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ABSTRACT

This study provides a preliminary investigation into the relationship between urbanization and traffic collisions by analyzing the spatial patterns in Sacramento County, California from 1998 to 2008 using urban land classifications and traffic collision data. The ArcGIS directional distribution tool was used to create standard deviational ellipses to investigate the distributional trend of urban land and traffic collisions over time. Statistical outputs representing changes of geographical centroids, elliptical areas, and standard distances (long and short axes) were then compared. Collisions were also subset by severity level to account for inherent differences in the spatial distribution of different types of collisions. The results provided insight into the macroscopic spatial patterns of urban land and traffic safety and their relationships. The limitations of the method and the need for further research were discussed. The approach in this study would be useful for other metropolitan areas with similarly changing development patterns and can be helpful in guiding future research comparing these two phenomena.

1. INTRODUCTION

Recent increase in urban population, coupled with residents' preference for a suburban lifestyle, have shaped the rapid and sprawling expansion toward rural areas at the periphery of urban regions in the United States. In the meantime, scholars have sought to describe this urbanization pattern and investigate its impacts on health and the environment. Ewing et al. *(1)* defined sprawl as the product of four factors that can be measured and analyzed: low residential density; a poor mix of homes, jobs and services; limited activity centers and downtown areas; and poor accessibility of the street network. While sprawl has long been suspected to be a major contributing factor in automobile and non-motorist traffic fatalities, there has been a lack of evidence to support this theory until recently. Lucy *(2)* constructed an index that measured the likelihood of someone being fatally injured in a traffic collision or homicide in different parts of a metropolitan area and found higher traffic fatality rates in exurban areas than those in central cities or the inner suburbs of fifteen metropolitan areas. Ewing et al. *(3)* presented that there was indeed a direct relationship between traffic fatalities, as an estimated 1% increase in the sprawl index (i.e., more compact, less sprawl) was associated with an all-mode traffic fatality rate decrease of 1.49% ($P < .001$) and pedestrian fatality rate decrease of 1.47% to 3.56%, after adjusting for pedestrian exposure ($P < 0.001$). Lambert and Meyer *(4)* confirmed these findings for 122 counties in the southeastern United States using a slightly different model.

A common theme throughout these studies is the fact that fatality rates decrease with population density. According to National Highway Traffic Safety Administration *(5)*, the fatality rate per vehicle miles traveled (VMT) in rural areas was 2.6 times higher than that of urban areas in 2008. In order to elaborate on what exactly causes this difference, Zwerling et al. *(6)* performed a risk-decomposition analysis to explore the factors associated with higher fatal crash involvement rates in rural communities and found that the major reason for higher fatality rates in rural areas is the injury fatality rate, or the likelihood of a fatality given a traffic-related injury. As the authors found that the severity of urban and rural injuries is comparable, this difference is largely because the response of emergency medical services and access to definitive care are delayed in more remote areas. Rural areas also have a slightly higher crash injury rate, or likelihood of being injured given a traffic collision, while urban areas have a slightly higher crash incidence density, or likelihood of a traffic collision given a certain level of VMT.

As described previously, there has been significant research on correlation between traffic collisions and the built environment in terms of planning factors like population density, land use mix and accessibility, etc. Much of the research is presented through cross-sectional studies, comparing collision rates between regions with different types of built environments; accordingly, they might not be used to assess the incremental impact of new growth and thus cannot provide insight about how the traffic safety may change in a particular area due to new development along its periphery. Also, because both traffic collisions and the built environment change over both space and time, a longitudinal study can be useful in providing additional insight into their relationship. This study introduces an approach to spatiotemporal investigation of macroscopic patterns and presents outputs from a spatial analysis of Sacramento County, California from 1998 to 2008. Metropolitan planning organizations or other regional agencies could use this type of information in determining how to accommodate new growth in a region in a way that would minimize traffic collision increases.

2. DATA

Data Descriptions

This study seeks to add the time dimension to the built environment literature by analyzing traffic collision data for Sacramento County over a time period during which the outskirts of the metropolitan area became urbanized. To this end, data were obtained for both land use and traffic collisions in Sacramento County from 1998 to 2008. Table 1 and 2 describe data used in the analysis in terms of area of land use and frequency of collisions by severity type.

