mile | | | 0.025 | 18.094 |
| Res. Low Density, 1/2-3/4 mile | | | −0.035 | −24.203 |
| Res. Medium Density, 1/2-3/4 mile | | | −0.049 | −32.565 |
| Res. High Density 1/2-3/4 mile | | | −0.044 | −31.105 |
| Bus. Low Density 1/2-3/4 mile | | | −0.079 | −52.493 |
| Bus. High Density 1/2-3/4 mile | | | −0.030 | −20.700 |
| Ind. 1/2-3/4 mile | | | −0.039 | −26.933 |
| Res. Low Density, 3/4-1 mile | | | 0.033 | 22.865 |
| Res. Medium Density, 3/4-1 mile | | | 0.063 | 42.400 |
| Res. High Density 3/4-1 mile | | | 0.002 | 1.396 |
| Bus. Low Density 3/4-1 mile | | | −0.070 | −50.072 |
| Bus. High Density 3/4-1 mile | | | 0.074 | 50.084 |
| Ind. 3/4-1 mile | | | 0.043 | 30.697 |
| $\lambda$ | 0.333* | 0.069 | 0.147 | 0.032 |

*Notes: Significance at the 1, 5, and 10% levels shown by ***, **, and *, respectively.*

## Table 2.4 Log Likelihood Tests

| Model | Log Likelihood | Degrees of Freedom | AIC | BIC |
|---|---|---|---|---|
| **Base Models: No Zoning Variables** | | | | |
| Probit | −1840.061 | 22 | 3724.122 | 3868.035 |
| SAR | −1838.980 | 23 | 3723.960 | 3874.415 |
| SAR$d^{-1}$ | −1839.615 | 23 | 3725.230 | 3875.685 |
| SEM | −1860.135 | 24 | 3768.270 | 3925.266 |
| SEM$d^{-1}$ | −1843.571 | 24 | 3735.143 | 3892.139 |
| SDM | −1821.144 | 44 | 3730.288 | 4018.114 |
| SDM$d^{-1}$ | −1817.655 | 44 | 3723.309 | 4011.135 |
| **Zoning Models** | | | | |
| Probit | −1811.343 | 46 | 3714.687 | 4015.595 |
| SAR | −1808.999 | 47 | 3711.999 | 4019.449 |
| SAR$d^{-1}$ | −1810.157 | 47 | 3714.314 | 4021.764 |
| SEM | −1865.249 | 48 | 3826.498 | 4140.490 |
| SEM$d^{-1}$ | −1861.738 | 48 | 3819.475 | 4133.467 |
| SDM | −1772.528 | 92 | 3729.057 | 4330.874 |
| SDM$d^{-1}$ | −1778.245 | 92 | 3740.491 | 4342.308 |

## Table 2.5 Spatial Probit Models: SDM

Dependent Variable: Non-auto Transportation Mode = 1

| Variable | Base | Base ($d^{-1}$) | SDM | SDM ($d^{-1}$) |
|---|---|---|---|---|
| Intercept | 1.222 | 1.729*** | −0.329 | 1.346 |
| HH size | −0.058** | −0.052*** | −0.067** | −0.061** |
| HH vehicles | −0.379*** | −0.363*** | −0.362*** | −0.377*** |
| HH bicycles | 0.063*** | 0.064*** | 0.054*** | 0.060*** |
| Male | 0.191*** | 0.175*** | 0.178*** | 0.181*** |
| Age | −0.013*** | −0.013*** | −0.014*** | −0.014*** |
| Income | −0.000 | −0.000 | −0.000 | −0.000 |
| College Degree | 0.036 | 0.040 | 0.037 | 0.036 |
| Employed | −0.069 | −0.098* | −0.092 | −0.090 |
| Tour distance | −0.013*** | −0.012*** | −0.013*** | −0.012*** |
| Tour crosses highway | −0.791*** | −0.795*** | −0.822*** | −0.834*** |
| Miles bike lanes < 1 M. | −0.031 | −0.058** | −0.015 | −0.063** |
| Miles bus routes < 0.5 M. | 0.010* | 0.003 | 0.011* | 0.003 |
| Bus stops < 0.5 M. | 0.011*** | 0.015*** | 0.009** | 0.013* |
| Rail stops < 0.5 M. | −0.106** | −0.139* | −0.061 | −0.145* |
| Miles rail lines < 1 M. | 0.016 | 0.028 | 0.035 | 0.039 |
| Intersections < 0.5 M. | 0.000 | 0.003 | −0.001 | 0.002 |
| CBG population/sq. mile | 0.000 | −0.000 | 0.000 | −0.000 |
| CBG jobs/sq. mile | 0.000 | −0.000 | 0.000 | −0.000 |
| Work stops | 0.046* | 0.046* | 0.045* | 0.039 |
| Shopping stops | −0.187*** | −0.197*** | −0.194*** | −0.200*** |
| Social stops | −0.111* | −0.108** | −0.130** | −0.119** |
| Res. Low Density, 0-1/4 mile | | | −0.013*** | −0.009 |
| Res. Medium Density, 0-1/4 mile | | | −0.012*** | −0.011 |
| Res. High Density 0-1/4 mile | | | −0.011** | −0.009 |
| Bus. Low Density 0-1/4 mile | | | −0.000 | −0.015 |
| Bus. High Density 0-1/4 mile | | | −0.006 | −0.003 |
| Ind. 0-1/4 mile | | | −0.008 | −0.014 |
| Res. Low Density, 1/4-1/2 mile | | | 0.018** | 0.025* |
| Res. Medium Density, 1/4-1/2 mile | | | 0.016* | 0.024* |
| Res. High Density 1/4-1/2 mile | | | 0.013 | 0.027** |
| Bus. Low Density 1/4-1/2 mile | | | −0.014 | −0.003 |
| Bus. High Density 1/4-1/2 mile | | | 0.005 | 0.023* |
| Ind. 1/4-1/2 mile | | | 0.008 | 0.024 |

| Variable | Base | Base ($d^{-1}$) | SDM | SDM ($d^{-1}$) |
|---|---|---|---|---|
| Res. Low Density, 1/2-3/4 mile | | | −0.020 | −0.020 |
| Res. Medium Density, 1/2-3/4 mile | | | −0.033** | −0.024 |
| Res. High Density 1/2-3/4 mile | | | −0.021 | −0.034* |
| Bus. Low Density 1/2-3/4 mile | | | −0.047 | −0.074 |
| Bus. High Density 1/2-3/4 mile | | | −0.018 | −0.049** |
| Ind. 1/2-3/4 mile | | | −0.014 | −0.022 |
| Res. Low Density, 3/4-1 mile | | | 0.024* | 0.024 |
| Res. Medium Density, 3/4-1 mile | | | 0.033** | 0.025 |
| Res. High Density 3/4-1 mile | | | −0.005 | 0.023 |
| Bus. Low Density 3/4-1 mile | | | −0.055 | −0.047 |
| Bus. High Density 3/4-1 mile | | | 0.047*** | 0.047** |
| Ind. 3/4-1 mile | | | 0.015 | 0.022 |
| (W)HH size | −0.346 | −0.214*** | −0.462 | −0.232*** |
| (W)HH vehicles | −0.486* | 0.015 | 0.028 | −0.195** |
| (W)HH bicycles | 0.109 | 0.112*** | −0.237 | 0.106** |
| (W)Male | 0.986 | −0.097 | 0.196 | −0.015 |
| (W)Age | −0.006 | −0.007 | −0.024 | −0.016*** |
| (W)Income | 0.002 | −0.001 | 0.002 | −0.000 |
| (W)College Degree | −0.152 | −0.089 | 0.533 | 0.013 |
| (W)Employed | 0.882 | −0.115 | 0.249 | −0.179 |
| (W)Tour distance | −0.032 | −0.005 | −0.030 | −0.006 |
| (W)Tour crosses highway | −0.351 | 0.189 | 0.427 | −0.329** |
| (W)Miles bike lanes < 1 M. | −0.016 | 0.045 | −0.060 | 0.056 |
| (W)Miles bus routes < 0.5 M. | 0.044 | 0.013 | 0.058** | 0.031* |
| (W)Bus stops < 0.5 M. | −0.013* | −0.015 | −0.011 | −0.013 |
| (W)Rail stops < 0.5 M. | 0.059 | 0.109 | 0.082 | 0.054 |
| (W)Miles rail lines < 1 M. | 0.051 | −0.002 | 0.026 | 0.043 |
| (W)Intersections < 0.5 M. | −0.001 | −0.004 | 0.002 | −0.003 |
| (W)CBG population/sq. mile | 0.000*** | 0.000*** | 0.000** | 0.000** |
| (W)CBG jobs/sq. mile | −0.000 | 0.000* | −0.000 | 0.000*** |
| (W)Work stops | 0.313 | −0.035 | 0.332 | −0.078 |
| (W)Shopping stops | −0.586* | 0.191** | −0.409 | 0.129 |
| (W)Social stops | 0.144 | −0.108 | −0.694 | −0.166 |
| (W)Res. Low Density, 0-1/4 mile | | | −0.031 | −0.003 |
| (W)Res. Medium Density, 0-1/4 mile | | | 0.006 | 0.003 |
| (W)Res. High Density 0-1/4 mile | | | 0.018 | −0.003 |
| (W)Bus. Low Density 0-1/4 mile | | | 0.026 | 0.062** |
| (W)Bus. High Density 0-1/4 mile | | | −0.019 | 0.001 |
| (W)Ind. 0-1/4 mile | | | 0.098* | 0.013 |
| (W)Res. Low Density, 1/4-1/2 mile | | | 0.049 | −0.002 |
| (W)Res. Medium Density, 1/4-1/2 mile | | | 0.011 | −0.005 |
| (W)Res. High Density 1/4-1/2 mile | | | 0.005 | −0.003 |
| (W)Bus. Low Density 1/4-1/2 mile | | | 0.091 | −0.040 |
| (W)Bus. High Density 1/4-1/2 mile | | | 0.026 | −0.037* |
| (W)Ind. 1/4-1/2 mile | | | −0.032 | −0.008 |
| (W)Res. Low Density, 1/2-3/4 mile | | | −0.339*** | −0.051 |
| (W)Res. Medium Density, 1/2-3/4 mile | | | −0.557*** | −0.066 |
| (W)Res. High Density 1/2-3/4 mile | | | −0.237** | −0.008 |
| (W)Bus. Low Density 1/2-3/4 mile | | | −0.618** | 0.017 |
| (W)Bus. High Density 1/2-3/4 mile | | | −0.247** | 0.029 |
| (W)Ind. 1/2-3/4 mile | | | −0.436*** | −0.042 |
| (W)Res. Low Density, 3/4-1 mile | | | 0.323*** | 0.043 |
| (W)Res. Medium Density, 3/4-1 mile | | | 0.679*** | 0.081 |
| (W)Res. High Density 3/4-1 mile | | | 0.168 | −0.030 |
| (W)Bus. Low Density 3/4-1 mile | | | 0.519 | 0.037 |
| (W)Bus. High Density 3/4-1 mile | | | 0.263** | 0.030 |
| (W)Ind. 3/4-1 mile | | | 0.441*** | 0.041 |
| $\rho$ | −0.805*** | 0.106 | −0.876*** | −0.373*** |

Table 2.6 Marginal Effects: SAR Model, Binary W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Direct | Indirect | Total |
| HH size** | −0.01026 | −0.00277 | −0.01304 |
| HH vehicles*** | −0.07215 | −0.01907 | −0.09123 |
| HH bicycles*** | 0.01023 | 0.00269 | 0.01292 |
| Male*** | 0.03658 | 0.00967 | 0.04625 |
| Age*** | −0.00268 | −0.00070 | −0.00338 |
| Income | −0.00001 | −0.00000 | −0.00001 |
| College Degree | 0.00748 | 0.00196 | 0.00943 |
| Employed | −0.01644 | −0.00430 | −0.02075 |
| Tour distance*** | −0.00253 | −0.00067 | −0.00319 |
| Tour crosses highway*** | −0.15219 | −0.04026 | −0.19246 |
| Miles bike lanes < 1 M. | −0.00250 | −0.00072 | −0.00322 |
| Miles bus routes < 0.5 M.*** | 0.00297 | 0.00079 | 0.00376 |
| Bus stops < 0.5 M.*** | 0.00151 | 0.00038 | 0.00189 |
| Rail stops < 0.5 M.*** | −0.02229 | −0.00589 | −0.02817 |
| Miles rail lines < 1 M.*** | 0.00996 | 0.00258 | 0.01254 |
| Intersections < 0.5 M. | −0.00001 | 0.00000 | −0.00000 |
| CBG population/sq. mile** | 0.00000 | 0.00000 | 0.00000 |
| CBG jobs/sq. mile* | 0.00000 | 0.00000 | 0.00000 |
| Work stops | 0.00781 | 0.00209 | 0.00990 |
| Shopping stops*** | −0.03612 | −0.00968 | −0.04579 |
| Social stops** | −0.02013 | −0.00521 | −0.02534 |
| Res. Low Density, 0-1/4 mile** | −0.00203 | −0.00053 | −0.00256 |
| Res. Medium Density, 0-1/4 mile** | −0.00188 | −0.00050 | −0.00238 |
| Res. High Density 0-1/4 mile*** | −0.00222 | −0.00058 | −0.00280 |
| Bus. Low Density 0-1/4 mile | 0.00116 | 0.00031 | 0.00147 |
| Bus. High Density 0-1/4 mile | −0.00093 | −0.00025 | −0.00118 |
| Ind. 0-1/4 mile | −0.00165 | −0.00044 | −0.00209 |
| Res. Low Density, 1/4-1/2 mile*** | 0.00329 | 0.00089 | 0.00418 |
| Res. Medium Density, 1/4-1/2 mile*** | 0.00309 | 0.00084 | 0.00393 |
| Res. High Density 1/4-1/2 mile*** | 0.00375 | 0.00100 | 0.00475 |
| Bus. Low Density 1/4-1/2 mile | −0.00081 | −0.00019 | −0.00100 |
| Bus. High Density 1/4-1/2 mile | 0.00080 | 0.00023 | 0.00103 |
| Ind. 1/4-1/2 mile* | 0.00248 | 0.00067 | 0.00315 |
| Res. Low Density, 1/2-3/4 mile | −0.00358 | −0.00097 | −0.00455 |
| Res. Medium Density, 1/2-3/4* mile | −0.00453 | −0.00123 | −0.00576 |
| Res. High Density 1/2-3/4 mile | −0.00409 | −0.00109 | −0.00517 |
| Bus. Low Density 1/2-3/4 mile | −0.00545 | −0.00137 | −0.00682 |
| Bus. High Density 1/2-3/4 mile | −0.00318 | −0.00087 | −0.00405 |
| Ind. 1/2-3/4 mile | −0.00376 | −0.00102 | −0.00477 |
| Res. Low Density, 3/4-1 mile | 0.00334 | 0.00091 | 0.00426 |
| Res. Medium Density, 3/4-1 mile** | 0.00600 | 0.00162 | 0.00762 |
| Res. High Density 3/4-1 mile | 0.00032 | 0.00009 | 0.00041 |
| Bus. Low Density 3/4-1 mile | −0.00618 | −0.00161 | −0.00779 |
| Bus. High Density 3/4-1 mile** | 0.00697 | 0.00184 | 0.00881 |
| Ind. 3/4-1 mile* | 0.00409 | 0.00111 | 0.00519 |

*Notes: Significance at the 1, 5, and 10% levels shown by ***, **, and *, respectively.*

Table 2.7: Elasticities: SAR Model, Binary W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Direct | Indirect | Total |
| HH size** | −0.062 | −0.017 | −0.078 |
| HH vehicles*** | −0.434 | −0.115 | −0.549 |
| HH bicycles*** | 0.062 | 0.016 | 0.078 |
| Age*** | −0.016 | −0.004 | −0.020 |
| Income | −0.000 | −0.000 | −0.000 |
| Tour distance*** | −0.015 | −0.004 | −0.019 |
| Miles bike lanes < 1 M. | −0.015 | −0.004 | −0.019 |
| Miles bus routes < 0.5 M.*** | 0.018 | 0.005 | 0.023 |
| Bus stops < 0.5 M.*** | 0.009 | 0.002 | 0.011 |
| Rail stops < 0.5 M.*** | −0.134 | −0.035 | −0.169 |
| Miles rail lines < 1 M.*** | 0.060 | 0.015 | 0.075 |
| Intersections < 0.5 M. | −0.000 | 0.000 | −0.000 |
| CBG population/sq. mile** | 0.000 | 0.000 | 0.000 |
| CBG jobs/sq. mile* | 0.000 | 0.000 | 0.000 |
| Work stops | 0.047 | 0.013 | 0.060 |
| Shopping stops*** | −0.217 | −0.058 | −0.275 |
| Social stops** | −0.121 | −0.031 | −0.152 |
| Res. Low Density, 0-1/4 mile** | −0.012 | −0.003 | −0.015 |
| Res. Medium Density, 0-1/4 mile** | −0.011 | −0.003 | −0.014 |
| Res. High Density 0-1/4 mile*** | −0.013 | −0.004 | −0.017 |
| Bus. Low Density 0-1/4 mile | 0.007 | 0.002 | 0.009 |
| Bus. High Density 0-1/4 mile | −0.006 | −0.001 | −0.007 |
| Ind. 0-1/4 mile | −0.010 | −0.003 | −0.013 |
| Res. Low Density, 1/4-1/2 mile*** | 0.020 | 0.005 | 0.025 |
| Res. Medium Density, 1/4-1/2 mile*** | 0.019 | 0.005 | 0.024 |
| Res. High Density 1/4-1/2 mile*** | 0.023 | 0.006 | 0.029 |
| Bus. Low Density 1/4-1/2 mile | −0.005 | −0.001 | −0.006 |
| Bus. High Density 1/4-1/2 mile | 0.005 | 0.001 | 0.006 |
| Ind. 1/4-1/2 mile* | 0.015 | 0.004 | 0.019 |
| Res. Low Density, 1/2-3/4 mile | −0.022 | −0.006 | −0.027 |
| Res. Medium Density, 1/2-3/4 mile* | −0.027 | −0.007 | −0.035 |
| Res. High Density 1/2-3/4 mile | −0.025 | −0.007 | −0.031 |
| Bus. Low Density 1/2-3/4 mile | −0.033 | −0.008 | −0.041 |
| Bus. High Density 1/2-3/4 mile | −0.019 | −0.005 | −0.024 |
| Ind. 1/2-3/4 mile | −0.023 | −0.006 | −0.029 |
| Res. Low Density, 3/4-1 mile | 0.020 | 0.005 | 0.026 |
| Res. Medium Density, 3/4-1 mile** | 0.036 | 0.010 | 0.046 |
| Res. High Density 3/4-1 mile | 0.002 | 0.001 | 0.002 |
| Bus. Low Density 3/4-1 mile | −0.037 | −0.010 | −0.047 |
| Bus. High Density 3/4-1 mile** | 0.042 | 0.011 | 0.053 |
| Ind. 3/4-1 mile* | 0.025 | 0.007 | 0.031 |

*Notes: Significance at the 1, 5, and 10% levels shown by ***, **, and *, respectively.*

