Network Robustness Index: A new method for identifying critical links and evaluating the performance of transportation networks

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Abstract

Highway planning efforts, especially those involving capacity expansions, have traditionally relied on the volume/capacity (V/C) ratio to identify “highly congested” or critical links, resulting in localized solutions that do not consider system-wide impacts. This paper presents a new, comprehensive, system-wide approach to identifying critical links and evaluating network performance. The approach considers network flows, link capacity and network topology. Moreover, it relies on readily available sources of data. Using three hypothetical networks, we demonstrate that the approach, known as the Network Robustness Index, yields different highway planning solutions than the traditional V/C ratio. Moreover, these solutions yield far greater system-wide benefits, as measured by travel-time savings, than solutions identified by the V/C ratio.

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1. Introduction

In the United States, the interstate highway system is undoubtedly one of the most critical components of the transportation system due to its role in facilitating economic growth, providing timely access for travelers and contributing to the nation’s defense. In recent years, the country has witnessed incredible growth in vehicle travel on the interstate system. Between 1991 and 2001, for example, overall vehicle travel increased by 38% and commercial truck travel increased by 42% (TRIP, 2003). Consequently, in many urban and suburban locations, the interstate system has become highly congested (Schrank and Lomax, 2005)—an unfortunate situation that is not remedied easily (Scott, 2002). Simply stated, it is impossible to expand all such sections and to meet all travel demand with a high level of service given the current fiscal environment. In a world of limited resources, where funds do not necessarily keep pace with the growing demand for infrastructure improvements, not to mention the increasingly costly maintenance of aging infrastructure, it is essential to make well-informed public policy choices when selecting specific segments for improvement (USDOT FHWA, 1996).

Certain regions of the country may rely on the interstate highway system more than others if their economic specializations and trading relationships with the rest of the nation and other countries are contingent upon truck transport. While not necessarily as congested as urban interstate sections, the economic consequences of even a relatively short-term disruption in travel on rural interstate links may be extremely serious for these regions, effectively cutting or severely curtailing access to other regions of the country, and even isolating the affected region from particular inputs or markets. For example, the 1994 Northridge,
CA earthquake is estimated to have resulted in nearly $1.5 billion in economic losses attributed to transportation interruptions (Davis, 1998). In 2004, a tanker truck accident along I-95 closed a mile-long section of interstate near Bridgeport, CT. The economic consequences of the closure were severe, with construction costs alone amounting to $4 million and another $11 million in emergency federal aid required to reopen the interstate (Scarpioni, 2004). Connecticut declared a state of emergency and heavily traveled portions of I-95 were completely closed to commercial truck traffic for several weeks (Associated Press, 2004). Commercial trucks were required to completely by-pass large portions of Connecticut and reroute through New York and Massachusetts while repairs to the interstate were made. The impact of this closure on the network was not only a function of the demand on the closed section itself, but also on the availability of alternative detour routes, their capacity and level of usage.

The removal or blockage of one or more network links, particularly those that are heavily traveled or those containing bridges, could have direct and serious economic consequences in terms of overall system travel-time increases, but also with respect to freight logistics/supply-chain management (Bell, 2000; Chen et al., 2002; Smith et al., 2003). Not only could supply routes and delivery schedules be disrupted, but also the costs associated with rescheduling and rerouting could be prohibitive for both suppliers and resellers. Rerouting traffic could also result in additional safety risks and congestion on alternate interstate segments, particularly if a large volume of commercial vehicle traffic were routed to links that were already operating at or close to capacity. Depending on the spatial layout of the network (i.e., network topology) and on specific origins and destinations, different types of traffic could have very difficult times rerouting in the event of a link failure (Bell, 2000).

Network “flexibility” addresses spatial organization in various infrastructure (e.g., communications and transportation) planning and engineering practices. Feitelson and Salomon (2000) identify network flexibility as a network attribute that relates to a network’s physical characteristics and to the level-of-service it provides users. The authors suggest that differences in network flexibility have important ramifications for spatial organization, particularly at the macro level. Morlok and Chang define “system capacity flexibility” as “the ability of a transport system to accommodate variations or changes in traffic demand while maintaining a satisfactory level of performance” (Morlok and Chang, 2004, pp. 405–406). A flexible highway network must therefore be able to adapt to changes in the quantity of traffic, freight commodity mix and spatial flows from one geographic area to another. Capacity flexibility is an important issue for two reasons. First, the seemingly endless growth in US road traffic coupled with a relatively stagnant highway infrastructure requires flexibility in terms of serving increasingly high levels of travel demand with a relatively constant supply of infrastructure capacity. Secondly, dramatic changes in trade patterns, the types of goods carried and the nature of transportation services needed require a flexible transportation infrastructure (Morlok and Chang, 2004).

