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A link-focused methodology for evaluating accessibility to emergency services

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ABSTRACT

This paper considers the development of a new measure for evaluating accessibility to emergency services via a road network called critical closeness accessibility (CCA). CCA quantifies the relative importance of each link in a roadway network with respect to its system-wide contribution to emergency service accessibility and is based on the network science/graph theory concept of closeness. CCA is a link-focused measure that used to evaluate accessibility on a link-by-link basis and can be used for disconnected networks. We introduce a relative importance-based weighting approach for both origins and destinations that can be applied to different types of nodes including generic link endpoints that represent individual intersections and roadway segments in GIS-based roadway maps as well as to physical locations. CAA offers a unique approach for evaluating accessibility that accounts for the spatial distribution of emergency service locations, the topology of the road network, and the engineering characteristics of the road network such as road types, capacities, volumes, and travel speeds.

1. Introduction

Many man-made systems including transportation infrastructure systems take the form of networks. As our world has become more highly connected there has been a great deal of interest in studying the principles that govern the underlying spatial characteristics and structure of different types of networked systems and how these characteristics are affected by planning and policy decisions. Roadway networks are extremely complex and are comprised of interconnected components that can interact with one another in intricate and often non-intuitive ways; and obtaining a better understanding of how accessibility is impacted by the complexities associated with the topology and physical characteristics of the roadway network is important with respect to making informed and accurate transportation planning decisions [15,35]. While interest in the spatial characteristics and structure of transportation networks is not new, the application of network science/complexity analysis and measures to transportation problems is limited [16]. Complex network theory or "network science" can offer unique approaches for evaluating different aspects of transportation-based accessibility.

This paper considers the development of a new approach for measuring accessibility to emergency service facilities (ESFs) via a road network called *critical closeness accessibility* (CCA). CCA quantifies the relative importance of each link in a roadway network with respect to its system-wide contribution to emergency service accessibility and is based on the network science/graph theory concepts of connectivity and closeness. The research provides a number of value-added contributions.

- CCA is a *link-focused* measure that quantifies accessibility on a link-by-link basis. Many existing transportation accessibility measurement approaches are *link-based* in that they utilize link impedance in the accessibility calculation; however, they evaluate the accessibility of a particular node or set of nodes (or zones) as opposed to assigning an accessibility value to the individual links in the network. We argue that place-based measures that use links in the accessibility calculation, but directly assign an accessibility value to a node or a set of nodes, are link-based as opposed to link-focused. As noted in [73] much of the research related to roadway networks tends to be node-centric and fails to recognize the link-centric nature of roadway infrastructure systems where the links as opposed to the nodes are the active elements.
- CCA directly builds on Dangalchev's [14] alternative formulation of closeness and the definition of *residual closeness*. First, residual closeness extends the concept of closeness to an arc where disconnected networks are addressed by allowing closeness to go to zero; however, it does not consider the importance of the disconnected nodes. Dangalchev points out that residual closeness is not substantially impacted by losses in connectivity resulting from disconnected networks. We feel that this is unlikely to be the case for many real-world networks such as transportation networks where disruptions can isolate portions of the population from essential services. Second, residual closeness is formulated in a manner that considers all nodes

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in the entire graph and weights them equivalently. We address both of the issues above by introducing a relative importance-based weighting approach that can be used for different subset typologies of nodes.

- The CCA weighting approach can be used for generic link endpoints representing intersections and individual roadway segments in GIS-based roadway maps as well as for actual physical locations. This approach provides an important contribution to the accessibility literature as only measures of destination attractiveness are currently considered. We use the actual endpoints of each roadway link in the CCA calculation as opposed to artificially creating origin and destination nodes via abstraction, thus preserving the actual connectivity of the roadway network being modeled.
- CAA offers a unique approach for evaluating accessibility that accounts for the spatial distribution of critical/important nodes, the topology of the road network (relative locations and connections between links and nodes), and the engineering characteristics of the road network such as road types, capacities, volumes, and travel speeds.

