The Effect of Street Network Design on Walking and Biking

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ABSTRACT

The objective of this research was to investigate whether a relationship exists between street network characteristics and the choice of transportation modes selected in a neighborhood. In this study, we controlled for factors such as street characteristics, vehicle volumes, activity levels, income levels, proximity to limited access highways and to the downtown area. The results suggest that all three of the fundamental characteristics of a street network – street connectivity, street network density, and street patterns – are statistically significant in affecting the choice to drive, walk, bike, or take transit.

Both increased intersection density and additional street connectivity were generally associated with more walking, biking, and transit use. Street patterns with gridded street networks, which tended to have higher street connectivity than average and much higher street network density, were associated with much more walking and biking. These results suggest that street network patterns are extremely important for encouraging non-automobile modes of travel. As our nation begins to focus on reducing vehicle miles traveled as a strategy to combat carbon production and cut energy use, it is increasingly imperative that we account for this relationship between the built environment and mode choice in our planning and design of the transportation system.

KEY WORDS

Street network, connectivity, density, sustainability, mode choice, walking, pedestrians, biking

INTRODUCTION

A transportation system that is based on multiple options for travel is generally thought to bring many benefits including increased efficiency, enhanced flexibility, and equity for all users (1). The ability to choose the right travel mode for the right situation helps reduce congestion as well as reduce economic and environmental costs. In addition, a transportation system with a diverse set of travel options tends to be more flexible, in that it can accommodate sudden and unanticipated problems or situations such emergency evacuations or abrupt jumps in oil prices. More travel choices also helps improve equity, not only by offering mobility to young people and the elderly, but also by providing options for people that may not be able to afford automobiles (2).

As we begin planning for a more diverse set of travel options in the U.S., it is increasingly important that we research and understand those factors that will facilitate the ready adoption of non-motorized and public transit travel. In this research we focus on how one aspect of the built environment, the street network, affects mode choice. The objective of the study is to assess how street network characteristics – in terms of street connectivity, street network density, and street patterns – influence mode choice in 24 California cities. We focus on mode choice because this data is readily available, but also because it is an indication of how people are actually using the transportation system on a daily basis. And along with trip frequency and trip length, mode choice determines how much people drive (3).

Much of the existing research on travel patterns focuses on the impact of land use or street design characteristics (3). Those studies that have sought to associate street network measures with travel are few in number and generally fail to account for the full range of street network measures.

In this research, we carry out a spatial analysis of mode share in 24 medium-sized California cities. The cities were selected from an initial database of over 150 California cities to best represent a geographically diverse collection of twelve medium-sized California cities with good safety records and twelve with poor safety records with respect to the number of street fatalities per capita. The safety records of these cities were taken into consideration during the city selection process as part of the original investigation exploring street network and road safety outcomes (4, 5)

Street network measures were combined with street characteristics, socioeconomic data, and traffic flow information in a GIS database. Statistical multinomial logistic regression mode share models were estimated at the Census Block Group level of geography for over 1,000 distinctly populated Block Groups. The goal of our research design is to capture the mode share implications of different street network patterns while controlling for variables such as vehicle volumes, income levels, and proximity to limited access highways and the downtown area.

Our study comes at an opportune time because there seems to be an increasing need for a more definitive understanding regarding the impact of street networks on travel. For instance, the Commonwealth of Virginia recently adopted a new street connectivity policy, in part to encourage the use of non-automobile modes of travel (6). However, this policy focuses only on street connectivity, which is just one characteristic that defines a street network. It is not clear if this policy will be successful without a fuller understanding of the character of a street network, which would come from also assessing the street network density and pattern of the street network. The problem is that there is little or no research currently available to help to guide changes like those in Virginia, which are intended to improve the performance of the street network.

Our overall goal with this study is to begin to fill this gap in knowledge concerning how street design patterns affect mode choice and other issues, including safety, that impinge on the sustainability of our communities. This paper focuses solely on the results pertaining to mode choice.

LITERATURE REVIEW

Over the course of the last century, there has been a dramatic shift in American street patterns and community design. Specifically there has been a transition from traditional gridded layouts of the first part of the twentieth century to increasingly more dendritic, tree-like networks of the post 1950 period (7, 8). In describing these changes, many observers focus on the shape and connectivity of the street networks but typically ignore another important factor – street network density – which has progressively decreased over the last half of the 1900s.

Interestingly, the most influential effort at promoting newer types of street networks in the 1900s did not come from planners or engineers but from a quite unexpected quarter – the Federal Housing Authority. Founded in 1934, the Federal Housing Administration (FHA) released their publications to recommend specific street patterns in the mid 1930s with Technical Bulletins No. 5 and 7 (9). The bulletins called the grid layout monotonous, with little character or appeal, uneconomical, and a safety issue (8). The publications endorsed hierarchical streets layouts that minimized through traffic and singled out cul-de-sacs as being one of the most attractive and profitable street types.

In its first fifteen years of existence, the FHA played a role in overseeing the production of over 22 million properties (8). As a result, their recommended design principles became accepted practice for developers and began to be included in many zoning regulations. In effect, the federal government became a driving force in determining the types of street networks getting built at the neighborhood level.

It was not until the early 1950s when transportation engineers began to actively recommend hierarchical cul-de-sac designs as the preferred street pattern. It is noteworthy that there was very little technical evidence or research supporting this radical change in how street networks were designed and constructed. Nonetheless in 1965, ITE published “Recommended Practice for Subdivision Streets” discouraging gridded street patterns. The report recommended curvilinear local streets with discontinuities to discourage through traffic, replacing four-way intersections with T-intersections where possible, and the use of cul-de-sacs. Although ITE published “Traffic Engineering for Neo-Traditional Neighborhood Design” in 1994, which promoted a return to more traditional patterns, the latest ITE guidelines for subdivision streets still maintain many of the same design principles discussed in the 1965 version (8).

The result was that from the 1940s through the late 1980s, very few new developments in the United States featured a gridded street pattern; instead, hierarchical layouts became the standard (8). Despite their fall from favor, connected street networks are widely considered to have some advantages, including directness of travel and more route choice options. These advantages are often thought to encourage non-automobile travel including walking, biking and transit (1). There is some research in the literature that has investigated the link between street pattern and various measures of travel behavior including mode choice. This literature is reviewed below (10).

In one particularly influential study, Newman and Kentworthy charted the overall fuel consumption in 32 worldwide cities measured against the population density of these places (11). They found a distinct relationship between fuel consumption and density, with fuel consumption decreasing as the density of the city increases. Newman furthers this examination of energy use and urban form by examining in more detail the New York City and San Francisco regions (11). In both locations, the amount of gasoline used increases exponentially with decreased density as one moves from the central city towards the outer suburbs where the maximum amount of energy is used. While these comparisons do not reveal what specific differences in urban form and travel patterns account for this relationship to fuel consumption, it is difficult to ignore the implication of these trends.

A number of studies have explicitly examined the relationship between travel pattern and various characteristics of the street network. The earliest of these studies were based on simulation programs and did not use measurements from real life examples. For example in 1984, Curtis et. al. modeled mode choice and fuel savings of conventional hierarchical street patterns versus several hypothetical street networks including a grid network (12). The results suggested that the gridded street network would save up to 30% in fuel costs; however, the authors contended that this difference was in part due to higher vehicle speeds on the grid network. In the early 1990s, Walter Kulash did a similar study based on simulation models. Kulash's simulation was also based on the assumption that gridded street network had higher average vehicle speeds. His simulations showed a 57% decrease in vehicle miles traveled (VMT) for neighborhood travel on a gridded street network (13).

McNally and Ryan, in another hypothetical study, found similar advantages for a connected street network when compared to a less connected, more contemporary street network (14). In yet another simulation study, this one sponsored by the American Society of Civil Engineers (ASCE), the findings were that streets networks heavy on cul-de-sacs increased travel demand on arterial roads by 75% and on collector roads by 80%, compared to a 43% lower VMT with a gridded street design (7).

A number of more recent empirical studies seem to support the earlier simulation studies regarding street networks and travel. For example, the Puget Sound Regional Council found that VMT dropped in the King County, Washington area by approximately 0.5% for every 10% increase in intersections per mile, with all other variables being held constant (15). In another series of case studies, the Portland Metro found that an increase from low connectivity to moderate connectivity reduced VMT by 2%, trip length by 2%, and vehicle delay by 14% (16).

