Development of Measures for Highway Criticality Assessment

Report Number: KTC-25-15

DOI: https://doi.org/10.13023/ktc.rr.2025.15

Kentucky Transportation Center
College of Engineering, University of Kentucky, Lexington, Kentucky

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Kentucky Transportation Cabinet
Commonwealth of Kentucky

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Research Report
KTC-25-15

Development of Measures for Highway Criticality Assessment

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March 2025

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
KTC-25-15		

4. Title and Subtitle
Development of Measures for Highway Criticality Assessment

5. Report Date
March 2025

6. Performing Organization Code

7. Author(s)
Xu Zhang, Mei Chen

8. Performing Organization Report No.
KTC-25-15

9. Performing Organization Name and Address
Kentucky Transportation Center
176 Raymond Building
University of Kentucky
Lexington, Kentucky 40506-0281

10. Work Unit No.

11. Contract or Grant No.
PL-38

12. Sponsoring Agency Name and Address
Kentucky Transportation Cabinet
200 Mero Street
Frankfort, Kentucky 40622

13. Type of Report and Period

14. Sponsoring Agency Code

15. Supplementary Notes
Prepared in cooperation with the Kentucky Transportation Cabinet.

16. Abstract
Existing network criticality assessments, often biased towards heavily used highways in populous areas by incorporating traffic and sociodemographic attributes, can lead to an underestimation of the vital role of rural infrastructure. Consequently, rural highways, particularly low-volume roads, often receive less consideration despite their critical role in network connectivity and local access to services and economic opportunities. To address this, we develop a criticality framework based on the egalitarian principle, which prioritizes equitable consideration of all network links regardless of traffic volume or population density, comprising two complementary measures. First, the normalized betweenness centrality quantifies a road's relative importance in efficiently connecting the local network by measuring the percentage of origin-destination pairs utilizing it within its neighborhood. Normalized betweenness centrality is employed to capture the essential role of rural roads in local connectivity, even with lower traffic volumes. Second, detour importance, an aggregate metric, assesses a road's contribution to network redundancy by tracking the percentage of trips diverted to it when other critical roads are disrupted. Detour importance further highlights their significance by quantifying their contribution to network resilience when primary routes are unavailable, a crucial aspect often overlooked in assessments focused solely on high-traffic corridors. To ensure accurate calculation of these measures, particularly in capturing the nuances of travel within local and potentially less congested rural networks, we leverage ubiquitous probe vehicle data for real-world travel times, which is central to our shortest-path analysis. The results from a Kentucky case study confirm the effectiveness and practical feasibility of our framework for large-scale applications due to its efficient algorithms and reliance on readily available data. This framework offers a more equitable approach to network criticality assessment, providing valuable insights for transportation planning and investment decisions that better reflect the importance of rural infrastructure for connectivity and community access.

17. Key Words
network criticality assessment, connectivity, accessibility, detour

18. Distribution Statement
Unlimited with approval of the Kentucky Transportation Cabinet

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	27	

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Chapter 1 Introduction

1.1 Background

Traditional highway investment prioritization processes focus on metrics such as safety, congestion, asset condition, and benefit-cost analysis to determine which projects will be funded. Rural highways, especially rural low-volume roadways, frequently receive lower priority despite often being critical to network connectivity and providing local communities access to services and economic opportunities. As such, state departments of transportation (DOTs) need robust mechanisms to quantify the strategic importance of roadways in terms of their network connectivity and accessibility.

1.2 Objectives

This report introduces an accessibility-based approach for evaluating the criticality of roadway segments in Kentucky. We developed this approach by:

- Reviewing existing methods to measure network redundancy, accessibility, and criticality as well as practices for using these in project selection.
- Collecting and integrating pertinent data, including roadway network, origin and destination (OD) data, and probe vehicle data.
- Investigating and calculating roadway redundancy and accessibility measures.
- Developing a roadway criticality index based on redundancy and accessibility measures.
- Developing a computationally efficient process suitable for statewide analysis.
- Conducting sensitivity analysis on parameters that figure into redundancy and accessibility measures, such as the service area radius or number of destinations deemed reachable by each segment.

The Kentucky Transportation Cabinet (KYTC) can use methods presented in this study to assess the strategic role of roadways in keeping rural communities connected and accessible. Information collected through these assessments can underpin a more equitable resource allocation process.

Chapter 2 Literature Review

This chapter summarizes the literature related to highway criticality assessment methods and metrics. The review focuses on existing methods and metrics and documents the data sources and computational processes required for their execution.

2.1 Previous KYTC Studies

As part of a review of its statewide planning process, KYTC funded a pilot study to evaluate accessibility and connectivity in Highway District 10. This study defined accessibility as the "residents' ability to reach employment opportunities and essential services such as groceries, household items, hospitals, and post-secondary education within a reasonable commuting time," and connectivity as "[reflecting] the scope, reliability, and safety of the transportation system used by residents to access those locations" (1). In each county, the project team met with local officials to discuss transportation issues, opportunities, and residents' travel destinations. They used this information to identify high-impact corridors in the District. The project team utilized the Kentucky Statewide Travel Demand Model (KYSTM) to evaluate the impact of potential improvements along identified corridors on District-wide accessibility. Accessibility was measured as the number of households and non-retail jobs within a 40- or 90-minute drive from each county seat.

The current Statewide Corridor Plan study lists accessibility (along with mobility and safety) as a key measure in the Tier 1 corridor screening process and Tier 2 corridor segment prioritization process (2). Accessibility is evaluated by using Kentucky Statewide Travel Demand Model (KYSTM) travel skims and land use data to determine how easily service centers, military bases, hospitals, educational facilities, and industrial parks can be accessed. Analysis done as part of this study involves converting point-of-interest data into TransCAD and ArcGIS formats. Eventually, a travel market analysis will be performed for Tier 2 analysis, which will evaluate total population and employment accessible to each corridor within reasonable travel time (e.g., 1-hour or 2-hour).