TABLE 1 Land Use Data (Unit: km^2)

Farmland Categories	1998	2000	2002	2004	2006	2008	Total
Urban and Built-up Land	610 (23.7%)	636 (24.7%)	647 (25.1%)	670 (26.0%)	710 (27.6%)	720 (28.0%)	3,994 (25.9%)
Grazing Land	669 (26.0%)	680 (26.4%)	668 (25.9%)	660 (25.7%)	635 (24.7%)	632 (24.5%)	3,945 (25.5%)
Farmland of Local Importance	137 (5.3%)	136 (5.3%)	153 (6.0%)	161 (6.3%)	170 (6.6%)	177 (6.9%)	934 (6.0%)
Prime Farmland	494 (19.2%)	467(18.1%)	453 (17.6%)	446 (17.3%)	432 (16.8%)	422 (16.4%)	2,714 (17.6%)
Farmland of Statewide Importance	274 (10.6%)	257 (10.0%)	246 (9.6%)	227 (8.8%)	207 (8.1%)	200 (7.8%)	1,412 (9.1%)
Unique Farmland	55 (2.1%)	63 (2.4%)	64 (2.5%)	61 (2.4%)	62 (2.4%)	63 (2.4%)	367 (2.4%)
Water	74 (2.9%)	74 (2.9%)	74 (2.9%)	74 (2.9%)	74 (2.9%)	73 (2.9%)	443 (2.9%)
Other Land	263 (10.2%)	261 (10.2%)	269 (10.4%)	273 (10.6%)	284 (11.0%)	286 (11.1%)	1,637 (10.6%)
Total	2,574	2,574	2,574	2,574	2,574	2,574	15,445

* Only urban and built-up land data were used in the analysis.

TABLE 2 Collision Data Used in the Analysis (Unit: Count)

Severity Type	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	Total
Fatal	83 (0.4%)	103 (0.6%)	105 (0.6%)	132 (0.6%)	141 (0.6%)	136 (0.6%)	127 (0.5%)	154 (0.6%)	119 (0.5%)	122 (0.6%)	84 (0.5%)	1,306 (0.5%)
Severe Injury	331 (1.7%)	327 (1.8%)	420 (2.0%)	426 (1.8%)	418 (1.7%)	422 (1.8%)	465 (1.8%)	465 (1.9%)	444 (2.0%)	483 (2.3%)	422 (2.3%)	4,623 (1.9%)
Other Visible Injury	2,618 (13.7%)	2,552 (13.7%)	2,702 (12.7%)	2,950 (12.8%)	2,929 (11.6%)	2,717 (11.5%)	2,838 (11.3%)	2,619 (10.7%)	2,422 (10.7%)	2,111 (9.9%)	2,008 (10.8%)	28,466 (11.7%)
Complaint of Pain	5,507 (28.9%)	5,549 (29.7%)	6,153 (28.9%)	6,344 (27.5%)	6,850 (27.1%)	6,507 (27.6%)	7,207 (28.6%)	6,970 (28.4%)	6,206 (27.3%)	5,952 (27.9%)	5,444 (29.2%)	68,689 (28.2%)
Property Damage Only (PDO)	10,524 (55.2%)	10,140 (54.3%)	11,886 (55.9%)	13,212 (57.3%)	14,951 (59.1%)	13,765 (58.5%)	14,588 (57.8%)	14,302 (58.4%)	13,546 (59.6%)	12,634 (59.3%)	10,699 (57.3%)	140,247 (57.6%)
Total	19,063	18,671	21,266	23,064	25,289	23,547	25,225	24,510	22,737	21,302	18,657	243,331

Land Coverage

Data regarding the urbanization of the Sacramento County were obtained from California Department of Conservation's Farmland Mapping and Monitoring Program (FMMP). The agency uses land use categorizations developed by the United States Department of Agriculture-Soil Conservation Service (USDA-SCS) as part of their nationwide Land Inventory and Monitoring (LIM) system. In this database, 0.0405 km^2 (10-acre) units of land are categorized as farmland, grazing land, urban and built-up land, other land (i.e., natural vegetation or rural development), or water. This study uses all land classified as "urban and built-up" to define the extent of urbanization in the region. The data are given as a polygon shapefile format and updated every two years, yielding six data sets of land use over the study timeline. The polygon data obtained from FMMP were converted into point features in order for it to be compatible with the directional distribution method. In order to represent the polygons in an unbiased manner, the point data were created by randomly generating points within the polygon, with the amount of point features generated proportional to the size of the polygon.

