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Investigating the associations between road network structure and non-motorist accidents

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ABSTRACT

Road networks channel traffic flow and can impact the volume and proximity of walking and bicycling. Therefore, the structure of road networks—the pattern by which roads are connected—can affect the safety of non-motorized road users. To understand the impact of roads' structural features on pedestrian and bicyclist safety, this study analyzes the associations between road network structure and non-motorist-involved crashes using data from 321 census tracts in Alameda County, California. Average geodesic distance, network betweenness centrality, and an overall clustering coefficient were calculated to quantify the structure of road networks. Three statistical models were developed using the geographically weighted regression (GWR) technique for the three structural factors, in addition to other zonal factors including traffic behavior, land use, transportation facility, and demographic features. The results indicate that longer average geodesic distance, higher network betweenness centrality, and a larger overall clustering coefficient were related to fewer non-motorist-involved accidents. Thus, results suggest that: (1) if a network is more highly centered on major roads, there will be fewer non-motorist-involved crashes; (2) a network with a greater average number of intersections on the shortest path connecting each pair of roads tends to experience fewer crashes involving pedestrians and bicyclists; and (3) the more clustered road networks are into several sub-core networks, the lower the non-motorist crash count. The three structural measurements can reflect the configuration of a network so that it can be used in other network analyses. More information about the types of road network structures that are conducive to non-motorist traffic safety can help to guide the design of new networks and the retrofitting of existing networks. The estimation results of GWR models explain the spatial heterogeneity of correlations between explanatory factors and non-motorist crashes, which can support regional agencies in establishing local safety policies.

1. Introduction

Walking and bicycling are highly promoted by many communities as a means to improve public health. However, although these travel modes together comprised 18.1% of all trips in California in 2011, they accounted for approximately 27% of all traffic fatalities in the state, totaling about 739 deaths from pedestrian- or bicyclist-involved accidents. In addition, pedestrians and bicyclists are more vulnerable road users, and are 30 and 12 times, respectively, more vulnerable than automobile drivers in the state (Grembek, 2012). As people are being encouraged to walk and bicycle more, it is important to make these travel modes as safe as possible. Research on improving road safety in North America is now turning its focus towards an integrated approach to land use and transportation planning that should improve road safety at the planning stage proactively (Wei and Lovegrove, 2012). By understanding the spatial impacts of road network patterns on non-motorist safety, community planners and engineers can consider or evaluate road safety proactively, in advance of construction, as part of future land use and transportation planning programs.

Road network patterns impact pedestrian and bicyclist safety by affecting the characteristics of traffic flow and travel behavior for both vehicles and non-motorists. The "structure" determines how direct a route is for drivers to follow and the number and types of turns encountered along the way. The connectivity, continuity, and shape of the route can affect vehicle speed and maneuvers, as well as driver visibility, thus impacting traffic safety (Haynes et al., 2007; Quddus, 2008).

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The geodesic distance between two roads is the smallest possible number of roads that constitute a route from an origin road to a destination road. A higher geodesic distance indicates that a road is likely to include a greater number of intersections to reach other roads in the network. In order to negotiate intersections, drivers must make sequential maneuvers including changing lanes, stopping, slowing down, and making turns, all of which can precipitate collisions. When making turns, drivers are generally focused on traffic coming from the opposite direction and may not check for pedestrians who share the same right-of-way for crossing the street. A network with higher geodesic distances also is likely to have more complicated routes, which increases the potential for conflict, particularly for drivers who are unfamiliar with the network. However, frequent maneuvers tend to force drivers to travel at slower speeds, increasing reaction time in the event of a conflict.

The network betweenness centrality quantifies the extent to which a network is centralized on major road links. A network with high centrality indicates low inter-connectivity and accessibility. Greater connectivity promotes increased vehicle accessibility. However, greater accessibility often leads to a higher proportion of vehicles taking shortcuts through neighborhoods instead of using arterial roads. Internal neighborhood roads are designed for low volumes of low-speed traffic, traveling to and from destinations within the neighborhood. Combining this local traffic (particularly non-motorized road users) with higher volumes of higher speed traffic has been shown to impact road safety negatively (Lovegrove and Sayed, 2006).

The clustering coefficient of a network determines whether the network is formed by sub-networks. A higher clustering coefficient means the network can be divided into several sub-clusters of local networks that are connected by arterial roads, such as the "loops and lollipops" pattern shown in Fig. 1. Residents must drive to local destinations such as the gateway interface between the local network and the arterial roads, leading to an increase in both traffic congestion and road safety risk, particularly as they necessarily involve turns at stop-controlled minor-major road intersections. A high clustering coefficient leads to an increase in the proportion of local-arterial road intersections and vehicle-kilometers-traveled, which, in turn, can impact the predicted collision rate and level of safety (Wei and Lovegrove, 2012).

