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Investigation of road network features and safety performance

Xuesong Wang[a,b,*], Xingwei Wu[a,b], Mohamed Abdel-Aty[c], Paul J. Tremont[a,b]

[a] School of Transportation Engineering, Tongji University, Shanghai 201804, China
[b] Road and Traffic Key Laboratory, Ministry of Education, Shanghai 201804, China
[c] Department of Civil, Environmental, and Construction Engineering, College of Engineering and Computer Science, University of Central Florida, Orlando, FL 32816-2450, United States

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A B S T R A C T

The analysis of road network designs can provide useful information to transportation planners as they seek to improve the safety of road networks. The objectives of this study were to compare and define the effective road network indices and to analyze the relationship between road network structure and traffic safety at the level of the Traffic Analysis Zone (TAZ). One problem in comparing different road networks is establishing criteria that can be used to scale networks in terms of their structures. Based on data from Orange and Hillsborough Counties in Florida, road network structural properties within TAZs were scaled using 3 indices: Closeness Centrality, Betweenness Centrality, and Meshedness Coefficient. The Meshedness Coefficient performed best in capturing the structural features of the road network. Bayesian Conditional Autoregressive (CAR) models were developed to assess the safety of various network configurations as measured by total crashes, crashes on state roads, and crashes on local roads. The models' results showed that crash frequencies on local roads were closely related to factors within the TAZs (e.g., zonal network structure, TAZ population), while crash frequencies on state roads were closely related to the road and traffic features of state roads. For the safety effects of different networks, the Grid type was associated with the highest frequency of crashes, followed by the Mixed type, the Loops & Lollipops type, and the Sparse type. This study shows that it is possible to develop a quantitative scale for structural properties of a road network, and to use that scale to calculate the relationships between network structural properties and safety.

1. Introduction

Traditional safety analyses mainly examine problems on existing networks, and as such, are reactive. In recent years, the advantages of conducting safety analyses prior to construction of road networks have become more apparent. In the United States, safety planning, as part of the transportation design process, is already underway in both research and practice. The Transportation Equity Act for the 21st Century (TEA-21) and the Safe, Accountable, Flexible, Efficient, Transportation Equity Act: A Legacy for Users (SAFETEA-LU) emphasized the necessity to plan for safety during the development process (U.S. DOT, 1998; U.S. DOT, 2009). Specifically, SAFETEA-LU required state and metropolitan planners to incorporate safety considerations at the design stage in all new projects in the US (U.S. DOT, 2009). Design stage safety planning is becoming more prevalent outside of the US. A review of the latest comprehensive transportation plans of 35 international metropolitan areas showed that safety considerations were being incorporated as an essential element of these transportation plans (Peng and Wang, 2011).

A critical step to incorporating safety into transportation planning is to develop models that can be used to reveal the safety features of macro-level variables such as road characteristics, demographics, and network structure. Road network structure is one macro level variable that plays an important role in trip route determination and in overall network safety. It is especially important to consider network structure at an early stage because it is difficult and costly to modify the network structure after its construction. However, methods for determining the safety of network structures prior to their construction have not been well developed, in part, because quantitative scaling of network structures has not been well developed. If metrics can be developed to quantify the characteristics of road network structures, then it will be possible to develop statistical models to evaluate the safety features of the planned and existing road networks. Several measures (e.g., Centrality, Clustering, and Meshedness Coefficients) have been developed to quantify road network features (Cardillo et al., 2006; Jiang and Claramunt, 2004). However, there are very few studies analyzing networks' safety performance using appropriate measures.

* Corresponding author at: School of Transportation Engineering, Tongji University, Shanghai 201804, China. Tel.: +86 21 69583946; fax: +86 21 65982897.
E-mail address: wangxs@tongji.edu.cn (X. Wang).

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The authors (Wang et al., 2012) applied the Meshedness Coefficient to measure different network structures in Orange County, Florida. They found the Meshedness Coefficient could effectively capture the characteristics of a Traffic Area Zone (TAZ) network. They also found that the relationship between safety and network structure was significant when a new approach that separately modeled crashes on state and local roads was used. In this study, data for traffic, crashes, roadway, demographic, and land use features of Orange and Hillsborough Counties in Florida were examined to assess the safety effect of road networks. Different road network measures were compared, and then Bayesian Conditional Auto Regressive models were developed to examine relationships among total crashes, state road crashes, local road crashes, and various network structures at the Traffic Analysis Zone (TAZ) level.

The primary objective of the present study was to compare the effectiveness of Closeness Centrality, Betweenness Centrality, and the Meshedness Coefficient in their ability to scale different network structures. Another purpose was to extend the separate modeling approach proposed by Wang et al. (2012) to determine whether the obtained results were consistent with their earlier findings based on data from different counties. This can be considered a further step toward relating macro-level safety to road network structures.