Bell (2000) offers the following definition of “network reliability”. “A network is reliable if the expected trip costs are acceptable even when users are extremely pessimistic about the state of the network” (Bell, 2000, p. 534). According to Bell, reliability pertains directly to instances of natural disaster when parts of the transportation network may fail and also to road space reallocation among competing transportation modes such as transit, pedestrians and cars. He points out that reliability has two dimensions: network connectivity and performance reliability. In the case of network connectivity, the more sparsely connected the network, the more difficult it may be for travelers to arrive at their destinations on schedule if there are segment blockages or failures. Measuring reliability is difficult as it includes both the physical infrastructure and the behavioral responses of travelers. Chen et al. (1999) consider capacity reliability as a network performance index that builds upon the network reliability concepts introduced by Bell and Iida (1997). Chen et al. (2002) define capacity reliability as “the probability that the network can accommodate certain traffic demand at a required service level, while accounting for drivers’ route choice behavior” (Chen et al., 2002, p. 227).

In this paper, we draw on both the flexibility and reliability concepts introduced by other researchers. Each offers important insights into the spatial layout of the physical highway network, the need to address capacity planning and, more generally, transportation planning from a system-wide perspective taking into account network topology. Current infrastructure management practices typically address the complex decision-making required just to manage demand on individual congested portions of the highway network by identifying critical highway segments using localized level-of-service (LOS) measures such as the volume/capacity \( V/C \) ratio (Bremmer et al., 2004; Dheenadayalu et al., 2004). A \( V/C \) ratio greater than one is indicative of congestion. When a high ratio is identified, improvements are implemented at the segment or corridor level to alleviate or reduce congestion on that particular segment. Often the solution to congestion planning problems is to simply add more capacity along existing highway segments. In effect, this is a localized solution. Performance improvements are measured via a decrease in travel times on specific segments in the local area of the improvement.

The localized \( V/C \) approach, however, may not enable traffic engineers and planners to identify the most critical highway segments or corridors in terms of maximizing system-wide, travel-time benefits associated with a highway improvement project. Bremmer et al. (2004) point out that traditional congestion measurements are based on volume and capacity information, but are often inadequate in many cases. Potential problems associated with the \( V/C \) ratio are...
ratio are illustrated in the hypothetical and greatly simplified network shown in Fig. 1.

A comparison of $V/C$ ratios suggests Link 2 is the more critical link—that is, the ratio on Link 2 is equal to 1, while the ratio on Link 1 is equal to 0.3. However, Link 1 carries three times the traffic volume of Link 2. If Link 1 were eliminated, or even partially blocked, rerouted traffic from Link 1 cannot be accommodated on Link 2 as it does not have the capacity to handle the additional traffic. On the other hand, if Link 2 were blocked, rerouted traffic can be accommodated easily on Link 1. Link 1 is actually the more critical link, although the $V/C$ ratio does not adequately reflect its importance to the highway network.

We believe the current, localized planning approach should be improved upon, as it does not consider system-wide impacts resulting from improvement projects. While implementing local solutions may result in localized benefits, these solutions may have limited, negligible or even adverse system-wide effects. Recent studies of induced travel in North America offer strong evidence that this is indeed the case (see Scott, 2002 for a review of such studies). An equal level of investment in another location or locations may provide more benefit to the network. We argue that it is time to reconsider the existing localized $V/C$-based planning approach and focus on a comprehensive system-wide approach to identifying critical infrastructure and evaluating network performance. Improvements should thus be evaluated in terms of maximizing the performance of the highway system from a system-wide perspective. This approach should complement existing local planning to prevent the spread of localized problems to other parts of the highway network.

Our research is based on the premise that a fundamental change in highway network design philosophy is needed. We believe that a transportation network should not only meet origin-destination (OD) demand, but should provide ample connectivity so as to not be overly vulnerable to disruptions on individual segments within the system. This directly supports the importance of the concepts of transportation flexibility and reliability. The underlying goal of the planning and management process should encourage the development of well connected highway networks that focus on spatial relationships between different segments, as well as using the traditional $V/C$ measure. In this paper, we introduce a new measure for identifying critical network links and evaluating network performance that considers not only traffic flows and capacity, but also network connectivity. We test how well the proposed measure performs compared to the traditional $V/C$ ratio by using three hypothetical networks, each of which is characterized by a different level of connectivity. We demonstrate that our approach, known as the Network Robustness Index, yields different highway planning solutions than the traditional $V/C$ ratio. Moreover, these solutions yield far greater system-wide benefits, as measured by travel-time savings, than solutions identified by the $V/C$ ratio.

The remainder of this paper is organized as follows. The next section presents a brief review of related literature. A discussion of key transportation indices, namely the gamma index and the $V/C$ ratio, follows in Section 3. Derivation and implementation of our new approach, the Network Robustness Index, is discussed in Section 4. The data employed in our study are described in detail in Section 5. Results are found in Section 6, followed by the conclusions in Section 7.