Table 2.8 Marginal Effects: SDM Model, Binary W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Direct | Indirect | Total |
| HH size** | −0.01286 | 0.00603 | −0.00683 |
| HH vehicles*** | −0.06941 | 0.03264 | −0.03677 |
| HH bicycles*** | 0.01032 | −0.00485 | 0.00547 |
| Male*** | 0.03407 | −0.01604 | 0.01802 |
| Age*** | −0.00267 | 0.00126 | −0.00142 |
| Income | −0.00001 | 0.00000 | −0.00000 |
| College Degree | 0.00703 | −0.00331 | 0.00372 |
| Employed | −0.01760 | 0.00826 | −0.00934 |
| Tour distance*** | −0.00242 | 0.00114 | −0.00128 |
| Tour crosses highway*** | −0.15734 | 0.07399 | −0.08334 |
| Miles bike lanes < 1 M. | −0.00297 | 0.00140 | −0.00157 |
| Miles bus routes < 0.5 M.* | 0.00208 | −0.00098 | 0.00110 |
| Bus stops < 0.5 M.** | 0.00177 | −0.00083 | 0.00094 |
| Rail stops < 0.5 M. | −0.01162 | 0.00548 | −0.00614 |
| Miles rail lines < 1 M. | 0.00678 | −0.00319 | 0.00359 |
| Intersections < 0.5 M. | −0.00011 | 0.00005 | −0.00006 |
| CBG population/sq. mile | 0.00000 | −0.00000 | 0.00000 |
| CBG jobs/sq. mile | 0.00000 | −0.00000 | 0.00000 |
| Work stops* | 0.00860 | −0.00404 | 0.00456 |
| Shopping stops*** | −0.03715 | 0.01747 | −0.01968 |
| Social stops** | −0.02484 | 0.01166 | −0.01317 |
| Res. Low Density, 0-1/4 mile*** | −0.00256 | 0.00120 | −0.00136 |
| Res. Medium Density, 0-1/4 mile*** | −0.00234 | 0.00110 | −0.00124 |
| Res. High Density 0-1/4 mile** | −0.00215 | 0.00101 | −0.00114 |
| Bus. Low Density 0-1/4 mile | −0.00003 | 0.00001 | −0.00002 |
| Bus. High Density 0-1/4 mile | −0.00121 | 0.00057 | −0.00064 |
| Ind. 0-1/4 mile | −0.00158 | 0.00074 | −0.00084 |
| Res. Low Density, 1/4-1/2 mile** | 0.00339 | −0.00159 | 0.00180 |
| Res. Medium Density, 1/4-1/2 mile* | 0.00301 | −0.00141 | 0.00159 |
| Res. High Density 1/4-1/2 mile | 0.00258 | −0.00121 | 0.00137 |
| Bus. Low Density 1/4-1/2 mile | −0.00264 | 0.00124 | −0.00140 |
| Bus. High Density 1/4-1/2 mile | 0.00097 | −0.00045 | 0.00051 |
| Ind. 1/4-1/2 mile | 0.00161 | −0.00075 | 0.00085 |
| Res. Low Density, 1/2-3/4 mile | −0.00391 | 0.00184 | −0.00207 |
| Res. Medium Density, 1/2-3/4 mile** | −0.00632 | 0.00298 | −0.00335 |
| Res. High Density 1/2-3/4 mile | −0.00410 | 0.00193 | −0.00217 |
| Bus. Low Density 1/2-3/4 mile | −0.00903 | 0.00424 | −0.00479 |
| Bus. High Density 1/2-3/4 mile | −0.00337 | 0.00159 | −0.00178 |
| Ind. 1/2-3/4 mile | −0.00271 | 0.00127 | −0.00144 |
| Res. Low Density, 3/4-1 mile* | 0.00453 | −0.00213 | 0.00240 |
| Res. Medium Density, 3/4-1 mile** | 0.00639 | −0.00301 | 0.00339 |
| Res. High Density 3/4-1 mile | −0.00090 | 0.00042 | −0.00048 |
| Bus. Low Density 3/4-1 mile | −0.01049 | 0.00493 | −0.00557 |
| Bus. High Density 3/4-1 mile*** | 0.00892 | −0.00420 | 0.00473 |
| Ind. 3/4-1 mile | 0.00292 | −0.00138 | 0.00155 |
| (W)HH size | −0.08839 | 0.04159 | −0.04681 |
| (W)HH vehicles | 0.00532 | −0.00248 | 0.00284 |
| (W)HH bicycles | −0.04547 | 0.02137 | −0.02410 |
| (W)Male | 0.03762 | −0.01767 | 0.01995 |
| (W)Age | −0.00468 | 0.00220 | −0.00248 |
| (W)Income | 0.00046 | −0.00021 | 0.00024 |
| (W)College Degree | 0.10217 | −0.04776 | 0.05440 |
| (W)Employed | 0.04803 | −0.02297 | 0.02507 |
| (W)Tour distance | −0.00588 | 0.00279 | −0.00309 |
| (W)Tour crosses highway | 0.08159 | −0.03795 | 0.04364 |
| (W)Miles bike lanes < 1 M. | −0.01139 | 0.00534 | −0.00605 |
| (W)Miles bus routes < 0.5 M.** | 0.01100 | −0.00517 | 0.00583 |
| (W)Bus stops < 0.5 M. | −0.00205 | 0.00097 | −0.00108 |
| (W)Rail stops < 0.5 M. | 0.01590 | −0.00753 | 0.00837 |
| (W)Miles rail lines < 1 M. | 0.00506 | −0.00239 | 0.00267 |
| (W)Intersections < 0.5 M. | 0.00045 | −0.00021 | 0.00024 |
| (W)CBG population/sq. mile** | 0.00002 | −0.00001 | 0.00001 |
| (W)CBG jobs/sq. mile | −0.00000 | 0.00000 | −0.00000 |
| (W)Work stops | 0.06333 | −0.02960 | 0.03372 |

| Variable | Direct | Indirect | Total |
|---|---|---|---|
| (W)Shopping stops | −0.07852 | 0.03718 | −0.04134 |
| (W)Social stops | −0.13294 | 0.06236 | −0.07058 |
| (W)Res. Low Density, 0-1/4 mile | −0.00601 | 0.00283 | −0.00318 |
| (W)Res. Medium Density, 0-1/4 mile | 0.00114 | −0.00054 | 0.00059 |
| (W)Res. High Density 0-1/4 mile | 0.00340 | −0.00159 | 0.00181 |
| (W)Bus. Low Density 0-1/4 mile | 0.00506 | −0.00239 | 0.00266 |
| (W)Bus. High Density 0-1/4 mile | −0.00363 | 0.00170 | −0.00193 |
| (W)Ind. 0-1/4 mile* | 0.01885 | −0.00885 | 0.01000 |
| (W)Res. Low Density, 1/4-1/2 mile | 0.00937 | −0.00440 | 0.00497 |
| (W)Res. Medium Density, 1/4-1/2 mile | 0.00202 | −0.00094 | 0.00109 |
| (W)Res. High Density 1/4-1/2 mile | 0.00101 | −0.00048 | 0.00053 |
| (W)Bus. Low Density 1/4-1/2 mile | 0.01733 | −0.00809 | 0.00925 |
| (W)Bus. High Density 1/4-1/2 mile | 0.00488 | −0.00228 | 0.00260 |
| (W)Ind. 1/4-1/2 mile | −0.00618 | 0.00291 | −0.00327 |
| (W)Res. Low Density, 1/2-3/4 mile*** | −0.06475 | 0.03043 | −0.03432 |
| (W)Res. Medium Density, 1/2-3/4 mile*** | −0.10647 | 0.05002 | −0.05645 |
| (W)Res. High Density 1/2-3/4 mile** | −0.04537 | 0.02132 | −0.02405 |
| (W)Bus. Low Density 1/2-3/4 mile** | −0.11828 | 0.05553 | −0.06275 |
| (W)Bus. High Density 1/2-3/4 mile** | −0.04730 | 0.02224 | −0.02506 |
| (W)Ind. 1/2-3/4 mile*** | −0.08333 | 0.03914 | −0.04420 |
| (W)Res. Low Density, 3/4-1 mile*** | 0.06179 | −0.02904 | 0.03275 |
| (W)Res. Medium Density, 3/4-1 mile*** | 0.12995 | −0.06106 | 0.06890 |
| (W)Res. High Density 3/4-1 mile | 0.03219 | −0.01514 | 0.01704 |
| (W)Bus. Low Density 3/4-1 mile | 0.09916 | −0.04657 | 0.05259 |
| (W)Bus. High Density 3/4-1 mile** | 0.05024 | −0.02356 | 0.02667 |
| (W)Ind. 3/4-1 mile*** | 0.08441 | −0.03965 | 0.04476 |

*Notes: Significance at the 1, 5, and 10% levels shown by ***, **, and *, respectively.*

Table 2.9 Elasticities: SDM Model, Binary W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Direct | Indirect | Total |
| HH size** | −0.077 | 0.036 | −0.041 |
| HH vehicles*** | −0.417 | 0.196 | −0.221 |
| HH bicycles*** | 0.062 | −0.029 | 0.033 |
| Age*** | −0.016 | 0.008 | −0.009 |
| Income | −0.000 | 0.000 | −0.000 |
| Tour distance*** | −0.015 | 0.007 | −0.008 |
| Miles bike lanes < 1 M. | −0.018 | 0.008 | −0.009 |
| Miles bus routes < 0.5 M.* | 0.012 | −0.006 | 0.007 |
| Bus stops < 0.5 M.** | 0.011 | −0.005 | 0.006 |
| Rail stops < 0.5 M. | −0.070 | 0.033 | −0.037 |
| Miles rail lines < 1 M. | 0.041 | −0.019 | 0.022 |
| Intersections < 0.5 M. | −0.001 | 0.000 | −0.000 |
| CBG population/sq. mile | 0.000 | −0.000 | 0.000 |
| CBG jobs/sq. mile | 0.000 | −0.000 | 0.000 |
| Work stops* | 0.052 | −0.024 | 0.027 |
| Shopping stops*** | −0.223 | 0.105 | −0.118 |
| Social stops** | −0.149 | 0.070 | −0.079 |
| Res. Low Density, 0-1/4 mile*** | −0.015 | 0.007 | −0.008 |
| Res. Medium Density, 0-1/4 mile*** | −0.014 | 0.007 | −0.007 |
| Res. High Density 0-1/4 mile** | −0.013 | 0.006 | −0.007 |
| Bus. Low Density 0-1/4 mile | −0.000 | 0.000 | −0.000 |
| Bus. High Density 0-1/4 mile | −0.007 | 0.003 | −0.004 |
| Ind. 0-1/4 mile | −0.010 | 0.004 | −0.005 |
| Res. Low Density, 1/4-1/2 mile** | 0.020 | −0.010 | 0.011 |
| Res. Medium Density, 1/4-1/2 mile* | 0.018 | −0.008 | 0.010 |
| Res. High Density 1/4-1/2 mile | 0.016 | −0.007 | 0.008 |
| Bus. Low Density 1/4-1/2 mile | −0.016 | 0.007 | −0.008 |
| Bus. High Density 1/4-1/2 mile | 0.006 | −0.003 | 0.003 |
| Ind. 1/4-1/2 mile | 0.010 | −0.005 | 0.005 |
| Res. Low Density, 1/2-3/4 mile | −0.024 | 0.011 | −0.012 |
| Res. Medium Density, 1/2-3/4 mile** | −0.038 | 0.018 | −0.020 |
| Res. High Density 1/2-3/4 mile | −0.025 | 0.012 | −0.013 |
| Bus. Low Density 1/2-3/4 mile | −0.054 | 0.025 | −0.029 |
| Bus. High Density 1/2-3/4 mile | −0.020 | 0.010 | −0.011 |
| Ind. 1/2-3/4 mile | −0.016 | 0.008 | −0.009 |
| Res. Low Density, 3/4-1 mile* | 0.027 | −0.013 | 0.014 |
| Res. Medium Density, 3/4-1 mile** | 0.038 | −0.018 | 0.020 |
| Res. High Density 3/4-1 mile | −0.005 | 0.003 | −0.003 |
| Bus. Low Density 3/4-1 mile | −0.063 | 0.030 | −0.033 |
| Bus. High Density 3/4-1 mile*** | 0.054 | −0.025 | 0.028 |
| Ind. 3/4-1 mile | 0.018 | −0.008 | 0.009 |
| (W)HH size | −0.531 | 0.250 | −0.281 |
| (W)HH vehicles | 0.032 | −0.015 | 0.017 |
| (W)HH bicycles | −0.273 | 0.128 | −0.145 |
| (W)Age | −0.028 | 0.013 | −0.015 |
| (W)Income | 0.003 | −0.001 | 0.001 |
| (W)Tour distance | −0.035 | 0.017 | −0.019 |
| (W)Miles bike lanes < 1 M. | −0.068 | 0.032 | −0.036 |
| (W)Miles bus routes < 0.5 M.** | 0.066 | −0.031 | 0.035 |
| (W)Bus stops < 0.5 M. | −0.012 | 0.006 | −0.007 |
| (W)Rail stops < 0.5 M. | 0.096 | −0.045 | 0.050 |
| (W)Miles rail lines < 1 M. | 0.030 | −0.014 | 0.016 |
| (W)Intersections < 0.5 M. | 0.003 | −0.001 | 0.001 |
| (W)CBG population/sq. mile** | 0.000 | −0.000 | 0.000 |
| (W)CBG jobs/sq. mile | −0.000 | 0.000 | −0.000 |
| (W)Work stops | 0.381 | −0.178 | 0.203 |
| (W)Shopping stops | −0.472 | 0.224 | −0.249 |
| (W)Social stops | −0.799 | 0.375 | −0.424 |
| (W)Res. Low Density, 0-1/4 mile | −0.036 | 0.017 | −0.019 |
| (W)Res. Medium Density, 0-1/4 mile | 0.007 | −0.003 | 0.004 |
| (W)Res. High Density 0-1/4 mile | 0.020 | −0.010 | 0.011 |
| (W)Bus. Low Density 0-1/4 mile | 0.030 | −0.014 | 0.016 |
| (W)Bus. High Density 0-1/4 mile | −0.022 | 0.010 | −0.012 |
| (W)Ind. 0-1/4 mile* | 0.113 | −0.053 | 0.060 |

| Variable | Direct | Indirect | Total |
|---|---|---|---|
| (W)Res. Low Density, 1/4-1/2 mile | 0.056 | −0.026 | 0.030 |
| (W)Res. Medium Density, 1/4-1/2 mile | 0.012 | −0.006 | 0.007 |
| (W)Res. High Density 1/4-1/2 mile | 0.006 | −0.003 | 0.003 |
| (W)Bus. Low Density 1/4-1/2 mile | 0.104 | −0.049 | 0.056 |
| (W)Bus. High Density 1/4-1/2 mile | 0.029 | −0.014 | 0.016 |
| (W)Ind. 1/4-1/2 mile | −0.037 | 0.017 | −0.020 |
| (W)Res. Low Density, 1/2-3/4 mile*** | −0.389 | 0.183 | −0.206 |
| (W)Res. Medium Density, 1/2-3/4 mile*** | −0.640 | 0.301 | −0.339 |
| (W)Res. High Density 1/2-3/4 mile** | −0.273 | 0.128 | −0.145 |
| (W)Bus. Low Density 1/2-3/4 mile** | −0.711 | 0.334 | −0.377 |
| (W)Bus. High Density 1/2-3/4 mile** | −0.284 | 0.134 | −0.151 |
| (W)Ind. 1/2-3/4 mile*** | −0.501 | 0.235 | −0.266 |
| (W)Res. Low Density, 3/4-1 mile*** | 0.372 | −0.175 | 0.197 |
| (W)Res. Medium Density, 3/4-1 mile*** | 0.781 | −0.367 | 0.414 |
| (W)Res. High Density 3/4-1 mile | 0.194 | −0.091 | 0.102 |
| (W)Bus. Low Density 3/4-1 mile | 0.596 | −0.280 | 0.316 |
| (W)Bus. High Density 3/4-1 mile** | 0.302 | −0.142 | 0.160 |
| (W)Ind. 3/4-1 mile*** | 0.508 | −0.238 | 0.269 |

*Notes: Significance at the 1, 5, and 10% levels shown by ***, **, and *, respectively.*

# CHAPTER 3: IMPLICATIONS OF LAND USE RESTRICTIONS FOR TRANSPORTATION BEHAVIOR

## 3.1 INTRODUCTION

The previous two chapters explore the relationship between transportation mode choice of individuals and the built environment. The first chapter finds support for previous literature that several built environment characteristics are significant in predicting transportation mode choice decisions. The second chapter introduces spatial dependence and heterogeneity into the modeling structure and also supports previous literature that certain built environment characteristics are associated with the decision between using auto or alternative forms of transportation. It is clear from the previous two chapters and previous literature that the link between urban form and transportation modes is supported, but to a varying degree. It is also clear that modeling the linkage between urban form and transportation behavior is particularly difficult due to a range of issues including disparate data sets, inconsistent levels of detail about consumer transportation behavior contained in data, and modeling issues that arise when attempting to isolate the impacts of urban form on transportation choices. As other authors have experienced (Boarnet and Sarmiento, 1998; Pinjari et al., 2011; Walker et al., 2011; Iacono et al., 2010), drawing conclusions about causality is difficult with the current dataset due to the lack of repeat observations over time.

This chapter addresses some of the major themes in the literature, areas in which the current study can add support for what others have found previously, and where there are still difficult questions to be answered. The primary interest in the link between the built environment and transportation choice stems from the desire for policy makers, city planners, transportation engineers, and citizens to understand how land use restrictions can affect the evolution of built environments and transportation behavior, with a keen interest in reducing congestion and dependence on automobiles in urban areas.

Transportation systems characterized by high levels of congestion increase time spent in traffic that could otherwise be spent in more productive pursuits such as working, shopping, or leisure. This chapter deals with these transportation problems and the role that zoning plays in the evolution of urban structures. As Boarnet (2011, p.198) laments, “The canonical method of studying this topic [land use-travel behavior research] has been to regress a measure of individual travel behavior on individual or household demographic characteristics and land use measures. This leaves almost no role for examining how land is developed, or why a city’s or neighborhood’s urban form develops in a particular way.” This study attempts to bridge that gap by incorporating the zoning laws that govern permissible usage of specific parcels of land, a key determinant of how a city develops. While the dataset used in the previous chapters does not permit the modeling of exactly why Denver developed the way it did, zoning restrictions give some insight into where city planners allowed different types of development to occur. The remainder of the chapter outlines the key problems at the forefront of built environment-land use research, with a focus on the consequences of land use restrictions. I first provide a summary overview of the findings from the previous two chapters, and then discuss how these findings fit into the context of research in the area throughout the rest of the chapter. Initially, transportation networks allowed for the expansion of urban centers due to the construction of rail, and later automobile networks. This transportation infrastructure helped fuel what is known today as urban sprawl, or the expansion of an urban area beyond what is socially optimal when all externalities are accounted for. I then discuss how land use restrictions may further exacerbate urban sprawl by restricting density in urban cores and, in some cases, dictate urban forms other than what would have evolved under purely market driven forces. Finally, I discuss the findings from previous chapters and their implications for urban planning policy, and suggest directions for further research on the subject.

## 3.2 SUMMARY OF FINDINGS

The findings of the present study, while far from conclusive, provide support for previous literature on the link between transportation behavior and the built environment. In addition, the dataset used in the current study represents a more granular level of detail with respect to built environment variables than previous studies, yet still supports many of the main findings in the literature. This study also tests new variables of land use restrictions missing from much of the previous work in this area of research. Findings generally support the notion that population density is positively associated with non-auto transportation. I also find support for previous findings that access to transport has a positive impact of transit usage, particularly transit level of service and number of stops. Diversity of land use, represented by higher percentages of business zoning, is also weakly associated with higher non-auto mode shares. Finally, residential zoning, which represents the most restrictive form of land use, is found to be negatively associated with non-auto forms of transportation, lending some support to findings from models testing the impact of land use restrictions on urban sprawl, an indirect but important association.

## 3.3 THE EVOLUTION OF TRANSPORTATION AND URBAN SPRAWL

Before the widespread use of the automobile, traditional urban form was characterized by households that often lived within close walking distance of neighborhood shops (Ryan and McNally, 1995). This type of land use pattern is often referred to today as neo- traditional. With the invention and widespread adoption of trains, urban centers began to develop around stops along train routes, and provided somewhat ideal conditions for the movement of people and goods to urban locations for both work and living purposes. With the majority of residential and work places located in close proximity to train stops, rail transportation became an efficient way to move people in and out of urban centers, while also providing an efficient way to transport goods to the same locations (Fischel, 2004). Between 1950 and 1990 in the U.S., central city populations declined by 17% while overall population grew by 72% (Baum-Snow, 2007). With the widespread adoption of the automobile and the building of far reaching highway infrastructure in the United States and elsewhere in the beginning of the 20th century, the cost of travel to more distant locations in and around urban centers was rapidly reduced for those who could afford an automobile. Baum-Snow (2007) estimates that, in the U.S., one new highway decreased the population in central cities by 18% on average during this time period. Many chose to move away from inner city locations to the suburbs, and the modern city was born, with multiple focal points of economic activity and expanding suburbs. Along with the expansion of the city has come many of the ills of modern urban centers, including reliance on automobiles, traffic congestion, and air pollution (Richards, 1969; Glaeser, 2004; Baum- Snow, 2007). In a study of U.S. cities, Kahn (2000) finds that suburban households drive 31% more than urban households, and that western households drive 31% more than northeastern households. Proponents of neo-traditional design point to such findings as evidence that neo-traditional urban form is ideal for reducing reliance on automobiles and alleviating externalities associated with traffic congestion.