Traffic Collision Data

Traffic collision data were obtained from California's Statewide Integrated Traffic Records System (SWITRS) which is a database maintained by California Highway Patrol that serves as a means to collect and process data gathered from a collision scene. To perform the spatial analyses for this research, the collisions were geocoded via the methods described by Bigham, et al *(7)*. SWITRS provides detailed information about each collision, including the date and time of the collision, the location where the collision occurred and the severity of the collision, etc. The collision severity in SWITRS has five levels: fatal, severe injury, other visible injury, complaint of pain, and property damage only (PDO). In order to capture the potential distributional difference due to severity level, the collision data were subset into the five different severity levels for each year of the analysis.

3. METHODS

Directional Distribution Using Standard Deviational Ellipse

The ArcGIS directional distribution tool was used to create standard deviational ellipses to investigate the distributional trend of urban land and traffic collisions over time *(8)*. The standard deviational ellipse method is not based on any distributional assumption and thus can be used to evaluate spatial patterns of any given data points over space. The present study applies this method to measure how urbanization and traffic collisions are distributed over space by estimating three parameters: mean center, standard deviation (Eq. 1) and orientation (Eq. 2) from the mean center toward the x- and y-directions.

The orientation represents the rotation of the long axis measured clockwise from noon. The ellipses drawn in this study represent one-standard deviation from the mean since two- or three-standard deviational ellipses do not capture the distinctive features of the different years or severity levels of collisions. Note that one standard deviation encompasses approximately 68% of all features when the underlying spatial pattern of features is concentrated in the center with fewer features toward the periphery (a spatial normal distribution); however, normal distribution is not required to preserve the validity of the output measures. The graphical output, referred to as the 'standard deviational ellipse', allows one to see whether the distribution of features is elongated and whether it has a particular orientation.

$$SDE_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{X})^2}{n}} \quad (1)$$

$$SDE_y = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{Y})^2}{n}}$$

where x_i and y_i are the coordinates for feature i, $\{\bar{X}, \bar{Y}\}$ represents the mean center for the features, and n is equal to the total number of features.

The angle of rotation θ is calculated as:

$$\tan\theta = \frac{A+B}{C} \quad (2)$$

$$A = \left(\sum_{i=1}^{n}\tilde{x}_i^{\,2} - \sum_{i=1}^{n}\tilde{y}_i^{\,2}\right)$$

$$B = \sqrt{\left(\sum_{i=1}^{n}\tilde{x}_i^{\,2} - \sum_{i=1}^{n}\tilde{y}_i^{\,2}\right)^2 + 4\left(\sum_{i=1}^{n}\tilde{x}_i\tilde{y}_i\right)^2}$$

$$C = 2\sum_{i=1}^{n}\tilde{x}_i\tilde{y}_i$$

where $\tilde{x}_i$ and $\tilde{y}_i$ are the deviations of the xy-coordinates from the mean center.

The standard deviations for the x-axis and y-axis are:

$$\sigma_x = \sqrt{\frac{\sum_{i=1}^{n}(\tilde{x}_i\cos\theta - \tilde{y}_i\sin\theta)^2}{n}} \quad (3)$$

$$\sigma_y = \sqrt{\frac{\sum_{i=1}^{n}(\tilde{x}_i\sin\theta - \tilde{y}_i\cos\theta)^2}{n}}$$

Mapping the distributional trend for a certain variable can be used to identify a relationship to particular physical features; in this case, the output identifies whether the distributional trend of traffic collisions can be used to establish a relationship with the urbanization of the area. The standard deviational ellipse has been used in previous studies for a variety of topics. Gardner *(9)* showed a distinct difference in directional trends between two archaeological sites in Southern Illinois, Svensson et al. *(10)* found identical genotypes of Francisella tularensis over different years in Sweden, and Siaway