2. Related literature

The respective literatures addressing aspects of highway capacity planning and the role of spatial considerations in urban planning are extensive. To a large degree, most highway capacity research tends to focus on methodologies for estimating or evaluating segment capacities and/or examining very specific capacity improvement projects and solutions. Much of the spatial planning literature addresses the need (or desire) for increased coordination/cooperation between spatial/geographic planners and transportation planners, and discusses potential benefits if a broader spatial planning context is employed. While there is some overlap between these two literatures, our focus is on the direct linkages between spatial planning and highway capacity needs and appropriate metrics for capturing those linkages. We summarize briefly a number of studies that are directly related to our research.

Clark and Watling (2005) propose a technique for estimating the probability distribution for total travel time on a road network assuming daily variations in the travel demand matrix. Morlok and Chang (2004) describe techniques used to measure the flexibility of a transportation system to accommodate changes in demand and traffic. The authors employ a network-wide approach for measuring flexibility based first on a traditional capacity modeling approach with fixed spatial patterns of traffic and then based on a dynamic approach where spatial patterns and cargo can vary. Dheenadayalu et al. (2004) examine the trade-off between the time spent collecting detailed link-specific capacity data and the accuracy sacrificed by using average capacity estimates for generalized link-type categories. Link-by-link capacity estimates provide more accurate capacity estimates, which can greatly improve travel demand modeling. The authors conclude that the most important localized capacity factors are the effective green time to signal cycle length ($g/C$) ratio and the number of lanes. Dheenadayalu et al. (2004) discuss how the
movement of goods and freight is widely underrepresented in regional science and geographical research even though a large body of traditional spatial theory has been developed with respect to transportation costs. The paper provides an overview of the emerging transport geography of logistics and freight distribution, and challenges the traditional assumption where transportation is considered a derived demand. The authors present the argument that logistical requirements underlie transportation as a component of an integrated demand. Chen et al. (2002) introduce a reliability evaluation framework, which combines reliability and uncertainty analysis, network equilibrium models, and sensitivity analysis to perform a probabilistic assessment of capacity and travel-time reliability. The authors demonstrate that stochastic conditions on road networks should be considered in determining network reliability.

Bell (2000) uses a game theory approach to evaluate the performance reliability of a transportation network. The author discusses the components of reliability and discusses the importance of network connectivity in detail. Arentze and Timmermans (2000) propose a spatial decision support system that allows users to consider a wide range of both land-use and transportation issues together. The system is used to model trip generation and is not directly related to identifying capacity improvement needs. Johnston and de la Barra (2000) demonstrate how an urban planning model, which includes land and travel markets with zones and networks, can be sequentially linked to a GIS-based land allocation model, which spatially allocates land uses by zone to provide a comprehensive evaluation of regional transportation and land-use policies. Iida (1999) outlines basic concepts, remaining problems, and future directions of road network reliability analysis. The author addresses the need to first analyze the reliability of the links that comprise the network prior to analyzing the reliability of the network itself. Taylor (1999) outlines the use of dense network modeling and network reliability in the planning and design of traffic management. The author applies reliability indices for the study of different trip movements within a network. Frohwein et al. (1999) present a multicriteria decision-making framework to aid the selection of roadway improvement projects. The authors examine three major factors in the model: crash-risk reduction, performance improvement and project cost. The decision tool enables the comparison of diverse projects on a common ground and provides information on the trade-offs that come with the selection of projects. Donaghy and Schintler (1998) present a dynamic model that can be used in optimal control exercises to determine what steps ought to be taken, when and where, and by how much to achieve planning objectives. The model is used to determine optimal levels of new construction and maintenance needed to keep pavement conditions at acceptable service levels to achieve desired peak-period congestion levels aimed at reducing VMT (vehicle miles traveled) and emissions of VOC (volatile organic compounds).

Ball and Golden (1989) build on previous work and show that the most vital arcs problem (MVAP) and the most important arcs problem (MIAP) are NP-hard. The authors provide a solvable approximation for MVAP. These problems involve identifying arcs whose removal from the network result in the greatest increase in the length of the shortest path between two specified nodes. Corley and Sha (1982) do not examine network reliability per se, but propose an algorithm for identifying the most vital links or nodes in a network whose removal results in the greatest increase in the shortest distance between two specific nodes. Ball (1979) presents an algorithm to compute reliability measures on a stochastic communications network. The reliability concepts discussed (i.e., the probability that nodes \( s \) and \( t \) can communicate for all node pairs \( s \) and \( t \), the probability that all operative node pairs can communicate, and the expected number of node pairs communicating) are not transportation related and do not address trip generation or the cost and capacity constraints on individual links within the network, but have a wide application pertaining to network performance in general.

In summary, the literature cited above is moving towards more realistic approaches to modeling and/or measuring network performance. Some of the sources examine spatially integrated approaches to measuring transportation network performance together with travel demand derived from land-use patterns. Other sources consider different modeling techniques to assess network reliability in terms of connectivity reliability (i.e., the probability that network nodes remain connected) and/or travel-time reliability (i.e., the probability that a trip between a given OD pair can be made within a specified time interval). Still, other sources address network reliability from a mathematical standpoint and discuss the necessary conditions for a “reliable” network. Our measure, presented in Section 4, takes the spatial aspect of these works further by considering not simply spatial location, but also network topology, which links different locations to one another—that is, the flexibility to get from one location to another.