Brueckner (2001)[p.66] defines urban sprawl as "spatial growth that is excessive relative to what is socially desirable urban decentralization". Brueckner (2001) identifies three forces that have led to urban sprawl: (1) population growth, (2) increasing household incomes, and (3) decreased commuting cost. He also identifies three reasons why urban sprawl becomes excessive: failure to account for (1) the amenity value of open space around cities, (2) the social cost of highway congestion, and (3) infrastructure costs of new development. The expansion of the city has led to an increasing reliance on the transportation network to traverse increasingly dispersed locations to accomplish daily shopping and work tasks. Recent attempts to address these issues through public planning have led to new movements in city design, such as new urbanism and transit oriented development, as well as a renewed focus on public transportation and multi- modal transportation networks (Glaeser, 2004).

City planners are faced with the monumental task of developing land use and transportation policies that balance a variety of competing objectives. With increased incomes and low costs of auto transport, households often express their desire for larger homes and more space by moving to suburban locations. At the same time, environmental and quality of life considerations suggest the provision of open space close to urban centers. This creates direct competition between city planners and suburban developers for un- touched land at the fringes of cities. Population growth and corresponding increases in traffic congestion cause increased premiums for land in centralized locations, while social justice considerations call for affordable housing. To further complicate matters, existing residents are often opposed to changes in their neighborhoods, and often have approval rights through local planning commissions that can block changes to land use, limiting options available to planners.

The city planner's objective is to guide urban development to produce vibrant places for economic, social, and recreational activity (Glaeser, 2004; Urban Land Institute, 2016). Some of the goals in creating a vibrant city include healthy environmental conditions, welcoming public spaces, and efficient transportation across the urban landscape. Urban sprawl and reliance on automobiles complicates attaining these goals. As suburban development expands the urban fringe, metropolitan areas are increasingly reliant on highways to move suburban residents into CBDs for work. New development requires street and sanitation infrastructure, and scattered development makes public transit difficult to provide efficiently. The result has been increased highway congestion and infrastructure costs, loss of open space, and continued reliance on automobile transportation. Urban governments have attempted to counteract these trends by increasing density and mixed use development within urban boundaries to encourage use of transit, increase social interactions, and reduce infrastructure costs (Geshkov and DeSalvo, 2012).

## 3.4 LAND USE RESTRICTIONS ENCOMPASSED IN ZONING LAWS

In most municipalities in the U.S., zoning codes determine the allowable size of a building on a piece of land, as well as its use type, which limits both the density and type of economic activity can take place on a parcel of land, even when it is privately owned. This type of restriction was first introduced in New York in 1916 (Datta and Sudhir, 2012). One of the few ways that city planners could isolate the negative effects of pollution on households was to segregate the source of pollution (the factories) from residential neighborhoods to minimize exposure to pollutants and other environmental toxins whose effects were not well known (Richards, 1969). During this time frame, zoning laws were considered necessary and, indeed, most likely improved the quality and livability of the urban landscape by segregating different land uses to different parts of a city. Zoning laws were largely successful in this pursuit, as environmental and public health regulations were not nearly as protective of consumers as they are today (Datta and Sudhir, 2012). With more recent consumer protections, zoning laws' separation of uses has been questioned, as integrated land use patterns are seen as part of the solution to providing more pedestrian oriented urban places that can reduce automobile reliance and decrease pressure on over-burdened transportation networks.

3.4.1 Uniform Zoning Districts. The most common technique employed with zoning laws is the uniform zoning district. This type of district restricts land use to a pre-specified type. This ensures that only land uses of similar types are allowed within close proximity to each other in most cases. The primary reasoning behind this technique is that grouping development types such as commercial, residential, and industrial together reduces the conflict amongst property owners, since all owners within the same district will generally prefer similar built environment settings. The problem with uniform zoning districts arises when the contiguous area of one zoning district is large and provides limited access to other types of land use. Since most land uses are necessary to complete the daily tasks of living, large contiguous areas of a single use land limit access to other types of land use and increase distances between places to work, shop, and live. Such land configurations are often counter to urban planning goals of providing pedestrian access to goods and services.

An example of the types of problems created by zoning laws is the single family residential zoning district. Many modern U.S. cities are characterized by large portions of their overall land area designated as single family zoning districts. While subtle nuances of each local government's definition of this type of zoning district may differ slightly, the overall idea is the same: only detached single family residential dwellings in low density configurations are allowed. In the best case scenario, these types of zoning districts are paired with adjacent low density business zones with high parking space requirements, resulting in the dominance and reliance on automobile transportation, often to the detriment of all other modes of transportation. Some of these districts, while having ample room for automobiles to drive and park, neglect the requirement for sidewalks where pedestrians can travel safely. Path dependence also plays a role in making these types of restrictions hard to change because it can be hard to convince owners under one zoning regime to allow use changes within close proximity to their properties (Wickersham, 2001).

In the current study, high percentages of low, medium, and high density residential zoning within a quarter mile of residences had a consistent negative effect on the propensity to walk. These results provide evidence that residential zoning may detract from policy goals of promoting non-auto transportation modes in urban locations. Within a quarter mile of survey respondents' residences in the current study, the average household zoning makeup had 60.1% of total land area designated as low-density residential, with medium and high density residential averaging an additional 10.0% and 13.9%, respectively, for a total of 84.0% of land area designated as residential zoning. While the remaining land area surrounding residences allowing for commercial purposes may be enough to meet daily shopping and employment tasks, depending on configuration and types of businesses in those areas, it is easy to see why the dominance of residential zoning may be preventing the creation of more walkable access to shopping and employment, and why survey respondents chose auto transportation on 84% of all tours in the sample.

3.4.2 Bulk Restriction. In addition to use restrictions, zoning codes often restrict the maximum height, size, density, and placement of buildings on a parcel. If bulk restrictions produce binding constraints to development density, these restrictions represent an upper limit on what the market would otherwise supply. One of the side effects of supply side restrictions is the artificial increase of rents in urban areas (Wickersham, 2001). These restrictions can be counterproductive to the goals of congestion alleviation and provision of efficient and highly used public transportation systems. If reducing congestion and increasing reliance on walking is a primary goal of planning boards, then minimum density restrictions would be a preferable policy. However, these types of restrictions are hard to implement because existing land owners have local legislative power to block increased density adjacent to their existing low density parcels through local zoning boards (Wickersham, 2001).

Density and intensity restrictions are typically employed by limiting the number of units per lot, number of lots per acre, or square footage of building space to the total lot area. If these restrictions are binding, which they often are, they represent a constrained supply, which often leads to some of the urban phenomenon seen over the past several decades: urban rents rising faster than incomes, astronomical rents near city centers, and higher suburban intensity than is desirable as developers attempt to meet the demand for housing in constrained urban environments by moving their development of residential to close by suburban locations where local planning boards are more accommodating (Wickersham, 2001; Glaeser, 2004). The current study indicates that population per square mile is approximately 8 times greater for survey respondents living within 2 miles of downtown than those living more than 2 miles from downtown. In the absence of zoning restrictions, this difference in density may have been significantly higher. Population density had a small but positive impact on propensity to take transit and walk in the MNL model, as well as a positive impact on non-auto transportation propensity in the SAR and SDM models. This provides weak evidence that density is associated with higher non-auto forms of transportation, but direction of causality cannot be established.

3.4.3 Other Land Restrictions. In addition to zoning codes, other land use restrictions can be employed by planning boards or local residents. The most common of these are the urban growth boundary and fiscal zoning. Urban growth boundaries are laws that demarcate the edge of an urban area, beyond which open space or agricultural land use are the only permissible uses (Anas and Pines, 2012). Urban growth boundaries have distortionary market effects by limiting the size of a city, and in some cases have other unintended consequences such as spawning suburban development. If not coupled with increased density within the city limits, these land use controls limit supply and escalate land values within the city limits Anas and Pines (2012).

Fiscal zoning is a term used to describe instances where high property taxes are used as a way to exclude poorer populations. The taxes are then used to provide large amounts of public goods locally, thereby reducing the burden of the tax on local residents by providing high amounts of public goods whose use is prohibited to people living outside the tax district (Anas and Pines, 2012). The most common example of this type of exclusionary tax structure is local school districts, where high property taxes in one area are used to increase quality in local schools that residents from other districts are not entitled to attend. High property taxes keep poorer households from buying in these districts, while local tax revenue is returned to property owners in the form of high quality public education (Anas and Pines, 2012). In the current study, data was not available on fiscal zoning, and Denver does not have an urban growth boundary. Data for future research in this area is available, however, as the survey sample includes the City of Boulder, which does have an urban growth boundary. Survey responses outside the city limits of Denver were excluded from the sample to ensure uniform treatment of the zoning variable, which varies by municipality.

## 3.5 MODELS OF LAND USE RESTRICTION AND URBAN STRUCTURE

The earliest theory of land use dates back to von Thunen (1821), who developed a mono-centric rent model of the city in which higher value production was located closer to city center, while less productive and less profitable production was located further from city center. This theory was the first to explain the declining rent gradient as distance from city center increases. Today's cities are more poly-centric in nature, with modern transportation infrastructure allowing for multiple centers of economic activity (Glaeser, 2004). However, the city center remains an important epicenter of economic activity in many of the cities across the U.S., often known as the central business district (CBD). CBDs in the modern urban landscape still represent an important agglomeration of businesses and services, and still exhibit much of what von Thunen (1821) originally proposed in his pioneering research. Much of today's modern CBDs are characterized by high value business services such as finance, corporate law firms, and consulting companies. Land values are high enough to warrant high cost construction of high density buildings that would otherwise not be cost feasible were they located in more remote locations of the urban landscape (Brueckner, 1999). The theoretical work of von Thunen (1821) modeling mono-centric circular cities with business activity occurring at city center and workers making trade-offs between rents and travel costs has been more recently formalized in the well known Alonso-Muth- Mills(AMM) model (Wheaton, 1974). The AMM model has been adapted in many ways to accommodate different features of urban structure. The primary features of the model are households who maximize a utility function consisting of consumption of housing, transportation to city center, and all other goods under a household budget constraint. The model assumes a mono-centric city design, with all employment at city center, and demand for housing driving rent prices higher at city center where commuting costs are lower. Additional features such as a housing supply function and policy restrictions are often added to the model. The additions of features to the basic AMM model allow researchers to study the impacts of urban growth boundaries, density restrictions, and other forms of land use restrictions on the allocation of populations in urban areas, and help theoretically explain why urban sprawl occurs. This study is concerned with the link between land use restrictions and transportation behavior, but it is important to understand that zoning laws can also produce urban sprawl and higher land prices, which indirectly impact transportation behavior by decreasing densities at urban centers and moving residences further from shops and employment.

Transportation networks are much more efficient at delivering high efficiency public transportation to high density urban networks than to sparsely populated suburban and rural locations because the usage of such networks can be spread among many more users (Brueckner, 2001). This can be seen in the current sample, where the average urban respondents has 23.39 miles of bus routes within 1/2 mile of home, while suburban respondents have only 5.41 miles, indicating higher level of service and access to transit for urban residents. With the advent of the modern day highway network, the cost in both travel time and fuel expenditure was reduced dramatically, making the trade-off between living in more remote locations with less expensive land and the increased costs in travel time much less than it would have been otherwise. This immense reduction in travel time to the urban fringe has allowed many would be urban dwellers to move further from the urban core to satisfy their demand for increasing housing sizes, cheaper rents or home prices, and less exposure to inner-city crime (Brueckner, 2001). In the sample used for this study, urban respondent tours average 9.3 miles and took 51.5 minutes, while suburban respondents tours average 11.13 miles and took 49.61 minutes. The trade-off of this move to the suburbs has been that the American household in general has become increasingly reliant on the automobile for the majority if not all of their transportation needs to facilitate working, shopping, and leisure activities in all but the densest urban cores (Glaeser, 2004). However, many think this reliance on the automobile is no longer a sustainable way to provide transportation around many of the nation's ever-increasing urban population centers. The stress currently being placed on the existing infrastructure of rapidly growing cities has led to large increases in congestion, increasing time spent in traffic and decreasing leisure time and worker productivity (Urban Land Institute, 2016).

In addition to transportation, zoning codes have also played a key role in the evolution of the built environment in most major urban areas. Significant effort has been spent modeling land use restriction effects on urban structure, with particular emphasis on land rents and city size. Most models stem from the mono-centric AMM urban model relying on distances from CBD as a key determinant of rent gradients, supply of new housing, and the edge of the city (which determines city size) (Geshkov and DeSalvo, 2012). Within this framework, many theoretical models find that land use restrictions which limit density lead to urban sprawl, drive land prices higher, and increase transportation infrastructure spending.

In general, findings of empirical research are consistent with theoretical hypotheses about the effect that land use restrictions have on urban form. In an extensive review of the literature on land use, housing prices, and city size, (Quigley and Rosenthal, 2005) highlight the difficulties of measuring effects and establishing causal relationships. Never- theless, studies generally find that land use restrictions constitute a supply restriction and cause urban sprawl, while policies that encourage higher density reduce urban sprawl.

In a representative study of Australian cities, Kulish et al. (2012) study the impact that zoning has on both transportation and supply of new housing. They find that cities with better transportation (lower transportation costs to city center) increases the ability of households to live further from the city center where rents are less costly. They also find that zoning which restricts density close to the CBD forces households to live further from the city and results in a more sprawling city. This effect makes it more challenging to provide optimal transportation to the outskirts of the city because transit routes must be spread over large distances. Finally, they find that zoning acts as an impediment to new housing development which reduces the supply of housing and increases the cost of housing for consumers. They find that continued population growth amplifies these effects and is consistent with other studies on increasing congestion in cities.

In another study using a sample of U.S. urbanized areas in 2000, Geshkov and DeSalvo (2012) find that minimum lot size and maximum floor to area ratio restrictions increase the size of urban areas, while land use restrictions that encourage density such as maximum lot- size zoning, urban growth boundaries, maximum building permit restrictions, minimum person per room controls, and impact fees contract urban areas. Anas and Pines (2012) model both congestion tolls and urban growth boundaries jointly and find that these policy instruments cause cities to become more compact, but also cause urban cities to be less populated, while increasing the creation and population of suburban cities. This has both the positive effect of decreasing congestion for urban core residents, while having an increased cost of providing local public goods at more suburban city locations. These findings suggest that dense, compact cities are beneficial for transportation, as does the current study. With a large majority of Denver's land area zoned as low density residential and the corresponding negative impacts on propensity to use non-auto transportation, policy should be adjusted to allow for higher densities and greater mixing of land uses. Low density residential represents some of the lowest density and use value of land possible, and limiting density of residential causes existing residential to be priced higher than it would be if more housing was available within the city limits.

Gyourko et al. (2008) survey over 2000 jurisdictions across the U.S., finding that the coastal regions tend to be the most highly regulated housing markets. Regulation can affect costs of development by delay, design restriction, and ease of challenging development rights judicially. They construct an index based on several facets of the land control spectrum and conclude that land regulation in general is heterogeneous across municipalities. Those communities with the most highly regulated environments tend to have land use controls in all measures of the index, including minimum lot size, exactions and open space requirements for new development, and slow approval processes. They also find that wealth is highly correlated with land use regulation. Gyourko et al. (2008) provides evidence of the highly localized nature of zoning laws. They also find evidence of fiscal zoning, ability of local residents to control land use, and the overall onerous restrictions in land use that can lead to higher priced urban centers and corresponding urban sprawl.

Ogura (2010) uses a gravity model to test the effects of growth controls on commuting flows, and finds that higher destination flows occur to places that restrict residential growth, giving weight to the hypothesis that land use restrictions force populations to suburban locations due to both lack of housing supply and increased housing prices in central cities.

The collective implications of the studies in this area of research show a correspondence between land use restrictions and urban sprawl. In the context of the present study, urban sprawl causes difficulty in providing efficient transportation. The findings of this study that residential zoning decreases propensity for non-auto transportation use coincide with the findings of these studies that zoning may also be exacerbating the transportation and congestion problem by forcing cities to sprawl beyond sizes which would provide more optimal conditions for efficient transportation infrastructure.

## 3.6 MODELS OF LAND USE AND TRANSPORTATION

In contrast to models dealing with the effects of land use restrictions on urban form, another body of literature takes the built environment as exogenous and focuses on the existing built environment as a determinant of travel behavior. This land use-travel behavior body of literature also suffers from a lack of adequate data to test many of the more interesting hypothesis about the relationship between travel and the built environment, but several common themes exists. The general construct of these models regress a travel behavior variable against built environment variables, while controlling for socioeconomic variables. Boarnet (2011) argues the main pitfall of this reduced form modeling approach is that such studies say nothing about how the built environment develops in a particular way. However, this approach does give insight into the relationship between certain aspects of the built environment as it exists that are useful in guiding planning policy for future development. From the previous section, we can generally accept the findings that sprawl is one outcome of zoning that restricts density and use, and that sprawl typically leads to higher congestion and auto usage.

Travel variables studied in this stream of literature started with trip generation (Boar- net and Sarmiento, 1998; Cao et al., 2009b) and expanded to include distance traveled (Manaugh et al., 2010), travel mode choice (Plaut, 2005; Pinjari et al., 2011; Rodrguez and Joo, 2004), and various other measures. Land use variables are defined by the five ”D’s”, density, diversity, design, destination accessibility, and distance to transit (Boarnet, 2011). Most data is aggregated at the census tract level due to availability, which hinders under- standing of the land use-built environment relationship at a more localized level. One benefit of the current study is that many of the built environment measures are localized to the census block level, a more granular level of detail that previous studies. This study’s general results provide some support for certain built environment factors affecting transportation mode choice, while having inconclusive results for built environment variables that others have found to be significant.

3.6.1 Density. Density measures typically used in the literature are population, housing unit or employment density per square unit of area. In a study of the San Fransisco Bay Area, Cervero and Kockelman (1997) find that higher density generally reduces vehicle miles traveled. Pinjari et al. (2011) find that employment is positively associated with non-motorized transportation modes. In the current study, both population and employment density are used. Chapter 1 cannot corroborate these studies' results that population and employment density increase the propensity for non-auto travel. The results in Chapter 1 indicate that, while statistically insignificant for the overall sample for transit and walking, the effect is extremely small, which has been the general finding of Cervero and Kockelman (1997), Pinjari et al. (2011), and others.

3.6.2 Diversity. Diversity measures the mix of residential and business land use. Common measures that have been developed are an entropy index (how evenly spread residential and commercial uses are across space) and dissimilarity index (how adjacent parcels' land uses differ) (Boarnet, 2011). Cervero and Kockelman (1997) find that land-use diversity reduces vehicle miles traveled, while Pinjari et al. (2011) finds that higher levels of mixed land use are associated with higher propensity for transit use.

One advantage of the current study is the use of zoning measures of land use which enable residential to be split into three different density classification, business (commercial) to be split into two classifications, and the inclusion of industrial land use. Unlike previous studies, these variables provide some insight into the dynamic evolution of the current environment by indicating the uses allowed on each parcel that may have resulted in current land use, rather than taking current land use as given. While some of the results of this study vary across models with respect to zoning variables, the most consistent result across all models is that increased residential zoning percentages surrounding places of residence increase the likelihood of driving. This is an important result, considering that the majority of both the study area and most urban areas is zoning of this type. The implications for policy is that efforts in integrate either mixed use or business zoning within these areas may increase the likelihood of non-auto travel, and should be considered if decreasing dependence on automobiles and alleviating traffic congestion are long term goals of a municipality.