2.2 Other State DOT Practices

NCHRP Synthesis 521 summarized state DOT practices for allocating resources to low-volume roadways (Average Daily Traffic [ADT] < 400) (3). While agencies recognize that low-volume roads are valuable for providing network coverage and access to economic activities, capturing these benefits in traditional engineering analyses is challenging. To address this challenge, additional quantitative measures, qualitative scores, and descriptive approaches are often used to evaluate low-volume roadway projects. Our literature review turned up only a few states that have applied network accessibility or criticality concepts (Table 2.1).

Table 2.1 State DOT Practices for Evaluating Accessibility and Criticality

State	Report Title	Data Used	Calculation Tool	Relevant Metrics
Virginia	Accessibility Measurement for Project Prioritization in Virginia	HERE network and speeds; US Census data; jobs data from LEHD LODES;	Sugar Access, an ArcMap add-on from Citilabs	Change in accessibility to jobs between the existing and improved conditions
Virginia	Methodology for Ranking Relative Importance of Structures to Virginia's Roadway Network	Structure database, Virginia highway network and traffic, VDOT POI GIS	Developed a spreadsheet-based "Importance Factor" (IF) scoring tool	IF score based on ADT, truck ADT, highway designation, ADT growth rate, "Bypass Impact" (bypass detour length), "Access Impact" (number of key facilities within 3 miles)
Colorado	I-70 Corridor Risk & Resilience Pilot Study	I-70 pilot site data	Developed an Asset Criticality Model	Criticality score based on AADT, F class, freight value, tourism value, social vulnerability index at county level, and system redundancy;
Kansas	Economic Impact of Closing Structurally Deficient or Functionally Obsolete Bridges on Very Low-Volume Roads	National Bridge Inventory	Google Earth	Detour length, vehicle operating cost
Kansas	Methodology to Measure the Benefits and Costs of Rural Road Closure a Kansas Case Study	Three rural counties with socioeconomic characteristics	TransCAD	Difference in total travel costs between with/without scenarios
Iowa	Evaluating the Criticality of Infrastructure	NA	N/A	Criticality: functional class, truck traffic, social vulnerability index, redundancy
Florida	2017 Auto Accessibility Report: Florida	TomTom data; Census block data; LEHD labor and job distribution data	GIS	The total number of jobs that can be reached within different travel time thresholds.
Oregon	Climate Change Vulnerability Assessment and Adaptation Options Study	State highways	N/A	Asset criticality based on tiered lifeline routes
Wyoming	Risk and Resiliency Plan for Critical Freight Transportation Assets	State's freight network	GIS	highway criticality rating based on freight corridor level, facility level, truck volume

Most relevant for this study is the Virginia DOT's SMART SCALE project prioritization process, which evaluates accessibility impacts for hundreds of projects (4). Table 2.2 summaries the three accessibility measures included in SMART SCALE. Data sources used to evaluate accessibility include HERE network and speed profiles as well as sociodemographic data from the US Census, including Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics (LODES). Measures are computed using the Sugar Access calculator, a proprietary ArcMap add-on developed by Citilabs (5). Beginning with a no-build scenario, the tool computes average access to jobs from each analysis zone (Census block group for auto or Census block for transit) to all other analysis zones within a project's influence area. Forty-five minutes is the threshold travel time (60 minutes on transit projects). Next, the build scenario is evaluated, with the same metric computed using post-project traffic conditions to determine the change in average job accessibility.

Table 2.2 Virginia SMART SCALE Accessibility Measures

ID	Measure Name	Weight	Measure Description	Measure Objective
A.1	Access to Jobs	60%	Change in average job accessibility per person within 45 minutes (within 60 minutes for transit projects)	Measure assesses the average change in access to employment opportunities in the region as a result of project implementation based on the GIS accessibility tool.
A.2	Access to Jobs for Disadvantaged Populations	20%	Change in average jobs accessibility per person for disadvantaged populations within 45 minutes (within 60 minutes for transit projects)	Measure assesses the average change in access to employment opportunities in the region as a result of project implementation based on the GIS accessibility tool.
A.3	Access to Multimodal Choices	20%	Assessment of the project support for connections between modes, and promotion of multiple transportation choices	Measure assigns more points for projects that enhance interconnections among modes, provide accessible and reliable transportation for all users, encourage travel demand management, and potential to support incident management.

The Virginia DOT Structure and Bridge Division uses a spreadsheet-based structure scoring tool to measure and rank the relative importance of state-maintained structures to the state highway network and economy (6). Data used in the calculation include ADT, truck ADT, highway designation, and ADT growth rate, Bypass Impact (i.e., bypass detour length), and Access Impact (i.e., number of key facilities including schools, hospitals, fire and rescue stations within three miles). The latter two metrics are particularly germane to this study. The spreadsheet calculates an importance factor (IF) based on a structure's traffic demand and its contribution to network connectivity.

Several states, including Colorado, Iowa, Oregon, and Wyoming, assess highway and freight infrastructure criticality in light of risks posed by extreme weather and climate events (7-10). Oregon DOT has adopted a unique method for evaluating criticality. The agency derives a criticality score based on multiple criteria, such as AADT, highway functional class, freight value, truck volume, freight network designation, and network redundancy. It uses pre-designated tiers to represent asset criticality: "Tier 1 Lifeline Routes are the most-critical highways, providing a backbone system for the parts of the state most vulnerable to a seismic event and for disaster recovery. Tiers 2 and 3 Lifelines are routes that increase the usability of the system and provide additional access, connectivity and redundancy to the Tier 1 Lifeline network" (9).