3. Overview of key transportation indices

Two measures are commonly used to evaluate different aspects of highway performance. The first, the \( V/C \) ratio, is used to evaluate congestion on specific highway segments. The ratio is a localized performance metric and thus does not consider the performance of the network as a whole. The second, the gamma index, is a connectivity index that considers for a network the relationship between the actual number of links and the maximum number of possible links. The value of gamma ranges between 0 and 1. A value of 1 indicates a completely connected network, and is extremely unlikely in reality (Rodrigue, 2003). The gamma index accounts only for network topology. It does not consider traffic between particular origin-destination
pairs or link capacities. For planar networks, the gamma index ($\gamma$) is computed

$$\gamma = \frac{e}{e_{\text{max}}}$$  \hspace{1cm} (1)

where $e$ is the actual number of links in the network and $e_{\text{max}}$ is the maximum number of links in the network (i.e., all nodes are completely connected). In turn, $e_{\text{max}}$ is computed as

$$e_{\text{max}} = 3(v - 2)$$  \hspace{1cm} (2)

where $v$ is the number of nodes in the network. The gamma index is a useful measure of the relative connectivity of the entire network.

While both the $V/C$ ratio and the gamma index provide useful planning and management information, we argue that neither measure is sufficient when used independently. A better measure for identifying critical highway segments is one that focuses on maximizing the travel-time savings over the entire network. Our proposed measure is based on the capacities of individual highway segments, the routing options for the origin-destination pairs using a particular segment, as well as the topology of the entire network. Due to the spatial considerations introduced by the topology, the highest-cost or highest-valued segments (i.e., those targeted for improvements) will not necessarily equate to the segments with the highest $V/C$ ratio. Rather, critical segments measured by the proposed measure are a function of the overall spatial characteristics of the network, system-wide travel times and system-wide demand. Although we measure the cost of rerouting purely in terms of travel time, the definition of cost could be extended to include traffic or vehicle specific information. Examples might include product losses associated with rerouting perishable goods, or medical costs associated with delays in emergency response.

4. Definition of the new index and its computation

We define a new measure, the Network Robustness Index (NRI), for evaluating the critical importance of a given highway segment (i.e., network link) to the overall system as the change in travel-time cost associated with rerouting all traffic in the system should that segment become unusable. In formulating our measure, let $x_a$ and $t_a$ represent respectively the flow (i.e., volume of traffic) and travel time on each link $a$ comprising the network. Furthermore, $t_a = t_a(x_a)$ where $t_a(x_a)$ represents the relationship between traffic flow and travel time for link $a$ (i.e., the link performance function or volume-delay curve for $a$). By definition, travel times computed using link performance functions are more realistic than those computed assuming no traffic and free-flow speeds.

Using the above notation, our link-specific index is derived in two steps. First, the system-wide, travel-time cost of removing the link, $c_a$, is given by the following equation:

$$c_a = \sum_a t_a x_a \delta_a$$  \hspace{1cm} (3)

where

$$\delta_a = \begin{cases} 1, & \text{if link } a \text{ is not the link removed} \\ 0, & \text{otherwise} \end{cases}$$

Second, this cost is compared to the system-wide, travel-time cost incurred when all links are present in the network (i.e., the base case). The equation is written as

$$q_a = c_a - c$$  \hspace{1cm} (4)

where

$$c = \sum_a t_a x_a$$  \hspace{1cm} (5)

and $q_a$ is the value of the NRI for link $a$ in units such as minutes. Although we define Eq. (4) in terms of change in travel-time cost, the index can be easily generalized to measure change in monetary cost.

The key to implementing the NRI given in Eq. (4) is computing realistic network flows and travel times for input to Eqs. (3) and (5). The user equilibrium assignment model first proposed by Wardrop (1952) is ideally suited to this task for at least two reasons. First, at equilibrium, no user of the network can improve his/her travel time by unilaterally changing routes. This condition is derived from the explicit incorporation of link performance functions into the model’s formulation. In other words, the model accounts for traffic congestion, which is, unfortunately, a characteristic of many highways today in the United States (Schrank and Lomax, 2005). Obviously, this condition is more realistic than assuming that users employ only shortest-time paths through the network, which, in terms of assignment, concentrates traffic on a small number of links forming the fastest routes between origin-destination pairs. In other words, the vast majority of links in the network receive no traffic at all.

A second argument supporting the user equilibrium assignment model concerns its ability to reflect the fact that users of the network who do not use a removed link may be rerouted as a consequence of the rerouting of users who do use the removed link. In other words, both users and non-users of links can be affected by their removal. Obviously, rerouting network users will impact link travel times.