3.6.3 Design. Design measures deal with the design of the transportation network. Of particular interest is the level to which the street network is laid out in a grid pattern, which increases connectivity between streets and facilitates transportation. Cervero and Kockelman (1997) find that pedestrian oriented designs generally reduce trip generation rates. Chandra and Thompson (2000) finds that infrastructure spending on highways pulls economic activity towards highways from locations further away from the highway infrastructure.

In the current study, measure of intersections is used as a proxy for design. In addition, the variable of whether a tour crosses a major highway is used as a proxy for impediments to biking or walking. Both Chapter 1 and 2 results indicate that number of intersections is insignificant and of the unexpected sign, with the expectation that increased number of intersections indicates a more connected street network and therefore better ability to complete trips by non-auto modes of transportation. This is counter to the findings of Pinjari et al. (2011), who find that street block density is associated with walking. However, Chapter 1 and 2 results indicate that tours crossing highways have a strong negative association with the propensity to use non-auto transportations modes. The implications of this result are that major highways provide a significant barrier to non- auto trips. City planners should carefully consider the role that major highway projects may play in segregating different areas of the urban landscape, as well as encouraging urban sprawl.

3.6.4 Destination Accessibility. Destination accessibility is a measure of the amount of destinations available for opportunities to shop, work, or recreate. Several different measures have been employed for this variable, including access to jobs and parking spaces (Cervero and Duncan, 2006). In an integrated model of home-work location and commuter trip length, Manaugh et al. (2010) finds that commuters who work in a different sub-region of Montreal than they live nearly double their average trip distance.

In the current study, tour distance addresses this aspect of the built environment. Tour distance is often thought of as a cost variable considered by the trip taker, but can also be seen as a measure of the trip length necessary to complete daily tasks of the survey respondent. Survey respondents with employment, shopping, and recreational opportunities closer to their residence will necessarily make shorter trips than those with goods and services located farther away. This variable was shown to be highly significant and had a negative impact on non-motorized modes in Chapter 1 results, and a negative impact on non-auto modes in Chapter 2. Zoning may prohibit the location of commercial uses within close enough proximity to encourage walking or biking over driving. In addition, employment density is shown in Chapter 1 to provide a significant but very small effect in encouraging transit usage. This provides support for previous research findings that proximity to goods, services, and employment is a key determinant in the choice to use non-auto modes of transportation (Ewing and Cervero, 2010).

3.6.5 Distance to Transit. Distance to transit is simply the distance to either bus or train stops by either straight line or network distance. The current study employs number of train and bus stops, and miles of bus and train routes within the respective distance bands from residences. This gives a more fine grained level of detail on not only the accessibility of transit, but also the level of transit service that is provided from a particular location. More miles of transit routes indicate greater accessibility to more locations and a higher level of service. Chapter 1 results indicate that number of transit stops was not statistically significant in predicting transit usage and was excluded from the final model; however, miles of both bus and train lines was statistically significant, indicating that a higher level of transit service is a strong predictor of propensity to use transit. In addition, while not a transit specific variable, miles of bike lanes was a strong predictor of the propensity to bike, indicating that access to bike specific infrastructure can increase bike usage. Chapter 2 results indicate that both mileage of transit routes and bus stops increase propensity for non-auto transportation, supporting the findings of Pinjari et al. (2011).

## 3.7 MULTI-MODAL TRANSPORTATION AND ZONING

One attempt to alleviate the problems associated with increasing populations and congestion on urban transportation networks has been the provision of multi-modal transportation. Multi-modal transportation focuses on providing travelers opportunities to use multiple modes of transportation to complete daily tasks. An example is park and ride stations that allow passengers to drive to parking lots close to their residences and use transit to complete their commutes to work. The main goal of multi-modal transportation networks is to provide options to travelers that reduce auto dependence and allow convenient switching between walking, biking, transit, and auto.

3.7.1 Walkability. The term walkability generally refers to the attractiveness of walking as a mode of transportation in a given area. It has also come to mean the ability to complete daily tasks of shopping, commuting, and leisure on foot. So what creates a walkable environment? Many studies have looked at what encourages or discourages walking within a specific area. Areas that encourage walking are typically characterized by safety of pedestrians, attractive aesthetics, and close proximity of shops and employment (Cervero, 1995; Glaeser, 2004). These areas are thought to encourage walking by making the time spent during travel on foot more enjoyable. In contrast, non-walkable locations are typically characterized by the lack of sidewalks, close proximity to high velocity auto traffic, and shopping and social locations located far apart where walking between such locations would represent a considerable time burden on travelers (Leslie et al., 2007).

Results from Chapter 1 show that within a quarter to half mile of residences, low and high density residential zoning increases the likelihood of walking trips of survey respondents with statistically significant coefficients in the overall sample and high density residential increases the likelihood of biking. In the urban subsample, low density residential decrease the likelihood of walking. This is inconsistent with the hypothesis that lack of access to shopping within close proximity of residences leads to less walking for the total sample but consistent for the urban subsample.

Low density business zoning decreases the likelihood of walking in the urban subsample, with statistically insignificant effects in the overall and suburban subsample. This result is also inconsistent with theory that close proximity of shopping can have a positive effect on walking propensity. Low density business zoning in the urban area of Denver may also indicate areas that are more oriented toward retail than office space.

High density business zoning was statistically insignificant in all samples. This result may be in line with theory, however it is hard to tell without more detailed analysis of the specific uses occurring in the suburban area of Denver. High density business zoning in suburban areas is more likely to be employment oriented, and may be the reason that high density business zoning does not encourage walking in the suburban sample. If indeed the high density business zoning areas in the suburban area of Denver are office parks, this complies with theory that touts the lack of pedestrian friendly environments in suburban locations such as lack of sidewalks, large parking lots, and long distances between areas of business activity (Cervero, 1995; Pinjari et al., 2009).

Industrial zoning decreases the likelihood of biking in the urban sample, but is statistically insignificant for the suburban subsample and full dataset. This also conforms with theory since land uses in industrial areas are often the most inhospitable to pedestrian use.

Results from Chapter 1 indicate that in the 1/4 to 1/2 mile distance band surrounding survey respondents' residences, low and high density residential zoning increases the propensity to walk in the overall and urban samples, with the suburban subsample coefficient being statistically insignificant. Whether these results comply with theory is hard to determine, but it may be the case that this measure of residential zoning intensity indicates that the respondent lives in a highly residential area with lower density and traffic volumes, and therefore walking is a more appealing form of transportation.

Industrial zoning also increases the likelihood of bike travel, with only the urban sample's coefficient being statistically significant. This is counter to theory which would indicate that presence of industrial decreases propensity to bike.

Results from Chapter 1 indicate that in the 1/2 to 3/4 mile distance band surrounding survey respondents' residences, high density residential decreased the propensity to bike in the urban subsample. Residential medium density zoning decreased the propensity to take transit in the overall sample, and residential low density decreased the propensity to take transit in the urban subsample. Although it is hard to determine the exact meaning of this result, it may comply with theory if it is picking up an effect of highly residential zoning through all three distance bands, in which case the high percentage of residential land use around a survey respondent's home makes the environment for walking more favorable due to access of low traffic residential streets and lower auto traffic volume.

Business high density zoning in this distance band shows a statistically significant negative effect for the overall sample, and a statistically insignificant. It is hard to tell what is causing this effect, however, this distance band is on the upper end of what is considered a walkable distance, and therefore may be a spurious effect.

Results from Chapter 1 indicate that in the 3/4 to 1 mile distance band, residential low density increased the use of transit in the urban subsample. Residential medium density zoning was associated with increased walking for the entire sample. All other residential zoning variables were insignificant. For the urban subsample, this result may indicate that being closer to the urban fringe encourages transit use. For the overall sample, this result is hard to interpret, as medium density residential would be expected to decrease walking for tours that involve accomplishing daily tasks.

Business low density zoning in this ban is associated with increased biking in the urban subsample. This may be indicative of urban residents willingness to bike to close by businesses within one mile of home. Industrial zoning within this band also increased transit usage for the urban subset. This may indicate that transit to areas less than a mile away, particularly if those industrial areas have employment or other commercial uses may be encourage urban residents to take transit.

3.7.2 Bicycling. Bicycling is another integral piece of the multi-modal transportation network. As a non-motorized form of transportation, it has the advantages of not producing pollution, increasing physical activity of those who use it, and alleviating congestion. Just as with walking, one of the major challenges of city planners is to create transportation networks that are hospitable to bicycles, which can increase the usage of bikes as a mode of transportation in urban areas. Many approaches to this exist, from the creation of bike lanes on city streets to separated bicycle and walking lanes that are isolated from automobile traffic all together.

Results from Chapter 1 show very few statistically significant effects of zoning on biking. Of the effects that are statistically significant, in the 0 to 1/4 mile distance band, high density residential zoning increases the propensity to bike in the overall sample. In the urban subsample, industrial zoning in the 0 to 1/4 mile distance decreases propensity to bike, industrial from the 1/4 to 1/2 mile band increases biking, residential high density decreases propensity to bike in the 1/2 to 3/4 mile distance band, and business low density increases the propensity to bike in the 3/4 to 1 mile distance band. In the urban subsample, business low density zoning increases the propensity to bike. The latter result is consistent with theory that increased access to goods and services increases the likelihood of non- motorized transportation modes. However, the effect of industrial zoning in the 1/4 to 1/2 mile distance band is reversed for the urban population, so results are somewhat inconclusive on this effect. In the 3/4 to 1 mile distance band, the only statistically significant effects are increased propensity to bike for the urban samples with increasing low density business zoning. This is consistent with the theory that increased access to shops within 1 mile may lead to increased non-auto travel behavior.

3.7.3 Public Transit. Public transportation is another integral piece of the multi-modal transportation system with the advantages of reducing congestion by transporting more people on a single bus or train, and while not as benign on pollution as the non-motorized forms of transportation, still provides some alleviation of air pollution associated with motorized transportation over autos. While increasing use of non-motorized forms of transportation revolves around creating spaces that are safe and pleasant for pedestrians and bikers, the key to increased pubic transportation usage is access. This means transit stops with convenient locations that allow passengers to access the locations they desire to visit, as well as providing frequency of service that does not drastically increase travel time when compared to other modes of transportation (Biba et al., 2010).

Results from Chapter 1 have very few statistically significant coefficients on the transit mode of transportation. In the overall sample, medium residential zoning was associated with decreased transit usage in the 1/2 to 3/4 mile zoning band. In the urban subsample, low density residential in the 1/2 to 3/4 distance band was associated with decrease transit usage, while low density residential and industrial zoning in the 3/4 to 1 mile distance band was associated with increased transit usage. Due to the low amount of transit trips in the survey, these results may be spurious and do not have any clear interpretation with respect to zoning's impact on transportation mode choice.

3.7.4 Multi-modal Transportation. Multi-modal transportation is the use of at least two of the four transportation modes in conjunction. Particular focus in multi-modal networks is the combination of transit with one of the other modes. Transit-bike and transit-walk transportation are the most congestion relieving of the multi-modal forms of transportation, while auto-transit can also have a significant impact on congestion as well when commuters drive to park-and- ride locations located on the urban fringe and use transit to access the CBD or other more densely populated ares of the city.

Chapter 2 addresses multi-modal forms of transportation by combining the transit, bike, and walk modes into non-auto transportation. Chapter 2 then compares auto with non-auto transportation and explores the impact different zoning makeups around a survey respondent's home with their transportation choices. Similar to results from Chapter 1, many of the coefficients on the zoning variables are statistically insignificant and have small effects. Of particular interest are the results that at least one of the spatial models have negative impacts on the propensity for non-auto transportation for low, medium, and high density residential within the 0 to 1/4 mile distance band. This supports the findings of previous studies that higher amounts of residential are associated with increased auto usage because the prohibit the location of businesses within walking and biking distances of residences, which are shorter than auto and transit distances. In the spatial Durbin model, the negative impact of all three residential zoning densities were the only statistically significant zoning effects other than a positive association of non auto travel with industrial zoning in the 3/4 to 1 mile band. This again supports theory that increases in residential zoning, which necessarily decreases business or industrial zoning and therefore access to goods and services, increases auto usage and decreases other forms of transportation. In several of the other models, the other impacts that were statistically significant were the positive impacts that high density business and industrial zoning in the 3/4 to 1 mile distance band had on non-auto transportation. This again confirms prior studies that access to goods and services in close proximity to residences can increase non-auto travel.

## 3.8 POLICY IMPLICATIONS AND FUTRE RESEARCH

The results of the study as a whole support some of the major findings in the literature connecting the built environment to transportation behavior, while others remain statistically ambiguous. Combining this study with results from previous research, several general themes and issues for city planners emerge as paramount in their quest to shape the evolution of urban spaces into vibrant city spaces that can flourish both economically and socially.

3.8.1 Modeling Considerations. This study employs the use of highly granular dataset and uses both canonical and spatial approaches to modeling the transportation-built environment relationship. Results from Chapter 2 indicate that the use of spatial models may be warranted and should be considered by city planners attempting to understand their own local built environment's effects on transportation behavior. As spatial data on transportation behavior becomes more widely available to city planners, there is an opportunity for using GIS to visually map, explore, and communicate spatial patters of land use and transportation behavior, which may help educate and influence city residents' travel behavior in the future. More research needs to be conducted on optimal modeling constructs for transportation infrastructure planning, and future studies should focus on collection of higher quality, spatially linked data that incorporates travel attitude preference questions into travel survey instruments to help control for the effect of travel preferences on model results. Further research is also needed to help establish directions of causality that have yet to be established by past research programs.

3.8.2 Urban Sprawl Considerations. Urban sprawl is a phenomenon that has been linked to increased auto usage and loss of open space within close proximity to urban cores. City planners should consider the implications of their policies and the unintended sprawl they may create. Urban sprawl increases the difficulty of providing efficient transportation networks to city residents, and should be seen as one of the consequences of density restrictions in urban cores. Additional consideration should be given to the provision of open space, parks, and natural environments close to city centers for residents to recreate. Lower density zoning may be part of the cause for suburban development, which directly competes for untouched rural land. Sprawl may also be a consequence of urban municipalities seeking increased tax revenue by allowing suburban development when population growth in urban areas outpace residential supply growth and drives rents in urban cores to un-affordable levels for sections of the local population. Regional collaboration between suburban and urban municipalities to develop growth strategies that consider transportation infrastructure will be paramount to integrated public services that address many of the problems associated with sprawl and urban expansion.

3.8.3 Social Justice Considerations. Increased demand for urban housing will continue to drive land prices in urban cores upward. Part of the city planner's objective should be to provide affordable housing options so that citizens of all income levels are provided opportunities to reside near urban centers. Several forces drive rents in urban centers, some of which are under the control of policy makers. Zoning represents a supply restriction, and restrictive zoning drives prices of existing real estate in urban cores higher than they may have been by restricting supply. One option available to city planners is to allow denser land uses closer to urban centers, which can help alleviate housing supply shortages. Planners should also consider allowing mixed use and business zonings scattered throughout historically low income neighborhoods to allow greater access to goods, services, and employment via non-motorized transportation. Since auto transportation represents the most expensive form of transportation, planners should consider strategies that increase access as a way to relieve low income households living costs by reducing transportation expenses.

3.8.4 Process Considerations. Zoning represents a restriction on the use of privately owned land. Zoning approval processes that are significantly onerous on developers represent an inefficiency that significantly increases the time to market of development projects. Most of the increased carrying costs of land during development are inevitably passed on to buyers when the project is completed, representing further upward pressure on rents in urban centers. Zoning boards should consider streamlining the approval process of development projects by clearly outlining permissible uses and having expedited approvals for projects that con- form to published standards. Approval processes that include input from local residents once development has commenced should be discouraged in favor of preemptive zoning change approvals of changes to with input from local residents so that the development process can be clearly outlined before future projects are proposed. This will further aid in streamlining the development process which may aid in keeping development costs and therefore eventual rents lower than they otherwise would be under approval processes that allow numerous project slowdowns based on public input.

3.8.5 Path Dependence Considerations. Many municipalities have begun to rewrite zoning codes to allow for more flexible development and redevelopment of urban landscapes. While this is a step in the right direction, planning boards' changes to existing laws are often short-sighted when considering the path dependence of real estate development. Due to the large expense of constructing buildings, planners should consider that new construction will exist for long periods of time, and may limit the ability to change the built environment for future growth. In addition, zoning laws, once in place, are extremely hard to change, as existing residents often oppose density and use changes once they have been codified in city zoning codes. Due to this path dependence, city planners should consider planning urban structures around potential growth on a time horizon that is more closely linked with building life durations, often a century or more. By planning for doubling or more of urban populations over that this time frame, city planners will make better decisions about the level of density allowed, and prevent wasteful redevelopment to accommodate future growth due to construction that was built under restrictive zoning regimes. For example, Denver is currently experiencing rapid population growth that is beyond what was most likely foreseen even a decade ago. In hindsight, space used for medium density residential projects built over the past decade would have been better used for much higher density to accommodate the increased urban population. However, due to the immense expense of constructing these buildings, it will likely be many decades before demand pressure is great enough to warrant reconstructing these spaces to higher density buildings. Due to this lack of foresight, the inevitable result is that more construction happens further from city center, with the corresponding problems of urban sprawl. Therefore, city planners should consider changes to zoning laws that define urban core boundaries and allow essentially unlimited density in these areas. Updates to public sanitation and transportation networks should be designed to accommodate these immense increases in density in the urban core areas. By allowing extreme density in urban cores, city planners may help combat urban sprawl, and thus help preserve access to open spaces close to cities. Often, the densest urban cores are places of vibrant economic and social activity. Vibrancy of extremely high density urban cores can already been seen in cities such as Manhattan and Singapore.

## 3.9 CONCLUSION

The previous two chapters study the relationship between the built environment and transportation behavior. This research can be seen as a first attempt in bridging the gap between two themes in the literature; studies linking land use regulation with increasing city size and congestion, and studies liking transportation behavior with the built environment. Many researchers present both theoretical and empirical evidence that land use restrictions codified in zoning codes leads to urban sprawl and other suboptimal built environment characteristics of urbanized areas over time. Other studies find evidence that the built environment can have a significant impact on travel behavior. The results from this study support earlier findings that lower density residential is associated with higher levels of automobile usage, but that the effect is minimal. The advantages of this study are that the fine level of detail in the zoning data allowed the study of land use restrictions at a more fine grained level than many of the previous studies.

Models covered in this study use data from the Denver metropolitan area. Duplication of this study's results across more cities in the U.S. would provide confidence that the findings of this study are robust to location. This study fails to model the evolution of the urban structure in Denver due to zoning regulations because of data limitations. A fruitful direction for research in this area will be the integrated modeling of land use restrictions with the evolution of urban structure and the evolution of transportation behavior simultaneously. This co-evolution of transportation networks, built environments, and travel preferences is part of a larger endogenous system of choices made by consumers and planning authorities. One of the major challenges will be to find or create data that can address these relationships. More robust models bringing land use restriction- urban sprawl models together with built environment-land use models would provide city planners with better guidance on how to address some of the most important externalities facing modern urban centers.