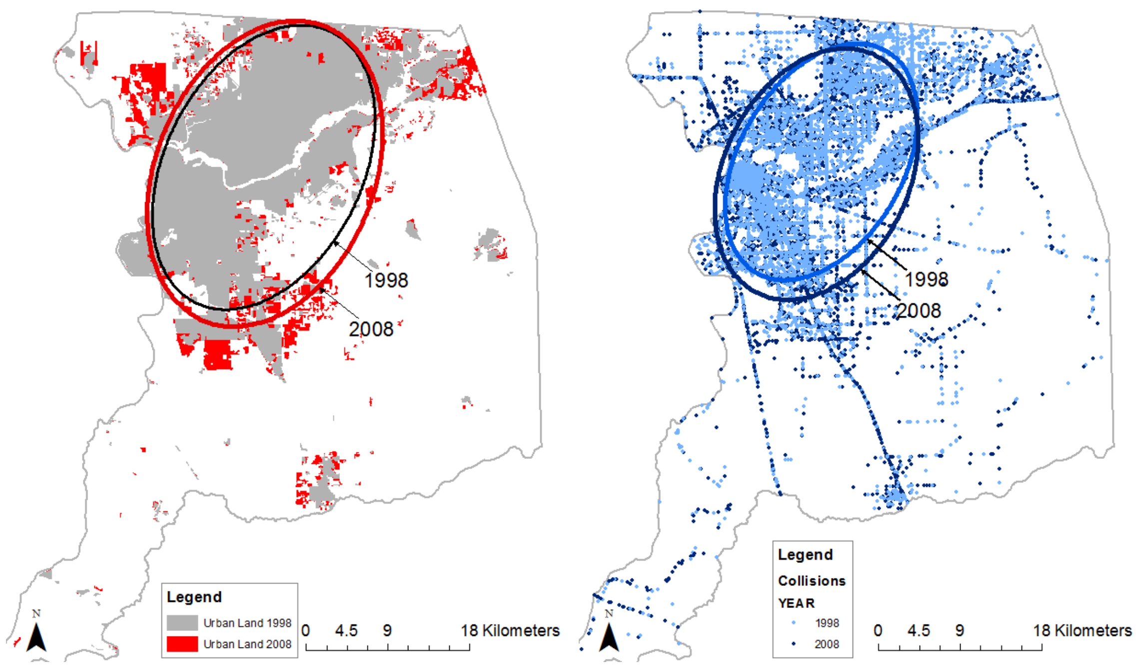
(11) showed that the distribution of similar radon measurements has a particular orientation in Fairfax County. Also, Xu et al. *(12)* found that settlement changes showed apparent anisotropy across the directions around the urban center, and Espinoza et al. *(13)* analyzed the directional distribution to determine the best possible accuracy of a new Vemco VR2W Positioning System.

Spatial distribution of traffic collisions

The spatial distribution of collisions may vary over time depending on a number of factors such as travel patterns, transportation infrastructure, the built environment, and other socio-demographic variables. Previous research has dealt with the spatial component of traffic collisions in different ways. Levine et al. *(14)* described the spatial patterns in Honolulu for motor vehicle collisions in 1990 at different times during the day and week. Their research showed that accidents are more likely to involve fatalities and be related to night-time driving and alcohol in the suburban areas, and these conditions spatially correlate with single-vehicle collisions and collisions with opposite direction vehicles On an area-wide level, Noland and Quddus *(15)* analyzed the impact of various area-wide factors on traffic fatalities at the census tract level. Data specifying land use type, road characteristics, demographics and road casualties were used as inputs in a negative binomial count data model, which analyzed the associations between these factors with traffic fatalities and injuries of different magnitudes. In terms of land use, the authors found that urbanized areas are associated with fewer traffic casualties (where casualties include injuries and fatalities), especially fatalities, while areas of high employment density had more traffic casualties. Similar studies have been performed on a county level by Noland and Oh *(16)* and Amoros et al *(17)*.