In a study specifically addressing street network measures, Cervero and Gorham found that denser and more connected transit-oriented street networks had much higher pedestrian mode shares than what they considered to be more automobile-oriented neighborhoods (17). The authors suggested that their focus on work trips is a limitation of the study but point out that much of the research in the literature showed an even bigger influence of street network characteristics on non-work trips (in particular on shopping trips). For example they cite Handy who, in looking at what she termed accessibility, suggested that people living in more accessible places drive as much as 40% fewer miles for shopping trips (18).

Cervero and Kockelman not only found increased non-automobile mode shares to be associated with dense developments, but also that gridded street networks, combined with parking restrictions, resulted in the biggest shift in mode shift, and in turn the largest VMT drop (19). Interestingly, they did not find the variable they used for measuring the pedestrian environment to be strongly correlated with any mode shift. On the other hand, Hess et. al. – comparing sites matched for population density, land uses, and income – observed that urban places with shorter block lengths supported by good sidewalks had an average of three times higher pedestrian volumes when compared to more suburban places with longer block lengths and an incomplete sidewalk network (20).

Not all of the research studies have found street networks to be significant factors in affecting travel and mode choice. Holdzclaw's results showed that street patterns had no significant effect on total VMT per household (21). In another report, Crane suggested that the transportation benefits of denser and more connected street networks are being oversold because improving access to the point of increasing walking trips will also increase trip frequencies and perhaps even overall travel on the transportation system (22). This begs the question – especially if the overall goal is related to sustainability – are more walking trips really a bad thing? Another study by Crane, this time with Crepeau, found no evidence that street patterns influenced differences in walking or driving for non-work trips (23). However, Crane and Crepeau did not explicitly consider street network density.

A common problem with all the research reviewed above is that they did not account for all three of the fundamental street network measures – street connectivity, street network measures, and street patterns. In our study, we focus on fully characterizing the differences between different types of networks and examine how the full range of street network design factors influences mode choice. Our goal is to establish a clear picture of the street network characteristics that might affect mode choice.

OVERVIEW OF STUDY

This research is based on eleven years of crash records from 24 California cities with populations between 30,000 and 100,000. The mode share analysis was done at the Block Group level of geography. According to the U.S. Census, a census Block Group is intended to average 250 to 500 housing units and vary in area depending on housing density. In our study, we have over 1,000 distinctly populated Block Groups at an average of approximately 43 Block Groups per city. We focused the study on California cities because of the large number and diversity of city types and in order to help maintain consistency in the data. In terms of city selection for the initial study, the objective was to find twelve medium-sized cities with good road safety records and twelve with poor records in order to get a wide range of outcomes in terms of safety since the initial goal of the research was to assess traffic safety. However, we also found that our city selection process resulted in a wide range of street and street network characteristics, in part due to the fact that the average year of incorporation was 1895 for the safer cities and 1932 for the less safe cities. The following cities were selected:

Safer Cities
- Alameda
- Berkeley
- Chico
- Cupertino
- Danville
- Davis
- La Habra
- Palo Alto
- San Luis Obispo
- San Mateo
- Santa Barbara
- Santa Cruz

Less Safe Cities
- Antioch
- Apple Valley
- Carlsbad
- Madera
- Morgan Hill
- Perris
- Redding
- Rialto
- Temecula
- Turlock
- Victorville
- West Sacramento

Description of Spatial Data

Network Level Data

The street network data was derived from a number of sources including the U.S. Census TIGER line files, the California Spatial Information Library, and the California Department of Transportation (CalTrans) records. Street network measures for characterizing both street connectivity and street network density were calculated using ArcGIS. Properly characterizing the street network requires answering three basic questions: how connected are the streets, how compact is the network, and what are the street network patterns. The approach to characterizing these properties will be discussed in the following paragraphs.

With regard to measuring the connectivity of a street network, one common measure is the link to node ratio. Link to node ratio is calculated by dividing the number of links (road segments between intersections) by the number of nodes (or intersections) (15, 24). The node count represents the total number of intersections including dead ends or cul-de-sacs. For example, adding a dead end cul-de-sac to a street network would add one link and one node to the total count while connecting two existing dead end cul-de-sacs would add one link without adding any additional nodes. Correspondingly, a new dead end would lower the link to node ratio and connecting two dead ends would increase the link to node ratio; thus, the higher the link to node value, the more connected the street network. A score of 1.4 or higher is typically considered to be indicative of a walkable community (15).

The second characteristic of the street network that we sought to measure was street network density. Intersection density is one way of characterizing street network density. It is typically measured by the number of intersections per unit area (the typical unit is often a square mile). Intersection density can be calculated separately for major streets and local streets in an attempt to give an indication of the type of intersections that make up the street network. Other typical measures of intersection density included average block size, dead end density, centerline street-mile density, and the connected node ratio. For additional background information on street network measures, please refer to our earlier paper (5).

We determine street network patterns using an adaptation of Stephen Marshall's concept of macroscopic and microscopic street networks as shown in Figure 1 (25). The concept differs from the standard functional classification of arterial, collector, and local roads in that Marshall's system is based upon street network structure. The Macro-level or Citywide Street network distinguishes streets that are generally continuous over a substantial portion of the city and likely services travel from one part of the city to another and, in many cases, trips to or from the city. The Micro-level or Neighborhood Street network generally serves residential neighborhood travel because these streets are on routes not continuous over a significant portion of the city. Marshall defines four types of Citywide Street network types: linear, tributary, radial, and grid; he then combines this with two Neighborhood Street network types: tree and grid.

Marshall presents the chart shown in Figure 1 in his book as a way to discuss the hybrid types of street patterns and account for the different levels of streets in the network; the chart was not originally intended to serve as a way to classify actual street networks (25). But our preliminary evaluation of this scheme suggested that it would be a good approach for classifying street pattern types in our study since we found that it was inclusive of most network types we encountered while at the same time providing a good way of adequately representing the different levels of the street network.

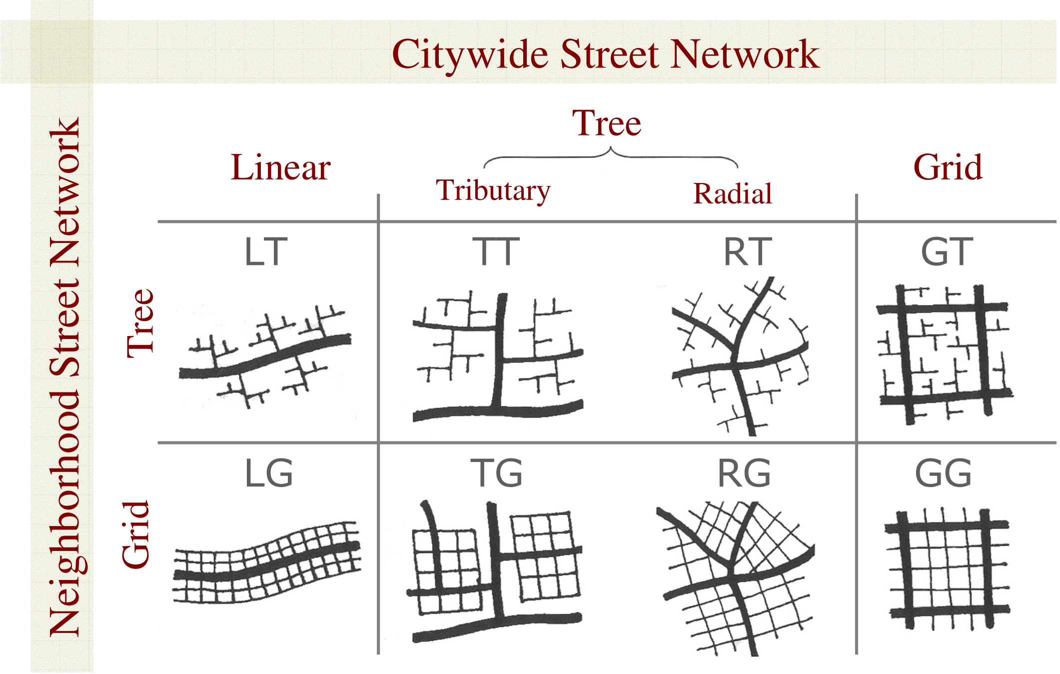


Figure 1 **Citywide – Neighborhood Street Network Classification System (25)**

However, in order to transition Marshall's pattern chart into a feasible street network classification system, we had to overcome a couple of obstacles. One drawback of Marshall's chart is the omission of curvilinear street types. Hence, we added a binary descriptor value representing whether or not the street network was generally curvilinear. Another drawback of trying to use Marshall's pattern chart in practice is that his streets only fall into two categories: Citywide or Neighborhood. This binary scheme is limiting and not consistent with how places and street networks are built in practice. As a result, we supplemented Marshall's system with an intermediate type of street that was neither a Citywide Street nor part of the Neighborhood Street network. This intermediate level street enables movement between neighborhoods but is not necessarily useful for city wide travel; accordingly, we labeled these streets the Inter-Neighborhood Streets.