Florida DOT partners with the University of Minnesota's Accessibility Observatory to evaluate how accessible jobs are to those with automobiles (11). Data sources used in accessibility calculations include TomTom MultiNet network and speed data for June 2015 – June 2017 as well as data on population and job distributions from LEHD LODES. Accessibility is calculated at the Census block level using a method similar to the one employed in the KYTC District 10 pilot study. First, travel time from each block to surrounding blocks is calculated. Next, the total number of jobs reachable within specified amounts of time is determined (intervals ranging from 10 to 60 minutes).

Two Kansas-based studies evaluated the operational impacts of closing bridges on low-volume rural roads so that county commissioners or practicing engineers could select effective rehabilitation or replacement plans for structurally deficient or functionally obsolete bridges (12, 13). Metrics employed in the studies included detour length, additional vehicle operating cost, and difference in total travel costs between with/without scenarios.

2.3 Existing Research

Table 2.3 summarizes studies that have focused on the network accessibility, connectivity, and vulnerability of highway and freight infrastructure (14-24). Compared to the state-of-the-practice, existing research covers a more diverse set of topics and network measures. Besides assessing the criticality of individual links, studies have investigated the impact from simultaneous disruption of multiple links or entire areas (19). In addition, researchers have evaluated network vulnerability from a risk-based perspective, accounting not only for impact or consequence of a link disruption due to hazardous events but also the probability of such events occurring (19, 22, 24).

A commonly used metric to assess roadway importance or criticality is change in system-level total travel time due to roadway disruption (14, 16, 17, 19, 22). While this measure is easy to understand and correlates with redundancy and accessibility to a certain degree, it does not fully capture redundancy (i.e., alternative routes in an area) or accessibility (i.e., ability to access employment opportunities and essential services). Of measures proposed in previous research, OD Connectivity — the number of distinct paths with acceptable travel time between each OD pair — is a good candidate for characterizing network redundancy (15, 18).

Two accessibility metrics — Change in Accessibility and Betweenness-Accessibility — have shown promise and were explored as a part of this study.

Change in Accessibility compares overall accessibility between normal conditions and conditions following a disruption in which a link is removed from the network (24). An origin's accessibility is evaluated by first dividing the attraction of each destination (represented by population in the study) by the generalized travel time from the origin to the destination. Calculated values from all destinations are then summed. Further refinement of this measure is possible. For example, by using an OD matrix to select destinations known to interact with each origin and replacing population with actual travel demand.

Betweenness-Accessibility expands on the betweenness centrality measure, which is used in statewide AADT estimation model and incorporates interaction opportunities represented by population and employment between OD pairs (23). As such, the measure provides "*a bridge between the concepts of betweenness from network analysis and accessibility from transport geography.*" This formulation resolves the problem of betweenness centrality only reflecting network topology and needing to be improved by incorporating sociodemographic characteristics as additional weights.

GIS and travel demand models are popular calculation tools. Responding to computational challenges associated with large networks, several studies have performed traffic assignment with an all-or-nothing approach and/or assumed link travel times are independent of traffic volumes (17-19, 22, 23). However, traffic diverted from a disrupted main corridor could significantly impact the detour. A key goal of this study was to develop effective and efficient computational approaches to account for traffic congestion impact so results are more realistic.

Table 2.3 Summary of Existing Research Studies

Title	Year	Authors	Data Used	Tool	Relevant Metrics
Application of Accessibility Based Methods for Vulnerability Analysis of Strategic Road Networks (14)	2006	Michael Taylor et al	Australian Main Road Network	NA	Change in generalized travel cost; Hansen integral accessibility index; Accessibility/Remoteness Index of Australia;
Network Evaluation Based on Connectivity Vulnerability (15)	2009	Fumitaka Kurauchi et al	Kansai region road network	NA	Link criticality index: degradation of OD connectivity without the link; OD Connectivity: number of distinct paths with acceptable travel time between each OD pair
Application of the Network Robustness Index to Identifying Critical Road-Network Links in Chittenden County, Vermont (16)	2010	James Sullivan et al	Chittenden County MPO demand model;	TransCAD; NRI Calculator based on Caliper Script	Network Robustness Index: the increase in total vehicle-hours of travel (VHTs)
Redundancy importance: Links as rerouting alternatives during road network disruptions (17)	2010	Erik Jenelius	Swedish national road network and travel demand data	Travel demand model	Redundancy importance: how much worse the next-best backup alternatives would be if the studied link itself would not be available.
A Quantitative Framework for Assessing Vulnerability and Redundancy of Freight Transportation Networks (18)	2013	Sarawut Jansuwan	Utah freight network from the Freight Analysis Framework (FAF); estimated truck O-D table	GIS, VB.NET, MapWindow mapping tool	OD Connectivity: the additional distance on the detour route; Freight VMT Increase; Route Diversity: number of efficient routes;
Road Network Vulnerability Analysis: Conceptualization, Implementation and Application (19)	2015	Erik Jenelius	Travel demand model data files	GIS and Travel demand model	Importance: difference in total travel times of all OD nodes between null and disruption scenarios
Quantifying the Criticality of Highway Infrastructure for Freight Transportation (20)	2017	Zahra Ashrafi et al	demand model data, hourly factors, value of time survey	Ontario's travel demand model	Economic criticality: increase in the cost of shipment delays as a function of shipment value, time delay, and value of time
Introducing the Resilience into the State Transportation Network (21)	2018	Xiaolong Wu	California state transport network	UCINET simulation tool	Path Betweenness Centrality Index
Assessing potential likelihood and impacts of landslides on transportation network vulnerability (22)	2020	Qian Zhang et al	Digital maps of landslide controlling factors; Oahu road network	GIS, AHP for landslide susceptibility	Vulnerability Index: combination of the susceptibility index of a hazard and the consequence index of failure (i.e. increase in system total travel time)