The index given in Eq. (4), including its parts as shown in Eqs. (3) and (5), is implemented in TransCAD®, a powerful geographic information system (GIS) for transportation applications. In part, our decision to use TransCAD® was based on the fact that the software includes the user equilibrium assignment model, which is critical to deriving inputs for our index. A program was written using the native programming language for TransCAD®, Caliper Script, for computing the index for each link in a network. Inputs to the program include a road network and an origin-destination trip matrix.

The program first computes the flow and travel-time inputs to Eq. (5) using the user equilibrium assignment
model. The program then disables sequentially each link in the network. Upon disabling a link, the program employs the user equilibrium assignment model to reroute all traffic through the network, thus creating the inputs to Eq. (3). The index shown in Eq. (4) is then calculated for the link. In total, the program runs the user equilibrium assignment model \( a + 1 \) times—once for the base case and once with each link \( a \) removed from the network.

5. Data

Three hypothetical road networks, each with different levels of connectivity, were constructed for our study. Our decision to use such networks, as opposed to one or more real-world networks, was guided in part by one objective of this study—that is, to evaluate the relationship between the gamma index (i.e., network connectivity) and costs due to network disruptions. We postulate an inverse relationship between such costs and values of the gamma index—that is, costs increase as values of the gamma index decrease. In other words, disruption severity is related not only to the size of origin-destination (OD) flows, but also to network connectivity, which affects travel times between origins and destinations.

Testing the hypothesis using a real-world example would have required historical information tracing a specific network’s evolution from a simple branching network with a low gamma index to a more complex circuit network with a high gamma index. From this information, it would have been necessary to reconstruct digital versions of the network for several times in the past. We deemed this task to be prohibitively expensive (assuming that such information is available in the first place) especially given the fact that another objective is to demonstrate the usefulness of our measure as compared to the traditional \( V/C \) ratio. Thus, our use of theoretically grounded networks and OD flows is justified for several reasons: first, they are inexpensive to construct; second, they can address both of our research objectives; and third, there is no evidence to suggest that the conclusions drawn from the use of such networks and OD flows will differ from those drawn from a real-world example.

Development of the hypothetical networks shown in Fig. 2 is based on well-known geographic theory and an empirical observation—respectively, Christaller’s (1966) Central Place Theory (CPT) and the rank-size rule. Both are used to construct the urban system or “nodes” for our road networks. According to CPT, settlements are arranged in a hierarchy and are spaced uniformly. For our urban system, there are three levels to the hierarchy, and all cities are spaced 50 km apart. According to the rank-size rule, the size of settlements in an urban system is inversely proportional to their ranks in the system. In other words, a settlement’s rank multiplied by its popula-

![Fig. 2. Road networks used in the study.](image-url)
tion equals the size of the city of highest order (i.e., the first-order city). In our urban system, however, the exact size (i.e., population) of a city is generated randomly following the rank-size rule. Specifically, a population range is specified for all settlements of a given order from which a specific size is generated using a uniform random number generator. The upper value of each range corresponds to the value determined by the rank-size rule. Thus, the population range for the first-order settlement is 550,000–600,000 people. The population ranges for the second- and third-order settlements are respectively 200,000–300,000 people and 50,000–200,000 people. Table 1 summarizes descriptive information concerning the size of settlements forming the nodes of the networks shown in Fig. 2.

The nodes forming the urban system are connected via a series of links, which vary in terms of their capacities (speed is assumed to be 100 km per hour for all links) and number of lanes. Furthermore, as can be seen in Fig. 2, there is a direct relationship between links, as characterized by these attributes, and the cities they connect. Specifically, second-order cities are connected to the first-order city by freeways characterized by three lanes in each direction, second-order cities are connected to one another by freeways with two lanes in each direction and finally, third-order cities are connected to one another and to second-order cities by two-lane rural highways with one lane in each direction. All capacities, derived from the Highway Capacity Manual 2000 (Transportation Research Board, 2000), are expressed in passenger cars per hour in each direction.

The number of trips generated in each city per day was determined by multiplying population by 1.5 (in other words, we assumed that each person makes, on average, 1.5 trips per day). In conjunction with Network 1 (see Fig. 2A), the following production-constrained gravity model was then used to derive the OD matrix of trips:

$$T_{ij} = \frac{O_i W_j C_{ij}^{\beta}}{\sum_{j=1}^{J} W_j C_{ij}^{\beta}}$$

(6)

where $T_{ij}$ is the number of trips between origin $i$ and destination $j$, $O_i$ is the number of trips generated in origin $i$, $W_j$ is the population of destination $j$, $C_{ij}$ is the shortest path distance in kilometers separating origin $i$ and destination $j$, and $\beta$ is a measure of distance decay set at 1.1.