4. RESULTS AND DISCUSSIONS

The results of the directional distribution analysis for built-up urban areas and traffic collisions are presented in Figures 1 to 6. Figure 1 visually shows the change of the distribution of built-up urban land and traffic collisions in Sacramento County from 1998 to 2008. Generally, the ellipses for both built-up urban land and traffic collisions have become larger over time. To investigate the trends of the size increase in elliptical areas of urban land and traffic collisions, the percent change in the area of the standard deviational ellipse and x- and y-standard distances over time are presented in Figure 2 and Figure 3. The steady increase in size confirms that there has been development on the outskirts of Sacramento County over the study period (Figure 2 and Figure 3-(a)). For instance, Figure 2 indicates that the ellipse for urban land in 2008 is 16% wider than that in 1998. Likewise, the elliptical areas for traffic collisions have become bigger (Figure 2 and Figure 3-(b)), which corresponds with the increasing size of the urbanization standard deviational ellipse over the same period. One exception is that the elliptical area for traffic collisions in 2008 decreased 3% from 2006. This is a potential effect of economic regression the mid-2000s in the U.S. that has caused an overall decrease in VMT nationwide by reducing the drivers' travel motivation. According to Research and Innovative Technology Administration Bureau of Transportation Statistics *(18)*, urban VMT and rural VMT decreased approximately 0.6% and 4.3% respectively in 2008 from 2007. Suburban areas seem to be more influenced than urban areas by the decrease in VMT; however, further investigation is needed to discover the underlying background of this interesting phenomenon.



(a) Urban Land **(b) Traffic Collisions**

FIGURE 1 Distribution of Standard Deviational Ellipses by Year.

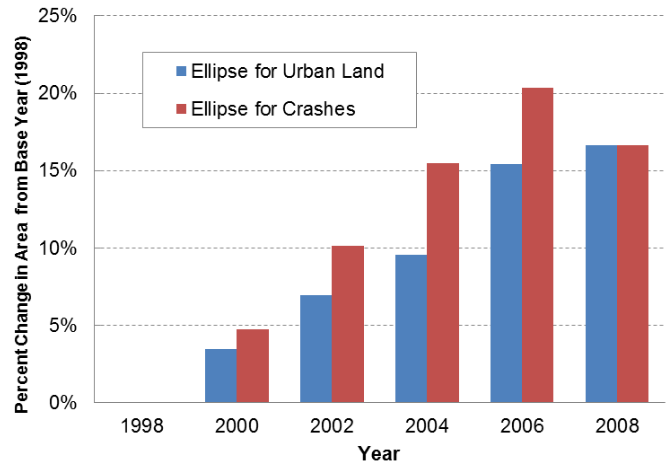
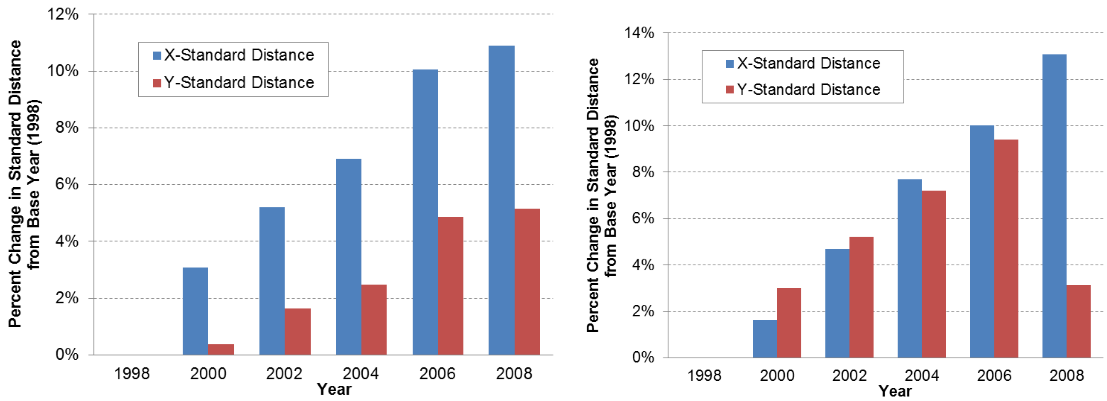


FIGURE 2 Percent Change in Ellipse Area for Urban Land and Traffic Collisions over Time.