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APPENDIX A

The utility that each respondent *n* receives from choosing mode *j* is $U_{nj}, j = Auto, Bike, Transit, Walk$. Assuming utility maximization, the respondent chooses mode *i* to satisfy the equation $U_{ni} > U_{nj} \forall j \neq i$. Representative utility is specified as $U_{nj} = V_{nj} + \varepsilon_{nj}$ where $V_{nj}$ is the observable part of utility. Then the probability that decision maker *n* chooses alternative *i* is:

$$P_{ni} = Prob(U_{ni} > U_{nj} \forall j \neq i)$$

$$= Prob(V_{ni} + \varepsilon_{ni} > V_{nj} + \varepsilon_{nj} \forall j \neq i)$$

$$= Prob(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj} \forall j \neq i)$$

Denoting the joint density of the random term ε as $f(\varepsilon_n)$ and $I(\cdot)$ the indicator function equal to 1 if mode *i* is chosen and 0 otherwise, the cumulative probability is then (Train, 2009):

$$P_{ni} = Prob(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj} \forall j \neq i)$$

$$= I(\varepsilon_{nj} - \varepsilon_{ni} < V_{ni} - V_{nj} \forall j \neq i) f(\varepsilon_n) d\varepsilon_n \varepsilon$$

# APPENDIX B

Table B.1 Moran's I and Geary's C Standard Deviate

| Dependent Variable: Non-auto Transportation Mode = 1 | | | | |
|---|---|---|---|---|
| Variable | Moran's I | Moran's I ($d^{-1}$) | Geary's C | Geary's C ($d^{-1}$) |
| HH size | 43.19 | 37.69 | 29.99 | 28.78 |
| HH vehicles | 32.63 | 28.15 | 21.89 | 24.72 |
| HH bicycles | 38.56 | 36.81 | 23.57 | 28.06 |
| Male | 4.18 | 3.07 | 2.83 | 2.29 |
| Age | 18.00 | 17.73 | 13.66 | 16.65 |
| Income | 46.63 | 46.23 | 30.87 | 33.45 |
| College Degree | 42.15 | 36.77 | 27.90 | 26.29 |
| Employed | 5.85 | 7.47 | 4.33 | 6.67 |
| Tour distance | 14.06 | 10.33 | 7.51 | 6.77 |
| Tour crosses highway | 22.51 | 23.14 | 14.49 | 16.11 |
| Miles bike lanes < 1 M. | 516.46 | 429.56 | 351.37 | 318.69 |
| Miles bus routes < 0.5 M. | 391.57 | 363.03 | 267.96 | 267.64 |
| Bus stops < 0.5 M. | 400.32 | 361.64 | 272.10 | 266.57 |
| Rail stops < 0.5 M. | 286.93 | 293.37 | 193.15 | 214.93 |
| Miles rail lines < 1 M. | 423.24 | 375.32 | 290.85 | 281.22 |
| Intersections < 0.5 M. | 282.20 | 271.81 | 204.13 | 213.95 |
| CBG population/sq. mile | 256.67 | 248.56 | 167.85 | 177.82 |
| CBG jobs/sq. mile | 103.34 | 105.14 | 56.14 | 78.66 |
| Work stops | −0.31 | 0.16 | −3.95 | 4.38 |
| Shopping stops | 2.29 | 2.44 | 0.29 | 1.87 |
| Social stops | −0.90 | 0.58 | −3.37 | −0.24 |
| Res. Low Density, 0-1/4 mile | 334.16 | 315.28 | 226.58 | 233.81 |
| Res. Medium Density, 0-1/4 mile | 230.01 | 241.05 | 168.71 | 188.35 |
| Res. High Density 0-1/4 mile | 318.67 | 311.84 | 212.33 | 224.37 |
| Bus. Low Density 0-1/4 mile | 98.03 | 148.02 | 68.76 | 111.48 |
| Bus. High Density 0-1/4 mile | 237.90 | 246.30 | 171.04 | 192.71 |
| Ind. 0-1/4 mile | 161.53 | 165.42 | 132.52 | 153.28 |
| Res. Low Density, 1/4-1/2 mile | 418.15 | 370.23 | 284.17 | 274.49 |
| Res. Medium Density, 1/4-1/2 mile | 395.50 | 349.75 | 278.58 | 267.65 |
| Res. High Density 1/4-1/2 mile | 404.78 | 366.12 | 265.39 | 262.76 |
| Bus. Low Density 1/4-1/2 mile | 211.83 | 214.33 | 133.69 | 155.44 |
| Bus. High Density 1/4-1/2 mile | 319.70 | 305.85 | 224.21 | 233.45 |
| Ind. 1/4-1/2 mile | 284.60 | 273.61 | 227.11 | 230.42 |
| Res. Low Density, 1/2-3/4 mile | 294.56 | 274.59 | 192.68 | 199.38 |
| Res. Medium Density, 1/2-3/4 mile | 220.58 | 231.20 | 162.65 | 177.95 |
| Res. High Density 1/2-3/4 mile | 224.31 | 232.23 | 144.56 | 171.27 |
| Bus. Low Density 1/2-3/4 mile | 272.75 | 256.65 | 173.15 | 183.29 |
| Bus. High Density 1/2-3/4 mile | 174.64 | 188.21 | 109.98 | 146.51 |
| Ind. 1/2-3/4 mile | 225.05 | 230.24 | 167.54 | 187.67 |
| Res. Low Density, 3/4-1 mile | 319.25 | 290.75 | 208.73 | 212.91 |
| Res. Medium Density, 3/4-1 mile | 249.32 | 254.80 | 179.52 | 190.11 |
| Res. High Density 3/4-1 mile | 206.42 | 216.58 | 133.21 | 161.10 |
| Bus. Low Density 3/4-1 mile | 260.20 | 250.91 | 171.58 | 177.84 |
| Bus. High Density 3/4-1 mile | 188.00 | 208.42 | 122.00 | 158.70 |
| Ind. 3/4-1 mile | 249.27 | 251.23 | 180.02 | 198.01 |

Table B.2 Direct Effects: SAR Model, Binary W

Dependent Variable: Non-auto Transportation Mode = 1

| Variable | Lower 95% | Posterior Mean | Upper 95% |
|---|---|---|---|
| HH size | −0.0194 | −0.0103 | −0.0021 |
| HH vehicles | −0.0901 | −0.0722 | −0.0546 |
| HH bicycles | 0.0055 | 0.0102 | 0.0153 |
| Male | 0.0198 | 0.0366 | 0.0540 |
| Age | −0.0035 | −0.0027 | −0.0019 |
| Income | −0.0002 | −0.0000 | 0.0002 |
| College Degree | −0.0087 | 0.0075 | 0.0233 |
| Employed | −0.0365 | −0.0164 | 0.0017 |
| Tour distance | −0.0036 | −0.0025 | −0.0015 |
| Tour crosses highway | −0.1842 | −0.1522 | −0.1178 |
| Miles bike lanes < 1 M. | −0.0050 | −0.0025 | 0.0001 |
| Miles bus routes < 0.5 M. | 0.0015 | 0.0030 | 0.0045 |
| Bus stops < 0.5 M. | 0.0006 | 0.0015 | 0.0025 |
| Rail stops < 0.5 M. | −0.0371 | −0.0223 | −0.0089 |
| Miles rail lines < 1 M. | 0.0062 | 0.0100 | 0.0138 |
| Intersections < 0.5 M. | −0.0003 | −0.0000 | 0.0003 |
| CBG population/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| CBG jobs/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| Work stops | −0.0016 | 0.0078 | 0.0163 |
| Shopping stops | −0.0478 | −0.0361 | −0.0250 |
| Social stops | −0.0383 | −0.0201 | −0.0037 |
| Res. Low Density, 0-1/4 mile | −0.0035 | −0.0020 | −0.0007 |
| Res. Medium Density, 0-1/4 mile | −0.0034 | −0.0019 | −0.0005 |
| Res. High Density 0-1/4 mile | −0.0036 | −0.0022 | −0.0009 |
| Bus. Low Density 0-1/4 mile | −0.0015 | 0.0012 | 0.0040 |
| Bus. High Density 0-1/4 mile | −0.0023 | −0.0009 | 0.0004 |
| Ind. 0-1/4 mile | −0.0037 | −0.0017 | 0.0002 |
| Res. Low Density, 1/4-1/2 mile | 0.0014 | 0.0033 | 0.0053 |
| Res. Medium Density, 1/4-1/2 mile | 0.0012 | 0.0031 | 0.0052 |
| Res. High Density 1/4-1/2 mile | 0.0020 | 0.0038 | 0.0058 |
| Bus. Low Density 1/4-1/2 mile | −0.0053 | −0.0008 | 0.0037 |
| Bus. High Density 1/4-1/2 mile | −0.0012 | 0.0008 | 0.0027 |
| Ind. 1/4-1/2 mile | 0.0003 | 0.0025 | 0.0047 |
| Res. Low Density, 1/2-3/4 mile | −0.0077 | −0.0036 | 0.0004 |
| Res. Medium Density, 1/2-3/4 mile | −0.0089 | −0.0045 | −0.0005 |
| Res. High Density 1/2-3/4 mile | −0.0084 | −0.0041 | 0.0001 |
| Bus. Low Density 1/2-3/4 mile | −0.0173 | −0.0055 | 0.0061 |
| Bus. High Density 1/2-3/4 mile | −0.0077 | −0.0032 | 0.0009 |
| Ind. 1/2-3/4 mile | −0.0080 | −0.0038 | 0.0001 |
| Res. Low Density, 3/4-1 mile | −0.0006 | 0.0033 | 0.0075 |
| Res. Medium Density, 3/4-1 mile | 0.0009 | 0.0060 | 0.0110 |
| Res. High Density 3/4-1 mile | −0.0041 | 0.0003 | 0.0051 |
| Bus. Low Density 3/4-1 mile | −0.0179 | −0.0062 | 0.0055 |
| Bus. High Density 3/4-1 mile | 0.0024 | 0.0070 | 0.0118 |
| Ind. 3/4-1 mile | 0.0002 | 0.0041 | 0.0083 |

Table B.3: Indirect Effects: SAR Model, Binary W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Lower 95% | Posterior Mean | Upper 95% |
| HH size | −0.0078 | −0.0028 | 0.0005 |
| HH vehicles | −0.0441 | −0.0191 | 0.0033 |
| HH bicycles | −0.0005 | 0.0027 | 0.0067 |
| Male | −0.0017 | 0.0097 | 0.0239 |
| Age | −0.0016 | −0.0007 | 0.0001 |
| Income | −0.0001 | −0.0000 | 0.0001 |
| College Degree | −0.0027 | 0.0020 | 0.0083 |
| Employed | −0.0133 | −0.0043 | 0.0015 |
| Tour distance | −0.0016 | −0.0007 | 0.0001 |
| Tour crosses highway | −0.0928 | −0.0403 | 0.0069 |
| Miles bike lanes < 1 M. | −0.0021 | −0.0007 | 0.0001 |
| Miles bus routes < 0.5 M. | −0.0001 | 0.0008 | 0.0021 |
| Bus stops < 0.5 M. | −0.0001 | 0.0004 | 0.0010 |
| Rail stops < 0.5 M. | −0.0150 | −0.0059 | 0.0009 |
| Miles rail lines < 1 M. | −0.0005 | 0.0026 | 0.0062 |
| Intersections < 0.5 M. | −0.0001 | 0.0000 | 0.0001 |
| CBG population/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| CBG jobs/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| Work stops | −0.0007 | 0.0021 | 0.0064 |
| Shopping stops | −0.0226 | −0.0097 | 0.0017 |
| Social stops | −0.0147 | −0.0052 | 0.0011 |
| Res. Low Density, 0-1/4 mile | −0.0014 | −0.0005 | 0.0001 |
| Res. Medium Density, 0-1/4 mile | −0.0014 | −0.0005 | 0.0001 |
| Res. High Density 0-1/4 mile | −0.0015 | −0.0006 | 0.0001 |
| Bus. Low Density 0-1/4 mile | −0.0004 | 0.0003 | 0.0014 |
| Bus. High Density 0-1/4 mile | −0.0009 | −0.0002 | 0.0001 |
| Ind. 0-1/4 mile | −0.0014 | −0.0004 | 0.0001 |
| Res. Low Density, 1/4-1/2 mile | −0.0001 | 0.0009 | 0.0023 |
| Res. Medium Density, 1/4-1/2 mile | −0.0001 | 0.0008 | 0.0023 |
| Res. High Density 1/4-1/2 mile | −0.0002 | 0.0010 | 0.0025 |
| Bus. Low Density 1/4-1/2 mile | −0.0017 | −0.0002 | 0.0010 |
| Bus. High Density 1/4-1/2 mile | −0.0003 | 0.0002 | 0.0010 |
| Ind. 1/4-1/2 mile | −0.0001 | 0.0007 | 0.0020 |
| Res. Low Density, 1/2-3/4 mile | −0.0030 | −0.0010 | 0.0003 |
| Res. Medium Density, 1/2-3/4 mile | −0.0036 | −0.0012 | 0.0003 |
| Res. High Density 1/2-3/4 mile | −0.0033 | −0.0011 | 0.0003 |
| Bus. Low Density 1/2-3/4 mile | −0.0060 | −0.0014 | 0.0019 |
| Bus. High Density 1/2-3/4 mile | −0.0030 | −0.0009 | 0.0003 |
| Ind. 1/2-3/4 mile | −0.0031 | −0.0010 | 0.0002 |
| Res. Low Density, 3/4-1 mile | −0.0003 | 0.0009 | 0.0030 |
| Res. Medium Density, 3/4-1 mile | −0.0003 | 0.0016 | 0.0045 |
| Res. High Density 3/4-1 mile | −0.0012 | 0.0001 | 0.0017 |
| Bus. Low Density 3/4-1 mile | −0.0066 | −0.0016 | 0.0016 |
| Bus. High Density 3/4-1 mile | −0.0003 | 0.0018 | 0.0050 |
| Ind. 3/4-1 mile | −0.0002 | 0.0011 | 0.0033 |

Table B.4: Total Effects: SAR Model, Binary W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Lower 95% | Posterior Mean | Upper 95% |
| HH size | −0.0248 | −0.0130 | −0.0027 |
| HH vehicles | −0.1224 | −0.0912 | −0.0650 |
| HH bicycles | 0.0069 | 0.0129 | 0.0203 |
| Male | 0.0256 | 0.0463 | 0.0707 |
| Age | −0.0046 | −0.0034 | −0.0023 |
| Income | −0.0002 | −0.0000 | 0.0002 |
| College Degree | −0.0112 | 0.0094 | 0.0307 |
| Employed | −0.0460 | −0.0207 | 0.0022 |
| Tour distance | −0.0046 | −0.0032 | −0.0018 |
| Tour crosses highway | −0.2538 | −0.1925 | −0.1432 |
| Miles bike lanes < 1 M. | −0.0069 | −0.0032 | 0.0001 |
| Miles bus routes < 0.5 M. | 0.0018 | 0.0038 | 0.0058 |
| Bus stops < 0.5 M. | 0.0008 | 0.0019 | 0.0031 |
| Rail stops < 0.5 M. | −0.0471 | −0.0282 | −0.0114 |
| Miles rail lines < 1 M. | 0.0080 | 0.0125 | 0.0179 |
| Intersections < 0.5 M. | −0.0004 | −0.0000 | 0.0004 |
| CBG population/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| CBG jobs/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| Work stops | −0.0020 | 0.0099 | 0.0210 |
| Shopping stops | −0.0655 | −0.0458 | −0.0294 |
| Social stops | −0.0477 | −0.0253 | −0.0048 |
| Res. Low Density, 0-1/4 mile | −0.0044 | −0.0026 | −0.0009 |
| Res. Medium Density, 0-1/4 mile | −0.0043 | −0.0024 | −0.0006 |
| Res. High Density 0-1/4 mile | −0.0048 | −0.0028 | −0.0011 |
| Bus. Low Density 0-1/4 mile | −0.0018 | 0.0015 | 0.0050 |
| Bus. High Density 0-1/4 mile | −0.0029 | −0.0012 | 0.0004 |
| Ind. 0-1/4 mile | −0.0048 | −0.0021 | 0.0003 |
| Res. Low Density, 1/4-1/2 mile | 0.0018 | 0.0042 | 0.0069 |
| Res. Medium Density, 1/4-1/2 mile | 0.0015 | 0.0039 | 0.0067 |
| Res. High Density 1/4-1/2 mile | 0.0024 | 0.0048 | 0.0076 |
| Bus. Low Density 1/4-1/2 mile | −0.0065 | −0.0010 | 0.0044 |
| Bus. High Density 1/4-1/2 mile | −0.0015 | 0.0010 | 0.0034 |
| Ind. 1/4-1/2 mile | 0.0004 | 0.0031 | 0.0062 |
| Res. Low Density, 1/2-3/4 mile | −0.0102 | −0.0046 | 0.0005 |
| Res. Medium Density, 1/2-3/4 mile | −0.0117 | −0.0058 | −0.0006 |
| Res. High Density 1/2-3/4 mile | −0.0112 | −0.0052 | 0.0001 |
| Bus. Low Density 1/2-3/4 mile | −0.0217 | −0.0068 | 0.0076 |
| Bus. High Density 1/2-3/4 mile | −0.0102 | −0.0040 | 0.0012 |
| Ind. 1/2-3/4 mile | −0.0104 | −0.0048 | 0.0001 |
| Res. Low Density, 3/4-1 mile | −0.0008 | 0.0043 | 0.0097 |
| Res. Medium Density, 3/4-1 mile | 0.0012 | 0.0076 | 0.0147 |
| Res. High Density 3/4-1 mile | −0.0052 | 0.0004 | 0.0064 |
| Bus. Low Density 3/4-1 mile | −0.0228 | −0.0078 | 0.0067 |
| Bus. High Density 3/4-1 mile | 0.0032 | 0.0088 | 0.0157 |
| Ind. 3/4-1 mile | 0.0002 | 0.0052 | 0.0109 |

Table B.5: Direct Effects: SAR Model, Inverse Distance W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Lower 95% | Posterior Mean | Upper 95% |
| HH size | −0.0191 | −0.0103 | −0.0023 |
| HH vehicles | −0.0843 | −0.0723 | −0.0600 |
| HH bicycles | 0.0058 | 0.0103 | 0.0149 |
| Male | 0.0214 | 0.0364 | 0.0516 |
| Age | −0.0033 | −0.0027 | −0.0021 |
| Income | −0.0002 | −0.0000 | 0.0002 |
| College Degree | −0.0077 | 0.0086 | 0.0247 |
| Employed | −0.0354 | −0.0166 | 0.0018 |
| Tour distance | −0.0035 | −0.0026 | −0.0016 |
| Tour crosses highway | −0.1732 | −0.1533 | −0.1337 |
| Miles bike lanes < 1 M. | −0.0045 | −0.0020 | 0.0006 |
| Miles bus routes < 0.5 M. | 0.0015 | 0.0029 | 0.0043 |
| Bus stops < 0.5 M. | 0.0008 | 0.0017 | 0.0026 |
| Rail stops < 0.5 M. | −0.0364 | −0.0229 | −0.0093 |
| Miles rail lines < 1 M. | 0.0069 | 0.0105 | 0.0140 |
| Intersections < 0.5 M. | −0.0003 | −0.0000 | 0.0003 |
| CBG population/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| CBG jobs/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| Work stops | −0.0014 | 0.0079 | 0.0161 |
| Shopping stops | −0.0464 | −0.0364 | −0.0263 |
| Social stops | −0.0373 | −0.0205 | −0.0041 |
| Res. Low Density, 0-1/4 mile | −0.0032 | −0.0019 | −0.0006 |
| Res. Medium Density, 0-1/4 mile | −0.0032 | −0.0018 | −0.0005 |
| Res. High Density 0-1/4 mile | −0.0034 | −0.0021 | −0.0008 |
| Bus. Low Density 0-1/4 mile | −0.0013 | 0.0012 | 0.0039 |
| Bus. High Density 0-1/4 mile | −0.0021 | −0.0008 | 0.0005 |
| Ind. 0-1/4 mile | −0.0035 | −0.0016 | 0.0003 |
| Res. Low Density, 1/4-1/2 mile | 0.0012 | 0.0030 | 0.0049 |
| Res. Medium Density, 1/4-1/2 mile | 0.0009 | 0.0027 | 0.0048 |
| Res. High Density 1/4-1/2 mile | 0.0019 | 0.0036 | 0.0055 |
| Bus. Low Density 1/4-1/2 mile | −0.0054 | −0.0011 | 0.0034 |
| Bus. High Density 1/4-1/2 mile | −0.0015 | 0.0005 | 0.0024 |
| Ind. 1/4-1/2 mile | 0.0002 | 0.0023 | 0.0044 |
| Res. Low Density, 1/2-3/4 mile | −0.0071 | −0.0033 | 0.0006 |
| Res. Medium Density, 1/2-3/4 mile | −0.0082 | −0.0042 | −0.0002 |
| Res. High Density 1/2-3/4 mile | −0.0080 | −0.0039 | 0.0004 |
| Bus. Low Density 1/2-3/4 mile | −0.0171 | −0.0053 | 0.0065 |
| Bus. High Density 1/2-3/4 mile | −0.0073 | −0.0029 | 0.0011 |
| Ind. 1/2-3/4 mile | −0.0073 | −0.0035 | 0.0003 |
| Res. Low Density, 3/4-1 mile | −0.0009 | 0.0030 | 0.0069 |
| Res. Medium Density, 3/4-1 mile | 0.0007 | 0.0057 | 0.0106 |
| Res. High Density 3/4-1 mile | −0.0044 | 0.0001 | 0.0049 |
| Bus. Low Density 3/4-1 mile | −0.0180 | −0.0062 | 0.0053 |
| Bus. High Density 3/4-1 mile | 0.0025 | 0.0067 | 0.0113 |
| Ind. 3/4-1 mile | 0.0001 | 0.0039 | 0.0079 |

