Street Network Types and Road Safety:
A Study of 24 California Cities

Wesley E. Marshall, Ph.D., P.E.

University of Connecticut
Center for Transportation and Urban Planning
Civil & Environmental Engineering

Present Contact Information:

University of Colorado Denver
Department of Civil Engineering
1200 Larimer Street
Campus Box 113
Denver, CO 80217
TEL: (303) 352-3741 FAX: (303) 556-2368
wesley.marshall@ucdenver.edu

Norman W. Garrick, Ph.D.

University of Connecticut
Center for Transportation and Urban Planning
Civil & Environmental Engineering
U-37, Storrs, CT 06269-2037
TEL: (860) 486-2990 FAX: (860) 486-2298
norman.garrick@uconn.edu

August 2009

Urban Design International (in print)

ABSTRACT

The paper examines the role of the street network in road safety outcomes. Data on more than 130,000 crashes occurring over nine years in 24 medium-sized California cities was input into a geographic information system (GIS) and evaluated against principal measures of street network density and connectivity at the Census Block Group level. Few studies have taken this more comprehensive approach of looking at the complete street network when it comes to safety, partly because until now this kind of holistic assessment would have been very difficult without recent advances in research tools such as GIS.

The results of this study suggest that street network characteristics do in fact play a role in road safety outcomes. Although the underlying factors contributing to this role are not yet known, our analysis showed safety outcomes to be associated with street network density. More specifically, our results indicate that the highest risk of fatal or severe crashes occurs with very low street network density and safety outcomes improve as the intersection density increases.

KEY WORDS

Street Networks, Street Patterns, Street Connectivity, Road Safety, Community Design

INTRODUCTION

With the growing interest in smart growth, traditional street patterns are returning in some quarters. Coincidental with this trend is a need for a more comprehensive approach to road safety that takes into account the complete street network. When it comes to trying to make our roads safer, we tend to focus on finding the most problematic locations and fixing those individual roads or intersections. The existing research follows this trend with most studies looking to distinguish amongst the safety outcomes of individual road segments or intersections. This traditional approach to road safety is by no means obsolete; the question this research raises is whether there is more to the story. More specifically, what role, if any, does the way we build our street network play in determining safety outcomes?

The basis for this research is an extensive dataset we developed based upon nine years of road safety records for 477 California cities. Focusing on the 159 cities with populations between 30,000 and 150,000, we found a wide variation of road fatality rates ranging from 0 to 23.6 fatalities per 100,000 people. Interestingly, the cities with lower fatality rates were not necessarily the ones where fewer crashes occurred but rather where the crashes that did occur were less severe. Such considerable differences in safety outcomes suggest that trying to figure out the factors contributing to these variations could be valuable in better understanding the community and street design characteristics that affect road safety. This study is based upon an empirical analysis of more than 130,000 crashes occurring over nine years in over 1,000 census Block Groups from 24 of these California cities.

The ultimate goal of this research is to increase our understanding of the underlying factors in the street network that shape safety outcomes. Few studies have taken this more comprehensive approach of looking at the complete street network when it comes to safety, partly because this kind of holistic assessment would have been very difficult, if not impossible, to carry out in the past without modern research tools such as GIS and the comprehensive databases that are now more widely available. Combined with the conventional road safety research focusing on the characteristics of individual streets and intersections, the findings of this study could help in the crafting of planning policies for reducing road fatalities for all users of the transportation system.

LITERATURE REVIEW

Over the course of the last century, there has been a dramatic shift in American street patterns and community design. Figure 1 depicts one researcher's view of this evolution of the street network starting with the medieval pattern shown on the far left of the figure. Such organic street networks eventually evolved into the traditional gridded street layouts strongly associated with the American streetcar suburbs mostly developed in the first two decades of the 1900s (Taylor 2001). The prevailing patterns over that time span were predicated upon walking being the most important mode of travel.

Starting in the later 1920s, a number of forces converged resulting in a gradual devolution in our approach to the design of both streets and street networks. By the end of World War II in the mid 1940s, the more traditional street network had largely been discarded essentially in an effort to better accommodate vehicular traffic.

The emphasis in Stephen Marshall's sketch below is on the change in the shape and connectivity of the street patterns going from the fully-connected networks of the 1920s to the increasingly more dendritic, tree-like networks of the post 1950 period. But it was not just the connectivity and the shape of the streets that changed but also the density – with increasingly less dense street networks over the last half of the 1900s. These various changes are often conflated by many observers of this evolution in the street network.

[Figure 1 about here]

One of the most important milestones in this evolution in the design of American street networks occurred in 1928 when architects Charles Stein and Henry Wright brought their interpretation of the English Garden City to the United States with Radburn, New Jersey (Canada Mortgage and Housing Corporation 2005). The Radburn plan was one of the first to challenge the traditional grid system with a network of oversized neighborhood blocks between thirty and fifty acres called “superblocks” (Southworth and Ben-Joseph 1997). Streets in this superblock structure were organized in the hierarchical structure that has become the norm in contemporary street networks. This structure included the liberal use of cul-de-sac streets. The intent was to eliminate the through movement of traffic on most residential streets and instead relegate them to collector roads and arterials. Stein reasoned:

> “The automobile was a disturbing menace to city life in the U.S.A…. The flood of motors had already made the gridiron pattern, which had formed the framework for urban real estate for over a century, as obsolete as a fortified town wall…. The checkerboard pattern made all the streets equally inviting to through traffic. Quiet and peaceful repose disappeared along with safety” (Southworth and Ben-Joseph 1997).

Stein’s statement that ‘all the streets are equally inviting to traffic’ is a common misperception of the gridiron patterns. In the best models of gridiron street patterns in America, such as that of Savannah (GA), there is a clear hierarchy of streets reinforced by subtle variations in design.

Interestingly, the most influential effort at promoting new types of networks 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 (Tunnard 1963). The bulletins re-enforced the concerns of Stein about grid networks, calling the layout monotonous with little character or appeal, uneconomical, and a safety issue (Southworth and Ben-Joseph 1997). The publications endorsed hierarchical streets layouts like those used by Stein in Radburn that minimized through traffic. They 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 (Southworth and Ben-Joseph 1997). 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 the driving force in determining the types of road networks that got built at the local 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. One of the few studies we found that looked at the performance of street networks and safety was a five-year study conducted by the Institute of Transportation Engineers (ITE) in Los Angeles in the early 1950s. This study reported a significantly lower number of crashes in hierarchical cul-de-sac layouts when compared to grid layouts (Southworth and Ben-Joseph 1997; Southworth and Ben-Joseph 2004). However, this study paid little attention to some important considerations including the actual street patterns, the density of these street networks, the potential for crash migration, or the observed levels of crash severity.

Nonetheless, this study was likely one of the factors that led ITE to change its engineering standards to favor the hierarchical system of streets. 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 (Southworth and Ben-Joseph 1997).

Despite their fall from favor, connected street networks were still widely considered to have some advantages, including directness of travel and more route choice options. Notwithstanding these advantages, the prevailing view seemed to have been that articulated by the Radburn architect Charles Stein, in that the trade-off for these benefits was increased through traffic on local roads and a reduction in safety (Lerner-Lam, Celniker et al. 1992).