Betweenness-accessibility: Estimating impacts of accessibility on networks (23)	2020	Georgios Sarlas, Kay Axhausen	TomTom network for Zurich, Swiss National Transport Model data	R packages	Betweenness-accessibility combining the concepts of centrality and gravity-based accessibility
Identification of critical sections of the Spanish transport system due to climate scenarios (24)	2020	Emilio Ortega et al	2016 Spanish trunk transport network	TITIM-GIStool; Global climate model INMCM4	Change in accessibility

In a recent publication, Jafino et al. (25) offered an insightful review and comparison of transportation network criticality metrics. Recognizing the lack of consensus about the formalization of network criticality, they evaluated conceptual and empirical differences between multiple criticality metrics. Based on these findings, the authors proposed a general guide for selecting metrics based on the policy problems encountered. Table 2.4 summarizes metrics identified in the paper. It describes each metric and documents computational techniques (e.g., whether socioeconomic factors are involved, whether traffic assignment is required, or whether to use all-or-nothing or user equilibrium for traffic assignment). Metrics are classified according to functionality (i.e., the primary transportation service the metric characterizes), ethical considerations (i.e., whether decisions about improvements should be made based on utilitarian or egalitarian principles), and geographic aggregation level (i.e., systemwide or localized aggregation).

Working in the context of Bangladesh, the authors compared link criticality rankings obtained from applying each metric to the country's freight transport network as well as seven distinct subnetworks within seven administrative regions. They found rankings for certain metrics showed high positive correlations across networks, indicating they would result in similar criticality assessments. The following metrics yielded similar rankings:

- Change in weighted total travel cost
- Change in expected user exposure
- Change in worst-case user exposure
- Change in unweighted total travel cost
- Change in weighted accessibility
- Change in network average efficiency

Rankings obtained from weighted betweenness centrality, unweighted betweenness centrality, and OD k-connectivity were more highly correlated than rankings generated using other metrics. The availability of nearby alternative links correlated poorly with other metrics, indicating links found to be critical using this metric would differ from links identified with other metrics. This finding validates the approach we took in this study of using both redundancy and accessibility to define criticality.

Jafino et al. proposed several guidelines for selecting criticality metrics:

1. Define an application or policy problem in terms of functionality, ethical principle, and aggregation level.
2. Filter out metrics that, based on correlation analysis, produce similar results.
3. Verify metrics ultimately selected are empirically dissimilar.

Other practical considerations (e.g., data availability, data quality, and computational cost) should also inform the selection of metrics.

Table 2.4 List of Criticality Metrics

No	Metric name	Description	Technical requirements: Origin-Destination (OD) matrix	Technical requirements: Transport network assignment	Technical requirements: Others	Conceptual dimensions represented (see Section 3): Functionality	Ethical	Aggregation	Relevant references
1	Change in weighted total travel cost	Increase in total travel cost (distance and traffic flow) among all origin-destination pairs due to disruptions on an element	Calculated with socio-economic factors	All-or-nothing or user equilibrium assignment	Complemented with an interdiction method	Travel cost	Utilitarian	Network-wide	(Balijepalli & Oppong, 2014; Dehghani, Flintsch, & McNeil, 2014; Du, Kishi, Aiura, & Nakatsuji, 2014; Gauthier, Furno, & El Faouzi, 2018)
2	Change in expected user exposure	The average impact of disruptions experienced by all users in the transport system	Calculated with socio-economic factors	All-or-nothing or user equilibrium assignment	Complemented with an interdiction method	Travel cost	Utilitarian	Network-wide	(Jenelius, 2009; Jenelius & Mattsson, 2015)
3	Change in worst-case user exposure	The maximum impact of disruptions among all users in the transport system	Calculated with socio-economic factors	All-or-nothing or user equilibrium assignment	Complemented with an interdiction method	Travel cost	Utilitarian	Network-wide	(Jenelius & Mattsson, 2015)
4	Change in unweighted total travel cost	Increase in total travel cost (only distance) among all origin-destination pairs due to disruptions on an element	Calculated without socio-economic factors	All-or-nothing assignment	Complemented with an interdiction method	Travel cost	Egalitarian	Network-wide	(Wang, Chan, & Li, 2014)
5	Change in region-based unweighted total travel cost	Increase in total travel distance among all origin-destination pairs within a certain sub-area where the element is located due to disruptions on an element	Calculated without socio-economic factors	All-or-nothing assignment	Complemented with an interdiction method	Travel cost	Egalitarian	Local	(Jenelius & Mattsson, 2015; Wang et al., 2014)
6	Change in weighted accessibility	Decrease in weighted (by transport demand/flow) accessibility due to disruptions of an element. The weight is determined by the socioeconomic activities	Calculated with socio-economic factors	All-or-nothing or user equilibrium assignment	Complemented with an interdiction method	Accessibility	Utilitarian	Network-wide	(Chen, Yang, Kongsomsaksakul, & Lee, 2007; Luathep et al., 2011; Wang et al., 2014)