In order to use this adapted classification method in our study, we had to manually classify the entire street network in our 24 cities. Using aerial photographs, we designated the Citywide Streets in each city by selecting streets that are generally continuous across a substantial portion of the city. In other words, the Citywide Street network consisted of those streets that were deemed to be significant connectors between distinct parts of the city. Streets adjacent to or leading to significant commercial or industrial land uses were also considered part of the Citywide Street network. The Inter-Neighborhood Streets were selected to represent connections between adjacent neighborhoods or multiple neighborhoods.

Figure 2 depicts the process of classifying the major and local streets in Carlsbad, California based on the Citywide, Inter-Neighborhood, and Neighborhood Street system using aerial photographs from Google Earth. The top images in Figure 2 display the limited access highways in Carlsbad. The middle set of images in Figure 2 shows the Citywide Street network. This picture offers a good indication of what streets would accommodate longer distance travel within Carlsbad and what streets would accommodate coming to or leaving Carlsbad. While most of the Citywide Streets extend across a significant portion of Carlsbad, there were a few selected in the northwest corner of the city because of their proximity to major commercial land uses. The bottom set of images in Figure 2 displays the Inter-Neighborhood Streets. Here we can begin to see the roads connecting the different residential neighborhoods of Carlsbad and start to get an idea of street network structure at the Inter-Neighborhood Street level. Using this approach, each Block Group in the database was classified by the predominant street network pattern in that Block Group.

This classification system not only provided a visual representation of the street network, but it also facilitated the creation of more detailed street network measurements. For instance, intersection density can now be broken down by intersection type in terms of the corresponding intersecting nodes for Citywide Street network intersections (the intersection of two Citywide Streets) or Citywide Street network – Inter-Neighborhood Street network intersections (the intersection a Citywide Street with an Inter-Neighborhood Street).

Street Level Data

For every street segment in the Citywide Street network, we collected the following street design characteristics using Google Earth:

- Total number of lanes
- Curb-to-curb distance
- Outside shoulder width

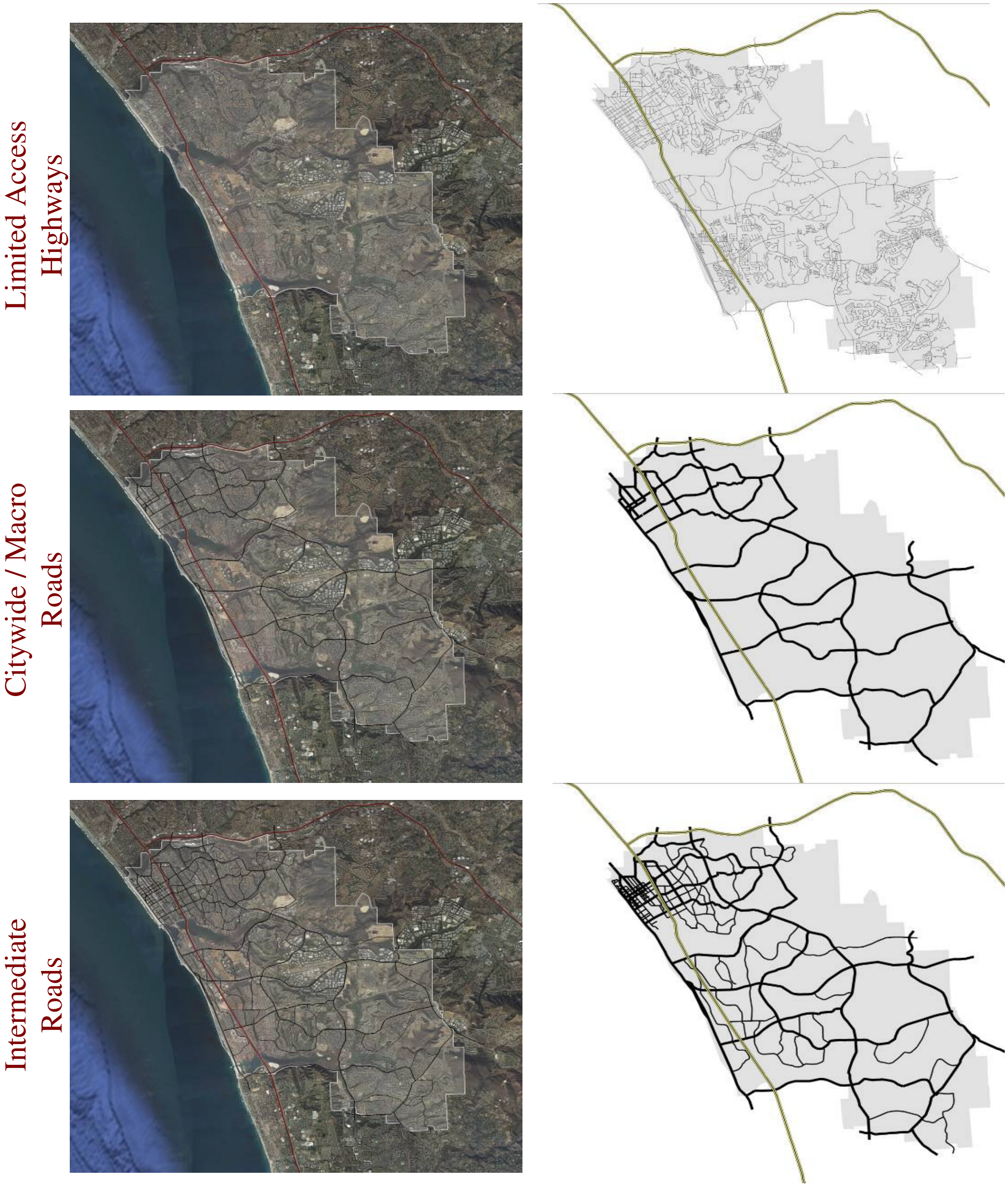


Figure 2 **Citywide/Macroscopic vs. Neighborhood/Microscopic Street Classification in Carlsbad, California**

- Inside shoulder width (when median present)
- Raised median width
- Painted median width
- On-street parking (0 = no, 1 = yes, 0.5 = along one side of street)
- Bike lanes (0 = no, 1 = yes, 0.5 = along one side of street)
- Curbs (0 = no, 1 = yes, 0.5 = along one side of street)
- Sidewalks (0 = no, 1 = yes, 0.5 = along one side of street)

Census Data

Census data from the year 2000 was collected and analyzed along with the street network data at the Census Block Group level of geography. This data included mode shares, travel time to work, household income levels, and demographic information such as age and race.

Traffic Data

Vehicle volumes, in terms of VMT, were estimated through the use of Average Annual Daily Traffic (AADT) counts carried out by each city. We geocoded the AADT data based on the nearest intersection and calculated average AADT for each street type – Citywide, Inter-neighborhood, and Neighborhood. This average AADT value was used to calculate VMT based on total street length by type. Since the number of AADT points on the Neighborhood Streets was relatively low, VMT was estimated on these streets using an average AADT value of 845, which is consistent with what CalTrans uses for all local streets in their VMT assessment. However, this did not seem to be an appropriate value for dead end streets, so in our calculations we used an AADT value of 250 in these cases.

Generally, we would expect that zones with higher VMTs be associated with more driving. However, the intent of including this variable is to control for the influence of high traffic volumes on mode choice.