2. Previous research

2.1. Macro-level safety models

The way to analyze safety at the macro-level is to model aggregated crashes in zones at certain level (e.g., census block groups, TAZs) with corresponding zonal macro-level variables (e.g., population, employment, and road characteristics). This macro-level safety models have the potential to play a critical role in safety planning. In an earlier study, Levine et al. (1995) used census block groups as the analysis unit to examine the relationship between macro level variables and crashes in Honolulu, Hawaii. Safety analyses at other spatially aggregated levels including the county level have been used to estimate crash frequencies (Aguero-Valverde and Jovanis, 2006; Noland and Oh, 2004; Huang et al., 2010). TAZs have typically served as the fundamental analysis unit in transportation planning, and they continue to be commonly used in zonal level safety analysis (Abdel-Aty et al., 2011; De Guevara et al., 2004; Hadayeghi et al., 2003, 2007; Hadayeghi et al., 2010; Miller and Shaw, 2001).

Various safety models have been developed to investigate the safety effects of TAZ level variables. For example, Hadayeghi et al. (2010) developed Geographically Weighted Poisson Regression models that included land use, traffic intensity, road network, and socioeconomic and demographic zonal characteristics as explanatory variables. Abdel-Aty et al. (2011) investigated the association between crash frequencies and various types of trip productions and attractions in combination with various road characteristics. They then developed safety measures to aid in making transportation planning decisions by linking trip and road variables to crash frequencies within TAZs.

These previous studies modeled crash frequencies at different levels. However, they all adopted the approach of modeling total crashes by including those occurring both within the zone and on the zone boundaries with features of the corresponding zones. Recently, Wang et al. (2012) found that for most collisions on state roads, the at-fault drivers were far from their home TAZ. Based on their analyses, they also found that collisions on state roads were strongly associated with certain features of state roads, and they demonstrated the effectiveness of separately modeling state road and local road crashes to capture different effects occurring on these different roadway functional classes.

Table 1
Summary of Macro-level features.

Category	Specific features
Demographic, economic and land use features	
Demographic features	Population, total number of households, population density, senior population and non-senior population
Economic features	Total employment, unemployment rate, number of vehicles per household
Land use features	Commercial, schools, hospitals and warehouse land types/area
Road network features	
Intersection facility	Number of intersections, intersection density, total number of roundabouts, signal density, number of signalized/unsignalized intersections
Road facility	Total arterial length, minor arterial length, total roadway length in TAZ area, road network structures
Traffic operational features	
Traffic volume	Total network volume in peak and off-peak periods
Aggregative features	Average travel speed, average saturation rate and average VKT

Macro level statistical modeling approaches have been further developed in recent years in an effort to improve the accuracy of their estimates. Generalized Linear Models (GLMs) for macro-level safety (Karlaftis and Tarko, 1998; Lord and Persaud, 2004; Ng et al., 2002; Noland and Quddus, 2004) were not able to meet the basic assumption of independent observations because adjacent units (i.e., TAZs) are spatially correlated. Thus, neither Poisson nor Negative Binomial regression models could yield accurate statistical estimates. Recently, Bayesian statistical methods have become popular in traffic safety analysis in part because they are able to correct for these spatial correlations (Aguero-Valverde and Jovanis, 2006; Hauer et al., 2002). Under the Bayesian approach, model parameters can be treated as random, and inferences are based on posterior distributions that combine the information from both observed data and prior distributions. Taking advantage of this information infusion capability, Bayesian Conditional Autoregressive (CAR) models can effectively accommodate the spatial autocorrelations of adjacent study units.

2.2. Macro-level risk factors

The macro-level factors investigated in the previous studies can be separated into three categories: (1) demographic, economic, and land use features, (2) road network features, and (3) traffic operational features. These are summarized in Table 1. Demographic features (De Guevara et al., 2004; Hadayeghi et al., 2003; Noland and Quddus, 2004; Quddus, 2008), economic features (Quddus, 2008; Khondakar et al., 2009) and land use features (Ng et al., 2002) were investigated to describe the general scale and features of TAZs. Ng et al. (2002) investigated the safety effects of 27 different types of land uses in Hong Kong. Road network features were previously represented by the facility size of intersections and/or roadways (Hadayeghi et al., 2003; Khondakar et al., 2009; Levine et al., 1995; Lovegrove et al., 2008; Quddus, 2008). Road network structure reflected the geometric nature of a TAZ and was closely related to safety, and was thus also considered as an important factor (Dumbaugh and Rae, 2009; Lovegrove and Sayed, 2006; Wang et al., 2012). Traffic operational features were represented by volume, Vehicle Miles Traveled (VMT) or Vehicle Kilometers Traveled (VKT) in research conducted by Hadayeghi et al. (2003), Lovegrove et al. (2008), and Quddus (2008).