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City-level urban form and traffic safety: A structural equation modeling analysis of direct and indirect effects

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ABSTRACT

While most existing studies have examined the impact of the community- and street-level built environment on traffic safety, few have provided empirical evidence on the associations between urban form characteristics and traffic safety at the city level. To this end, this article first created a detailed list of 23 variables to measure city-level urban form of 100 major Urban Areas (UAs) in the United States and then applied factor analysis to construct five latent variables which describe urban form. Factor analysis is also used to define mediator variables reflecting citywide transportation network features and dependent variable of traffic safety. Structural Equation Modeling (SEM) is then used to investigate how city-level urban form, directly and indirectly (through mediators of transportation network features), affects traffic safety. Based on the statistical results, urban traffic is safer in UAs with more uniform job-housing balance among their different tracts, more polycentric design, and less low-density sprawl. In addition to spatial variation in employment and urban density that have significant direct effect on traffic safety, improving transportation network connectivity and increasing the supply of public transit facilities and upper-level transport infrastructures can decrease traffic fatalities indirectly, through encouraging the use of non-driving transport modes. It is estimated that a 10% increase in urban density as well as a 10% increase in even spatial distribution of employment can reduce the rate of fatal crashes by > 15%, on average. These findings demonstrate the importance of incorporating city-level land-use policies into the planning practices, in terms of traffic safety.

1. Introduction

The motorization that accompanies global urbanization has turned traffic safety into a primary challenge for city planners and transportation engineers, especially those serving in urban areas (UAs). Indeed, these areas experience a higher frequency of traffic crashes than rural areas. Recent studies show that the total cost of traffic crashes exceeds the cost of congestion in UAs; in UAs with a population over three million, this cost is about double the cost of congestion (AAA Study, NewsRoom, 2015). The problem is so acute that traffic crashes are now regarded as the costliest side effects of transportation infrastructure. On average, the death rate by traffic crashes in the 50 most populous U.S. metropolitan areas was 82 per million residents in 2009 (Morbidity and Mortality Weekly Report, 2009). Yet this mean hides a considerable variation (range from 44 to 178), which demonstrates the need for more research to understand how urban characteristics affect traffic safety so as to better inform planners and policy makers.

Enhancing traffic safety in UAs commands to comprehensively investigate various elements related to the transportation system of cities, such as users (including drivers, passengers and pedestrians) and their behavioral patterns, vehicles (including bikes, passenger cars and transit utilities), infrastructure (including roadways and traffic control devices), transportation network, traffic flow, and urban form or land-use features (Road Safety, World Bank, 2015; Najaf et al., 2017). Much literature has emphasized the influence of land-use patterns across various geographic scales on traffic safety, especially at the street and community levels (Dumbaugh and Rae, 2009; Ewing and Dumbaugh, 2009; Marshall and Garrick, 2011). However, the safety impact of city-level urban form characteristics is most often overlooked; this would include the shape and land-use pattern of a city and the citywide spatial distribution of sociodemographic components, which are major determinants of the layout of transportation network and travel demand in cities (Newman and Kenworthy, 1989, 1991; Bento et al., 2005). Also, substantial empirical evidence has demonstrated that travel behaviors (e.g., mode choice and vehicle mileage traveled, VMT) vary across cities with different urban form features (Zhang et al., 2012a, 2012b; Ewing et al., 2014), and that traffic risks are largely associated with travel behavior decisions and outcomes (Jovanis and Chang, 1986;

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Noland, 1995; Clark and Cushing, 2004). It is thus crucial to study both the direct and indirect relationships between urban form and traffic safety consequences.

This research thus contributes to the traffic safety literature through a city-level analysis of traffic crashes in US urban areas, with a focus on the impact of urban form characteristics. Specifically, we aim to answer three research questions: 1) How to define better city-level urban form features for traffic safety studies? 2) What are the direct and indirect relationships (both the strength and direction) between the factors of urban form and traffic safety? 3) What specific city-scale land-use strategies in planning practices have the potential to improve traffic safety? This article first creates a detailed list of 23 variables to measure city-level urban form of 100 major UAs in the US and then applies factor analysis to construct five latent variables that describe urban form. We further use factor analysis to define mediator variables, reflecting citywide transportation network features, and dependent variable of traffic safety. Structural Equation Modeling (SEM) is the analytical method employed to investigate how city-level urban form, directly and indirectly (through mediators of transportation network features) can impact traffic safety. SEM is widely regarded as a powerful multivariate statistical approach to account for complex relationships between multiple exogenous and endogenous variables and to estimate direct and indirect relationships between them.

The rest of this paper is organized as follows. Section 2 reviews the existing literature on the relationship between urban form and traffic safety. In addition, this section talks about the advantages of the SEM technique compared to other traditional modeling approaches and presents an overview of how this technique has been used in other areas of transportation analysis. Section 3 introduces the analytical process based on the SEM approach. Section 4 describes the data, including the set of cities used in the study and the variables assembled for the analysis. Section 5 summarizes the modeling results and discusses the results of the calibrated models. Advantages and limitations of this research are discussed in Section 6, while conclusions and policy implications are drawn in Section 7.