The daily trip volumes generated by the model were then assigned via the user equilibrium assignment model to links comprising Network 1. At this point, however, we discovered that the daily capacities for all links were exceeded—an unrealistic situation. To resolve this problem, we reduced incrementally the trip volumes in the OD matrix by 5%, rerunning the user equilibrium assignment model after each reduction. We achieved realistic flows on the network with a 60% reduction. In other words, the OD matrix of trips produced by Eq. (6) was adjusted by multiplying its values by 0.4. Also, the same OD matrix was applied to all three networks developed for this study.

With 90 links, the well-connected road network shown in Fig. 2A has a gamma index of 0.86. The second network (i.e., see Fig. 2B) was constructed by removing randomly 16 links from the first network. The only criterion enforced during this process was that all nodes had to be connected to other nodes via a minimum of two links. Two reasons account for this. First, the NRI cannot be computed for any link if one or more nodes become isolated from other nodes as would be the case if all links to such nodes were removed. In this case, trips originating and destined to such nodes would be stranded at the outset, affecting the index’s computation. Second, the NRI cannot be computed for a link if that link is the only link left connecting a node to other nodes in the urban system. Again, trips originating and destined to such a node would be stranded when the link is removed, affecting the index’s computation for that particular link. The gamma index for the second network is 0.70, indicating a relatively well-connected network.

Finally, the third network, shown in Fig. 2C, was constructed by removing randomly 16 links from the second network. Again, the minimum link criterion was enforced. The third network is sparsely connected with 58 links and a gamma index of 0.55. When interpreting values of the gamma index, it is necessary to compute a minimum value, which is context specific. For the networks shown in Fig. 2, this value is 0.34 reflecting the fact that for 37 cities only 36 links are necessary to form a network connecting all cities. In such a minimally connected network, each city would be connected to one and only one other city.

### 6. Results

#### 6.1. Evaluation of network performance using the Network Robustness Index

An immediate question concerning the use of the NRI is how well a particular transportation network performs when specific links are disrupted due to natural (e.g., mudslides, earthquakes) or human-induced (e.g., vehicle collisions, terrorism) occurrences. Results for the three networks developed for this study are mapped in Fig. 3 and summarized in Table 2. It should be noted that the range of values for the NRI across the three networks (i.e., a minimum of 385,964 min for Network 1 and a maximum of 2,826,270,837 min for Network 3) precluded the display of absolute values in Fig. 3. Instead, the values of the NRI shown are measured in terms of percentage change from the base case for each network. Although this
solution permits the display of values across networks using a consistent classification scheme, it must be remembered that the results across networks cannot be compared directly in terms of absolute differences in percentage change. The reason for this is that a 1% change equates to a different absolute value of the NRI for each network: 1,234,564 min for Network 1, 1,747,328 min for Network 2 and 7,520,484 min for Network 3.

Network 1, with 90 links and a gamma index of 0.86, performs very well when its links are disrupted one link at a time. The average increase in system-wide travel time from the base case is 1,534,613 min, or 1.24% (Table 2). The maximum increase is 5,510,403 min, or 4.46% (Table 2). As seen in Fig. 3A, the highest values of the NRI are, with one exception, associated with high-capacity links connecting nodes that serve as important origins and destinations for trips. At the same time, the increase in the average system-wide \( V/C \) ratio over the base case is merely 0.02, or 2.89% (computed from values in Table 2). Moreover, in the presence of network disruptions, traffic does not exceed capacity on any link. In the case of Network 1, these results suggest that the system is flexible enough to adapt to disruptions for even heavily traveled, centralized links. Thus, traffic is rerouted without a high cost to the system as a whole.

As anticipated, Network 2, with 74 links and a gamma index of 0.70, does not perform nearly as well as Network 1 when its links are disrupted one link at a time. The average increase in system-wide travel time from the base case is 10,681,980 min, or 6.11% (Table 2), which is even larger than the maximum value of the NRI found for Network 1 (i.e., 5,171,577 min larger). In fact, 44 links in Network 2 (i.e., 59%) are associated with absolute values of the NRI that exceed the maximum value found for Network 1. As seen in Fig. 3B, such values tend to occur in more sparsely connected areas of the network where fewer links are available to handle rerouted traffic. The highest value of the NRI is 119,516,890 min (Table 2). This value is almost 22 times greater than that for Network 1. In the case of Network 2, we clearly see that certain links are very critical or highly valued with respect to the overall performance of the network. This implies that the network is not flexible enough to allow traffic to be easily rerouted when these links are disabled. Finally, as expected, the mean value of the average system-wide \( V/C \) ratio is greater for Network 2 than Network 1—that is, 0.99 and 0.71, respectively (Table 2).