Table B.6: Indirect Effects: SAR Model, Inverse Distance W

Dependent Variable: Non-auto Transportation Mode = 1

| Variable | Lower 95% | Posterior Mean | Upper 95% |
|---|---|---|---|
| HH size | −0.0029 | −0.0008 | 0.0006 |
| HH vehicles | −0.0164 | −0.0058 | 0.0041 |
| HH bicycles | −0.0005 | 0.0008 | 0.0025 |
| Male | −0.0018 | 0.0029 | 0.0083 |
| Age | −0.0006 | −0.0002 | 0.0002 |
| Income | −0.0000 | −0.0000 | 0.0000 |
| College Degree | −0.0010 | 0.0007 | 0.0033 |
| Employed | −0.0052 | −0.0014 | 0.0008 |
| Tour distance | −0.0006 | −0.0002 | 0.0001 |
| Tour crosses highway | −0.0355 | −0.0122 | 0.0086 |
| Miles bike lanes < 1 M. | −0.0006 | −0.0002 | 0.0001 |
| Miles bus routes < 0.5 M. | −0.0002 | 0.0002 | 0.0007 |
| Bus stops < 0.5 M. | −0.0001 | 0.0001 | 0.0004 |
| Rail stops < 0.5 M. | −0.0053 | −0.0018 | 0.0013 |
| Miles rail lines < 1 M. | −0.0006 | 0.0008 | 0.0024 |
| Intersections < 0.5 M. | −0.0000 | −0.0000 | 0.0000 |
| CBG population/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| CBG jobs/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| Work stops | −0.0005 | 0.0006 | 0.0023 |
| Shopping stops | −0.0085 | −0.0030 | 0.0020 |
| Social stops | −0.0054 | −0.0016 | 0.0011 |
| Res. Low Density, 0-1/4 mile | −0.0005 | −0.0001 | 0.0001 |
| Res. Medium Density, 0-1/4 mile | −0.0005 | −0.0001 | 0.0001 |
| Res. High Density 0-1/4 mile | −0.0005 | −0.0002 | 0.0001 |
| Bus. Low Density 0-1/4 mile | −0.0001 | 0.0001 | 0.0005 |
| Bus. High Density 0-1/4 mile | −0.0003 | −0.0001 | 0.0001 |
| Ind. 0-1/4 mile | −0.0004 | −0.0001 | 0.0001 |
| Res. Low Density, 1/4-1/2 mile | −0.0002 | 0.0002 | 0.0008 |
| Res. Medium Density, 1/4-1/2 mile | −0.0002 | 0.0002 | 0.0007 |
| Res. High Density 1/4-1/2 mile | −0.0002 | 0.0003 | 0.0009 |
| Bus. Low Density 1/4-1/2 mile | −0.0007 | −0.0001 | 0.0003 |
| Bus. High Density 1/4-1/2 mile | −0.0001 | 0.0000 | 0.0003 |
| Ind. 1/4-1/2 mile | −0.0002 | 0.0002 | 0.0007 |
| Res. Low Density, 1/2-3/4 mile | −0.0010 | −0.0003 | 0.0002 |
| Res. Medium Density, 1/2-3/4 mile | −0.0012 | −0.0003 | 0.0003 |
| Res. High Density 1/2-3/4 mile | −0.0012 | −0.0003 | 0.0002 |
| Bus. Low Density 1/2-3/4 mile | −0.0022 | −0.0004 | 0.0007 |
| Bus. High Density 1/2-3/4 mile | −0.0010 | −0.0002 | 0.0002 |
| Ind. 1/2-3/4 mile | −0.0011 | −0.0003 | 0.0002 |
| Res. Low Density, 3/4-1 mile | −0.0002 | 0.0002 | 0.0010 |
| Res. Medium Density, 3/4-1 mile | −0.0003 | 0.0004 | 0.0016 |
| Res. High Density 3/4-1 mile | −0.0005 | −0.0000 | 0.0005 |
| Bus. Low Density 3/4-1 mile | −0.0020 | −0.0004 | 0.0008 |
| Bus. High Density 3/4-1 mile | −0.0004 | 0.0005 | 0.0017 |
| Ind. 3/4-1 mile | −0.0002 | 0.0003 | 0.0012 |

Table B.7: Total Effects: SAR Model, Inverse Distance W

Dependent Variable: Non-auto Transportation Mode = 1

| Variable | Lower 95% | Posterior Mean | Upper 95% |
|---|---|---|---|
| HH size | −0.0207 | −0.0111 | −0.0023 |
| HH vehicles | −0.0932 | −0.0781 | −0.0635 |
| HH bicycles | 0.0062 | 0.0111 | 0.0163 |
| Male | 0.0226 | 0.0392 | 0.0570 |
| Age | −0.0036 | −0.0029 | −0.0022 |
| Income | −0.0002 | −0.0000 | 0.0002 |
| College Degree | −0.0080 | 0.0093 | 0.0270 |
| Employed | −0.0389 | −0.0180 | 0.0019 |
| Tour distance | −0.0037 | −0.0028 | −0.0017 |
| Tour crosses highway | −0.1954 | −0.1655 | −0.1388 |
| Miles bike lanes < 1 M. | −0.0048 | −0.0021 | 0.0006 |
| Miles bus routes < 0.5 M. | 0.0016 | 0.0031 | 0.0046 |
| Bus stops < 0.5 M. | 0.0008 | 0.0018 | 0.0028 |
| Rail stops < 0.5 M. | −0.0390 | −0.0247 | −0.0102 |
| Miles rail lines < 1 M. | 0.0074 | 0.0113 | 0.0152 |
| Intersections < 0.5 M. | −0.0004 | −0.0000 | 0.0003 |
| CBG population/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| CBG jobs/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| Work stops | −0.0017 | 0.0085 | 0.0172 |
| Shopping stops | −0.0510 | −0.0394 | −0.0279 |
| Social stops | −0.0403 | −0.0221 | −0.0046 |
| Res. Low Density, 0-1/4 mile | −0.0034 | −0.0020 | −0.0007 |
| Res. Medium Density, 0-1/4 mile | −0.0034 | −0.0019 | −0.0005 |
| Res. High Density 0-1/4 mile | −0.0037 | −0.0023 | −0.0009 |
| Bus. Low Density 0-1/4 mile | −0.0014 | 0.0013 | 0.0043 |
| Bus. High Density 0-1/4 mile | −0.0023 | −0.0009 | 0.0005 |
| Ind. 0-1/4 mile | −0.0037 | −0.0017 | 0.0003 |
| Res. Low Density, 1/4-1/2 mile | 0.0013 | 0.0033 | 0.0052 |
| Res. Medium Density, 1/4-1/2 mile | 0.0010 | 0.0030 | 0.0050 |
| Res. High Density 1/4-1/2 mile | 0.0020 | 0.0039 | 0.0059 |
| Bus. Low Density 1/4-1/2 mile | −0.0059 | −0.0012 | 0.0036 |
| Bus. High Density 1/4-1/2 mile | −0.0016 | 0.0006 | 0.0026 |
| Ind. 1/4-1/2 mile | 0.0002 | 0.0025 | 0.0048 |
| Res. Low Density, 1/2-3/4 mile | −0.0077 | −0.0035 | 0.0006 |
| Res. Medium Density, 1/2-3/4 mile | −0.0089 | −0.0045 | −0.0002 |
| Res. High Density 1/2-3/4 mile | −0.0087 | −0.0042 | 0.0004 |
| Bus. Low Density 1/2-3/4 mile | −0.0183 | −0.0057 | 0.0068 |
| Bus. High Density 1/2-3/4 mile | −0.0078 | −0.0031 | 0.0012 |
| Ind. 1/2-3/4 mile | −0.0082 | −0.0038 | 0.0003 |
| Res. Low Density, 3/4-1 mile | −0.0009 | 0.0032 | 0.0075 |
| Res. Medium Density, 3/4-1 mile | 0.0008 | 0.0061 | 0.0115 |
| Res. High Density 3/4-1 mile | −0.0046 | 0.0001 | 0.0052 |
| Bus. Low Density 3/4-1 mile | −0.0193 | −0.0066 | 0.0060 |
| Bus. High Density 3/4-1 mile | 0.0027 | 0.0072 | 0.0121 |
| Ind. 3/4-1 mile | 0.0001 | 0.0043 | 0.0087 |

Table B.8: Direct Effects: SDM Model, Binary W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Lower 95% | Posterior Mean | Upper 95% |
| HH size | −0.0216 | −0.0129 | −0.0045 |
| HH vehicles | −0.0825 | −0.0694 | −0.0569 |
| HH bicycles | 0.0054 | 0.0103 | 0.0155 |
| Male | 0.0181 | 0.0341 | 0.0502 |
| Age | −0.0033 | −0.0027 | −0.0021 |
| Income | −0.0002 | −0.0000 | 0.0002 |
| College Degree | −0.0102 | 0.0070 | 0.0253 |
| Employed | −0.0352 | −0.0176 | 0.0008 |
| Tour distance | −0.0032 | −0.0024 | −0.0016 |
| Tour crosses highway | −0.1800 | −0.1573 | −0.1338 |
| Miles bike lanes < 1 M. | −0.0098 | −0.0030 | 0.0036 |
| Miles bus routes < 0.5 M. | 0.0001 | 0.0021 | 0.0040 |
| Bus stops < 0.5 M. | 0.0004 | 0.0018 | 0.0031 |
| Rail stops < 0.5 M. | −0.0279 | −0.0116 | 0.0054 |
| Miles rail lines < 1 M. | −0.0014 | 0.0068 | 0.0150 |
| Intersections < 0.5 M. | −0.0005 | −0.0001 | 0.0003 |
| CBG population/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| CBG jobs/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| Work stops | 0.0011 | 0.0086 | 0.0163 |
| Shopping stops | −0.0475 | −0.0372 | −0.0276 |
| Social stops | −0.0414 | −0.0248 | −0.0074 |
| Res. Low Density, 0-1/4 mile | −0.0039 | −0.0026 | −0.0012 |
| Res. Medium Density, 0-1/4 mile | −0.0038 | −0.0023 | −0.0009 |
| Res. High Density 0-1/4 mile | −0.0036 | −0.0021 | −0.0007 |
| Bus. Low Density 0-1/4 mile | −0.0028 | −0.0000 | 0.0028 |
| Bus. High Density 0-1/4 mile | −0.0026 | −0.0012 | 0.0002 |
| Ind. 0-1/4 mile | −0.0036 | −0.0016 | 0.0005 |
| Res. Low Density, 1/4-1/2 mile | 0.0005 | 0.0034 | 0.0063 |
| Res. Medium Density, 1/4-1/2 mile | 0.0003 | 0.0030 | 0.0060 |
| Res. High Density 1/4-1/2 mile | −0.0002 | 0.0026 | 0.0057 |
| Bus. Low Density 1/4-1/2 mile | −0.0083 | −0.0026 | 0.0029 |
| Bus. High Density 1/4-1/2 mile | −0.0018 | 0.0010 | 0.0039 |
| Ind. 1/4-1/2 mile | −0.0018 | 0.0016 | 0.0053 |
| Res. Low Density, 1/2-3/4 mile | −0.0082 | −0.0039 | 0.0004 |
| Res. Medium Density, 1/2-3/4 mile | −0.0110 | −0.0063 | −0.0017 |
| Res. High Density 1/2-3/4 mile | −0.0085 | −0.0041 | 0.0005 |
| Bus. Low Density 1/2-3/4 mile | −0.0216 | −0.0090 | 0.0039 |
| Bus. High Density 1/2-3/4 mile | −0.0080 | −0.0034 | 0.0014 |
| Ind. 1/2-3/4 mile | −0.0072 | −0.0027 | 0.0017 |
| Res. Low Density, 3/4-1 mile | 0.0002 | 0.0045 | 0.0090 |
| Res. Medium Density, 3/4-1 mile | 0.0014 | 0.0064 | 0.0116 |
| Res. High Density 3/4-1 mile | −0.0061 | −0.0009 | 0.0041 |
| Bus. Low Density 3/4-1 mile | −0.0242 | −0.0105 | 0.0038 |
| Bus. High Density 3/4-1 mile | 0.0038 | 0.0089 | 0.0136 |
| Ind. 3/4-1 mile | −0.0013 | 0.0029 | 0.0073 |
| (W)HH size | −0.1888 | −0.0884 | 0.0191 |
| (W)HH vehicles | −0.1100 | 0.0053 | 0.1235 |
| (W)HH bicycles | −0.1113 | −0.0455 | 0.0151 |
| (W)Male | −0.2829 | 0.0376 | 0.3509 |
| (W)Age | −0.0125 | −0.0047 | 0.0035 |
| (W)Income | −0.0019 | 0.0005 | 0.0027 |
| (W)College Degree | −0.1406 | 0.1022 | 0.3818 |
| (W)Employed | −0.2344 | 0.0480 | 0.3315 |
| (W)Tour distance | −0.0177 | −0.0059 | 0.0053 |
| (W)Tour crosses highway | −0.0915 | 0.0816 | 0.2757 |
| (W)Miles bike lanes < 1 M. | −0.0237 | −0.0114 | 0.0003 |
| (W)Miles bus routes < 0.5 M. | 0.0019 | 0.0110 | 0.0205 |
| (W)Bus stops < 0.5 M. | −0.0063 | −0.0021 | 0.0023 |
| (W)Rail stops < 0.5 M. | −0.0607 | 0.0159 | 0.0880 |
| (W)Miles rail lines < 1 M. | −0.0120 | 0.0051 | 0.0218 |
| (W)Intersections < 0.5 M. | −0.0007 | 0.0005 | 0.0018 |
| (W)CBG population/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| (W)CBG jobs/sq. mile | −0.0000 | −0.0000 | 0.0000 |
| (W)Work stops | −0.0817 | 0.0633 | 0.2090 |

| Variable | Lower 95% | Posterior Mean | Upper 95% |
|---|---|---|---|
| (W)Shopping stops | −0.2187 | −0.0785 | 0.0509 |
| (W)Social stops | −0.3913 | −0.1329 | 0.1230 |
| (W)Res. Low Density, 0-1/4 mile | −0.0152 | −0.0060 | 0.0027 |
| (W)Res. Medium Density, 0-1/4 mile | −0.0096 | 0.0011 | 0.0121 |
| (W)Res. High Density 0-1/4 mile | −0.0057 | 0.0034 | 0.0132 |
| (W)Bus. Low Density 0-1/4 mile | −0.0186 | 0.0051 | 0.0284 |
| (W)Bus. High Density 0-1/4 mile | −0.0150 | −0.0036 | 0.0078 |
| (W)Ind. 0-1/4 mile | 0.0000 | 0.0189 | 0.0369 |
| (W)Res. Low Density, 1/4-1/2 mile | −0.0005 | 0.0094 | 0.0194 |
| (W)Res. Medium Density, 1/4-1/2 mile | −0.0115 | 0.0020 | 0.0140 |
| (W)Res. High Density 1/4-1/2 mile | −0.0105 | 0.0010 | 0.0122 |
| (W)Bus. Low Density 1/4-1/2 mile | −0.0119 | 0.0173 | 0.0459 |
| (W)Bus. High Density 1/4-1/2 mile | −0.0077 | 0.0049 | 0.0170 |
| (W)Ind. 1/4-1/2 mile | −0.0240 | −0.0062 | 0.0128 |
| (W)Res. Low Density, 1/2-3/4 mile | −0.0957 | −0.0648 | −0.0350 |
| (W)Res. Medium Density, 1/2-3/4 mile | −0.1438 | −0.1065 | −0.0692 |
| (W)Res. High Density 1/2-3/4 mile | −0.0786 | −0.0454 | −0.0134 |
| (W)Bus. Low Density 1/2-3/4 mile | −0.2145 | −0.1183 | −0.0265 |
| (W)Bus. High Density 1/2-3/4 mile | −0.0788 | −0.0473 | −0.0148 |
| (W)Ind. 1/2-3/4 mile | −0.1194 | −0.0833 | −0.0509 |
| (W)Res. Low Density, 3/4-1 mile | 0.0322 | 0.0618 | 0.0926 |
| (W)Res. Medium Density, 3/4-1 mile | 0.0871 | 0.1300 | 0.1720 |
| (W)Res. High Density 3/4-1 mile | −0.0036 | 0.0322 | 0.0695 |
| (W)Bus. Low Density 3/4-1 mile | −0.0004 | 0.0992 | 0.2000 |
| (W)Bus. High Density 3/4-1 mile | 0.0136 | 0.0502 | 0.0857 |
| (W)Ind. 3/4-1 mile | 0.0525 | 0.0844 | 0.1164 |