Road network structure has been shown to have a significant impact on traffic safety, especially for pedestrians and bicyclists (Dumbaugh and Zhang, 2013; Marshall and Garrick, 2010, 2011; Rifaat and Tay, 2009; Rifaat et al., 2010, 2011, 2012; Wei and Lovegrove, 2012). Previous studies have attempted to classify road network patterns into different types, and then employ them in the analysis with collision frequency or severity data. However, the classification process is too subjective, as different researchers may understand and judge the same network differently, especially if the network is of a mixed type. Moreover, merely classifying networks by pattern does not directly explain how their accessibility, connectivity, and shape impact traffic safety. To overcome these issues, this study employed measurements of network structure, including the network average geodesic distance, betweenness centrality, and clustering coefficient, to quantify the characteristics of road network patterns. A geographically weighted regression (GWR) model was employed to evaluate the association between network structure characteristics and non-motorist-collision frequency. Other variables related to land use, travel behavior, transportation facility, and demographics also were included in the regression to control the potential causal factors other than the structure. The network structure measurements introduced in this research can also be useful for geographic engineers to quantify other networks (e.g., municipal water or other utility systems). The GWR model utilized in the analysis demonstrates an application of the method that is already built into Geographic Information Systems (GIS) software such as ArcGIS. Not only can the GWR method take into account the spatial interaction between adjacent study units, it can also generate local parameter estimations in various study units to help guide local policies. By understanding the road network structure's effects on traffic safety, the results of the analysis can help planners and engineers take traffic safety into account when planning or retrofitting a road network.

1.1. Literature review

1.1.1. Safety studies on different road network structures

The traffic-safety implications of various road network patterns have been a major concern of urban designers and traffic engineers. Southworth and Owens (1993) classified road network patterns in the United States into five categories: gridiron, fragmented parallel, warped parallel, loops and lollipops, and lollipops on a stick (see Fig. 1). Among these patterns, which is the safest for non-motorized road users? This question triggered the first comparison in the 1950s of accident rates between grid and curvilinear patterns (Southworth and Ben-Joseph, 1996). Research found that the grid pattern experienced a substantially higher accident rate than the limited-access pattern. Additionally, results from a series of recent studies using statistical models imply that discontinuous networks such as "loops and lollipops" generally perform more safely than the gridiron pattern (Ben-Joseph, 1995; Lovegrove and Sayed, 2006; Rifaat et al., 2010; Sun and Lovegrove, 2013), but they are associated with an increase in the severity of crashes involving pedestrians and cyclists (Pawlovich et al., 2006; Marshall and Garrick, 2010; Rifaat et al., 2011, 2012; Ewing et al., 2005). It was argued that a cul-de-sac pattern could be related to more severe collisions for non-motorists due to the presence of frequent curves and loops that could restrict drivers' sight distance. In turn, this could result in lower levels of perception and reduced reaction times, and in the ability of drivers to reduce vehicle speed, which can increase the severity of pedestrian injuries in the case of a collision. In addition, road curvature may cause difficulties for drivers in maintaining vehicle stability and maneuverability, which also reduces drivers' ability to decrease vehicle speed in critical situations. Moreover, limited access streets may induce some pedestrians to exercise less caution when using the roads because they perceive these streets to be safer (Rifaat et al., 2012).

These studies reveal that road network patterns do indeed impact traffic safety. However, in order to describe road network

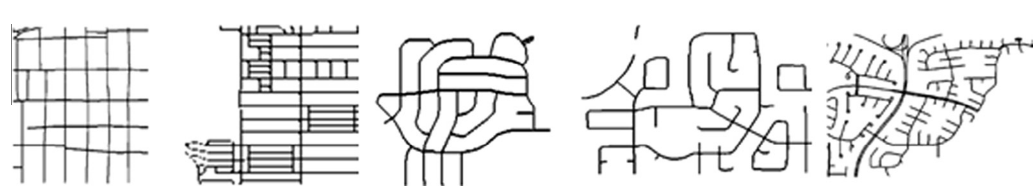

Fig. 1. Five categories of road network patterns obtained from Alameda County, California (from left to right: gridiron, fragmented parallel, warped parallel, loops and lollipops, and lollipops on a stick).