7	Change in unweighted daily accessibility	Decrease in unweighted, topological-based accessibility due to disruptions of an element	Calculated without socio-economic factors	All-or-nothing assignment	Complemented with an interdiction method	Accessibility	Egalitarian	Network-wide	(Luathep et al., 2011; Wang et al., 2014)
8	Traffic flow	Empirical traffic flow of the transport network	Not required	Not required	Empirical traffic flow	Travel cost	Utilitarian	Local	(Zhou, Fang, Thill, Li, & Li, 2015)
9	Traffic density	Traffic volume over capacity. Normally used as an approximation of congestion	Not required	Not required	Empirical traffic flow and road capacity (e.g. number of lanes)	Travel cost	Utilitarian	Local	(Scott et al., 2006; Zhou et al., 2015)
10	Weighted betweenness centrality	The traffic flow among the economic centroids. The traffic flow is determined by the socioeconomic profiles	Calculated with socio-economic factors	All-or-nothing or user equilibrium assignment	-	Travel cost	Utilitarian	Local	(Aydin, Duzgun, Wenzel, & Heinimann, 2018; Demirel, Kompil, & Nemry, 2015; Kermanshah & Derrible, 2016; Wang & Cullinane, 2014)
11	Exposure to disaster	Overlay of natural disaster maps with the transport network. This is often used for disaster preparedness studies	Not required	Not required	Overlays maps of natural disasters	Connectivity	Utilitarian	Local	(Kermanshah & Derrible, 2016; Koks et al., 2019; Sohn, 2006)
12	Nearby alternative elements	Number of other elements that are located within an x kilometre distance from an element.	Not required	Not required	GIS analysis	Connectivity	Egalitarian	Local	(Snelder, van Zuylen, & Immers, 2012)
13	Unweighted betweenness centrality	Betweenness centrality calculated based on the shortest paths among the economic centroids	Calculated without socio-economic factors	All-or-nothing assignment	-	Travel cost	Egalitarian	Local	(Aydin, Casali, Sebnem Duzgun, & Heinimann, 2019; Demirel et al., 2015; Kermanshah & Derrible, 2016; Wang & Cullinane, 2014)
14	Change in network average efficiency	Decrease in network efficiency due to disruptions of an element	Calculated without socio-economic factors	All-or-nothing assignment	Complemented with an interdiction method	Travel cost	Egalitarian	Network-wide	(Dehghani et al., 2014; Issacharoff, Lämmer, Rosato, & Helbing, 2008; Nagurney & Qiang, 2008)

15	OD k-connectivity	Decrease in the number of distinct shortest paths among all origin-destination pair due to a disruption of an element	Calculated without socio-economic factors	All-or-nothing assignment	The assignment has to be complemented with a network distinct path algorithm	Connectivity	Egalitarian	Network-wide	(Mishra, Welch, & Jha, 2012; Shier, 1979)
16	Minimum link cut centrality	The frequency of a link's appearance in the cut sets of all pairs of economic centroids	Not required	Not required	Uses cut set algorithms from network theory	Connectivity	Egalitarian	Network-wide	(Snelder et al., 2012)
17	Unsatisfied demand	Amount of transport activity that cannot take place due to disruptions of an element	Calculated with socio-economic factors	All-or-nothing or user equilibrium assignment	Complemented with an interdiction method	Connectivity	Utilitarian	Network-wide	(Baroud, Barker, Ramirez-Marquez, & Rocco, 2014; Qiang & Nagurney, 2012)

Source: Jafino et al. (2020)

Chapter 3 Measures of Highway Criticality

Our measure of segment criticality is based on the composite score based of two metrics — betweenness centrality (BC) and detour importance (DI). BC measures a segment's importance in providing regional connectivity and accessibility, while DI quantifies a segment's significance as a detour route when other roadways in a region face disruptions.

3.1 Data Sources

We used the following data to develop and test the centrality metric:

- AllRds network with functional classification (FC) information from KYTC's HIS
- Traffic analysis zones and out-of-state road network from KYSTDM
- US Census Bureau Census block group zones
- Statewide probe vehicle speed data for 2018 – 2019 licensed from HERE Technologies

3.2 Betweenness Centrality

Definition

In graph theory, a link's BC is the number of shortest paths that pass through that link. Areas with dense roadway networks or populations (i.e., more nodes or smaller zones and thus more OD pairs) tend to have higher BC values than areas with sparse networks or less concentrated populations. To counter the bias toward areas with dense networks, we normalized the BC of link *e* using the total number of OD pairs in link's neighborhood. The normalized BC of link *e*, referred to as $BC(e)$, can be written as:

$$BC(e) = \frac{\sum_{s,t \in V, s \neq t} \frac{\sigma(s,t|e)}{\sigma(s,t)}}{N(N-1)}$$

where: V is the set of road nodes or TAZ centroids; $\sigma(s,t)$ is the number of shortest paths from the origin *s* to the destination *t*; $\sigma(s,t|e)$ is the number of the shortest paths passing through link *e*; and N is the number of nodes or zones in the neighborhood of link e.

In essence, *BC(e)* indicates the percentage of shortest paths that link *e* belongs to among all shortest paths between all OD pairs in a region. For example, if the neighborhood of a given link contains 100 nodes, the number of OD pairs between all nodes is 100×99 = 9,900 shortest paths within the neighborhood. If this link is on 99 of these shortest paths, its *BC* value is $99/9900 = 0.01$. Roads with higher BC values have greater importance in a region.

Implementation Considerations

Observed Travel Time

When determining shortest paths, observed travel time is used to reflect real-world traffic conditions. It was calculated using link length and average travel speed aggregated from 2018 – 2019 HERE probe speed data. For the few roads where probe speeds were unavailable, we used countywide average speed by FC from the same HERE speed dataset.

Region Size
We defined region as the area that covers all destinations reachable in a given timeframe. After evaluating several options, we defined the link's neighborhood as an area covered by a 60-minute travel time radius around the link, allowing a maximum of 120 minutes trip travel time. This area reasonably encompasses most trips that would potentially use this link, except for perhaps interstate highways. Expanding region size would increase computational time significantly but have little effect on overall *BC* rankings.

Node- or Zone- Based BC
Two approaches are available to calculate BC based on whether road nodes or TAZ centroids are used as OD pairs. Our analysis found statewide rankings using the two approaches are very similar. However, the zone-based approach greatly reduces the number of OD pairs that require a shortest-path calculation. It also enables better integration with other data items aggregated at the TAZ level (e.g., sociodemographic data, zonal travel demand matrices). More importantly, it allows for detour analysis that would be very difficult to perform under the node-to-node scheme given the level of details in the highway network. As such, we selected the zone-based approach for BC analysis.