2. Literature review

2.1. Urban form and traffic safety

Urban form is generally defined as the physical configuration of the parts that constitute a city or an UA and the citywide spatial distribution of specific socio-demographic factors, both of which are deemed to affect citywide transportation layout, planning and policies. In other words, all urban form variables are spatially associated and measured at the UA scale. Some literature also refers to the notion of urban form as land-use patterns or urban spatial structure (Portland Plan, 2008).

Urban form can be apprehended at three different levels of geographic detail. First is the street level: streets of an UA are designed in a way to accommodate different types of users (e.g., pedestrians, passenger cars, transit vehicles and trucks), different types of facilities (e.g., traffic control devices, transportation equipment and transit stations) and different types of functions (e.g., vehicle movement, bicycle movements, pedestrian activities, shopping and recreational activities). Second is community-level urban form. Communities have primary responsibility to serve the basic needs of residents and other daily users and provide facilities and opportunities to residents for different types of neighborhood activities. Community design is essential to the livability of the urban environment, while designing and locating various activity centers, such as schools, parks, or libraries, mixed-use buildings and entertainment facilities, are the main functions of community-level urban form. The third one is city-level urban form. Some of the main functions of the city-level urban form include the overall existing physical and activity-based form of a city, planning for future growth (e.g., planning for transit-oriented developments, community centers, neighborhood districts and corridors), planning for existing and future land uses (e.g., commercial, residential and mixed-use areas) and also planning for future development of the UA (i.e., how to design corridors, transit systems, community centers, pedestrian-oriented commercial centers, mixed-use areas and industrial areas to maximize the efficiency of the urban activities) (Urban Form and Neighborhood Design, 2014).

Multiple variables are recommended to measure city-level urban form (Bento et al., 2005; Mohan, 2008): a) city shape, which measures how much the outline of the UA deviates from a circular shape, ranging from 0 to 1, where 1 indicating a circular UA, b) density of the transportation network, which measures the area density of roadways in the UA, c) spatial distribution of population, which measures how the population is distributed with respect to the CBD, d) job-housing balance, which measures the ratio of jobs versus housing, e) pattern of residential land-uses, which measures the distribution pattern of residential areas in the UA and basically represents the centralization of population around the Central Business District (CBD), f) population centrality, which measures the distribution of population radially from the CBD, g) employment centrality, and h) employment density gradient.

The spatial structure of the UA influences many different urban features such as traffic safety, accessibility, sustainability, efficiency, equity, environment and economics (Bento et al., 2005). Of interest to this study, Mohan (2008) studied traffic fatalities in 56 large cities around the world, in addition to American cities with a population over 100,000. Results showed that simply improving vehicle safety and roadway conditions would not be enough to significantly decrease the fatality rate, because of the wide variation in fatality rates across and within different income levels. Urban form was then suggested as one of the main factors that determine the fatality rate in an UA. Based on the spatial pattern of employment layout, a city's urban form can generally be divided into monocentric and polycentric city models. The monocentric configuration (Alonso, 1964) has been the first formal model of urban structure, featuring a unique center, the CBD. In contrast, in polycentric UAs, the proportion of employment in the CBD has decreased over the time; some new employment centers have emerged outside the CBD and the employment distribution becomes more even geographically (Lin et al., 2012).

Urban sprawl is one of the major urban form aspects associated with traffic safety. Urban sprawl is the uncontrolled spreading of low-density urban development onto undeveloped lands near the UA fringe. This development pattern increases the need for vehicles and may consequently decrease traffic safety. Urban sprawl increases the probability of traffic crashes not only by increasing VMT, but also by decreasing the density and compactness of development in the UA. A density increase is often associated with mixed land-use development in smaller areas; known consequences include enhanced walkability and reduced traffic fatalities (Ewing et al., 2003). The latter study presented a composite compactness index and identified it as an influential factor of the number of traffic fatalities. It showed that traffic fatality rates were higher in areas with more urban sprawl. More specifically, the results indicated that for every 1% increase in the index (i.e., less sprawl), the fatality rate decreases by 1.49%, especially the pedestrian fatality rate. Similarly, Frumkin (2002) discussed the impact of sprawling features (i.e., low-density and segregated land use and car dependence) on traffic crashes, pedestrian injuries, and fatalities. He advocated for the positive role of social equity and justice in urban design and the need for better planning to reduce public health costs such as traffic crashes.

Safety in transportation has been regarded as one of the main principles to build urban environments, and design streets and communities (Dumbaugh and Rae, 2009). Some of the effective street/community-level urban form factors examined in the vast traffic safety literature include roadway functional classification, the level of pedestrian activities, retail configuration, neighbor and community density, development patterns (e.g., transit-oriented development, sprawl and suburban development), block size, type and level of accessibility,