Network 3, with 58 links and a gamma index of 0.55, is the least connected of the three networks developed for this study and would not be considered a particularly reliable network with respect to Bell’s (2000) definition of a reliable network. When individual links are disabled one at a time, the average increase in system-wide travel time from the base case is very large—291,680,128 min, or 38.79%
The maximum increase, as noted earlier, is an extraordinary 2,826,270,837 min, or 375.81% (Table 2). The costs associated with rerouting traffic in this network would be excessive, as the number of alternative link choices is extremely limited. Although many links are associated with high values of the NRI, there are some notable exceptions, as shown in Fig. 3C. As expected, the low values of the index tend to occur at the periphery of the network. However, unlike Networks 1 and 2, three links near the center of Network 3 are associated with minute decreases in the NRI of less than 1% from the base case. This finding might be considered unexpected, but further demonstrates the usefulness of the index and its value in identifying critical infrastructure. In this case, the negative values of the NRI suggest that at least one of the three links could be eliminated from the network without any adverse consequences for the system. In fact, system-wide travel time would be improved slightly (i.e., less than the base case). Finally, as expected, the mean value of the average system-wide V/C ratio is significantly greater for Network 3 than Network 2—that is, 1.82 and 0.99, respectively (Table 2). In a sparsely connected network such as Network 3, disruptions on almost any link can lead to very serious system-wide congestion problems as demonstrated by a mean increase in system-wide travel times of nearly 40% and a mean average system-wide V/C ratio well over 1.0.

As noted earlier, one objective of this study is to evaluate the relationship between network connectivity and the NRI. The discussion above suggests that values of the
NRI increase as values of the gamma index decrease (i.e., an inverse relationship). To test this relationship formally, we employed two statistical techniques: the Kruskal–Wallis test and the Wilcoxon Rank Sum test. The choice of such nonparametric tests was guided by results from Shapiro-Wilk tests of normality applied to the NRI distributions for each network. In all three cases, values of the NRI were not normally distributed, thus violating a key assumption underlying equivalent parametric tests—that is, ANOVA and the independent-samples t-test. A Kruskal–Wallis test statistic of 139 with two degrees of freedom was significant at the 0.0001 significance level suggesting that values of the NRI do vary according to network connectivity. Two Wilcoxon rank sum tests (i.e., one comparing the NRI values for Networks 1 and 2, and the other, Networks 2 and 3) confirmed that values of the NRI varied according to our expectation. The respective test statistics, both significant at the 0.0001 significance level, were 8775 and 5577.

6.2. Identification of critical infrastructure using the Network Robustness Index and the volume/capacity ratio

Earlier in this paper, we argued that the NRI and the traditional V/C ratio will offer different solutions to the task of identifying critical infrastructure in a network. In this section, we investigate the issue by comparing each network’s average V/C ratios (i.e., average of two directions), obtained for the base case, to their corresponding values of the NRI. The base-case average V/C ratios for each network are mapped in Fig. 4 and summarized in Table 2. As expected, there exists a statistically significant inverse relationship between network connectivity (i.e., as measured by the gamma index) and values of the average V/C ratio. Specifically, a Kruskal–Wallis test statistic of 105 with two degrees of freedom was significant at the 0.0001 significance level suggesting that values of the average V/C ratio vary according to network connectivity. Two Wilcoxon rank sum tests (i.e., one comparing the average V/C ratio values for Networks 1 and 2, and the other, Networks 2 and 3) confirmed that values of the average V/C ratio varied according to our expectation. The respective test statistics, both significant at the 0.0001 significance level, were 7690 and 5375.

For each network, a scatterplot of the relationship between the NRI and the average V/C ratio is found in Fig. 5. A linear or monotonic relationship between the two measures would suggest that their respective solutions to critical infrastructure identification are similar. This is clearly not the case for any of the three networks given the scatter of points. To test the strength of the relationship between the two measures formally, we employed the Spearman rank-order correlation coefficient, a nonparametric alternative to the Pearson product-moment correlation coefficient. Again, our decision to use the test was guided by the NRI distributions, which were not normally distributed. For Networks 1, 2 and 3, the correlation coefficients (with p-values in parentheses) are, respectively, 0.06 (0.5789), 0.49 (0.0001) and 0.64 (0.0001). These values suggest that as network connectivity decreases, the degree of similarity between the solutions identified by the two measures increases. This is not unexpected given the fact that fewer links means that there are fewer options to reroute traffic when computing the NRI. However, despite increasing similarity, important differences remain between the solutions identified by each measure, as exemplified by the results shown in Table 3. For each network, this table lists the top 10 links identified according to each measure (i.e., links are ranked from highest to lowest values). As seen in Table 3, there is little to no correspondence between the ranking of links according to the NRI and the V/C ratio. In other words, the measures offer unique solutions to the identification of critical infrastructure.

When the results of Table 3 are compared for each index (i.e., the NRI versus the V/C ratio), we see the extent to which the solutions identified by the indices differ. With Network 1 (i.e., the most robust and reliable network),
there are no common links that appear in the top 10. As the reliability and connectivity of the transportation network decreases, we see an increasing similarity between the results. In Network 2, three common links are identified by each index (i.e., links 6, 18 and 77). However, the ranking of the links differs demonstrating that even in cases where there is some overlap priorities vary. In Network 3, we see an overlap of six links in the top ten (i.e., links 18, 22, 54, 57, 59 and 67). Both indices point to link 54 as being the most critical link in the system. As was the case in Network 2, the ranking of the other critical links is completely different. In terms of the top five links, the NRI suggests that the most critical links to the system are 54, 59, 82, 77 and 67. The V/C ratio suggests the most critical links are 54, 9, 34, 67 and 22. Only two of the top five links are the same.