The result was that from the 1950s through the late 1980s, very few new developments in the United States featured a gridded street pattern; instead, hierarchical layouts became the standard (Southworth and Ben-Joseph 1997). By 1992, this pattern of building hierarchical street networks had started to change with over fifty neo-traditional neighborhood design projects either in the planning stages or in construction (Lerner-Lam, Celniker et al. 1992). With this small influx of more traditional street designs came a growing body of research specifically looking at the implication of street patterns on factors such as car use and congestion.

Most of this initial research in the early 1990s looking at the influence of the street network was theoretical and based on simulation programs. One simulation study sponsored by the American Society of Civil Engineers (ASCE) concluded that streets networks heavy on cul-de-sac design 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 (Taylor 2001). Overall VMT and traffic reductions with increased street connectivity make intuitive sense, but this relationship does not necessarily impact safety except to the extent that a lower VMT should mean fewer crashes due to the lower exposure rate. But the ASCE study also found that the connected network reduced travel times and speeds, factors that could theoretically impact safety outcomes as well.

In spite of these results, few, if any, of these studies even mention the potential for the street network impacting road safety outcomes. To our knowledge, the relationship between street network types and road safety has not been the subject of much contemporary research. When safety is mentioned, the focus tends to be on the relationship of street connectivity to fire and emergency efficiency and cost. For example, a 2000 study in Raleigh, North Carolina and a more recent one in Charlotte, North Carolina found that increased connectivity and a denser road network dramatically increased the total service area and decreased the potential response time for emergency responders (Handy, Paterson et al. 2003).

As we have stated, most existing road safety research focuses on individual road segment or intersection characteristics. But some of this safety research has hinted at the potential relationship between street networks and road safety. For example, researchers have linked overall higher crash rates to urban roads compared to higher fatality rates on uncongested rural roads (Janke 1991; Litman 2008). In a study from England, Graham and Glaister found that pedestrian casualties increase as intersection density increases from a low to medium level but then decrease as intersection density moves toward a high level (Graham and Glaister 2003). Also, Noland and Quddus found that wards with densely populated areas had fewer traffic fatalities and that increased minor street length densities were associated with decreases in slight injuries (Noland and Quddus 2004). These results notwithstanding, researchers continue to overlook the potential impact of the street network on road safety outcomes.

Looking back at street network literature, the authors of the ASCE study found that more connected networks tended to see a reduction in travel speeds while other researchers have shown that even small reductions in vehicle speeds can help increase road safety, especially in terms of crash severity (Leaf and Preusser 1998; Stuster and Coffman 1998; Litman 2008). A more recent report jointly published by the OECD and the European Conference of Ministers of Transport (ECMT) found that more than 50% of drivers at any time are above the speed limit and that speeding is a contributing factor in one-third of all crashes. The report goes on to say that reducing average vehicle speeds by only 5% will reduce injury crashes by 10% and road fatalities by 20% (Organisation for Economic Co-operation and Development (OECD) and European Conference of Ministers of Transport (ECMT) 2006). These results showing lower speeds on connected networks hints at the potential impact on safety of different types of networks, but as we have stated, this potential for the street network to impact safety has, to our knowledge, not been the subject of extensive research. With the continued growth of neo-traditional neighborhood design and smart growth, there is a pressing need to better understand street networks and their impact on road safety. Our goal with this research is to start to address this void.

DATA & METHODOLOGY

The groundwork for this investigation started with a preliminary analysis of fatality rates in 159 California cities. This original assessment focused on California cities because of the easy availability of data and the large number and diversity of city types. Also by focusing just on California cities, we maintained consistency with issues such as road classification, crash reporting methodology, and crash severity definition. Based on a notable relationship between road safety and the year of incorporation of the city, with many of the post 1950s cities experiencing higher fatality rates, we decided to conduct a more in-depth analysis of a smaller number of these California cities.

This section details the city selection process, summarizes the data we collected, and overviews the processing of this data. As stated in the literature review, the 1950s represent a transition period when the typical street network changed from a highly-connected grid system into a sparser, more dendritic arrangement (Southworth and Ben-Joseph 1997). The possibility that the type of street network could play a role in road safety supports the case for taking a more comprehensive approach than current safety research. As a result, the central information collected for this study consisted of data for assessing the street network and crash outcomes.

City Selection

In order to carry out the more comprehensive examination of street network characteristics and safety outcomes, we selected twelve cities with good road safety records and twelve with poorer road safety records located throughout California. The selected cities are listed below:

Safer Cities

- Alameda
- Berkeley
- Chico

Less Safe Cities

- Antioch
- Apple Valley
- Carlsbad

- Cupertino
- Danville
- Davis
- La Habra
- Palo Alto
- San Luis Obispo
- San Mateo
- Santa Barbara
- Santa Cruz
- Madera
- Morgan Hill
- Perris
- Redding
- Rialto
- Temecula
- Turlock
- Victorville
- West Sacramento

The criterion for grouping the cities was fatality rate. The cities were also selected to be similar in population. The selected cities made for good test cases in this study because they are cities where, for the most part, traffic is locally generated. Table 1 summarizes crash data used in the city selection process as well as data on the year of incorporation, income, and vehicle miles traveled (VMT). The year of incorporation was not taken into account in grouping the cities, but the fact that the safer cities were on average incorporated 37 years before the less safe cities suggests that the two groups might also have very different street networks.

[Table 1 about here]

Income was considered as one measure of socio-economic differences in these cities. The safer cities had an average median income over 22% higher than the less safe group; this may be indicative of differences in the vehicle fleet and may play a role in the safety outcomes. On the other hand, vehicle miles traveled (VMT) estimates for the two groups of cities turned out to be within 5% of one another. VMT was estimated from average annual daily traffic (AADT) counts that the Federal Highway Administration (FHWA) collects as part of the Highway Performance Monitoring System (HPMS).

Upon selection of the 24 study cities, the focus turned toward expanding the database and collecting data at a finer resolution than the city scale, particularly in terms of street network and crash data.

Street Network Data

The transportation network information came from multiple sources including the U.S. Census 2000 TIGER line files, the California Spatial Information Library, and the California Department of Transportation. Census TIGER files from the year 2000 were selected to best match the crash data, which spans from 1997 to 2005. ArcGIS was used to facilitate much of the data processing including computing centerline miles of each road type (highway, major road, and local roads) as well as the number of road links, intersections, and dead ends. These ArcGIS counts were used to calculate street network measures including connectivity indices such as the link to node ratio and the connected node ratio as well as street network density indices such as intersection density, dead end density, and average block size.

For the link to node ratio, the number of links (road segments between intersections) is divided by the number of nodes (or intersections) (Ewing 1996; Litman 2005). The node count in this case represents the total number of intersections, including the dead ends of cul-de-sacs. As a result, a higher number of dead ends effectively reduces the link to node ratio of the network; accordingly, the higher the link to node value, the more connected the street network. The connected node ratio (CNR) represents the number of real (non-dead end) intersections divided by the total number of intersections including dead ends; CNR is also a measure of connectivity (Handy, Paterson et al. 2003). Most literature uses a link to node ratio of 1.4 and a CNR of 0.75 as the minimum connectivity required for a walkable community (Handy, Paterson et al. 2003; Litman 2005).