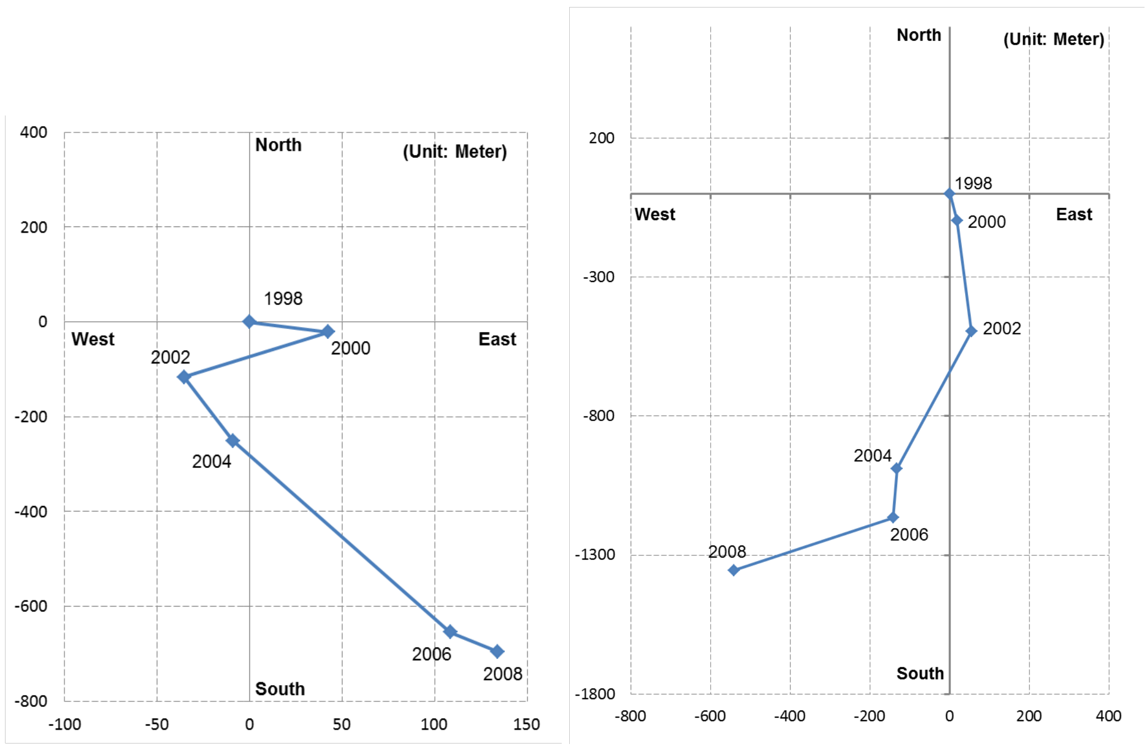


(a) Urban Land **(b) Traffic Collisions**

FIGURE 3 Percent Change in x- and y-Standard Distances over Time.

Figure 4 shows the change in the mean center of each of the standard deviational ellipses and provides insight into the overall direction of new development (Figure 4-(a)) and the movement of the geographic center for traffic collisions (Figure 4-(b)) over time. New development tended to be in the southern and eastern portions of the region rather than northern and western portions, but the geographic center for traffic collisions shifted slightly toward the southern and western portions of the region. In other words, while the y-center's shift downwards corresponds to the shift in urbanization, the x-coordinate moved in the opposite direction (west rather than east). The discrepancy between the growth patterns of urban land and traffic collisions is partially attributed to the shape of the street networks connecting to other regions because the distribution of collisions expands only along the street network while urban areas grow without any directional constraint. As shown in Figure 1-(b), there are two parallel roads stretched from the center toward the Southwest where collisions increased over the years.

These roads affected the shape of collision ellipse and thus shift the y-center downward as shown in Figure 4-(b).



(a) Urban Land **(b) Traffic Collisions**

FIGURE 4 Change in x- and y-Center over Time.