Table B.9: Indirect Effects: SDM Model, Binary W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Lower 95% | Posterior Mean | Upper 95% |
| HH size | 0.0021 | 0.0060 | 0.0103 |
| HH vehicles | 0.0239 | 0.0326 | 0.0405 |
| HH bicycles | −0.0075 | −0.0049 | −0.0024 |
| Male | −0.0245 | −0.0160 | −0.0079 |
| Age | 0.0009 | 0.0013 | 0.0016 |
| Income | −0.0001 | 0.0000 | 0.0001 |
| College Degree | −0.0122 | −0.0033 | 0.0047 |
| Employed | −0.0003 | 0.0083 | 0.0164 |
| Tour distance | 0.0007 | 0.0011 | 0.0016 |
| Tour crosses highway | 0.0551 | 0.0740 | 0.0886 |
| Miles bike lanes < 1 M. | −0.0017 | 0.0014 | 0.0046 |
| Miles bus routes < 0.5 M. | −0.0019 | −0.0010 | −0.0000 |
| Bus stops < 0.5 M. | −0.0015 | −0.0008 | −0.0002 |
| Rail stops < 0.5 M. | −0.0024 | 0.0055 | 0.0134 |
| Miles rail lines < 1 M. | −0.0073 | −0.0032 | 0.0006 |
| Intersections < 0.5 M. | −0.0001 | 0.0001 | 0.0003 |
| CBG population/sq. mile | −0.0000 | −0.0000 | 0.0000 |
| CBG jobs/sq. mile | −0.0000 | −0.0000 | 0.0000 |
| Work stops | −0.0078 | −0.0040 | −0.0006 |
| Shopping stops | 0.0120 | 0.0175 | 0.0228 |
| Social stops | 0.0035 | 0.0117 | 0.0200 |
| Res. Low Density, 0-1/4 mile | 0.0005 | 0.0012 | 0.0019 |
| Res. Medium Density, 0-1/4 mile | 0.0004 | 0.0011 | 0.0018 |
| Res. High Density 0-1/4 mile | 0.0003 | 0.0010 | 0.0017 |
| Bus. Low Density 0-1/4 mile | −0.0013 | 0.0000 | 0.0013 |
| Bus. High Density 0-1/4 mile | −0.0001 | 0.0006 | 0.0012 |
| Ind. 0-1/4 mile | −0.0002 | 0.0007 | 0.0017 |
| Res. Low Density, 1/4-1/2 mile | −0.0031 | −0.0016 | −0.0002 |
| Res. Medium Density, 1/4-1/2 mile | −0.0029 | −0.0014 | −0.0002 |
| Res. High Density 1/4-1/2 mile | −0.0027 | −0.0012 | 0.0001 |
| Bus. Low Density 1/4-1/2 mile | −0.0014 | 0.0012 | 0.0039 |
| Bus. High Density 1/4-1/2 mile | −0.0019 | −0.0005 | 0.0009 |
| Ind. 1/4-1/2 mile | −0.0025 | −0.0008 | 0.0009 |
| Res. Low Density, 1/2-3/4 mile | −0.0002 | 0.0018 | 0.0039 |
| Res. Medium Density, 1/2-3/4 mile | 0.0008 | 0.0030 | 0.0052 |
| Res. High Density 1/2-3/4 mile | −0.0002 | 0.0019 | 0.0041 |
| Bus. Low Density 1/2-3/4 mile | −0.0018 | 0.0042 | 0.0102 |
| Bus. High Density 1/2-3/4 mile | −0.0007 | 0.0016 | 0.0038 |
| Ind. 1/2-3/4 mile | −0.0008 | 0.0013 | 0.0034 |
| Res. Low Density, 3/4-1 mile | −0.0043 | −0.0021 | −0.0001 |
| Res. Medium Density, 3/4-1 mile | −0.0056 | −0.0030 | −0.0007 |
| Res. High Density 3/4-1 mile | −0.0020 | 0.0004 | 0.0030 |
| Bus. Low Density 3/4-1 mile | −0.0017 | 0.0049 | 0.0117 |
| Bus. High Density 3/4-1 mile | −0.0065 | −0.0042 | −0.0017 |
| Ind. 3/4-1 mile | −0.0035 | −0.0014 | 0.0006 |
| (W)HH size | −0.0086 | 0.0416 | 0.0906 |
| (W)HH vehicles | −0.0589 | −0.0025 | 0.0526 |
| (W)HH bicycles | −0.0072 | 0.0214 | 0.0536 |
| (W)Male | −0.1654 | −0.0177 | 0.1322 |
| (W)Age | −0.0017 | 0.0022 | 0.0059 |
| (W)Income | −0.0013 | −0.0002 | 0.0009 |
| (W)College Degree | −0.1758 | −0.0478 | 0.0668 |
| (W)Employed | −0.1571 | −0.0230 | 0.1093 |
| (W)Tour distance | −0.0025 | 0.0028 | 0.0085 |
| (W)Tour crosses highway | −0.1297 | −0.0380 | 0.0431 |
| (W)Miles bike lanes < 1 M. | −0.0002 | 0.0053 | 0.0113 |
| (W)Miles bus routes < 0.5 M. | −0.0097 | −0.0052 | −0.0009 |
| (W)Bus stops < 0.5 M. | −0.0010 | 0.0010 | 0.0030 |
| (W)Rail stops < 0.5 M. | −0.0422 | −0.0075 | 0.0285 |
| (W)Miles rail lines < 1 M. | −0.0105 | −0.0024 | 0.0056 |
| (W)Intersections < 0.5 M. | −0.0008 | −0.0002 | 0.0003 |
| (W)CBG population/sq. mile | −0.0000 | −0.0000 | −0.0000 |
| (W)CBG jobs/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| (W)Work stops | −0.0999 | −0.0296 | 0.0399 |

| Variable | Lower 95% | Posterior Mean | Upper 95% |
|---|---|---|---|
| (W)Shopping stops | −0.0233 | 0.0372 | 0.1035 |
| (W)Social stops | −0.0610 | 0.0624 | 0.1861 |
| (W)Res. Low Density, 0-1/4 mile | −0.0013 | 0.0028 | 0.0074 |
| (W)Res. Medium Density, 0-1/4 mile | −0.0058 | −0.0005 | 0.0046 |
| (W)Res. High Density 0-1/4 mile | −0.0062 | −0.0016 | 0.0028 |
| (W)Bus. Low Density 0-1/4 mile | −0.0134 | −0.0024 | 0.0086 |
| (W)Bus. High Density 0-1/4 mile | −0.0037 | 0.0017 | 0.0070 |
| (W)Ind. 0-1/4 mile | −0.0174 | −0.0089 | −0.0000 |
| (W)Res. Low Density, 1/4-1/2 mile | −0.0093 | −0.0044 | 0.0003 |
| (W)Res. Medium Density, 1/4-1/2 mile | −0.0067 | −0.0009 | 0.0054 |
| (W)Res. High Density 1/4-1/2 mile | −0.0058 | −0.0005 | 0.0049 |
| (W)Bus. Low Density 1/4-1/2 mile | −0.0215 | −0.0081 | 0.0059 |
| (W)Bus. High Density 1/4-1/2 mile | −0.0081 | −0.0023 | 0.0037 |
| (W)Ind. 1/4-1/2 mile | −0.0059 | 0.0029 | 0.0114 |
| (W)Res. Low Density, 1/2-3/4 mile | 0.0156 | 0.0304 | 0.0459 |
| (W)Res. Medium Density, 1/2-3/4 mile | 0.0311 | 0.0500 | 0.0694 |
| (W)Res. High Density 1/2-3/4 mile | 0.0058 | 0.0213 | 0.0377 |
| (W)Bus. Low Density 1/2-3/4 mile | 0.0129 | 0.0555 | 0.1036 |
| (W)Bus. High Density 1/2-3/4 mile | 0.0070 | 0.0222 | 0.0386 |
| (W)Ind. 1/2-3/4 mile | 0.0232 | 0.0391 | 0.0575 |
| (W)Res. Low Density, 3/4-1 mile | −0.0447 | −0.0290 | −0.0147 |
| (W)Res. Medium Density, 3/4-1 mile | −0.0829 | −0.0611 | −0.0385 |
| (W)Res. High Density 3/4-1 mile | −0.0332 | −0.0151 | 0.0018 |
| (W)Bus. Low Density 3/4-1 mile | −0.0975 | −0.0466 | 0.0002 |
| (W)Bus. High Density 3/4-1 mile | −0.0410 | −0.0236 | −0.0062 |
| (W)Ind. 3/4-1 mile | −0.0567 | −0.0396 | −0.0240 |

Table B.10: Total Effects: SDM Model, Binary W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Lower 95% | Posterior Mean | Upper 95% |
| HH size | −0.0112 | −0.0068 | −0.0024 |
| HH vehicles | −0.0434 | −0.0368 | −0.0312 |
| HH bicycles | 0.0028 | 0.0055 | 0.0082 |
| Male | 0.0097 | 0.0180 | 0.0267 |
| Age | −0.0018 | −0.0014 | −0.0011 |
| Income | −0.0001 | −0.0000 | 0.0001 |
| College Degree | −0.0058 | 0.0037 | 0.0135 |
| Employed | −0.0185 | −0.0093 | 0.0004 |
| Tour distance | −0.0017 | −0.0013 | −0.0008 |
| Tour crosses highway | −0.0944 | −0.0833 | −0.0730 |
| Miles bike lanes < 1 M. | −0.0052 | −0.0016 | 0.0019 |
| Miles bus routes < 0.5 M. | 0.0001 | 0.0011 | 0.0021 |
| Bus stops < 0.5 M. | 0.0002 | 0.0009 | 0.0017 |
| Rail stops < 0.5 M. | −0.0146 | −0.0061 | 0.0031 |
| Miles rail lines < 1 M. | −0.0007 | 0.0036 | 0.0079 |
| Intersections < 0.5 M. | −0.0003 | −0.0001 | 0.0002 |
| CBG population/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| CBG jobs/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| Work stops | 0.0006 | 0.0046 | 0.0087 |
| Shopping stops | −0.0249 | −0.0197 | −0.0149 |
| Social stops | −0.0220 | −0.0132 | −0.0040 |
| Res. Low Density, 0-1/4 mile | −0.0021 | −0.0014 | −0.0006 |
| Res. Medium Density, 0-1/4 mile | −0.0020 | −0.0012 | −0.0005 |
| Res. High Density 0-1/4 mile | −0.0019 | −0.0011 | −0.0004 |
| Bus. Low Density 0-1/4 mile | −0.0015 | −0.0000 | 0.0015 |
| Bus. High Density 0-1/4 mile | −0.0014 | −0.0006 | 0.0001 |
| Ind. 0-1/4 mile | −0.0020 | −0.0008 | 0.0003 |
| Res. Low Density, 1/4-1/2 mile | 0.0003 | 0.0018 | 0.0034 |
| Res. Medium Density, 1/4-1/2 mile | 0.0002 | 0.0016 | 0.0031 |
| Res. High Density 1/4-1/2 mile | −0.0001 | 0.0014 | 0.0030 |
| Bus. Low Density 1/4-1/2 mile | −0.0044 | −0.0014 | 0.0015 |
| Bus. High Density 1/4-1/2 mile | −0.0010 | 0.0005 | 0.0021 |
| Ind. 1/4-1/2 mile | −0.0010 | 0.0009 | 0.0028 |
| Res. Low Density, 1/2-3/4 mile | −0.0043 | −0.0021 | 0.0002 |
| Res. Medium Density, 1/2-3/4 mile | −0.0059 | −0.0033 | −0.0009 |
| Res. High Density 1/2-3/4 mile | −0.0046 | −0.0022 | 0.0003 |
| Bus. Low Density 1/2-3/4 mile | −0.0111 | −0.0048 | 0.0020 |
| Bus. High Density 1/2-3/4 mile | −0.0041 | −0.0018 | 0.0008 |
| Ind. 1/2-3/4 mile | −0.0038 | −0.0014 | 0.0009 |
| Res. Low Density, 3/4-1 mile | 0.0001 | 0.0024 | 0.0047 |
| Res. Medium Density, 3/4-1 mile | 0.0008 | 0.0034 | 0.0061 |
| Res. High Density 3/4-1 mile | −0.0032 | −0.0005 | 0.0022 |
| Bus. Low Density 3/4-1 mile | −0.0127 | −0.0056 | 0.0021 |
| Bus. High Density 3/4-1 mile | 0.0021 | 0.0047 | 0.0073 |
| Ind. 3/4-1 mile | −0.0007 | 0.0015 | 0.0039 |
| (W)HH size | −0.1024 | −0.0468 | 0.0099 |
| (W)HH vehicles | −0.0574 | 0.0028 | 0.0655 |
| (W)HH bicycles | −0.0593 | −0.0241 | 0.0081 |
| (W)Male | −0.1525 | 0.0199 | 0.1864 |
| (W)Age | −0.0066 | −0.0025 | 0.0019 |
| (W)Income | −0.0010 | 0.0002 | 0.0014 |
| (W)College Degree | −0.0716 | 0.0544 | 0.2032 |
| (W)Employed | −0.1259 | 0.0251 | 0.1710 |
| (W)Tour distance | −0.0094 | −0.0031 | 0.0028 |
| (W)Tour crosses highway | −0.0481 | 0.0436 | 0.1493 |
| (W)Miles bike lanes < 1 M. | −0.0126 | −0.0060 | 0.0002 |
| (W)Miles bus routes < 0.5 M. | 0.0010 | 0.0058 | 0.0108 |
| (W)Bus stops < 0.5 M. | −0.0032 | −0.0011 | 0.0012 |
| (W)Rail stops < 0.5 M. | −0.0325 | 0.0084 | 0.0466 |
| (W)Miles rail lines < 1 M. | −0.0063 | 0.0027 | 0.0114 |
| (W)Intersections < 0.5 M. | −0.0004 | 0.0002 | 0.0009 |
| (W)CBG population/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| (W)CBG jobs/sq. mile | −0.0000 | −0.0000 | 0.0000 |
| (W)Work stops | −0.0426 | 0.0337 | 0.1130 |

| Variable | Lower 95% | Posterior Mean | Upper 95% |
|---|---|---|---|
| (W)Shopping stops | −0.1121 | −0.0413 | 0.0267 |
| (W)Social stops | −0.2092 | −0.0706 | 0.0649 |
| (W)Res. Low Density, 0-1/4 mile | −0.0079 | −0.0032 | 0.0015 |
| (W)Res. Medium Density, 0-1/4 mile | −0.0050 | 0.0006 | 0.0063 |
| (W)Res. High Density 0-1/4 mile | −0.0030 | 0.0018 | 0.0070 |
| (W)Bus. Low Density 0-1/4 mile | −0.0097 | 0.0027 | 0.0153 |
| (W)Bus. High Density 0-1/4 mile | −0.0081 | −0.0019 | 0.0041 |
| (W)Ind. 0-1/4 mile | 0.0000 | 0.0100 | 0.0195 |
| (W)Res. Low Density, 1/4-1/2 mile | −0.0003 | 0.0050 | 0.0103 |
| (W)Res. Medium Density, 1/4-1/2 mile | −0.0060 | 0.0011 | 0.0073 |
| (W)Res. High Density 1/4-1/2 mile | −0.0056 | 0.0005 | 0.0064 |
| (W)Bus. Low Density 1/4-1/2 mile | −0.0066 | 0.0092 | 0.0246 |
| (W)Bus. High Density 1/4-1/2 mile | −0.0040 | 0.0026 | 0.0090 |
| (W)Ind. 1/4-1/2 mile | −0.0127 | −0.0033 | 0.0067 |
| (W)Res. Low Density, 1/2-3/4 mile | −0.0501 | −0.0343 | −0.0183 |
| (W)Res. Medium Density, 1/2-3/4 mile | −0.0758 | −0.0565 | −0.0368 |
| (W)Res. High Density 1/2-3/4 mile | −0.0417 | −0.0241 | −0.0071 |
| (W)Bus. Low Density 1/2-3/4 mile | −0.1133 | −0.0628 | −0.0134 |
| (W)Bus. High Density 1/2-3/4 mile | −0.0424 | −0.0251 | −0.0082 |
| (W)Ind. 1/2-3/4 mile | −0.0633 | −0.0442 | −0.0267 |
| (W)Res. Low Density, 3/4-1 mile | 0.0171 | 0.0328 | 0.0484 |
| (W)Res. Medium Density, 3/4-1 mile | 0.0470 | 0.0689 | 0.0907 |
| (W)Res. High Density 3/4-1 mile | −0.0020 | 0.0170 | 0.0360 |
| (W)Bus. Low Density 3/4-1 mile | −0.0002 | 0.0526 | 0.1055 |
| (W)Bus. High Density 3/4-1 mile | 0.0072 | 0.0267 | 0.0456 |
| (W)Ind. 3/4-1 mile | 0.0279 | 0.0448 | 0.0621 |

Table B.11: Direct Effects: SDM Model, Inverse Distance W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Lower 95% | Posterior Mean | Upper 95% |
| HH size | −0.0204 | −0.0117 | −0.0037 |
| HH vehicles | −0.0843 | −0.0720 | −0.0598 |
| HH bicycles | 0.0065 | 0.0114 | 0.0163 |
| Male | 0.0186 | 0.0345 | 0.0505 |
| Age | −0.0033 | −0.0027 | −0.0022 |
| Income | −0.0002 | −0.0000 | 0.0002 |
| College Degree | −0.0097 | 0.0069 | 0.0248 |
| Employed | −0.0350 | −0.0171 | 0.0017 |
| Tour distance | −0.0031 | −0.0023 | −0.0014 |
| Tour crosses highway | −0.1795 | −0.1593 | −0.1408 |
| Miles bike lanes < 1 M. | −0.0220 | −0.0121 | −0.0026 |
| Miles bus routes < 0.5 M. | −0.0028 | 0.0006 | 0.0038 |
| Bus stops < 0.5 M. | 0.0006 | 0.0025 | 0.0047 |
| Rail stops < 0.5 M. | −0.0531 | −0.0278 | −0.0013 |
| Miles rail lines < 1 M. | −0.0053 | 0.0074 | 0.0200 |
| Intersections < 0.5 M. | −0.0003 | 0.0004 | 0.0012 |
| CBG population/sq. mile | −0.0000 | −0.0000 | 0.0000 |
| CBG jobs/sq. mile | −0.0000 | −0.0000 | 0.0000 |
| Work stops | 0.0000 | 0.0074 | 0.0154 |
| Shopping stops | −0.0480 | −0.0382 | −0.0291 |
| Social stops | −0.0394 | −0.0228 | −0.0062 |
| Res. Low Density, 0-1/4 mile | −0.0040 | −0.0017 | 0.0006 |
| Res. Medium Density, 0-1/4 mile | −0.0044 | −0.0021 | 0.0003 |
| Res. High Density 0-1/4 mile | −0.0041 | −0.0018 | 0.0004 |
| Bus. Low Density 0-1/4 mile | −0.0075 | −0.0029 | 0.0015 |
| Bus. High Density 0-1/4 mile | −0.0029 | −0.0006 | 0.0018 |
| Ind. 0-1/4 mile | −0.0054 | −0.0026 | 0.0003 |
| Res. Low Density, 1/4-1/2 mile | 0.0006 | 0.0047 | 0.0090 |
| Res. Medium Density, 1/4-1/2 mile | 0.0006 | 0.0046 | 0.0090 |
| Res. High Density 1/4-1/2 mile | 0.0011 | 0.0051 | 0.0096 |
| Bus. Low Density 1/4-1/2 mile | −0.0093 | −0.0005 | 0.0080 |
| Bus. High Density 1/4-1/2 mile | 0.0001 | 0.0044 | 0.0088 |
| Ind. 1/4-1/2 mile | 0.0000 | 0.0046 | 0.0096 |
| Res. Low Density, 1/2-3/4 mile | −0.0095 | −0.0037 | 0.0020 |
| Res. Medium Density, 1/2-3/4 mile | −0.0109 | −0.0045 | 0.0022 |
| Res. High Density 1/2-3/4 mile | −0.0126 | −0.0065 | −0.0002 |
| Bus. Low Density 1/2-3/4 mile | −0.0328 | −0.0142 | 0.0045 |
| Bus. High Density 1/2-3/4 mile | −0.0161 | −0.0093 | −0.0023 |
| Ind. 1/2-3/4 mile | −0.0101 | −0.0042 | 0.0018 |
| Res. Low Density, 3/4-1 mile | −0.0016 | 0.0045 | 0.0105 |
| Res. Medium Density, 3/4-1 mile | −0.0024 | 0.0047 | 0.0117 |
| Res. High Density 3/4-1 mile | −0.0028 | 0.0043 | 0.0114 |
| Bus. Low Density 3/4-1 mile | −0.0272 | −0.0090 | 0.0098 |
| Bus. High Density 3/4-1 mile | 0.0019 | 0.0090 | 0.0165 |
| Ind. 3/4-1 mile | −0.0018 | 0.0042 | 0.0103 |
| (W)HH size | −0.0699 | −0.0443 | −0.0200 |
| (W)HH vehicles | −0.0666 | −0.0373 | −0.0098 |
| (W)HH bicycles | 0.0052 | 0.0202 | 0.0349 |
| (W)Male | −0.0633 | −0.0027 | 0.0575 |
| (W)Age | −0.0048 | −0.0030 | −0.0013 |
| (W)Income | −0.0005 | −0.0001 | 0.0004 |
| (W)College Degree | −0.0451 | 0.0026 | 0.0504 |
| (W)Employed | −0.0941 | −0.0342 | 0.0229 |
| (W)Tour distance | −0.0034 | −0.0011 | 0.0013 |
| (W)Tour crosses highway | −0.1105 | −0.0628 | −0.0093 |
| (W)Miles bike lanes < 1 M. | −0.0007 | 0.0107 | 0.0225 |
| (W)Miles bus routes < 0.5 M. | 0.0005 | 0.0059 | 0.0118 |
| (W)Bus stops < 0.5 M. | −0.0058 | −0.0025 | 0.0007 |
| (W)Rail stops < 0.5 M. | −0.0353 | 0.0103 | 0.0557 |
| (W)Miles rail lines < 1 M. | −0.0072 | 0.0081 | 0.0241 |
| (W)Intersections < 0.5 M. | −0.0017 | −0.0006 | 0.0005 |
| (W)CBG population/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| (W)CBG jobs/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| (W)Work stops | −0.0521 | −0.0148 | 0.0218 |

| Variable | Lower 95% | Posterior Mean | Upper 95% |
|---|---|---|---|
| (W)Shopping stops | −0.0023 | 0.0246 | 0.0493 |
| (W)Social stops | −0.0831 | −0.0318 | 0.0170 |
| (W)Res. Low Density, 0-1/4 mile | −0.0047 | −0.0005 | 0.0033 |
| (W)Res. Medium Density, 0-1/4 mile | −0.0035 | 0.0007 | 0.0045 |
| (W)Res. High Density 0-1/4 mile | −0.0046 | −0.0006 | 0.0034 |
| (W)Bus. Low Density 0-1/4 mile | 0.0028 | 0.0118 | 0.0211 |
| (W)Bus. High Density 0-1/4 mile | −0.0041 | 0.0002 | 0.0043 |
| (W)Ind. 0-1/4 mile | −0.0042 | 0.0024 | 0.0089 |
| (W)Res. Low Density, 1/4-1/2 mile | −0.0059 | −0.0005 | 0.0049 |
| (W)Res. Medium Density, 1/4-1/2 mile | −0.0069 | −0.0009 | 0.0048 |
| (W)Res. High Density 1/4-1/2 mile | −0.0062 | −0.0006 | 0.0047 |
| (W)Bus. Low Density 1/4-1/2 mile | −0.0210 | −0.0077 | 0.0063 |
| (W)Bus. High Density 1/4-1/2 mile | −0.0135 | −0.0071 | −0.0009 |
| (W)Ind. 1/4-1/2 mile | −0.0085 | −0.0015 | 0.0054 |
| (W)Res. Low Density, 1/2-3/4 mile | −0.0242 | −0.0096 | 0.0046 |
| (W)Res. Medium Density, 1/2-3/4 mile | −0.0278 | −0.0125 | 0.0021 |
| (W)Res. High Density 1/2-3/4 mile | −0.0163 | −0.0016 | 0.0130 |
| (W)Bus. Low Density 1/2-3/4 mile | −0.0353 | 0.0033 | 0.0449 |
| (W)Bus. High Density 1/2-3/4 mile | −0.0095 | 0.0055 | 0.0199 |
| (W)Ind. 1/2-3/4 mile | −0.0236 | −0.0080 | 0.0065 |
| (W)Res. Low Density, 3/4-1 mile | −0.0066 | 0.0082 | 0.0228 |
| (W)Res. Medium Density, 3/4-1 mile | −0.0011 | 0.0154 | 0.0321 |
| (W)Res. High Density 3/4-1 mile | −0.0212 | −0.0056 | 0.0097 |
| (W)Bus. Low Density 3/4-1 mile | −0.0372 | 0.0071 | 0.0456 |
| (W)Bus. High Density 3/4-1 mile | −0.0113 | 0.0058 | 0.0224 |
| (W)Ind. 3/4-1 mile | −0.0061 | 0.0078 | 0.0227 |