Intersection density is typically measured as the number of intersections per unit area, typically a square mile. Overall intersection density includes the total number of nodes or intersections, including dead ends; alternatively, real intersection density does not include dead ends in the calculation and dead end intersection density only includes cul-de-sacs.

Average block size is simply the average area of the street blocks within a specified area. Although seemingly straightforward, average block size can be somewhat problematic for certain street patterns that are irregular with blocks that are difficult to define.

Average block size and intersection density represent street network density, as opposed to street connectivity. One significant problem seen throughout the existing literature is the inconsistent application of street network measures. In many cases, the authors use a street network density measure to assess what they call connectivity; but a connected street network is not necessarily a dense street network and vice versa. Our study looks at both network density and street connectivity in order to get a clear understanding of how each of these characteristics affects safety outcomes.

Census data from the year 2000 was also collected and then analyzed with the street network data at both the city scale and U.S. Census Block Group level of geography. A Block Group is theoretically designed to average 250 to 500 housing units and to vary in area depending upon housing density. The result was over 1,000 distinctly populated Block Groups at an average of approximately 43 Block Groups per city.

One additional item of interest that we looked at was an estimate of when various parts of the road network were developed. Adapted from a methodology developed by James Spero of the California Fire and Resource Assessment Program (FRAP) for the purposes of assessing fire protection risk and Tim Duane of UC Berkeley to assess the historic levels and spatial distribution of human settlement in the Sierra Nevada region, we estimated the road network development of our cities. This was done by using the U.S. Census of Population and Housing long form question, *Year Structure Built*, to tally the number of housing units built by decade for each Block Group (Duane 1996; California Environmental Protection Agency 2002). The purpose of this effort was to provide a comprehensive assessment of the evolution of the street network patterns with time of these California cities.

Figure 2 depicts the road network and development patterns (shown at the same scale for comparison) of two cities from each group. A visual assessment of Figure 2 reveals that each of the four cities has an older area with a gridiron street network; however, the cities from the less safe group, Turlock and Rialto, have been expanded upon more recently while much of Santa Cruz and San Mateo were built in the first half of the twentieth century. These patterns are generally representative of the other cities within their respective groups. Additionally, Figure 3 presents Block Group level examples for each year of development period from our database. Each time period illustrates typical street network characteristics in terms of street patterns, street network density, and street connectivity.

[Figure 2 about here]

[Figure 3 about here]

Crash Data

Crash data was collected from two sources for the years 1997 through 2005: fatal crashes from the Fatality Analysis Reporting System (FARS) and non-fatal crashes from the California Highway Patrol Statewide Integrated Traffic Records System database (SWITRS). The California crash databases specify five levels of crash outcome severity: fatal, severe injury, visible injury, minor injury, and property damage only (PDO).

For our analysis, we needed to associate each crash with its correct location on the map using the geocoding capabilities of GIS. For the fatal crashes occurring after 2001, these were coded with latitude and longitude information in the FARS database and could easily be located. For the rest of the fatal crashes and all of the non-fatal crashes, our goal was a successful geocode that would place the crash at the nearest intersection on the road where the crash occurred. The initial geocoding effort found a success rate of approximately 86%. A second geocoding attempt was made using a list of alternate road names and route numbers, which brought the success rate up to over 98%. Two large-scale crash geocoding projects in South Carolina and Riverside County, California found an 80% success rate, so these results compare favorably (Filian and Higelin 1996; Sarusua, Ogle et al. 2008).

ANALYSIS

In the following sections, we first analyze the data at the city scale and then at the smaller Block Group level of geography. The scope of the phase of the research reported here is to further our understanding of what can be determined with respect to road safety by analyzing the street network.

Analysis at the City Scale

Table 2 summarizes the city scale results. As determined during the city selection process, the average populations of the two groups of cities are within 9% of one another and the safer cities are about twice as dense as the less safe cities. In terms of the street network, the main difference seems to be related more to street network density rather than connectivity. While the density of total intersections in the less safe cities is nearly 38% lower than that of the safer cities, values such as the link to node ratio and the connected node ratio are similar for the two groups of cities. Both sets of connectivity indices (the link to node ratio and connected node ratio) seem to characterize what would be considered moderate street connectivity for both sets of cities (Handy, Paterson et al. 2003). Additionally, the difference in major road densities between the safe and less safe cities is also noteworthy in that the lower density of major roads in the less safe cities might be indicative of the relative size of these roads. With a lower density of roads, there might be a tendency to build much bigger roads to serve the traffic volumes.

Since the goal of this research is to evaluate the potential relationship between surface street network characteristics and safety, we felt it would be reasonable to remove the limited access highway crashes from the analysis. However, we are cognizant of the fact that a potentially valid reason for not removing the highway crashes is that some local road networks, whether due to reasons such as limited connectivity or high traffic congestion, have the potential to generate more highway trips and possibly an overall crash migration from the local street network onto the highways. As a result, we examined the safety results at the city scale for all crashes and then again with the highway crashes excluded as shown in Table 2. Since the results without the highway crashes closely resemble those for all crashes, we made the assumption that there was no significant crash migration in one set of cities as compared to the other and feel that it is justifiable to focus our analysis on the data with the highway crashes excluded.

For the crash analysis at the city scale, we present fatal and severe crash rates per 100,000 population as well as three crash risk factors.

- Risk of Injury = Chance of a crash resulting in any injury including a fatality
- Risk of Severe Injury = Chance of a crash resulting in a severe injury or fatality
- Risk of Fatality = Chance of a crash resulting in a fatality

All three risk factors are calculated for each city and averaged across both the safer and less safe groups of cities.

Overall, we found similar rates for severe injury crashes in the two groups of cities but a much higher rate for fatal crashes in the less safe cities. In fact, the rate of fatal crashes per 100,000 population on the surface street network is more than 270% higher in the less safe cities than in the safer cities; in comparison, the rate of severe injury crashes is just over 14% higher in the less safe cities.

Contributing to this outcome is the fact that the risk of injury is about the same for both sets of cities but the risk of fatality is much higher for the less safe cities. In other words, the two groups of cities differ not so much in terms of the number of crashes but more in terms of the level of severity of the crashes that do occur. As the crash outcome increases in severity, the difference between the two cities becomes even more pronounced.

[Table 2 about here]

Analysis at the Block Group Scale

In order to establish a clearer indication of the impact on safety outcomes of the street network, we analyzed the cities based upon U.S. Census Block Groups. If our results hold for both sets of cities, this helps assuage concerns about overall differences between the two groups of cities like income or speed enforcement biasing the results. In this analysis, we categorized our over 1,000 populated Block Groups using street connectivity and street intersection density measures, respectively. The link to node ratio was used to represent street connectivity and real intersection density to represent street network density. These two parameters were chosen because they are easy to calculate but more importantly, preliminary assessments found them to correlate better with safety outcomes than the other network measures.