Figure 5 shows the change in ratio between the elliptical area for traffic collisions by severity type and the elliptical area for urban land over time. The ellipses for fatal collisions are generally larger than those for urban land and cover a larger area than any other types of collisions. Research has shown that fatal collisions are likely to be more dispersed to the outskirts than those for any other severity types. For example, a ratio of 1.25 for fatal collisions in 1998 shown on the top left in Figure 5 conveys that the ellipse polygon is 1.25 times the elliptical area for urban land. On the other hand, PDO collisions are around a ratio of 0.75 through the years, which means the collisions occurred in the relatively smaller ellipses compared to the urban land ellipses. The trends for the PDO, complaint of pain and other visible injury collisions follow a similar trend, while those for collisions resulting in severe injuries or fatalities fluctuate significantly. Percent change in the elliptical area by severity type is shown in Figure 6. The elliptical areas for PDO, complaint of pain and other visible injury collisions have become up to 25% larger compared to the base year 1998 while the elliptical areas for collisions of severe injuries and fatalities have fluctuated over time. This fluctuation may be related to a smaller sample size that might not effectively represent the overall trends of the fatal and severe injury collisions.

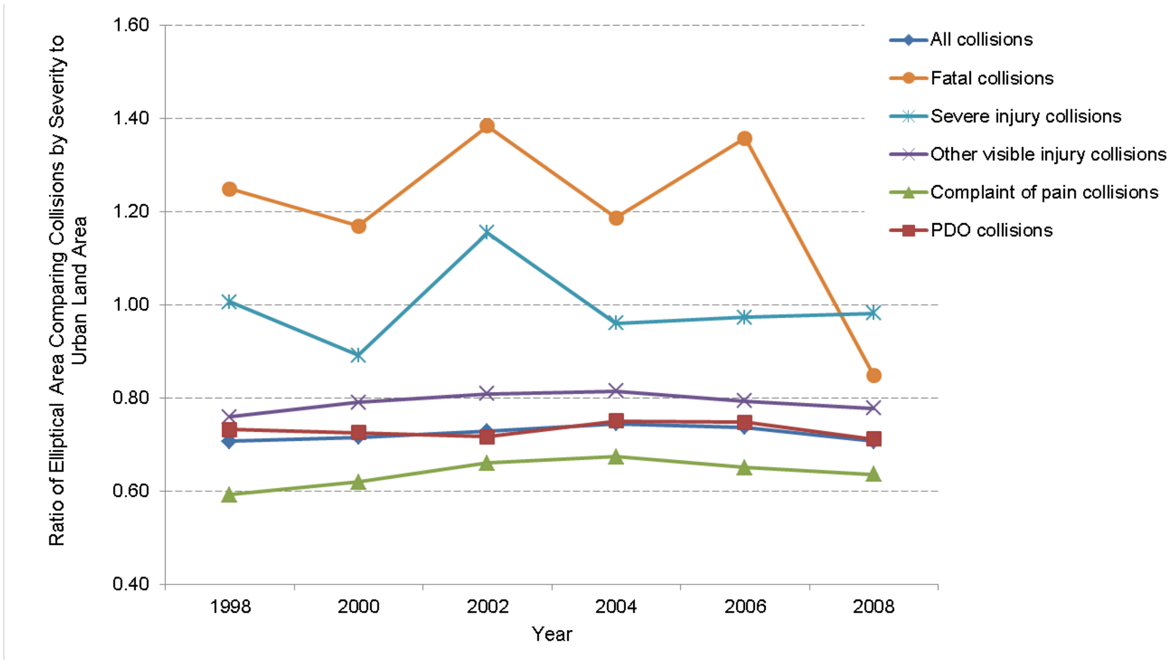


FIGURE 5 Change in Ratio of Elliptical Area Comparing Collisions by Severity to Urban Land Area