In order to account for the overall level of activity in an area, we used a proxy measure based upon a simplified gravity model strategy and the relative levels of population and employment that was originally conceived by Daniel Graham and Stephen Glaister (26, 27). The idea is to establish the relative activity of a zone in terms of the population and employment of that particular zone as well as the population and employment of other zones with respect to the distance between them. The following equation is a proxy for the amount of activity in each zone (26, 27).

$$\mathrm{PP}_i = \sum_j \frac{P_j}{d_{ij}} \qquad\qquad \mathrm{PE}_i = \sum_j \frac{E_j}{d_{ij}}$$

In the above equations, PP_i represents the trips generated by Block Group i by the proximate population and PE_i the trips generated by Block Group i by the proximate employment. P_i is the level of population, E_i is the level of employment, and d_{ij} is the centroid-to-centroid distance between zones. The centroid-to-centroid distances are calculated in terms of feet with a distance of 1' used to calculate the intra-zone proxy values.

The proximate employment variable and proximate population variable were also used in our study to calculate a proxy for the relative level of mixed land uses by dividing the proxy for employment by the proxy for population. At the Block Group level of geography, this value helps identify the relative mix of employment and population.

Statistical Methodology

The fundamental question we are trying to answer with this research is the following: how are street network measures correlated to mode choice? While mode choice modeling is best known for being used in transportation planning and the four-step travel demand model, our model focuses on how certain characteristics of the street and street network affect travel to work patterns in terms of mode choice. In either case, the basic structure is the same and typically based on the logit model. The following generalized logit equation establishes the probability of choosing a specific mode (28):

$$P_i = \frac{e^{u_i}}{\sum_{i=1}^{k} e^{u_i}}$$

where: P_i = The probability of somebody choosing mode I = 1, 2, …, k

u_i = Utility function describing the relative attractiveness of mode i

$\sum_{i=1}^{k} e^{u_i}$ = Sum of the functions for all available mode alternatives

The probability of choosing a certain mode depends upon this utility function relative to the utility functions for all other mode options. In a traditional four-step model, the utility function of the logit equation normally contains variables such as in-vehicle travel time, out-of-vehicle travel time, and the cost associated with each mode for a particular type of trip between two specific zones. The utility function in our study primarily consists of street and street network characteristics.

In terms of modes, we model four types in this study: transit, walking, biking, and driving. In order to account for four separate categorical outcomes, a multinomial logistic regression model is used (29). A multinomial logistic regression simultaneously considers binary logit model for every possible combination of outcomes; in this case, four different outcomes is equivalent to six binary logit models (30). One assumption of the multinomial logistic regression model is that the probabilities related to the choices sum to one:

$$P(\text{Transit}) + P(\text{Walking}) + P(\text{Biking}) + P(\text{Driving}) = 1$$

For such a probability-based model, the multinomial logistic regression equation is as follows (30):

$$P(y_i=1|x_i) = \frac{1}{1+\sum_{j=2}^{J} e^{(x_i\beta_j)}} \quad \text{for } m = 1$$

$$P(y_i=m|x_i) = \frac{e^{(x_i\beta_m)}}{1+\sum_{j=2}^{J} e^{(x_i\beta_j)}} \quad \text{for } m > 1$$

where: y = Dependent Variable

J = Number of categorical outcomes = 4 mode choices

$P(y=m|x)$ = Probability of choosing mode m given x

x_i = Independent predictor variable

β = Estimated coefficient representing effects of the independent variable

Description of Experiment

Using the multinomial logistic regression model, we investigated the statistical relationship between mode choice and street network measures including street connectivity, street network density, and types of street patterns. Also considered were design characteristics of the Citywide Streets including the total number of lanes, outside shoulder width, and the percent of Citywide Streets with medians, on-street parking, bike lanes, and curbs or sidewalks. We also tested and analyzed interactions amongst selected variables; in particular, we tested interactions among street connectivity, street network density, street network pattern, and Citywide Street design variables.

Variables controlled for in our models include income levels, proximity to limited access highways or the downtown area, the proxy variable for Block Group activity levels, the proxy for mixed land uses, and vehicle volumes. Due to relative magnitude of the vehicle volume counts and average income compared to the rest of the data, the data for these two variables was scaled down and standardized to range from 0 to 1 so that the statistical coefficients could be estimated and the direction of the effect could be more easily observed. Consistent data representing the level of transit service was not available for all 24 cities in the database. Since transit use is linked to the level of transit available in an area, it is difficult to establish firm conclusions about the transit results since we did not have a measure of transit availability; however, separating transit use from the other non-automobile mode shares allowed us better understand the association of the street network with the other modes. Table 1 displays the summary statistics of the variables tested.

A number of variables were also tested but not used in our final models due to the fact that they showed high correlation with other variables already included in the model. The variables that were not included in the models because they were highly correlated with another variable include:

Street Network Measures

- Centerline Miles of Street (total and by type)
- Centerline Miles of Street per Square Mile (total and by type)
- Percent of Streets by Type
- Connected Node Ratio
- Average Block Size

Street Level Data (for Citywide Streets only)

- Curb to Curb Distance
- % of Citywide Street Length with Sidewalks

Miscellaneous

- Population
- Population Density
- Employment Density
- Mode Share Data
- Average Travel Time to Work

Table 1 Summary Statistics of Variables at the Census Block Group Level

	Mean	S.D.	Minimum	Maximum
Mode Choice				
Transit Mode Share	0.0523	0.0681	0	0.4378
Walking Mode Share	0.0454	0.0812	0	0.9043
Biking Mode Share	0.0264	0.0442	0	0.3986
Driving Mode Share	0.8651	0.1427	0.0287	1
Street Network Measures				
Intersection Density (intersections / sq. mi.)	176.0	98.8	7.9	559.0
Dead End Density (dead ends / sq. mi.)	32.0	27.7	0	209.0
Citywide / Inter-Neighborhood Intersection Density	60.1	68.8	0	523.0
Link to Node Ratio (# links / # intersections)	1.20	0.20	0.40	2.00
Curvilinear (0, 1)	0.20	0.40	0	1
Street Level Data for Citywide Streets				
Avg. Total Number of Lanes	3.00	1.10	0	7.00
Avg. Outside Shoulder Width	1.70	2.60	0	12.00
% of Citywide Street Length with Raised Median	0.50	0.50	0	1
% of Citywide Street Length with Painted Median	0.40	0.50	0	1
% of Citywide Street Length with On-Street Parking	0.50	0.40	0	1
% of Citywide Street Length with Bike Lanes	0.30	0.30	0	1
% of Citywide Street Length with Curbs	0.80	0.30	0	1
Traffic Data				
Vehicle Miles Traveled (VMT)	30,440	36,586	1,475	502,272
VMT standardized from 0 to 1	0.10	0.10	0	1
Proxy for Activity	0.30	0.30	0	1
Miscellaneous				
Distance from City Center (miles)	1.8	1.4	0.0	9.0
Bisecting or Adjacent Limted Access Highway (0, 1)	0.30	0.40	0	1
Income	$57,268	$21,549	$11,956	$128,223
Income standardized from 0 to 1	0.40	0.20	0	1
Proxy for Mixed Land Uses	0.40	0.00	0.30	1

RESULTS

The results from the multinomial logistic regression are displayed in Table 2. Other than outside shoulder width on the Citywide Streets, every independent predictor variable in the dataset turned out to be significantly associated with mode choice. Also significant were the interaction terms of the street pattern classification variable by intersection density, the link to node ratio, and the average total number of lanes, respectively. We also added a three-way interaction of the street pattern type by both intersection density and the link to node ratio, which turned out to be significant. Due to all of the interaction terms, interpreting the results directly from Table 2 is complicated. Therefore, in interpreting the results we focus on the change in mode share predicted by the models based upon a discrete change to a single variable. Rather than trying to reconcile three different coefficients for a variable such as intersection density, this approach allows us to hold all other variables at their mean and simply observe how modes shares would change if the intersection density were different. The results in Table 3 were calculated for the six most frequently occurring street patterns.

Street Network Measures

Street Network Density

Intersection density had different effects depending on both the mode being considered as well as street pattern type. In terms of transit, increased intersection density was only associated with increased transit use in the radial Citywide Streets and gridded Neighborhood Streets ('RG') pattern; while in every other street pattern type, increased intersection density had little effect or a negative effect on transit mode share. With respect to both walking and biking, increased intersection density was almost always associated with an increase in both of these non-motorized mode shares.