The link to node ratio was grouped into the following four categories for our analysis:

- Low Connectivity: Link to Node Ratio from 0 to 1.1
- Low-Medium Connectivity: Link to Node Ratio from 1.1 to 1.25
- Medium-High Connectivity: Link to Node Ratio from 1.25 to 1.4
- High Connectivity: Link to Node Ratio greater than 1.4

Generally, a link to node value of 1.4 or higher is considered to indicate a walkable community (Litman 2005). In fact, many subdivision regulations, for instance those in Orlando, Florida and Middletown, Delaware, require link to node values of 1.4 or higher (Handy, Paterson et al. 2003). For these calculations, the node value includes all intersections with dead ends.

The real intersection density was grouped into the following four categories:

- Low Street Network Density: Less than 81 real intersections per square mile
- Low-Medium Street Network Density: 81 to 143 real intersections / sq. mi.
- Medium-High Street Network Density: 144 to 224 real intersections / sq. mi.
- High Street Network Density: Greater than 225 real intersections / sq. mi.

If we assume a perfectly rectilinear and orthogonal grid street network, 81 real intersections / sq. mi. equates to a 9x9 grid with 660’ block lengths, 144 real intersections / sq. mi. equates to a

12x12 grid with 480’ block lengths, and 225 real intersections / sq. mi. equates to a 15x15 grid with approximate block lengths of 375’. Actual Blocks are rarely perfect grids, but the idea of the measures given is to be able to visualize the level of density each category represents.

Figure 4 illustrates street connectivity and street network density for the four example cities, shown at the same scale, in terms of the link to node ratio and real intersection density categories, respectively. This figure illustrates the point that high street connectivity does not necessarily correlate with high street network density even though, as we have discussed, they are often treated as being interchangeable. For example, the highly connected Block Groups in the center of Rialto (lower right city in Figure 4) have a low-medium level of intersection density.

In fact, over 25% of the Block Groups in the safer cities fell into the two densest intersection density categories as well as in the two lowest connectivity categories. Additionally, over 20% of the Block Groups in the less safe cities fell into the two sparsest intersection density categories as well as in the two highest connectivity categories. This means that we must analyze street connectivity and network density as distinct variables, each with potential to affect road safety outcomes. Additionally, it will be important to consider the interaction of street connectivity and network density in terms how these factors might influence one another with respect to the safety outcomes.

[Figure 4 about here]

In terms of the crash data, normalization based upon population at this scale is problematic because some Block Groups are likely to have more through (non-local) traffic than other Block Groups thereby negating the importance of the population size. Thus, in order to get a better overall assessment of safety at the Block Group level of analysis, we focus on the three risk factors rather than crash totals. As with the city level analysis, we removed the limited access highway crashes from the analysis.

The rest of this section presents the block group analysis based first on street connectivity in terms of the link to node ratio and then by street network density in terms of real intersection density. We also recognize that the interaction between these two parameters is important and investigate this interaction in the last section in which we present the results of a statistical analysis.

Street Connectivity (Link to Node Ratio) & Network Density (Real Intersection Density) Analysis

In this section we report the results of our investigation for the city's Block Groups based on four categories of the link to node ratio, which is a measure of street connectivity, and four categories of intersection density, a measure of network density. Table 3 summarizes the connectivity results and Table 4 the network density results based on more than 1,000 Block Groups located in 24 cities throughout California.

Although not every highly connected Block Group is compact and dense, the average street network density does in fact increase with increased connectivity. The range of intersection densities seen in the safer cities is much higher than that seen in the less safe cities; so even though the two groups of cities exhibit similar connectivity values, the safer cities do so while having a more compact street network. On the other hand, street connectivity across the four real intersection density categories is similar for both sets of cities. Additionally, the highest real intersection density category in both groups of cities only corresponds to approximately a 1.35 link to node ratio, which does not place it in the highest connectivity category.

In terms of safety outcomes, for both groups of cities, all three risk factors decrease as the level of connectivity or the network density increases. The rate decrease is most pronounced for fatality risk and the least for injury risk. In other words, both increased connectivity and increased network density appear to have much more of an effect on risk of fatality than on less catastrophic types of crash outcomes. Although this pattern holds for both the safer and less safe cities, respectively, for every level of connectivity or network density, the risk of injury or death is always greater for the less safe city.

For example in terms of street connectivity, the risk of severe injury drops from 3.3% in the least connected Block Groups of the safer cities to 1.5% in the most connected Block Groups of these same cities. However in terms of network density, the severe injury risk drops from 3.8% in the sparest Block Groups of the safer cities to 2.2% in the low-medium network density category. At the same time in the less safe cities, the risk of severe injury risk drops from 4.3% to only 2.7% from low to high street connectivity and from 4.5% to 3.1% when street network density increases from the lowest real intersection density category to low-medium. In terms of fatality risk, the safer cities saw a drop from 0.5% to 0.2% across the four link to node ratio categories with increasing connectivity and from 1.8% to 0.9% in the less safe cities. For real intersection density, the fatality risk drops from 0.5% to 0.3% in the safer cities with increasing network density and from 1.7% to 0.9% in the less safe cities. Of note is the fact that the least dense category for both group of cites appears to be significantly less safe that the other three categories of intersection density.

[Table 3 about here]

[Table 4 about here]

Statistical Model Relating Street Connectivity & Street Network Density to Road Safety

Based on the observed trends relating street connectivity and street density to road safety, we developed a statistical model to better understand the interrelationship between these factors. In this section of the report, we discuss the results of a two-factor factorial analysis of variance (ANOVA) assessment that takes into account both street connectivity (in terms of the link to node ratio) and street network density (in terms of real intersection density). The response variable that is considered in this analysis is the logit transformation of the risk of severe injury – the chance that a crash results in a severe injury including a fatality. The logit transformation, ln(p/(1-p)), was used in order to achieve a dependent variable with a linear distribution where p represents the severe injury crash risk.

As mentioned in the previous sections, the difference between the groups of cities or between types of Block Groups is more pronounced for the risk of fatality than for the risk of severe injury. Nonetheless, for this statistical analysis we decided to use the logit transformation of the risk of severe injury as the response variable because fatal crashes are such rare occurrences that in many instances we do not have the required degrees of freedom to reach a rigorous statistically significant conclusion. In the model we control for city group.

The linear model for this analysis is:

$$Y_{ijk} = \mu + D_i + C_j + (DC)_{ij} + G_k + \varepsilon_{ijk} \qquad j = 1, 2, 3, 4 \begin{cases} i = 1, 2, 3, 4 \\ k = 1, 2 \end{cases}$$

with: Y_{ijk} = The logit transformation of the risk that a crash results in a fatality or severe injury
D_i = Real Intersection Density Categories (4 = highest density)
C_j = Link to Node Ratio Category (4 = highest connectivity)
$(DC)_{ij}$ = Interaction Effect (Real Int. Density*Link to Node Ratio)
G_k = City Group (Safer Cities or Less Safe Cities)
ε_{ijk} = Random Error

The results indicated that there is a statistically significant relationship between street network characteristics and severe injury risk. Table 5 displays the full analysis of variance results for city group, street connectivity, street network density, as well as the interaction between each of these factors with respect to the chance of a crash resulting in a fatality or severe injury. Not unexpectedly, the city group factor (whether the city was in the safer or less safe group) was statistically significant with respect risk of severe injury. In addition, the model revealed that there is a statistically significant relationship between real intersection density and risk of severe injury. There was no statistically significant relationship between the link to node ratio and the risk of a severe or fatal outcome or the interaction term between intersection density and link to node ratio.