Out-of-State Road Network and Zones
For highways near the state border, areas within a 60-minute travel time radius often reach into the neighboring states. To address this issue, we included out-of-state highways and zones within their neighborhood to fully account for their regional importance. We merged out-of-state highways from KYSTDM with the AllRds to create a more complete network for analysis. Out-of-state zones from the KYSTDM could also be used. However, our analysis showed this would underestimate BC values of roads at or near the state border due to their larger sizes and sparser zonal structures compared to those in-state. To mitigate this border effect, zones on both sides of the border need to have similar sizes. To this end, we used Census block groups to replace KYSTDM TAZs outside Kentucky. Figure 3.1 displays statewide BC rankings.

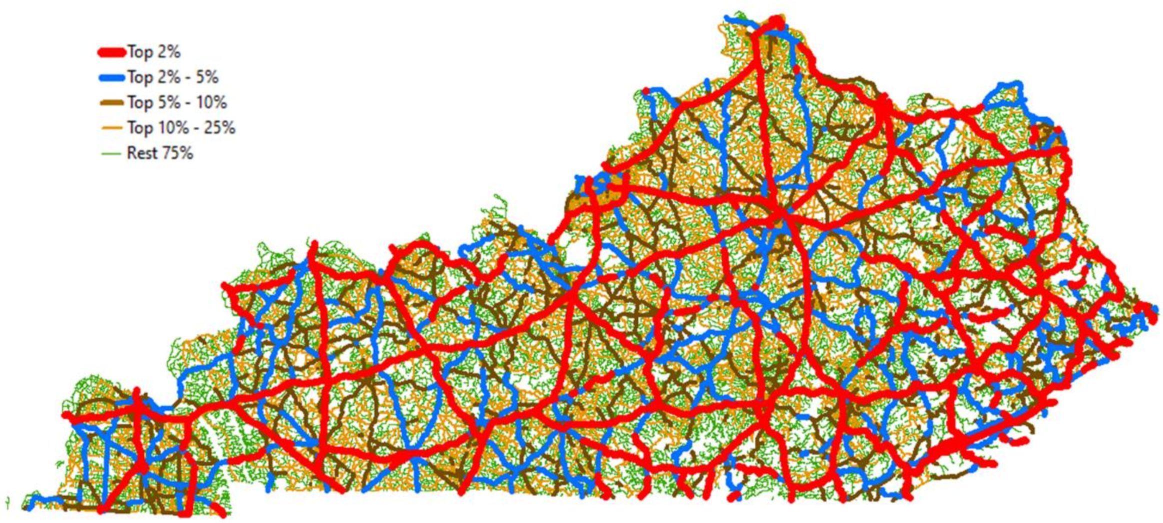

Figure 3.1 Statewide Betweenness Centrality Ranking

3.3 Detour Importance

Definition

Detours significantly influence highway network connectivity and resilience during disruptive events. To identify possible detours and evaluate their importance, we first identified all ODs within a neighborhood that use a segment under normal operating conditions. We then calculated how many of these trips (one trip per OD pair) are diverted to the detours when the segment is disrupted.

Figure 3.2 illustrates this approach for the Eggner Ferry Bridge. Our analysis identified 34,177 ODs (or trips) within its 60-minute neighborhood that normally use the bridge (map on the left). The map on the right side of Figure 3.2 shows the percentage change in trips on each link if the bridge closes — 24,238 or 71% of all trips would use I-24 to its north as the detour, while 8,880 or 26% of trips would divert to Donelson Parkway in Tennessee.

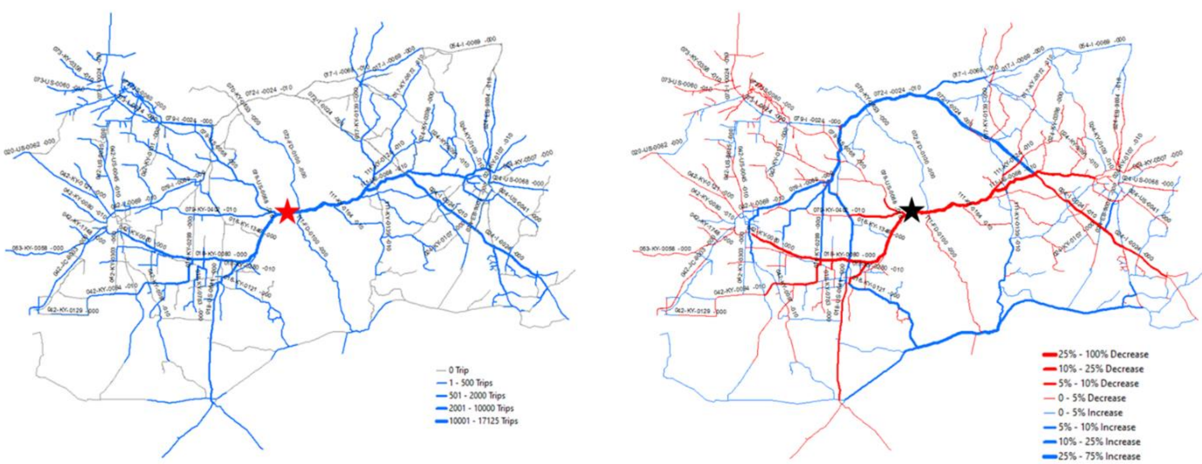

Figure 3.2 Change of Trips due to Closure of the Eggner Ferry Bridge on US-68

Based on before-and-after analyses of selected segments, we determined which link is on the detours of which highway segments and the number of trips from each segment diverted to the link. Accordingly, the importance of the link as a detour to all other highways was computed as:

$$DT_a = \sum_{i=1}^{k} BC_i \times p_i \times w_i$$

where DT_a is the detour score of link a; BC_i is the BC value of the segment i whose detour includes link a; p_i is the percentage of trips originally using segment i rerouted through link a when segment i is disrupted; w_i represents the weight associated with a certain attribute of the disrupted segment i; and k is the number of segments whose detours use link a.