Table B.12: Indirect Effects: SDM Model, Inverse Distance W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Lower 95% | Posterior Mean | Upper 95% |
| HH size | 0.0010 | 0.0033 | 0.0060 |
| HH vehicles | 0.0141 | 0.0202 | 0.0268 |
| HH bicycles | −0.0049 | −0.0032 | −0.0017 |
| Male | −0.0151 | −0.0097 | −0.0047 |
| Age | 0.0005 | 0.0008 | 0.0010 |
| Income | −0.0000 | 0.0000 | 0.0001 |
| College Degree | −0.0073 | −0.0020 | 0.0027 |
| Employed | −0.0004 | 0.0048 | 0.0102 |
| Tour distance | 0.0004 | 0.0006 | 0.0009 |
| Tour crosses highway | 0.0316 | 0.0448 | 0.0582 |
| Miles bike lanes < 1 M. | 0.0006 | 0.0034 | 0.0064 |
| Miles bus routes < 0.5 M. | −0.0011 | −0.0002 | 0.0008 |
| Bus stops < 0.5 M. | −0.0013 | −0.0007 | −0.0002 |
| Rail stops < 0.5 M. | 0.0004 | 0.0078 | 0.0156 |
| Miles rail lines < 1 M. | −0.0059 | −0.0021 | 0.0015 |
| Intersections < 0.5 M. | −0.0003 | −0.0001 | 0.0001 |
| CBG population/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| CBG jobs/sq. mile | −0.0000 | 0.0000 | 0.0000 |
| Work stops | −0.0043 | −0.0021 | −0.0000 |
| Shopping stops | 0.0071 | 0.0107 | 0.0146 |
| Social stops | 0.0018 | 0.0064 | 0.0117 |
| Res. Low Density, 0-1/4 mile | −0.0002 | 0.0005 | 0.0011 |
| Res. Medium Density, 0-1/4 mile | −0.0001 | 0.0006 | 0.0013 |
| Res. High Density 0-1/4 mile | −0.0001 | 0.0005 | 0.0012 |
| Bus. Low Density 0-1/4 mile | −0.0004 | 0.0008 | 0.0022 |
| Bus. High Density 0-1/4 mile | −0.0005 | 0.0002 | 0.0008 |
| Ind. 0-1/4 mile | −0.0001 | 0.0007 | 0.0016 |
| Res. Low Density, 1/4-1/2 mile | −0.0026 | −0.0013 | −0.0002 |
| Res. Medium Density, 1/4-1/2 mile | −0.0026 | −0.0013 | −0.0002 |
| Res. High Density 1/4-1/2 mile | −0.0028 | −0.0014 | −0.0003 |
| Bus. Low Density 1/4-1/2 mile | −0.0023 | 0.0001 | 0.0025 |
| Bus. High Density 1/4-1/2 mile | −0.0026 | −0.0012 | −0.0000 |
| Ind. 1/4-1/2 mile | −0.0028 | −0.0013 | −0.0000 |
| Res. Low Density, 1/2-3/4 mile | −0.0006 | 0.0011 | 0.0028 |
| Res. Medium Density, 1/2-3/4 mile | −0.0006 | 0.0013 | 0.0031 |
| Res. High Density 1/2-3/4 mile | 0.0001 | 0.0018 | 0.0037 |
| Bus. Low Density 1/2-3/4 mile | −0.0014 | 0.0040 | 0.0095 |
| Bus. High Density 1/2-3/4 mile | 0.0006 | 0.0026 | 0.0047 |
| Ind. 1/2-3/4 mile | −0.0005 | 0.0012 | 0.0029 |
| Res. Low Density, 3/4-1 mile | −0.0030 | −0.0013 | 0.0004 |
| Res. Medium Density, 3/4-1 mile | −0.0034 | −0.0013 | 0.0006 |
| Res. High Density 3/4-1 mile | −0.0033 | −0.0012 | 0.0008 |
| Bus. Low Density 3/4-1 mile | −0.0028 | 0.0025 | 0.0078 |
| Bus. High Density 3/4-1 mile | −0.0048 | −0.0025 | −0.0005 |
| Ind. 3/4-1 mile | −0.0029 | −0.0012 | 0.0005 |
| (W)HH size | 0.0054 | 0.0124 | 0.0206 |
| (W)HH vehicles | 0.0023 | 0.0107 | 0.0203 |
| (W)HH bicycles | −0.0105 | −0.0057 | −0.0013 |
| (W)Male | −0.0162 | 0.0007 | 0.0173 |
| (W)Age | 0.0003 | 0.0009 | 0.0015 |
| (W)Income | −0.0001 | 0.0000 | 0.0002 |
| (W)College Degree | −0.0147 | −0.0008 | 0.0128 |
| (W)Employed | −0.0066 | 0.0096 | 0.0273 |
| (W)Tour distance | −0.0004 | 0.0003 | 0.0010 |
| (W)Tour crosses highway | 0.0023 | 0.0180 | 0.0333 |
| (W)Miles bike lanes < 1 M. | −0.0066 | −0.0030 | 0.0002 |
| (W)Miles bus routes < 0.5 M. | −0.0034 | −0.0017 | −0.0001 |
| (W)Bus stops < 0.5 M. | −0.0002 | 0.0007 | 0.0017 |
| (W)Rail stops < 0.5 M. | −0.0162 | −0.0029 | 0.0095 |
| (W)Miles rail lines < 1 M. | −0.0071 | −0.0023 | 0.0021 |
| (W)Intersections < 0.5 M. | −0.0001 | 0.0002 | 0.0005 |
| (W)CBG population/sq. mile | −0.0000 | −0.0000 | −0.0000 |
| (W)CBG jobs/sq. mile | −0.0000 | −0.0000 | −0.0000 |
| (W)Work stops | −0.0063 | 0.0042 | 0.0151 |

| Variable | Lower 95% | Posterior Mean | Upper 95% |
|---|---|---|---|
| (W)Shopping stops | −0.0146 | −0.0069 | 0.0006 |
| (W)Social stops | −0.0047 | 0.0090 | 0.0236 |
| (W)Res. Low Density, 0-1/4 mile | −0.0009 | 0.0001 | 0.0013 |
| (W)Res. Medium Density, 0-1/4 mile | −0.0013 | −0.0002 | 0.0010 |
| (W)Res. High Density 0-1/4 mile | −0.0009 | 0.0002 | 0.0013 |
| (W)Bus. Low Density 0-1/4 mile | −0.0062 | −0.0033 | −0.0008 |
| (W)Bus. High Density 0-1/4 mile | −0.0012 | −0.0000 | 0.0012 |
| (W)Ind. 0-1/4 mile | −0.0026 | −0.0007 | 0.0012 |
| (W)Res. Low Density, 1/4-1/2 mile | −0.0014 | 0.0001 | 0.0016 |
| (W)Res. Medium Density, 1/4-1/2 mile | −0.0014 | 0.0002 | 0.0019 |
| (W)Res. High Density 1/4-1/2 mile | −0.0014 | 0.0001 | 0.0017 |
| (W)Bus. Low Density 1/4-1/2 mile | −0.0017 | 0.0022 | 0.0062 |
| (W)Bus. High Density 1/4-1/2 mile | 0.0002 | 0.0020 | 0.0039 |
| (W)Ind. 1/4-1/2 mile | −0.0015 | 0.0004 | 0.0025 |
| (W)Res. Low Density, 1/2-3/4 mile | −0.0013 | 0.0027 | 0.0070 |
| (W)Res. Medium Density, 1/2-3/4 mile | −0.0006 | 0.0035 | 0.0082 |
| (W)Res. High Density 1/2-3/4 mile | −0.0037 | 0.0005 | 0.0048 |
| (W)Bus. Low Density 1/2-3/4 mile | −0.0129 | −0.0009 | 0.0096 |
| (W)Bus. High Density 1/2-3/4 mile | −0.0057 | −0.0015 | 0.0027 |
| (W)Ind. 1/2-3/4 mile | −0.0019 | 0.0023 | 0.0068 |
| (W)Res. Low Density, 3/4-1 mile | −0.0067 | −0.0023 | 0.0019 |
| (W)Res. Medium Density, 3/4-1 mile | −0.0096 | −0.0044 | 0.0003 |
| (W)Res. High Density 3/4-1 mile | −0.0030 | 0.0015 | 0.0061 |
| (W)Bus. Low Density 3/4-1 mile | −0.0131 | −0.0019 | 0.0109 |
| (W)Bus. High Density 3/4-1 mile | −0.0066 | −0.0016 | 0.0030 |
| (W)Ind. 3/4-1 mile | −0.0066 | −0.0022 | 0.0018 |

Table B.13: Total Effects: SDM Model, Inverse Distance W

| Dependent Variable: Non-auto Transportation Mode = 1 | | | |
|---|---|---|---|
| Variable | Lower 95% | Posterior Mean | Upper 95% |
| HH size | −0.0146 | −0.0084 | −0.0027 |
| HH vehicles | −0.0610 | −0.0517 | −0.0435 |
| HH bicycles | 0.0048 | 0.0082 | 0.0116 |
| Male | 0.0137 | 0.0248 | 0.0367 |
| Age | −0.0024 | −0.0020 | −0.0016 |
| Income | −0.0001 | −0.0000 | 0.0001 |
| College Degree | −0.0073 | 0.0050 | 0.0178 |
| Employed | −0.0249 | −0.0123 | 0.0012 |
| Tour distance | −0.0022 | −0.0016 | −0.0010 |
| Tour crosses highway | −0.1287 | −0.1145 | −0.1010 |
| Miles bike lanes < 1 M. | −0.0157 | −0.0087 | −0.0019 |
| Miles bus routes < 0.5 M. | −0.0020 | 0.0005 | 0.0027 |
| Bus stops < 0.5 M. | 0.0004 | 0.0018 | 0.0034 |
| Rail stops < 0.5 M. | −0.0383 | −0.0199 | −0.0010 |
| Miles rail lines < 1 M. | −0.0037 | 0.0053 | 0.0144 |
| Intersections < 0.5 M. | −0.0002 | 0.0003 | 0.0008 |
| CBG population/sq. mile | −0.0000 | −0.0000 | 0.0000 |
| CBG jobs/sq. mile | −0.0000 | −0.0000 | 0.0000 |
| Work stops | 0.0000 | 0.0053 | 0.0109 |
| Shopping stops | −0.0348 | −0.0275 | −0.0207 |
| Social stops | −0.0284 | −0.0164 | −0.0043 |
| Res. Low Density, 0-1/4 mile | −0.0029 | −0.0012 | 0.0005 |
| Res. Medium Density, 0-1/4 mile | −0.0032 | −0.0015 | 0.0002 |
| Res. High Density 0-1/4 mile | −0.0029 | −0.0013 | 0.0003 |
| Bus. Low Density 0-1/4 mile | −0.0054 | −0.0021 | 0.0011 |
| Bus. High Density 0-1/4 mile | −0.0021 | −0.0004 | 0.0013 |
| Ind. 0-1/4 mile | −0.0039 | −0.0019 | 0.0002 |
| Res. Low Density, 1/4-1/2 mile | 0.0005 | 0.0034 | 0.0065 |
| Res. Medium Density, 1/4-1/2 mile | 0.0004 | 0.0033 | 0.0065 |
| Res. High Density 1/4-1/2 mile | 0.0008 | 0.0037 | 0.0070 |
| Bus. Low Density 1/4-1/2 mile | −0.0068 | −0.0004 | 0.0059 |
| Bus. High Density 1/4-1/2 mile | 0.0000 | 0.0032 | 0.0064 |
| Ind. 1/4-1/2 mile | 0.0000 | 0.0033 | 0.0069 |
| Res. Low Density, 1/2-3/4 mile | −0.0069 | −0.0027 | 0.0014 |
| Res. Medium Density, 1/2-3/4 mile | −0.0080 | −0.0032 | 0.0016 |
| Res. High Density 1/2-3/4 mile | −0.0091 | −0.0047 | −0.0002 |
| Bus. Low Density 1/2-3/4 mile | −0.0234 | −0.0102 | 0.0034 |
| Bus. High Density 1/2-3/4 mile | −0.0115 | −0.0067 | −0.0016 |
| Ind. 1/2-3/4 mile | −0.0074 | −0.0030 | 0.0013 |
| Res. Low Density, 3/4-1 mile | −0.0011 | 0.0033 | 0.0074 |
| Res. Medium Density, 3/4-1 mile | −0.0018 | 0.0034 | 0.0083 |
| Res. High Density 3/4-1 mile | −0.0020 | 0.0031 | 0.0080 |
| Bus. Low Density 3/4-1 mile | −0.0195 | −0.0065 | 0.0071 |
| Bus. High Density 3/4-1 mile | 0.0013 | 0.0065 | 0.0119 |
| Ind. 3/4-1 mile | −0.0013 | 0.0030 | 0.0074 |
| (W)HH size | −0.0499 | −0.0319 | −0.0144 |
| (W)HH vehicles | −0.0469 | −0.0266 | −0.0073 |
| (W)HH bicycles | 0.0037 | 0.0145 | 0.0252 |
| (W)Male | −0.0443 | −0.0020 | 0.0414 |
| (W)Age | −0.0034 | −0.0022 | −0.0009 |
| (W)Income | −0.0004 | −0.0000 | 0.0003 |
| (W)College Degree | −0.0324 | 0.0018 | 0.0360 |
| (W)Employed | −0.0663 | −0.0246 | 0.0170 |
| (W)Tour distance | −0.0024 | −0.0008 | 0.0009 |
| (W)Tour crosses highway | −0.0787 | −0.0449 | −0.0072 |
| (W)Miles bike lanes < 1 M. | −0.0005 | 0.0077 | 0.0161 |
| (W)Miles bus routes < 0.5 M. | 0.0003 | 0.0042 | 0.0083 |
| (W)Bus stops < 0.5 M. | −0.0042 | −0.0018 | 0.0005 |
| (W)Rail stops < 0.5 M. | −0.0250 | 0.0074 | 0.0392 |
| (W)Miles rail lines < 1 M. | −0.0049 | 0.0058 | 0.0172 |
| (W)Intersections < 0.5 M. | −0.0012 | −0.0004 | 0.0004 |
| (W)CBG population/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| (W)CBG jobs/sq. mile | 0.0000 | 0.0000 | 0.0000 |
| (W)Work stops | −0.0378 | −0.0106 | 0.0155 |

| Variable | Lower 95% | Posterior Mean | Upper 95% |
|---|---|---|---|
| (W)Shopping stops | −0.0017 | 0.0178 | 0.0360 |
| (W)Social stops | −0.0602 | −0.0228 | 0.0124 |
| (W)Res. Low Density, 0-1/4 mile | −0.0033 | −0.0003 | 0.0024 |
| (W)Res. Medium Density, 0-1/4 mile | −0.0025 | 0.0005 | 0.0032 |
| (W)Res. High Density 0-1/4 mile | −0.0033 | −0.0004 | 0.0024 |
| (W)Bus. Low Density 0-1/4 mile | 0.0020 | 0.0085 | 0.0150 |
| (W)Bus. High Density 0-1/4 mile | −0.0030 | 0.0001 | 0.0031 |
| (W)Ind. 0-1/4 mile | −0.0030 | 0.0017 | 0.0064 |
| (W)Res. Low Density, 1/4-1/2 mile | −0.0042 | −0.0003 | 0.0035 |
| (W)Res. Medium Density, 1/4-1/2 mile | −0.0049 | −0.0007 | 0.0035 |
| (W)Res. High Density 1/4-1/2 mile | −0.0046 | −0.0004 | 0.0034 |
| (W)Bus. Low Density 1/4-1/2 mile | −0.0151 | −0.0056 | 0.0048 |
| (W)Bus. High Density 1/4-1/2 mile | −0.0097 | −0.0051 | −0.0007 |
| (W)Ind. 1/4-1/2 mile | −0.0062 | −0.0011 | 0.0037 |
| (W)Res. Low Density, 1/2-3/4 mile | −0.0171 | −0.0069 | 0.0033 |
| (W)Res. Medium Density, 1/2-3/4 mile | −0.0197 | −0.0090 | 0.0016 |
| (W)Res. High Density 1/2-3/4 mile | −0.0117 | −0.0011 | 0.0094 |
| (W)Bus. Low Density 1/2-3/4 mile | −0.0254 | 0.0024 | 0.0320 |
| (W)Bus. High Density 1/2-3/4 mile | −0.0067 | 0.0040 | 0.0142 |
| (W)Ind. 1/2-3/4 mile | −0.0169 | −0.0058 | 0.0047 |
| (W)Res. Low Density, 3/4-1 mile | −0.0045 | 0.0058 | 0.0163 |
| (W)Res. Medium Density, 3/4-1 mile | −0.0008 | 0.0110 | 0.0229 |
| (W)Res. High Density 3/4-1 mile | −0.0152 | −0.0041 | 0.0069 |
| (W)Bus. Low Density 3/4-1 mile | −0.0268 | 0.0051 | 0.0330 |
| (W)Bus. High Density 3/4-1 mile | −0.0081 | 0.0041 | 0.0159 |
| (W)Ind. 3/4-1 mile | −0.0043 | 0.0056 | 0.0157 |