Overall, the risk of severe injury significantly decreases as the density of the network increases. However, it is important to note that correlation does not prove causality and we do not yet fully understand the underlying facts leading to these results. The fact that the network characteristics correlate with risk of different crash outcomes suggests that differences in vehicle speed might be an important contributing factor to the patterns we are observing. This study needs to be expanded to investigate this contingency and the factors in design that might be contributing to the observed outcomes.

[Table 5 about here]

CONCLUSIONS

The results of this study suggest that street network characteristics do in fact play a notable role in road safety outcomes. Although the underlying factors contributing to this role are not yet known, our analysis showed safety outcomes to be associated with street network density. Real intersection density proved to be strongly correlated to observed differences in safety outcomes; this held true in describing the key differences between the safe and less safe cities as well in the safety outcomes at the Block Group scale of analysis. More specifically, our results indicate that the highest risk of fatal or severe crashes occurs with very low intersection density and safety outcomes improve as the intersection density increases. This pattern is consistent for both groups of cities we examined: California cities with low fatality rates and those with high fatality rates.

Overall, it is important to remember that the safety analysis takes place at the U.S. Census Block Group level of geography rather than at the City scale. Our results find similar trends between street network characteristics and road safety outcomes for both sets of cities, which helps negate the possibility of other differences between the cities like income or speed enforcement playing a major role. In order to understand the underlying causes of these trends we will need to expand our study to look at factors such as such as road character and exposure. However, the fact that the network characteristics correlate with risk of different crash outcomes suggests that differences in vehicle speed might be an important contributing factor to the patterns we are observing.

Overall, this research highlighted the fact that the differences in the way we build communities with regard to the street network have the potential to affect road safety outcomes. Bearing this in mind, these results could help expand the scope of typical transportation safety research; otherwise, our ability to fully appreciate what makes a transportation system safe will continue to be limited. Scrutinizing our transportation system from a more comprehensive perspective can only help inform planning policies and put us on a path toward a better and more complete understanding of how place design and road safety interact.

REFERENCES

California Environmental Protection Agency (2002). Environmental Protection Indicators for California (EPIC).

Canada Mortgage and Housing Corporation. (2005). "Residential Street Pattern Design." Retrieved October 25, 2005, from https://www03.cmhc-schl.gc.ca/b2c/catalog/product.do?next=cross#.

Duane, T. (1996). Human Settlement, 1850-2040. Sierra Nevada Ecosystem Project, Final Report to Congress, University of California, Davis. **II:** 235-360.

Ewing, R. (1996). Best Development Practices: Doing the Right Thing and Making Money at the Same Time. Washington, D.C., APA Planners Press.

Filian, R. and J. Higelin. (1996). "Traffic Engineering in a GIS Environment: Highlighting Progress of the County of Riverside Geographic Information System Based Accident Records System." Retrieved July 15, 2008, from http://gis.esri.com/library/userconf/proc95/to050/p029.html.

Graham, D. and S. Glaister (2003). "Spatial Variation in Road Pedestrian Casualties: The Role of Urban Scale, Density and Land-Use Mix." Urban Studies **40**(8): 1591-1607.

Handy, S., R. Paterson, et al. (2003). Planning for Street Connectivity: Getting from Here to There. Planning Advisory Service Report 515, American Planning Association.

Janke, M. (1991). "Accidents, Mileage, and the Exaggeration of Risk." Accident Analysis and Prevention **23**(3): 183-188.

Leaf, W. A. and D. F. Preusser (1998). Literature Review on Vehicle Travel Speeds and Pedestrian Injuries, National Highway Traffic Safety Administration, USDOT.

Lerner-Lam, E., S. P. Celniker, et al. (1992). "Neo-Traditional Design and Its Implications for Traffic Engineering." ITE Journal **62**(1): 17-25.

Litman, T. (2005). "Roadway Connectivity: Creating More Connected Roadway and Pathway Networks." Retrieved October 25, 2005, from http://www.vtpi.org/tdm/tdm116.htm.

Litman, T. (2008). "Evaluating Safety and Health Impacts." TDM Encyclopedia, from http://www.vtpi.org/tdm/tdm58.htm#_Toc65190624.

Noland, R. and M. Quddus (2004). "A Spatially Disaggregate Analysis of Road Casualties in England." Accident Analysis and Prevention **36**(6): 973-984.

Organisation for Economic Co-operation and Development (OECD) and European Conference of Ministers of Transport (ECMT) (2006). Speed Management.

Sarusua, W., J. H. Ogle, et al. (2008). Location, Location, Location: Using GPS to Identify Crash Location -- South Caroline Experience. TRB 87th Annual Meeting Compendium of Papers DVD.

Southworth, M. and E. Ben-Joseph (1997). Street and the Shaping of Towns and Cities. New York, McGraw-Hill.

Southworth, M. and E. Ben-Joseph (2004). Reconsidering the Cul-de-sac. Access. **24**.

Stuster, J. and Z. Coffman (1998). Synthesis of Safety Research Related to Speed and Speed Limits, Federal Highway Administration

Taylor, J. (2001). "Transportation and Community Design: the Effects of Land Use and Street Pattern on Travel Behavior." Retrieved October 25, 2005, from http://www.sustainable-communities.agsci.ubc.ca/bulletins/TB_issue_11_Transportation_edit.pdf.

Tunnard, C. (1963). Man-Made America. New Haven, Yale University Press.

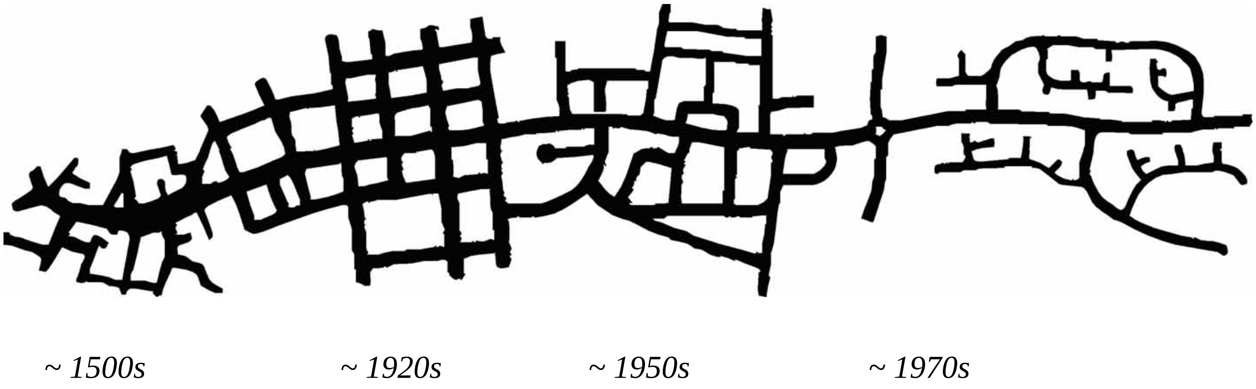

Figure 1 **Evolution of Street Patterns, Adapted from S. Marshall (Marshall 2005)**