Looking at the tributary Citywide Streets and tree-like Neighborhood Streets pattern type ('TT') as an example, the average walking and biking mode shares in a 'TT' street pattern are 2.3% and 1.7%, respectively, as shown in Table 3. In Table 3 we also present the predicted value for each mode share if we were, for example, to change the overall intersection density from 81 to 144 to 225 to 324 intersections/square-mile (these levels correspond to the number of intersections that would be found in a hypothetical 9x9, 12x12, 15x15, and 18x18 mile-square grid). The results suggest that walking would increase from 1.9% to 3.7% and biking would increase from 1.3% to 4.1% if intersection density increased from the low level of 81 to the high level of 324 intersections/square-mile. In other words, increasing intersection density from 81 to 324 in a tributary Citywide Streets and tree-like Neighborhood Streets pattern type ('TT') is associated with an increase in combined walking and biking mode shares from 3.2% to 7.8%.

In addition to overall intersection density, we also tested the density of dead end intersections as well as the density of Citywide / Inter-Neighborhood intersections in order to better understand the effects of the different mix of intersection types. Although the density of dead end cul-de-sacs was statistically significant, it did not result in much impact on driving mode share. However, an increase in dead end intersection density was generally associated with a decrease in both walking and biking mode shares and an increase in transit use. This result suggests that increasing the amount of dead ends in a street network increases the likelihood of a trip requiring a circuitous route, resulting in a negative impact on walking and biking. Interestingly, the same trend was also seen with the Citywide / Inter-Neighborhood intersection density variable. This suggests that networks with a high number of major intersections reduce the viability of walking or biking.

Street Connectivity

The overall trend for street connectivity was that increased link to node ratio was associated with a decrease in driving for all street pattern types. This ranged from very small reductions in driving mode share for most street patterns to the much more substantial shift away from driving (from 93.0% to 82.5% for an increase in the link to node ratio from 1.1 to 1.55) for a tributary Citywide Streets and gridded Neighborhood Streets pattern type ('TG').

In terms of transit, walking, and biking, the results for street connectivity were mixed, similar to those seen with dead end density. For instance, in street pattern types 'TT', 'RT', and 'RG', the more transit use that was associated with an increase in street connectivity was also accompanied by less walking and biking. Overall driving mode share remained consistent; rather, it was the mix of transit, walking, and biking mode shares that shifted.

Street Patterns

Based on the results of the statistical models, street patterns are highly significant in mode choices. Looking across Table 3, we can begin to compare the influence of street pattern type. However, a direct comparison is misleading because each of these streets patterns is, in practice, built at different densities with a wide range of complementary features. Therefore when considering mode share results with respect to the street pattern classification system, we need to keep in mind that, in actuality, certain street pattern types also tend to exhibit higher intersection densities, higher street connectivity, fewer lanes on Citywide Streets, more on-street parking, and a more complete network of curbs and sidewalks.

One interesting comparison that can be made is amongst the three network types with gridded Neighborhood Streets. Although all three types exhibit similar levels of street network density and street connectivity, the tributary Citywide Streets and gridded Neighborhood Streets pattern type ('TG') does not reach nearly the same level of walking and biking mode shares found in the other gridded Neighborhood street pattern types. Because street pattern type 'TG' has the least connected Citywide Street network, this result would suggest that both Citywide Street connectivity and Neighborhood Street connectivity are both important in facilitating non-automobile travel.

Data on Street Characteristics

The characteristics of the street that were considered in the analysis included the total number of lanes, outside shoulder width, as well as the presence of bike lanes, curbs or sidewalks, and the presence of raised and painted medians. Overall, the only one of these variables *not* significant in the mode choice models was the width of the outside shoulders. The results demonstrate that more lanes on the Citywide Streets may have conflicting effects on mode share, depending upon the street network type. For instance in the less connected tree-like Neighborhood Street networks, more lanes on the Citywide Streets was associated with more driving. This was also the case for the tributary Citywide Streets and gridded Neighborhood Streets pattern type ('TG'). On the other hand, in the gridded pattern types 'RG' and 'GG', we found a *decrease* in driving with more lanes on the Citywide streets.

A possible explanation is that in the less connected street patterns, most non-automobile travel must use the Citywide Street network for travel over any significant distance; thus, more travel lanes might see lower non-motorized mode shares due to a less desirable pedestrian or biking environment on these streets. Conversely in the more connected street networks, walking and biking trips can be done on the Neighborhood Streets for longer distance travel. Hence, more lanes on the Citywide Streets are less of a detriment than in the less connected street patterns.

Other street design features such as the presence of on-street parking, bike lanes, and curbs or sidewalks are all associated with less driving. This drop in driving was found for all street patterns and generally associated with increases in all three non-automobile modes of travel. Individually, the presence of any one of these factors seemed to have a maximum 5% reduction in driving mode share. For example, the presence of curbs or sidewalks on the Citywide Streets in a ‘GG’ street pattern type (gridded Citywide Streets and gridded Neighborhood Streets) resulted in a drop in driving from 93.0% to 77.9%. Although significant in the models, the presence of a raised median did not seem to have much of an influence on mode choice. However, a painted median tended to increase driving and decrease transit, walking, and biking mode shares for all street pattern types.

Miscellaneous Variables

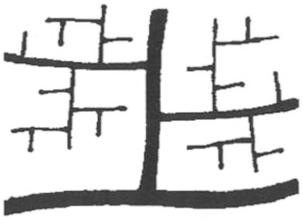
In terms of the control variables, higher vehicle volumes were associated with more walking but less use of transit and bicycles. The proxy for the activity level associated with a Block Group was significant and positively correlated with transit use and walking but negatively correlated with bicycling. The proxy for mixed land uses indicated that higher levels of mixed use were strongly associated with more transit, walking, and biking. With respect to distance from the city center, the results indicated more walking and biking but less transit use when closer to the downtown area. A Block Group bisected by or adjacent to a limited access highway was associated with more bicycling but less transit and walking. Higher incomes were also correlated with reductions to transit, walking, and biking mode shares.