For example, assume link A is used as detour when two highway segments are closed (not necessarily at the same time). Highway segment 1 has a BC value of 0.05, and 30% of trips that normally travel through segment 1 reroute through link A. Highway segment 2 has a BC value of 0.01, and 40% of its original trips detour through link A. If all segments have equal weight (i.e., $w = 1$) the detour score of link A is calculated as:

$$DT_A = 0.05 \times 0.3 \times 1 + 0.01 \times 0.4 \times 1 = 0.019$$

Implementation Considerations

Important Segments

Our detour analyses focused on the top 5% of links based on BC rankings. This could be expanded to include additional roads (e.g. 5% – 10% roads). These (often shorter) links from the AllRds network were consolidated into longer segments bound by two intersections in the collector and above network. This produced 5,125 segments for analysis. The BC value of the consolidated segment equals the length weighted average of link-level BC values.

Detour Strategies

We evaluated several detour strategies, including allowing detours that (1) use all roadways, (2) only use roadways with a FC of collector or higher, and (3) use only equivalent roads (same or higher FC). Based on preliminary analysis we chose four detour strategies for statewide analysis:

(1) Allow detours on highways classified as collector or above
(2) Allow detour on equivalent highways only, except that FC1 and FC2 traffic can detour to FC3 highways
(3) Allow detour on roads that are one FC below the disrupted highway
(4) Allow detour on roads that are two FCs below the disrupted highway

For each detour strategy, we first rerouted trips for all ODs that could be connected under a specified detour restriction. For disconnected ODs, we expanded the detour network to include local roads with a BC value greater than 0. Local roads with a positive BC value they play a role in local network connectivity, such as providing access between roads classified as collectors and above, and zone centroids.

Restrictive detour strategies generally funnel more trips onto roadways with higher FCs, which could substantially increase travel time. **Figure 3.3** illustrates this tendency using KY-15 in Jackson, which is classified as FC3. Under normal conditions, the shortest path for the selected OD pair takes 5.1 min (red shading). If KY-15 is disrupted and the detour has to be routed onto roadways with an equivalent FC, the only viable option in the region requires vehicles to make a big circle from KY-15 South to Hal Rogers Parkway West to I-75 North to Mountain Parkway East (green shading). This trip requires 215.5 minutes. But if the detour could use roadways one FC lower, the shortest path directs vehicles onto KY-80, KY-114, and then KY-205 (shaded brown). This trip requires 139.7 minutes. If the detour could use roadways up to two FCs lower, the best option is to route vehicles onto KY-52 and KY-11 (shaded blue). This trip has a duration of 66.4 minutes. With no FC restriction imposed, the shortest path directs vehicles onto KY-1812, a minor collector (shaded purple). This route has the shortest travel time — 12 minutes.

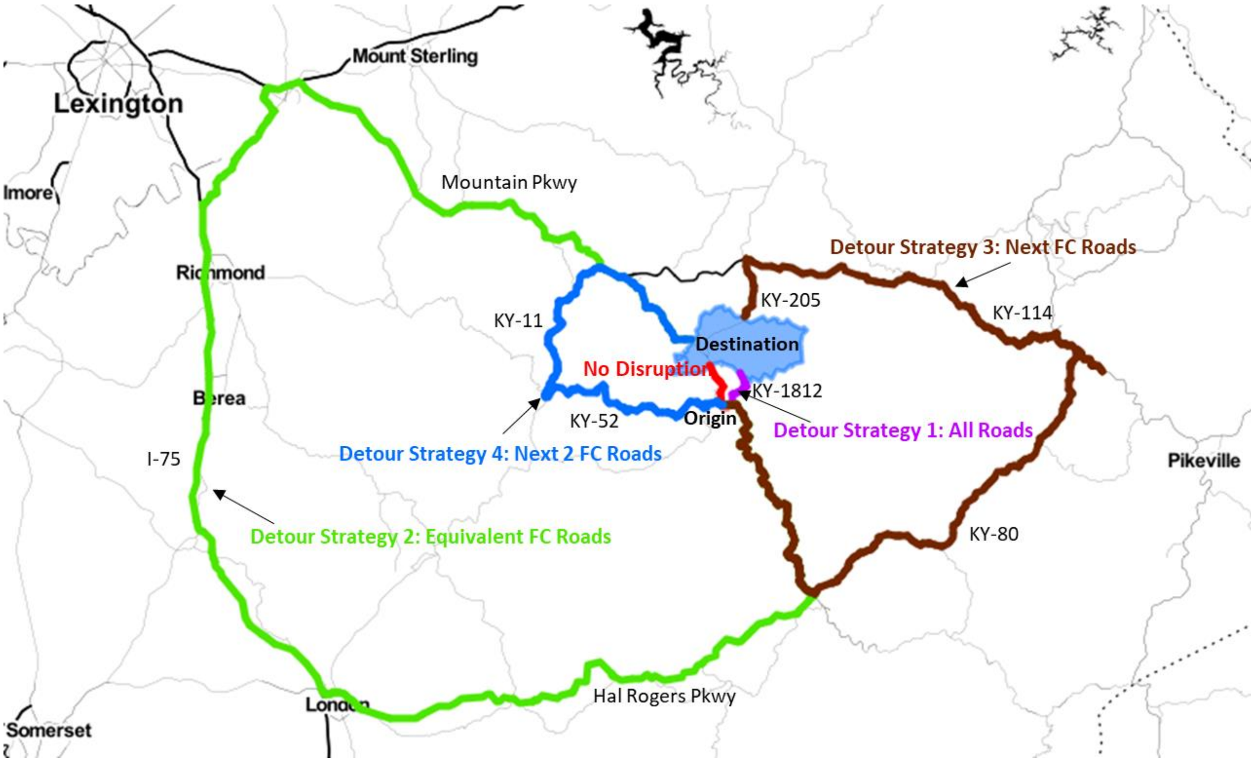

Figure 3.3 Detours with Different Strategies for an OD Pair Passing Through KY-15