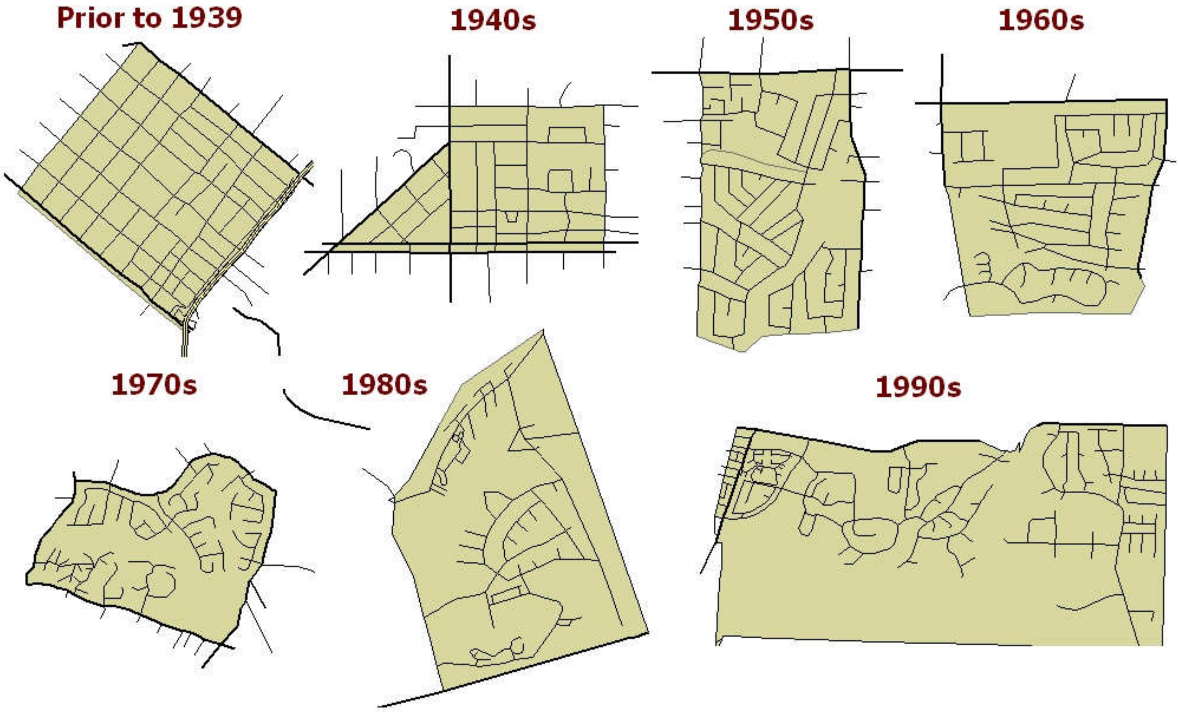

Figure 2 Example Block Groups by Year of Development

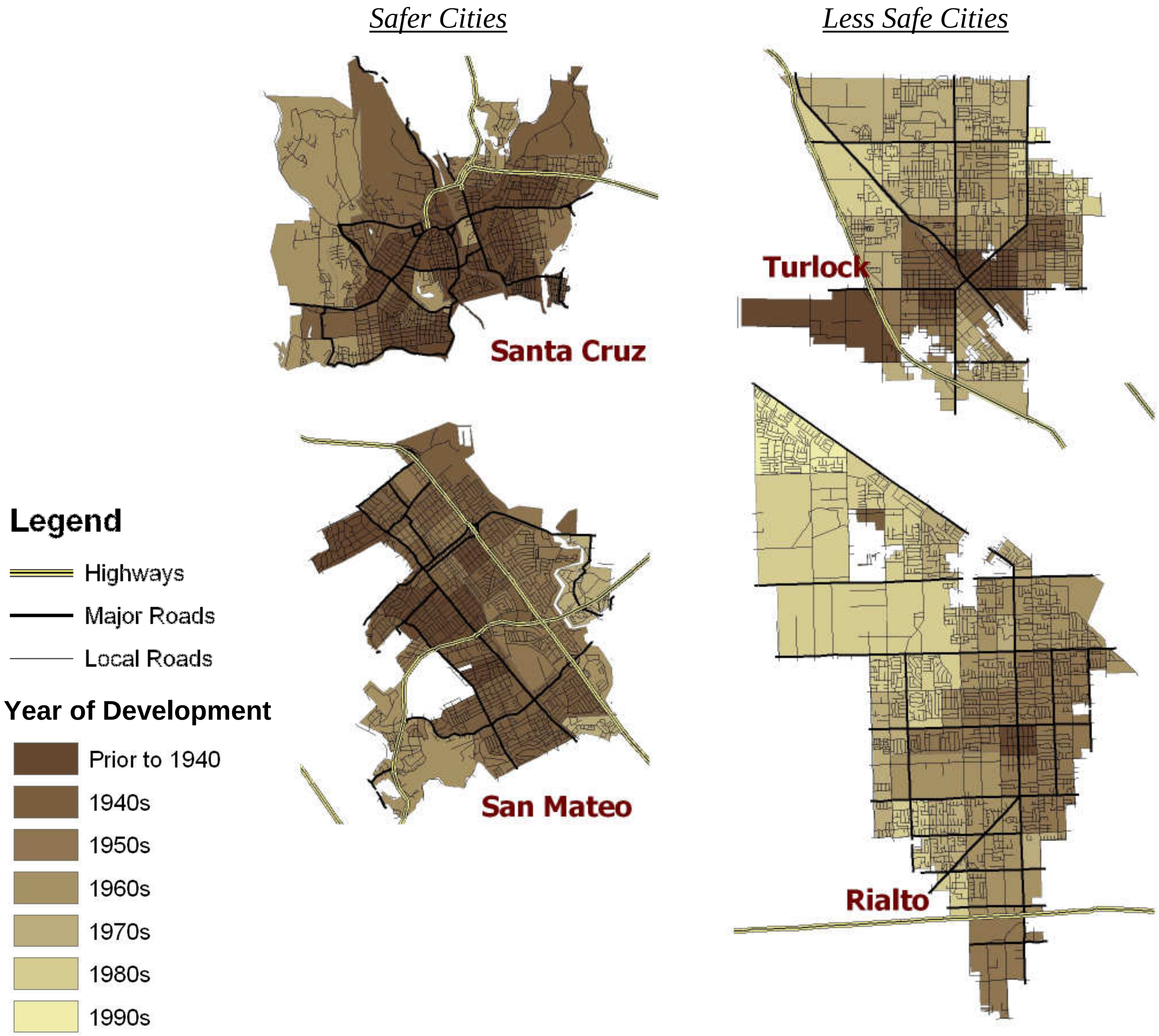

Figure 3 **Street Network Comparison of 4 Cities with Year of Development**

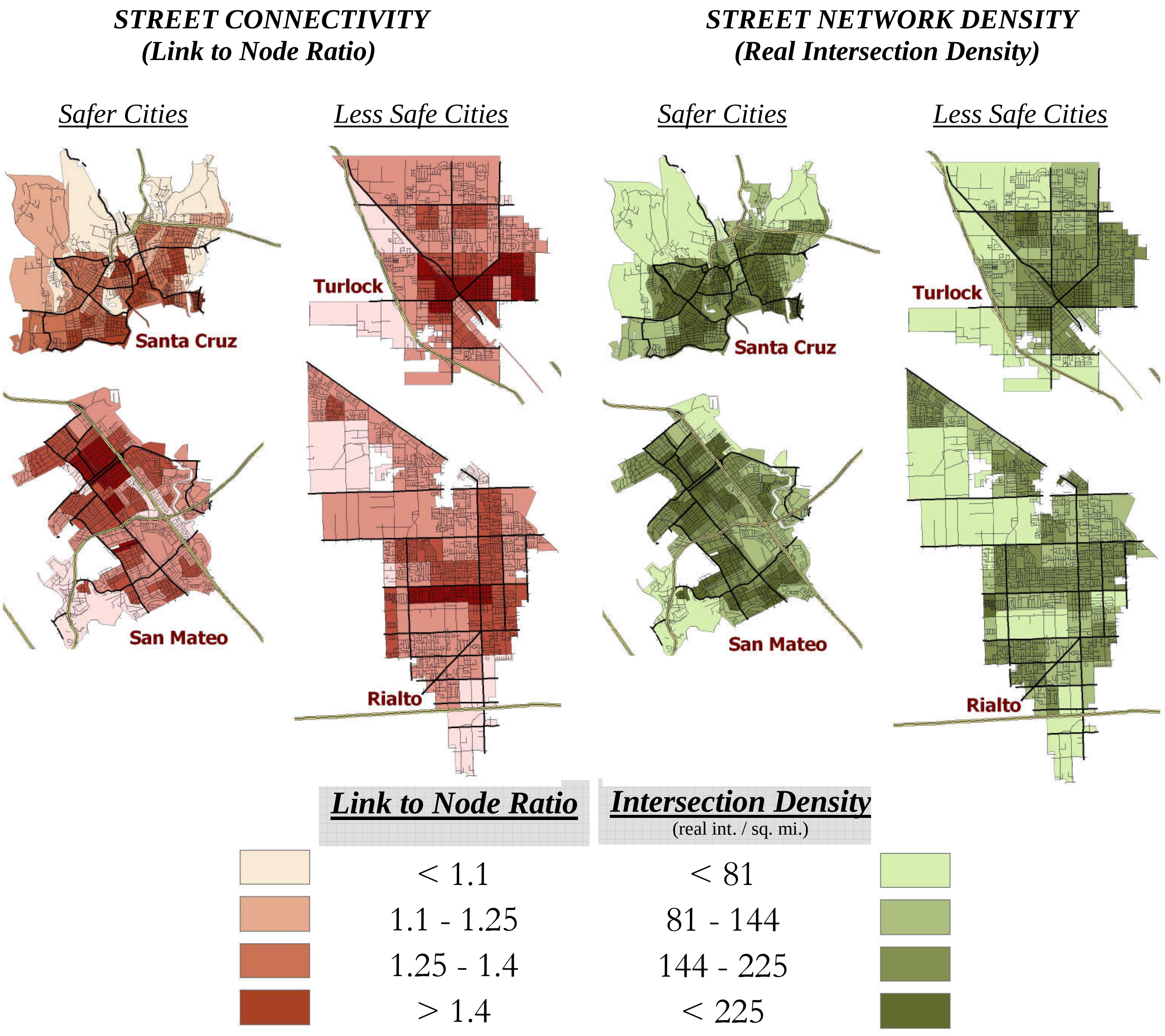

Figure 4 Street Connectivity (Link to Node Ratio) and Street Network Density (Real Intersection Density) Comparison of 4 Cities at the Same Scale

Table 1 Basic City Crash Data by Group

	SAFER CITIES	LESS SAFE CITIES	DIFFERENCE
Year of Incorportation (average)	1895	1932	
Population (2000 average)	65,719	59,845	-8.9%
Population Density (2000 population per square mile)	5,736	2,673	-53.4%
Income (2000 average)	$59,989	$46,408	-22.6%
Vehicle Miles Traveled (average daily VMT from HPMS)	626,608	656,967	4.8%
Total Fatal Crashes (average per city per year per 100,000 population)	3.1	10.1	225.8%
Fatal Crashes Not on Limited Access Highways (average per city per year per 100,000 population)	2.3	8.6	273.9%

Table 1 City Scale Street Network & Crash Data by Group

			12 SAFER CITIES	12 LESS SAFE CITIES	DIFFERENCE
		Block Group Year of Development (average)	1957	1972	
		City Population (2000 average)	65,719	59,845	-8.9%
		Population Density (city average in people / square mile)	5,736	2,673	-53.4%
Street Network Density & Connectivity Indices		**Real Intersection Density** (city average per sq. mi.)	106.2	62.7	-41.0%
		Dead End Density (city average per sq. mi.)	32.8	23.9	-27.1%
		Total Intersection Density (city average per sq. mi.)	139.0	86.6	-37.7%