Table 2 Multinomial Logistic Regression Mode Share Model

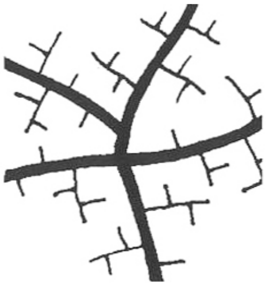
		Transit Model (with respect to Driving)			Pedestrian Model (with respect to Driving)			Bicycling Model (with respect to Driving)		
	Variables	**Coefficient**	**S.E.**	**β/S.E.**	**Coefficient**	**S.E.**	**β/S.E.**	**Coefficient**	**S.E.**	**β/S.E.**
	Intercept	-15.8925	1.1954	-13.2947	-2.0963	0.7042	-2.9769	-8.2641	1.0566	-7.8214
	Street Network Measures									
Street Pattern Type	'GG' = Citywide Grid, Neighborhood Grid	1.2496	1.2610	0.9910	-11.9819	0.8249	-14.5253	-9.7152	1.2336	-7.8755
	'GT' = Citywide Grid, Neighborhood Tree	6.3239	1.2801	4.9402	-4.3404	0.8498	-5.1076	-1.3507	1.2837	-1.0522
	'LT' = Citywide Linear, Neighborhood Tree	9.1772	1.3614	6.7410	3.1124	0.8919	3.4896	1.0323	1.4508	0.7115
	'RG' = Citywide Radial, Neighborhood Grid	15.1989	6.1852	2.4573	9.8073	7.9204	1.2382	34.3978	7.4238	4.6334
	'RT' = Citywide Radial, Neighborhood Tree	7.3611	1.4490	5.0801	-0.9243	1.0358	-0.8924	-0.3918	1.6290	-0.2405
	'TG' = Citywide Tributary, Neighborhood Grid	3.9161	1.4802	2.6457	-7.4373	1.2203	-6.0946	-7.4963	1.3955	-5.3718
	'TT' = Citywide Tributary, Neighborhood Tree	7.7071	1.2090	6.3748	-4.1307	0.7317	-5.6453	0.3033	1.0777	0.2814
	'LG' = Citywide Linear, Neighborhood Grid	-	-	-	-	-	-	-	-	-
	Intersection Density	0.0036	0.0005	6.8000	0.0013	0.0004	3.4759	0.0039	0.0006	6.8118
Interaction Terms	(Intersection Density)('GG')	0.0166	0.0017	9.7076	0.0336	0.0018	19.0909	0.0262	0.0027	9.8868
	(Intersection Density)('GT')	-0.0093	0.0027	-3.4925	-0.0002	0.0027	-0.0803	0.0075	0.0041	1.8480
	(Intersection Density)('LT')	-0.0319	0.0063	-5.1040	-0.0250	0.0062	-4.0323	-0.0213	0.0088	-2.4315
	(Intersection Density)('RG')	-0.0410	0.0214	-1.9159	-0.0438	0.0285	-1.5368	-0.1149	0.0269	-4.2714
	(Intersection Density)('RT')	-0.0186	0.0041	-4.5146	-0.0132	0.0040	-3.3333	0.0128	0.0064	1.9907
	(Intersection Density)('TG')	0.0058	0.0041	1.3981	0.0141	0.0052	2.7115	0.0114	0.0043	2.6389
	(Intersection Density)('TT')	-0.0155	0.0013	-11.7424	0.0126	0.0013	9.5455	-0.0059	0.0015	-3.9730
	(Intersection Density)('LG')	-	-	-	-	-	-	-	-	-
	Link to Node Ratio									
Interaction Terms	(Link to Node Ratio)('GG')	-1.2065	0.9278	-1.3004	8.4639	0.5983	14.1466	6.7743	0.9064	7.4739
	(Link to Node Ratio)('GT')	-4.1615	0.9502	-4.3796	2.9288	0.6304	4.6459	1.0618	0.9672	1.0978
	(Link to Node Ratio)('LT')	-6.7898	1.0526	-6.4505	-2.3966	0.7068	-3.3908	-0.0368	1.1827	-0.0311
	(Link to Node Ratio)('RG')	-11.8143	4.4388	-2.6616	-7.8482	5.6852	-1.3805	-24.1000	5.3444	-4.5094
	(Link to Node Ratio)('RT')	-5.4370	1.1035	-4.9271	0.0901	0.7906	0.1140	0.1136	1.2678	0.0896
	(Link to Node Ratio)('TG')	-0.9865	1.0760	-0.9168	7.2047	0.8762	8.2227	6.3816	1.0204	6.2540
	(Link to Node Ratio)('TT')	-5.2365	0.8944	-5.8548	3.2162	0.5400	5.9559	-0.4815	0.8047	-0.5984
	(Link to Node Ratio)('LG')	-	-	-	-	-	-	-	-	-
Interaction Terms	(Intersection Density)(Link to Node Ratio)('GG')	-0.0141	0.0012	-12.0513	-0.0225	0.0012	-18.2927	-0.0198	0.0018	-10.7609
	(Intersection Density)(Link to Node Ratio)('GT')	0.0041	0.0020	2.0553	0.0012	0.0021	0.5825	-0.0050	0.0031	-1.6052
	(Intersection Density)(Link to Node Ratio)('LT')	0.0241	0.0055	4.4059	0.0160	0.0054	2.9412	0.0168	0.0075	2.2311
	(Intersection Density)(Link to Node Ratio)('RG')	0.0284	0.0153	1.8562	0.0338	0.0204	1.6569	0.0806	0.0192	4.1979
	(Intersection Density)(Link to Node Ratio)('RT')	0.0127	0.0033	3.8720	0.0126	0.0031	4.0777	-0.0081	0.0052	-1.5689
	(Intersection Density)(Link to Node Ratio)('TG')	-0.0089	0.0029	-3.0941	-0.0125	0.0037	-3.3875	-0.0104	0.0030	-3.4899
	(Intersection Density)(Link to Node Ratio)('TT')	0.0099	0.0010	10.2280	-0.0096	0.0011	-9.0000	0.0060	0.0011	5.3304
	(Intersection Density)(Link to Node Ratio)('LG')	-	-	-	-	-	-	-	-	-
	Dead End Density	0.0054	0.0003	15.8601	-0.0058	0.0004	-13.7264	-0.0041	0.0005	-8.3636
	Citywide / Inter-Neighborhood Intersection Density	0.0005	0.0001	3.6090	-0.0022	0.0001	-15.5634	-0.0022	0.0002	-11.2953
	Curvilinear (0, 1)	0.0213	0.0195	1.0923	-0.2643	0.0249	-10.6145	0.3163	0.0266	11.8910
	Street Level Data									
	Avg. Total No. of Lanes	-0.2448	0.0108	-22.6667	-0.0414	0.0129	-3.2093	-0.0219	0.0155	-1.4129
Interaction Terms	(Avg. Total No. of Lanes)('GG')	0.3742	0.0160	23.3875	0.0980	0.0184	5.3261	0.2613	0.0232	11.2629
	(Avg. Total No. of Lanes)('GT')	-0.0731	0.0190	-3.8474	0.0303	0.0213	1.4225	-0.1486	0.0283	-5.2509
	(Avg. Total No. of Lanes)('LT')	0.1679	0.0281	5.9751	-0.0673	0.0342	-1.9678	-0.3748	0.0522	-7.1801
	(Avg. Total No. of Lanes)('RG')	0.5391	0.0395	13.6481	0.1776	0.0606	2.9307	0.1804	0.0584	3.0890
	(Avg. Total No. of Lanes)('RT')	0.0574	0.0248	2.3145	0.0756	0.0380	1.9895	-0.2627	0.0465	-5.6495
	(Avg. Total No. of Lanes)('TG')	-0.4274	0.0466	-9.1717	-0.5726	0.0548	-10.4489	-0.1813	0.0520	-3.4865
	(Avg. Total No. of Lanes)('TT')	-	-	-	-	-	-	-	-	-
	(Avg. Total No. of Lanes)('LG')	-	-	-	-	-	-	-	-	-
	Avg. Outside Shoulder Width	0.0427	0.0024	17.5000	0.0698	0.0026	26.6412	-0.0123	0.0034	-3.5860
	% of Citywide Street Length with Raised Median	0.1096	0.0141	7.7730	-0.1735	0.0153	-11.3399	0.3134	0.0195	16.0718
	% of Citywide Street Length with Painted Median	-0.1480	0.0137	-10.8029	-0.2241	0.0162	-13.8333	-0.2542	0.0193	-13.1710
	% of Citywide Street Length with On-Street Parking	0.3403	0.0226	15.0575	0.2375	0.0259	9.1699	0.4639	0.0315	14.7270
	% of Citywide Street Length with Bike Lanes	0.0584	0.0203	2.8768	0.1982	0.0230	8.6174	0.6220	0.0266	23.3835
	% of Citywide Streetd Length with Curbs	0.2808	0.0360	7.8000	0.5624	0.0398	14.1307	0.0073	0.0495	0.1471
	Miscellaneous									
	VMT (standardized from 0 to 1)	-0.6698	0.0914	-7.3282	1.2962	0.0899	14.4182	-1.9398	0.1833	-10.5827
	Proxy for Activity	1.8077	0.0350	51.6486	0.2195	0.0385	5.7013	-1.8507	0.0513	-36.0760
	Proxy for Mixed-Use	12.4131	0.2119	58.5800	9.5220	0.2106	45.2137	15.5296	0.2695	57.6237
	Distance from City Center (miles)	0.0351	0.0072	4.8750	-0.2934	0.0095	-30.8842	-0.3182	0.0122	-26.0820
	Bisecting or Adjacent Limted Access Highway (0, 1)	-0.2727	0.0150	-18.1800	-0.1232	0.0167	-7.3772	0.2675	0.0197	13.5787
	Income (standardized from 0 to 1)	-2.4035	0.0445	-54.0112	-4.8041	0.0542	-88.6365	-2.7475	0.0647	-42.4652