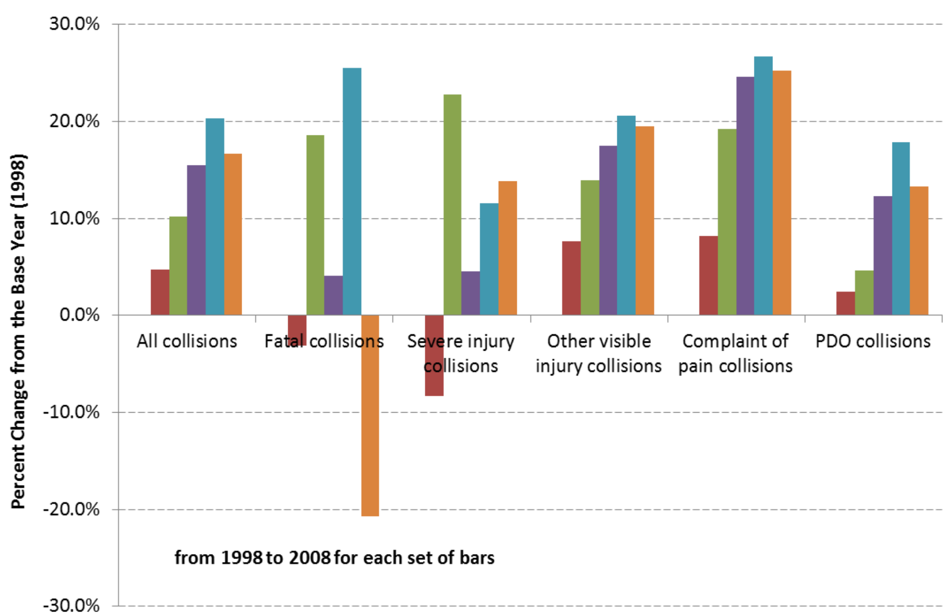


FIGURE 6 Change in Area of Standard Deviational Ellipse by Collision Severity over Time.

Directional distribution analysis provides overall insight into the spatial patterns of urbanization and traffic collisions; however, there are, limitations of applying directional distribution analysis to urban land and traffic collisions. First, the standard deviational ellipse assumes a mono-centric spatial plane whereas urban areas can have multiple centers. However, Sacramento County is suitable for this analysis because the county is essentially a single metropolitan area with both the population and employment being highly concentrated. Most of the population is distributed on the western and northern region that would be relevant to mean center of an ellipse. Consequently, the directional distribution tool using standard deviational ellipses generated a variety of useful and meaningful statistics such as geographic mean center, standard distances, and rotation of the axes for the case region. Secondly, standard deviational ellipses might not give a suitable explanation because of the difference between fundamentally evolving patterns of urban areas and traffic collisions. For example, while urban areas evolve without directional restriction, traffic collisions are restricted to the street network. This type of pattern can be seen by showing that although urbanization is evolving toward the east remotely, the roads connecting two urban areas are detouring around the south. This effect causes urbanization and traffic collisions to have different directional distributions. We experienced this case in Sacramento County with respect to the shift in mean center of urban land and traffic collisions.

5. CONCLUSION

In the past decade, the relationship between urbanization in the outskirts of metropolitan areas and transportation safety has become a focus of both scholars and government agencies. This study focused on a longitudinal analysis of urbanization and traffic collisions to overcome the limits of cross-sectional studies that have been carried out on this topic. Accordingly, the study presented explicit measurements of spatial patterns of urbanization and traffic collisions and provided insights into how certain relationships have a spatial dimension over time by looking at a metropolitan region during a significant growth period. The results of this study can help one understand the spatiotemporal characteristics of both urbanization and traffic collisions and their relationships. This information is potentially beneficial to those who work on macroscopic transportation planning and design. In addition, the method used in the study can potentially be useful for analyzing population growth, urban development trends or other spatially distributed phenomena.

Urbanization is a comprehensive concept that is comprised of numerous variables such as the built environment, socio-demographic characteristics or other factors. While this analysis provides some insight into the spatiotemporal trends of urbanization and traffic collisions, further work is needed to investigate other possible factors that may influence traffic safety. For example, changes over time in unemployment rate, population density or other attributes that can represent urbanization may have a significant influence on traffic safety, and the relationship between these attributes will give more insight into the spatiotemporal pattern of traffic safety. The current method focuses only on the correlation between two variables over space. Thus, evaluation of this spatial pattern using a more rigorous statistical analysis would help the study reliability. Furthermore, there are several features of this study that can be built upon in future research. First, the FMMP's land use data used in this study is a relatively crude estimator for urbanization. More extensive land use data or road network data would result in more precise outputs providing more clear insights into the relationship between traffic collisions and the built environment. Secondly, a three-dimensional representation of the spatiotemporal trends in these features would allow future analyses to take into account the concentration of both urbanization and traffic collisions over time.

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