		Block Size (city average in acres)	18.2	34.5	89.6%
		Link to Node Ratio (L2N: city average)	1.34	1.29	-3.7%
		Connected Node Ratio (CNR: city average)	0.76	0.73	-3.9%
		Highway Density (city avg. in centerline miles per sq. mi.)	0.4	0.3	-25.0%
		Major Road Density (city avg. in centerline miles per sq. mi.)	1.8	1.0	-44.4%
		Local Road Density (city avg. in centerline miles per sq. mi.)	15.1	11.2	-25.8%
Crash Data All Roads		**Total Fatal Crashes** per 100,000 pop. (city average per year)	3.1	10.1	225.8%
		Total Severe Injury Crashes per 100,000 pop. (city average per year)	15.6	17.3	10.9%
	RISK FACTORS	**Risk of Injury:** Avg. Chance of a Crash Resulting in Any Injury including a Fatality (city average)	36.37%	36.09%	-0.8%
		Risk of Severe Injury: Avg. Chance of a Crash Resulting in a Fatality or Severe Injury (city average)	1.79%	3.27%	82.7%
		Risk of Fatality: Avg. Chance of a Crash Resulting in a Fatality (city average)	0.30%	1.22%	306.7%
Crash Data Not on Highways		**Fatal Crashes Not on Highways** per 100,000 pop. (city average per year)	2.3	8.6	273.9%
		Severe Injury Crashes Not on Highways per 100,000 pop. (city average per year)	14.0	16.0	14.3%
	RISK FACTORS	**Risk of Injury:** Avg. Chance of a Non-Highway Crash Resulting in Any Injury including a Fatality (city average)	36.95%	36.04%	-2.5%
		Risk of Severe Injury: Avg. Chance of a Non-Highway Crash Resulting in a Fatality or Severe Injury (city average)	1.77%	3.18%	79.7%
		Risk of Fatality: Avg. Chance of a Non-Highway Crash Resulting in a Fatality (city average)	0.24%	1.13%	370.8%