Table 3 Expected Change in Mode Shares

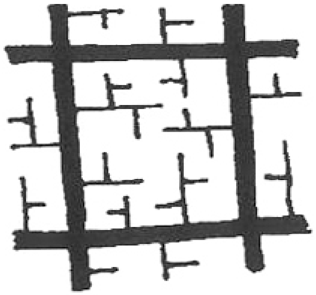
TT



RT



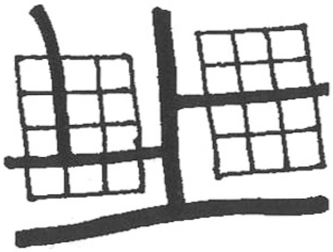
GT



	TT				RT				GT			
	Transit	**Walking**	**Biking**	**Driving**	**Transit**	**Walking**	**Biking**	**Driving**	**Transit**	**Walking**	**Biking**	**Driving**
Avg. Mode Share by Street Pattern Type	**3.66%**	**2.28%**	**1.71%**	**92.35%**	**1.80%**	**0.95%**	**0.54%**	**96.71%**	**2.35%**	**2.01%**	**0.98%**	**94.66%**
Intersection Density												
81	3.81%	1.94%	1.29%	92.96%	1.80%	0.82%	0.38%	97.00%	2.49%	1.65%	0.65%	95.21%
144	3.65%	2.30%	1.74%	92.31%	1.80%	0.99%	0.60%	96.62%	2.38%	1.93%	0.90%	94.79%
225	3.44%	2.85%	2.56%	91.15%	1.79%	1.25%	1.05%	95.91%	2.24%	2.36%	1.37%	94.03%
324	3.18%	3.69%	4.06%	89.07%	1.76%	1.66%	2.10%	94.47%	2.07%	3.00%	2.29%	92.65%
Dead End Density												
0	2.90%	2.91%	2.03%	92.16%	1.45%	1.20%	0.64%	96.72%	1.97%	2.42%	1.11%	94.49%
30	3.42%	2.45%	1.80%	92.33%	1.70%	1.00%	0.56%	96.73%	2.33%	2.04%	0.99%	94.65%
60	4.02%	2.06%	1.59%	92.33%	2.01%	0.84%	0.50%	96.66%	2.74%	1.71%	0.87%	94.68%
Citywide / Inter-Neighborhood Intersection Density												
0	3.61%	2.42%	1.81%	92.17%	1.78%	1.00%	0.57%	96.66%	2.30%	2.21%	1.07%	94.42%
60	3.73%	2.13%	1.60%	92.55%	1.83%	0.88%	0.50%	96.79%	2.37%	1.94%	0.94%	94.74%
120	3.85%	1.87%	1.41%	92.88%	1.89%	0.77%	0.44%	96.91%	2.45%	1.70%	0.83%	95.02%
Link to Node Ratio												
1.1	3.42%	2.40%	1.74%	92.44%	1.60%	1.05%	0.62%	96.74%	1.88%	1.96%	1.04%	95.12%
1.25	4.17%	2.05%	1.65%	92.13%	1.97%	0.88%	0.48%	96.67%	2.41%	2.02%	0.97%	94.60%
1.4	5.06%	1.75%	1.55%	91.63%	2.43%	0.74%	0.38%	96.46%	3.08%	2.08%	0.90%	93.94%
1.55	6.14%	1.50%	1.46%	90.91%	2.99%	0.62%	0.29%	96.10%	3.93%	2.13%	0.84%	93.10%
Avg. No. of Lanes on Citywide Streets												
2	4.48%	2.34%	1.72%	91.46%	2.33%	0.90%	0.80%	95.97%	3.44%	2.01%	1.19%	93.36%
4	2.80%	2.19%	1.68%	93.32%	1.62%	0.97%	0.46%	96.96%	1.86%	2.01%	0.86%	95.27%
6	1.74%	2.05%	1.63%	94.58%	1.12%	1.04%	0.26%	97.58%	1.00%	1.99%	0.62%	96.40%
Bisecting or Adjacent to Limited Access Highway (0, 1)												
0	3.99%	2.36%	1.86%	91.79%	1.92%	0.97%	0.57%	96.54%	2.49%	2.06%	1.03%	94.41%
1	3.09%	2.12%	1.45%	93.34%	1.47%	0.87%	0.44%	97.22%	1.92%	1.84%	0.80%	95.44%
Distance from City Center (miles)												
0	3.30%	4.03%	3.18%	89.49%	1.55%	2.59%	1.61%	94.24%	2.17%	3.29%	1.67%	92.86%
1	3.48%	3.06%	2.36%	91.11%	1.62%	1.96%	1.19%	95.24%	2.28%	2.49%	1.23%	94.01%
2	3.65%	2.31%	1.74%	92.30%	1.69%	1.47%	0.87%	95.97%	2.38%	1.87%	0.90%	94.85%
3	3.82%	1.74%	1.27%	93.17%	1.76%	1.10%	0.64%	96.50%	2.48%	1.40%	0.66%	95.45%
4	3.98%	1.31%	0.93%	93.78%	1.83%	0.82%	0.46%	96.88%	2.58%	1.05%	0.48%	95.88%
% of Citywide Street Length with On-Street Parking												
0%	3.24%	2.10%	1.44%	93.22%	1.63%	0.89%	0.47%	97.01%	2.01%	1.81%	0.79%	95.39%
50%	3.79%	2.33%	1.79%	92.08%	1.93%	0.99%	0.59%	96.49%	2.37%	2.02%	0.99%	94.63%
100%	4.43%	2.59%	2.23%	90.75%	2.27%	1.11%	0.74%	95.88%	2.78%	2.25%	1.23%	93.74%
% of Citywide Street Length with Bike Lanes												
0%	3.61%	2.15%	1.42%	92.81%	1.76%	0.88%	0.42%	96.93%	2.33%	1.93%	0.85%	94.90%
50%	3.69%	2.36%	1.92%	92.03%	1.81%	0.97%	0.58%	96.64%	2.38%	2.11%	1.15%	94.35%
100%	3.76%	2.58%	2.59%	91.07%	1.86%	1.07%	0.79%	96.29%	2.44%	2.32%	1.56%	93.68%
% of Citywide Street Length with Curbs												
0%	2.97%	1.48%	1.73%	93.82%	1.45%	0.61%	0.54%	97.40%	1.89%	1.27%	0.98%	95.86%
50%	3.39%	1.94%	1.72%	92.95%	1.66%	0.81%	0.54%	96.99%	2.15%	1.68%	0.98%	95.19%
100%	3.86%	2.54%	1.70%	91.90%	1.90%	1.06%	0.54%	96.50%	2.46%	2.20%	0.98%	94.36%
% of Citywide Street Length with Raised Medians												
0%	3.46%	2.51%	1.45%	92.59%	1.68%	1.06%	0.44%	96.82%	2.22%	2.21%	0.82%	94.74%
50%	3.65%	2.29%	1.69%	92.37%	1.77%	0.97%	0.51%	96.74%	2.34%	2.03%	0.96%	94.67%
100%	3.84%	2.10%	1.97%	92.09%	1.87%	0.89%	0.60%	96.64%	2.47%	1.86%	1.12%	94.55%
% of Citywide Street Length with Painted Medians												
0%	3.91%	2.52%	1.92%	91.65%	1.91%	1.04%	0.60%	96.44%	2.54%	2.26%	1.12%	94.09%
50%	3.66%	2.27%	1.71%	92.36%	1.78%	0.94%	0.53%	96.75%	2.37%	2.03%	0.99%	94.61%
100%	3.42%	2.05%	1.51%	93.02%	1.66%	0.84%	0.47%	97.03%	2.21%	1.83%	0.87%	95.09%

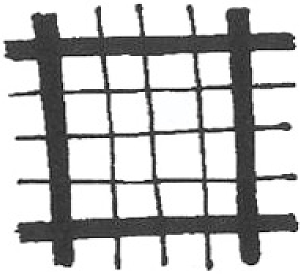
Table 3 Expected Change in Mode Shares (continued)