We believe that this work provides a unique, highly relevant and usable decision support methodology that fills a niche at the union of network science, emergency service, and transportation accessibility research. CCA can be applied at different geographical scales, to all types of critical/important facilities, to different types of nodes, and at vastly different scales. The methodology is described and illustrated on a small hypothetical network and is then demonstrated in a real-world application on portions of an actual GIS-based transportation planning network using an off-the-shelf software for transportation network applications called TransCAD™. The paper is organized as follows. Section 2 provides a discussion on the use of travel models in transportation planning and how transportation infrastructure investment and policy decisions are shaped by outputs from these models. A discussion of relevant literature is presented in Section 3. The CCA methodology is introduced in Section 4, which includes an example implementation of the CCA along with detailed calculations. Section 5 focuses on a real-world application of CCA. A summary of our research contributions, concluding remarks and suggestions for future work is outlined in Section 6.

2. Transportation planning, travel models and decision-making

Timely access to emergency services including police, fire, rescue, and medical care is essential to the overall health, safety, and general welfare of any population; and the roadway infrastructure system can greatly affect accessibility to these services. Distance-comparable locations within a given road network are not equally accessible. Some locations are more or less accessible than others based on factors such as the structural characteristics of the roadway infrastructure, network topology, and the surrounding geographical features [39]. Consequently, the everyday lives of people are impacted by not only the distances between where they live and where they are going but also by the characteristics of the existing roadway system, as the road network can enhance (or diminish) accessibility to emergency services and other important locations. GIS-based modeling has been successfully applied in a variety of residential and business planning decisions as well as in the context of some transportation planning problems [25,40,67]; and in recent years accessibility has become more of a focus in the land-use/transportation planning and policy arenas as the realization of the magnitude of economic, social and environmental implications associated with accessibility issues has become more evident [54,61,67]. While accessibility is a well-known concept, there is no consensus on how it should be measured or even defined. How accessibility is defined and measured as well as the level of detail of the analysis are critical in the context of planning decisions, as different types of decisions require different performance measures, different assumptions, as well as different analysis tools and solution techniques.

In the United States, state, regional and municipal transportation agencies are largely responsible for the planning, construction, maintenance and governance responsibilities associated with the various transportation infrastructure systems within their respective jurisdictions [70]. To facilitate accurate and timely travel demand forecasts as well as to gain a better understanding of the current operational status of existing transportation systems, decision makers often rely on sophisticated, large-scale, statewide transportation planning models which are ideal for projecting current travel patterns and estimating travel demand on the roadway network. Outputs from these models are often used to direct funding and policy decisions such as new roadway construction and the selection and prioritization of roadway maintenance projects. Unfortunately, these models do not specifically address accessibility or emergency service issues. It is therefore challenging to predict and/or evaluate emergency response and emergency service routing. This can result in planning decisions that ignore the most critical roadway links in the network with respect to facilitating accessibility to emergency services.

This research is largely motivated by the lack of accessibility-based decision support modeling tools available to transportation planners [25,61,67]. The CCA can be used within the existing travel modeling framework to specifically evaluate roadway-based accessibility concerns such as: identifying specific links and/or portions of the road network that are the most important in terms of facilitating system-wide access; identifying specific links and/or portions of the road network and their corresponding populations and locations that are at an inherent disadvantage for receiving critical emergency services; and assisting with new ESF location decisions and emergency route planning.

3. Background

In this paper we connect concepts from a number of different problem domains including transportation planning, emergency service management, facility location decisions, and accessibility modeling/measurement using a methodological approach based on network science and graph theory. The body of literature in each problem domain, as well as the body of literature addressing network science/graph theory methodologies and their applications is quite extensive and a range of solution methodologies are employed depending on the scope of the problem, the type of network being considered, and the availability of empirical data. We do not attempt to provide a comprehensive review of the literature in each problem domain or to detail the history and evolution of network science. Instead, we focus on providing a general background on network science and include examples of how network analysis and graph theory has been applied to transportation network planning problems, specifically with regard to accessibility-based performance measures for roadway systems. The literature review is organized into three subsections: 3.1. Network science and infrastructure networks, 3.2. Accessibility and roadway networks, and 3.3. Emergency services and facility location.

3.1. Network science and infrastructure networks

The term *network science* describes an evolving research area that includes applications and problems that are largely inspired by the study of non-trivial, real-world networked systems such as transportation, physical, biological and social networks [31]. Like other complex networks, transportation networks possess topological and geometric variations that can be described by a set of nodes representing distinct spatial locations and a set of links that characterize the connections between the nodes [73]. While much of the network science related research authored by physical scientists tends to focus on the statistical properties of different systems; much of the network science related research authored by transportation engineers, planners, and geographers