Table 3 Block Group Scale Street Network Data by Link to Node Ratio Category

			12 SAFER CITIES LINK TO NODE RATIO (links / total nodes)				**12 LESS SAFE CITIES LINK TO NODE RATIO** (links / total nodes)			
			0 to 1.1	**1.1 to 1.25**	**1.25 to 1.4**	**1.4+**	**0 to 1.1**	**1.1 to 1.25**	**1.25 to 1.4**	**1.4+**
		Block Groups (total number)	134	203	187	124	74	171	104	45
		% of Block Groups (within city group)	20.7%	31.3%	28.9%	19.1%	18.8%	43.4%	26.4%	11.4%
		Avg. Block Group Year of Development	1964	1960	1946	1941	1975	1977	1968	1955
		Avg. Block Group Population (2000)	1,133	1,456	1,110	1,140	1,086	2,164	1,975	1,449
		Population Density (block group avg. in people / sq. mi.)	6,324	7,491	11,158	10,750	3,177	4,069	5,174	5,103
		Avg. Dist. from City Center (block group avg. in miles)	1.87	1.75	1.27	0.97	3.29	2.65	1.99	1.17
Street Network Density & Connectivity Analysis		**Real Intersection Density** (block group avg. per sq. mi.)	140.2	172.5	260.1	276.3	84.4	107.2	131.1	174.4
		Dead End Density (block group avg. per sq. mi.)	15.1	10.9	3.0	1.7	16.8	24.2	15.1	3.4
		Total Intersection Density (block group avg. per sq. mi.)	155.3	183.4	263.1	278.0	101.2	131.4	146.2	177.8
		Block Size (block group average in acres)	123.1	36.4	13.2	10.2	205.1	81.1	34.3	20.9
		Link to Node Ratio (L2N: block group average)	0.98	1.18	1.32	1.46	1.01	1.18	1.32	1.48
		Connected Node Ratio (CNR: block group average)	0.69	0.79	0.92	0.96	0.68	0.75	0.87	0.95
		Highway Density (block group avg. in centerline miles per sq. mi.)	1.47	1.16	0.51	0.30	1.27	0.73	0.56	0.48
		Major Road Density (block group avg. in centerline miles per sq. mi.)	4.16	4.33	7.04	8.04	3.35	2.80	3.03	3.69
		Local Road Density (block group avg. in centerline miles per sq. mi.)	24.6	26.4	37.3	37.6	16.5	18.3	22.3	26.2
Crash Data Not on Highways	***RISK FACTORS***	**Risk of Injury:** Avg. Chance of a Non-Highway Crash Resulting in Any Injury including a Fatality (block group avg.)	40.99%	38.47%	39.05%	37.66%	41.58%	42.11%	34.79%	33.65%
		Risk of Severe Injury: Avg. Chance of a Non-Highway Crash Resulting in a Fatality or Severe Injury (block group avg.)	3.31%	1.87%	1.81%	1.48%	4.25%	4.02%	3.30%	2.67%
		Risk of Fatality: Avg. Chance of a Non-Highway Crash Resulting in a Fatality (block group avg.)	0.51%	0.33%	0.21%	0.18%	1.78%	1.29%	1.07%	0.91%

Table 4 Block Group Scale Street Network Data by Real Intersection Density Category

		12 SAFER CITIES REAL INTERSECTION DENSITY (real intersections / square mile)				**12 LESS SAFE CITIES REAL INTERSECTION DENSITY** (real intersections / square mile)			
		0 to 81	**81 to 144**	**144 to 225**	**225+**	**0 to 81**	**81 to 144**	**144 to 225**	**225+**
	Block Groups (total number)	59	132	231	227	150	120	99	25
	% of Block Groups (within city group)	9.1%	20.3%	35.6%	35.0%	38.1%	30.5%	25.1%	6.3%
	Avg. Block Group Year of Development	1966	1962	1953	1944	1976	1973	1967	1958
	Avg. Block Group Population (2000)	1,405	1,458	1,269	1,003	1,807	2,277	1,495	1,146
	Population Density (block group avg. in people / sq. mi.)	2,601	6,213	8,929	12,123	1,634	4,883	6,671	8,287
	Avg. Dist. from City Center (block group avg. in miles)	2.30	1.78	1.42	1.19	3.08	2.27	1.93	1.26
Street Network Density & Connectivity Analysis	**Real Intersection Density** (block group avg. per sq. mi.)	50.8	120.1	197.9	317.8	48.8	115.2	183.3	270.4
	Dead End Density (block group avg. per sq. mi.)	23.6	41.3	41.2	25.4	17.3	34.6	38.5	32.7
	Total Intersection Density (block group avg. per sq. mi.)	74.4	161.4	239.1	343.2	66.1	149.8	221.8	303.1
	Block Size (block group average in acres)	335.0	40.1	25.5	13.3	146.3	58.9	40.6	20.8
	Link to Node Ratio (L2N: block group average)	1.00	1.13	1.25	1.34	1.17	1.21	1.27	1.35
	Connected Node Ratio (CNR: block group average)	0.67	0.76	0.84	0.93	0.75	0.74	0.84	0.90
	Highway Density (block group avg. in centerline miles per sq. mi.)	1.16	1.64	1.08	0.13	0.65	0.79	0.81	1.04
	Major Road Density (block group avg. in centerline miles per sq. mi.)	2.65	3.90	5.54	7.92	1.84	3.35	4.15	4.77
	Local Road Density (block group avg. in centerline miles per sq. mi.)	10.8	20.7	29.8	44.3	11.4	20.1	28.2	36.8
Crash Data Not on Highways ***RISK FACTORS***	**Risk of Injury:** Avg. Chance of a Non-Highway Crash Resulting in Any Injury including a Fatality (block group avg.)	40.57%	39.86%	39.01%	38.10%	38.86%	38.45%	40.50%	38.27%
	Risk of Severe Injury: Avg. Chance of a Non-Highway Crash Resulting in a Fatality or Severe Injury (block group avg.)	3.84%	2.22%	1.73%	1.89%	4.51%	3.11%	3.24%	3.78%
	Risk of Fatality: Avg. Chance of a Non-Highway Crash Resulting in a Fatality (block group avg.)	0.50%	0.28%	0.24%	0.34%	1.73%	0.89%	1.10%	1.18%

Table 5 **Full Analysis of Variance Two-Factor Factorial with Blocking: Logit Transformation of Fatal or Severe Injury Crash Risk by Real Intersection Density and Link to Node Ratio**

Dependent Variable:
Logit Transformation of Fatal or Severe Injury Crash Risk

Source	**DF**	**Sum of Squares**	**Mean Square**	**F-Value**
Model	16	195.137516	12.196095	7.64
Error	1008	1608.862515	1.596094	
Corrected Total	1024	1804.000030		

Source	**Pr > F**
Model	< 0.0001
Error	
Corrected Total	

R-Square	**Coeff Var**	**Root MSE**	**Dep. Var Mean**
0.108169	-29.640600	1.263366	-4.262282

Source	**DF**	**Type I SS**	**Mean Square**	**F-Value**
City Group	1	146.274452	146.274452	91.65
Real Int. Density	3	20.369052	6.789684	4.25
Link to Node Ratio	3	7.480642	2.493548	1.56
Interaction (Int.Den*L2N)	9	21.013370	2.334819	1.46

Source	**Pr > F**
City Group	< 0.0001
Real Int. Density	0.0054
Link to Node Ratio	0.1969
Interaction (Int.Den*L2N)	0.1570