TG



RG

GG



	TG				RG				GG			
	Transit	**Walking**	**Biking**	**Driving**	**Transit**	**Walking**	**Biking**	**Driving**	**Transit**	**Walking**	**Biking**	**Driving**
Avg. Mode Share by Street Pattern Type	**4.18%**	**3.93%**	**3.39%**	**88.51%**	**7.73%**	**3.65%**	**4.66%**	**83.95%**	**9.00%**	**8.79%**	**4.09%**	**78.13%**
Intersection Density												
81	5.94%	4.69%	2.72%	86.64%	5.94%	1.73%	5.59%	86.74%	8.93%	5.08%	2.84%	83.15%
144	5.10%	4.35%	3.00%	87.55%	6.45%	2.18%	5.30%	86.08%	8.98%	6.14%	3.23%	81.65%
225	4.19%	3.93%	3.38%	88.50%	7.15%	2.91%	4.94%	85.00%	9.01%	7.81%	3.79%	79.39%
324	3.27%	3.47%	3.91%	89.35%	8.06%	4.13%	4.51%	83.29%	8.96%	10.40%	4.56%	76.08%
Dead End Density												
0	3.67%	4.48%	3.71%	88.14%	7.03%	4.04%	5.01%	83.92%	8.27%	9.54%	4.33%	77.85%
30	4.34%	3.78%	3.29%	88.59%	8.27%	3.39%	4.42%	83.91%	9.80%	8.06%	3.85%	78.30%
60	5.12%	3.18%	2.92%	88.78%	9.70%	2.84%	3.89%	83.57%	11.53%	6.77%	3.40%	78.30%
Citywide / Inter-Neighborhood Intersection Density												
0	3.98%	4.60%	3.96%	87.47%	7.16%	4.65%	5.92%	82.27%	8.07%	11.55%	5.35%	75.03%
60	4.13%	4.07%	3.50%	88.30%	7.45%	4.12%	5.25%	83.18%	8.46%	10.31%	4.78%	76.45%
120	4.29%	3.59%	3.10%	89.02%	7.74%	3.64%	4.65%	83.97%	8.85%	9.17%	4.27%	77.70%
Link to Node Ratio												
1.1	2.58%	2.87%	1.59%	92.95%	5.02%	4.69%	6.95%	83.34%	8.40%	9.93%	3.21%	78.47%
1.25	3.49%	3.50%	2.55%	90.46%	6.41%	4.09%	5.57%	83.92%	8.69%	9.35%	3.62%	78.34%
1.4	4.67%	4.22%	4.05%	87.06%	8.13%	3.54%	4.44%	83.89%	8.99%	8.80%	4.08%	78.13%
1.55	6.16%	5.01%	6.32%	82.52%	10.22%	3.04%	3.51%	83.23%	9.29%	8.28%	4.59%	77.85%
Avg. No. of Lanes on Citywide Streets												
2	7.15%	6.38%	3.80%	82.66%	6.71%	3.45%	4.36%	85.48%	8.28%	8.57%	3.45%	79.70%
4	2.10%	2.10%	2.85%	92.95%	11.18%	4.20%	5.53%	79.09%	10.16%	9.09%	5.27%	75.48%
6	0.57%	0.64%	1.97%	96.82%	17.93%	4.90%	6.76%	70.40%	12.26%	9.48%	7.93%	70.33%
Bisecting or Adjacent to Limited Access Highway (0, 1)												
0	4.53%	4.06%	3.67%	87.74%	8.02%	3.70%	4.83%	83.45%	9.37%	8.91%	4.25%	77.47%
1	3.54%	3.68%	2.88%	89.91%	6.32%	3.39%	3.83%	86.46%	7.45%	8.23%	3.40%	80.92%
Distance from City Center (miles)												
0	3.88%	5.47%	4.86%	85.79%	7.09%	5.23%	6.91%	80.77%	8.39%	11.10%	5.28%	75.23%
1	4.12%	4.19%	3.63%	88.06%	7.57%	4.02%	5.18%	83.23%	9.04%	8.62%	4.00%	78.33%
2	4.35%	3.18%	2.69%	89.77%	8.01%	3.06%	3.85%	85.07%	9.65%	6.62%	3.00%	80.72%
3	4.57%	2.41%	1.99%	91.04%	8.43%	2.32%	2.84%	86.40%	10.22%	5.05%	2.23%	82.50%
4	4.78%	1.81%	1.46%	91.95%	8.83%	1.75%	2.09%	87.33%	10.75%	3.82%	1.65%	83.78%
% of Citywide Street Length with On-Street Parking												
0%	3.58%	3.54%	2.72%	90.16%	6.24%	3.18%	3.43%	87.15%	7.19%	7.63%	2.96%	82.22%
50%	4.16%	3.92%	3.37%	88.55%	7.22%	3.50%	4.23%	85.06%	8.27%	8.34%	3.62%	79.78%
100%	4.83%	4.32%	4.16%	86.69%	8.32%	3.83%	5.18%	82.68%	9.47%	9.07%	4.41%	77.06%
% of Citywide Street Length with Bike Lanes												
0%	4.13%	3.67%	2.67%	89.53%	7.71%	3.55%	4.21%	84.54%	8.98%	8.53%	3.66%	78.83%
50%	4.19%	4.00%	3.60%	88.22%	7.77%	3.84%	5.62%	82.77%	9.02%	9.19%	4.87%	76.92%
100%	4.23%	4.33%	4.82%	86.62%	7.79%	4.13%	7.47%	80.61%	9.01%	9.86%	6.46%	74.67%
% of Citywide Street Length with Curbs												
0%	3.36%	2.47%	3.45%	90.72%	6.23%	2.29%	4.78%	86.69%	7.29%	5.43%	4.31%	82.96%
50%	3.81%	3.23%	3.42%	89.54%	7.05%	2.99%	4.72%	85.24%	8.16%	7.00%	4.21%	80.64%
100%	4.32%	4.21%	3.37%	88.10%	7.95%	3.88%	4.64%	83.53%	9.07%	8.95%	4.08%	77.90%
% of Citywide Street Length with Raised Medians												
0%	3.96%	4.31%	2.89%	88.83%	7.29%	4.10%	3.88%	84.72%	8.59%	9.52%	3.56%	78.33%
50%	4.17%	3.94%	3.37%	88.52%	7.65%	3.73%	4.51%	84.11%	9.04%	8.71%	4.15%	78.09%
100%	4.39%	3.59%	3.93%	88.09%	8.01%	3.39%	5.22%	83.37%	9.51%	7.94%	4.84%	77.71%
% of Citywide Street Length with Painted Medians												
0%	4.44%	4.33%	3.79%	87.45%	7.84%	3.73%	4.78%	83.64%	9.28%	9.27%	4.35%	77.10%
50%	4.17%	3.92%	3.38%	88.53%	7.39%	3.39%	4.28%	84.94%	8.81%	8.47%	3.92%	78.81%
100%	3.92%	3.54%	3.01%	89.53%	6.96%	3.07%	3.82%	86.14%	8.34%	7.73%	3.52%	80.41%

CONCLUSION

The aim of this research was to learn more about how street networks influence the diversity of modes in a transportation system. Our results suggest that all three of the fundamental measures of a street network – street connectivity, street network density, and street patterns – are highly significant and associated with influencing the choice to drive, walk, bike, or take transit. Although this research concentrated on journey-to-work mode share data, much of the existing literature showed an even greater influence of street network characteristics on non-work trips. In carrying out this inquiry, we controlled for a range of factors including vehicle volumes, activity levels, income levels, and proximity to limited access highways or the downtown area. The basis for this analysis was a GIS database encompassing over 1,000 census Block Groups in 24 California cities.

Street pattern type played a considerable role in mode choice. However, due to several significant interaction terms, it is important to consider street pattern type in combination with street network density, street connectivity, and street characteristics. Increased street network density, in terms of intersection density, was generally associated with more walking and biking. At the same time, increased street connectivity, as measured by the link to node ratio, was generally associated with a decrease in driving. While higher intersection density generally equates to an increase in conflict points, more walking and biking in these street networks does not necessarily entail a reduction in safety. In fact, the results of the initial research paper on these cities indicate that the highest risk of fatal or severe road crashes occur with very low intersection density and safety outcomes improve as the intersection density increases (4).

The presence of street features commonly associated with more pedestrian and bicycle friendly places – such as on-street parking, bike lanes, and sidewalks – were generally correlated with more walking, biking, and transit use. However, the average number of lanes on the Citywide Streets had very different associations with transit, walking, and biking mode shares, depending upon the street pattern type. Interestingly, while more travel lanes were associated with reductions in transit, walking, and biking mode shares in the less connected street pattern types, more lanes were also associated with increases in these mode shares for the more connected street pattern types.

For all types of street patterns, street network characteristics and street design factors play a major role in how people use the transportation system on a daily basis. Our results suggest that the dense, gridded street network with more urban street features are associated with much more walking and biking. Providing such a range of travel options in the transportation system increases efficiency, enhances flexibility, promotes equity, and is a better overall use of limited resources.

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