Also, as shown in Table 3 for each network, the total value of the NRI obtained by summing the values for the top 10 links comprising each measure’s solution, demonstrates the degree to which the two measures differ. From a system-wide perspective, the NRI solutions can deliver greater savings in terms of additional travel time incurred should such links be improved to withstand disruptions due to natural or human-induced occurrences. As shown for Network 1, for example, if the 10 links were improved according to the V/C ratio, the total travel-time savings would be 15,135,102 min. By comparison, if links were improved according to the NRI, the total savings would be 38,733,874 min—an increase of 23,598,772 min. Similar findings are shown for Networks 2 and 3. In all instances, the NRI outperforms the V/C ratio in terms of travel-time savings.

<table>
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<tr>
<th>Rank</th>
<th>NRI solution</th>
<th>V/C ratio solution (base case)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Link ID</td>
<td>NRI value (min)</td>
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<tr>
<td></td>
<td>Link ID</td>
<td>V/C ratio value</td>
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<td>Total</td>
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7. Conclusions

The primary objective of this paper was to introduce a new measure for determining the value of an individual segment or link within the overall highway system in the context of identifying critical links to serve as the best locations for highway improvement projects. We maintain that it is essential to make such improvements and transportation planning decisions from a system-wide perspective as opposed to approaching these decisions based on localized needs or measures such as the $V/C$ ratio. We demonstrate that our measure, the Network Robustness Index (NRI), provides a better indication of the value associated with individual links of a highway network than the traditional $V/C$ ratio. Instead of basing a link’s value or cost on the $V/C$ ratio, the NRI takes into account the spatial relationships and rerouting possibilities associated with the network’s topology, the OD demand and the capacity of individual highway segments.

Three hypothetical networks, each with a different degree of network connectivity, were used to illustrate how the NRI points to different solutions with respect to identifying the “most valuable” or critical links in a network. As demonstrated, such links do not necessarily equate to the segments with the highest $V/C$ ratio. Our results show that evaluating a transportation system as a whole using the NRI provides better planning solutions than those obtained using the traditional localized $V/C$ approach applied to the most congested segments. Moreover, this approach is better able to address concerns for emergency preparedness, supply-chain logistics and network robustness. We find that adding capacity directly in or around high $V/C$ ratio segments does not yield the best overall system-wide improvements in travel time. In some situations, adding links in other locations (i.e., where the $V/C$ ratio is not the highest) results in maximizing system-wide travel-time improvements.

Our work is related directly to previous studies that focus on the flexibility and the reliability of the highway system in transportation planning and engineering. The concepts of network flexibility and reliability offer valuable insights into the importance of the physical design of the highway network and the need to address transportation planning from a system-wide perspective, which may be further challenged in the real-world due to inter-jurisdictional planning. This research builds logically upon recent publications that discuss the need to better define and measure transportation system performance concepts such as flexibility and reliability by actually demonstrating how a performance metric like the NRI that is a function of the spatial characteristics of the network, system-wide travel times and system-wide demand, outperforms a commonly used localized metric like the $V/C$ ratio with respect to transportation planning decisions. The ease with which this metric can be calculated using existing algorithms in GIS software such as TransCAD makes it ideal for actual implementation and use in real-world planning networks.

The data currently contained within the travel demand forecasting model within any city or region could be directly applied in this method to obtain a list of system-critical links for consideration by policy makers. No additional data collection is required further suggesting that the NRI is a valuable measure for immediate use.

Obviously, future research must focus on practical applications of the NRI using real-world networks, as opposed to hypothetical ones such as those we have used in the current paper to evaluate properties of the index. Given the strength of our results, it seems likely that in real-world situations involving well-connected networks, the critical infrastructure solutions offered by the NRI and the $V/C$ ratio will continue to differ. Moving beyond such simple comparisons, one can envision many ways in which various organizations can employ our index. Emergency management organizations, for example, after identifying critical links, could draft link-specific contingency plans for rerouting traffic should a natural (e.g., mudslide) or human-induced (e.g., the 2004 tanker truck accident along I-94 near Bridgeport, CT) incident necessitate the closure of a critical link. In an era of heightened security due to threats of terrorism, critical links could be targeted for enhanced surveillance either through the installation of cameras or more highway patrols by policing organizations. Like emergency management organizations, firms involved in supply-chain management may also want to prepare link-specific plans to ensure that their customers’ needs continue to be met in the event of a network disruption. Finally, planning organizations may seek to enhance the reliability and flexibility of existing networks by recommending the construction of new links in areas identified by the NRI as being particularly crucial to overall system performance. These examples are illustrative of the many practical applications of the NRI.

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References


References