Our discussions with the study's advisory panel highlighted the importance of restricting detours in a way that prioritizes higher FC roads, especially when commercial vehicles are a major consideration. But this consideration must be balanced against the fact too many restrictions could produce unreasonable results. Overall, Detour Strategy 4, which allows the use roadways two FCs lower, offers a good compromise and was selected to calculate statewide detour importance scores.

Detour Weighting Schemes

We considered several weighting schemes, including equal weight (i.e. $w = 1$), segment length, segment VMT, plus three FC-based variations (Table 3.1). The first option assigns FC1 roads a weight of 7 and lowers the weight by 1 as FC increases. Numbers in parentheses are normalized values obtained after dividing the weight by 7 to make it comparable with the other two options. The second option adopts weights used in the SHIFT Congestion component. Because these weights are quite similar, they may not effectively differentiate among roads in different FCs. The third option balances the first two, differentiating between highway types (interstates/freeways, arterials, collectors, and local roads) while keeping the weights closer for FCs of the same highway type.

Table 3.1 Functional Class–Based Weighting Schemes

Functional Class	Inverse FC Weights (1)	SHIFT VHD Weights (2)	Adjusted Weights (3)
1 (Interstate)	7 (1)	1	1
2 (Other freeways or expressways)	6 (0.86)	0.95	0.95
3 (Other Principal Arterial)	5 (0.71)	0.90	0.8
4 (Minor Arterial)	4 (0.57)	0.85	0.7
5 (Major Collector)	3 (0.43)	0.80	0.5
6 (Minor Collector)	2 (0.29)	0.75	0.4
7 (Local)	1 (0.14)	0.70	0.2

Based on the results, using equal weights implies that we did not differentiate characteristics (e.g. volume, length, FC) of all critical highways (i.e., those being disrupted) in the analysis. The VMT-weighted scheme favored detours near heavily traveled interstates, and the length-weighted approach favored detours in areas with relatively sparse networks. FC-based schemes provide a good balance, particularly the third option (adjusted FC weights).

Figure 3.4 displays the statewide ranking of detour importance using a hybrid detour strategy (initially identifying routes two FCs below the disrupted highway and, if this option is viable, locating routes whose BC > 0) and adjusted FC weighting scheme.

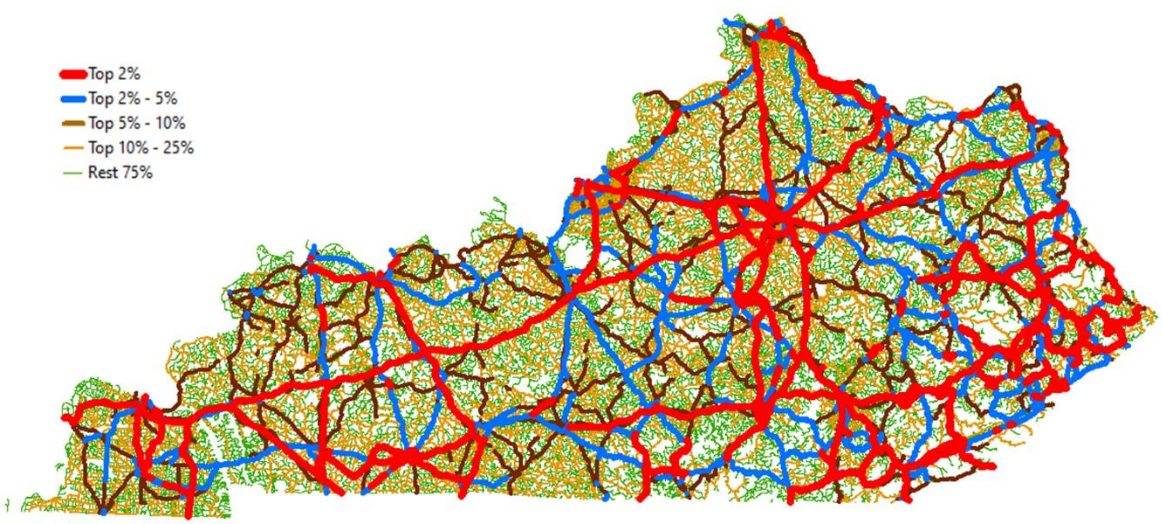

Figure 3.4 Statewide Detour Ranking

3.4 Overall Highway Criticality Score

After obtaining BC and DT percentile ranking scores for all roadways, we calculated the overall highway criticality score with the following formula:

$$C_e = [\alpha * BC_{scaled} + (1-\alpha) * DT_{scaled}]_{scaled}$$

where: BC_{scaled} and DT_{scaled} are the percentile rank of the BC score and detour score of link e among all links statewide, respectively; α varies from 0 to 1 and represents the weight assigned to the BC score; α = 0.5 if equal weight is given to BC and detour scores. The final HCS score is a scaled value representing a link's percentile ranking in the state.

Using equal weights for BC and DT, Figure 3.5 displays statewide percentile rankings for overall highway criticality scores. The value of α can be adjusted based on application context.

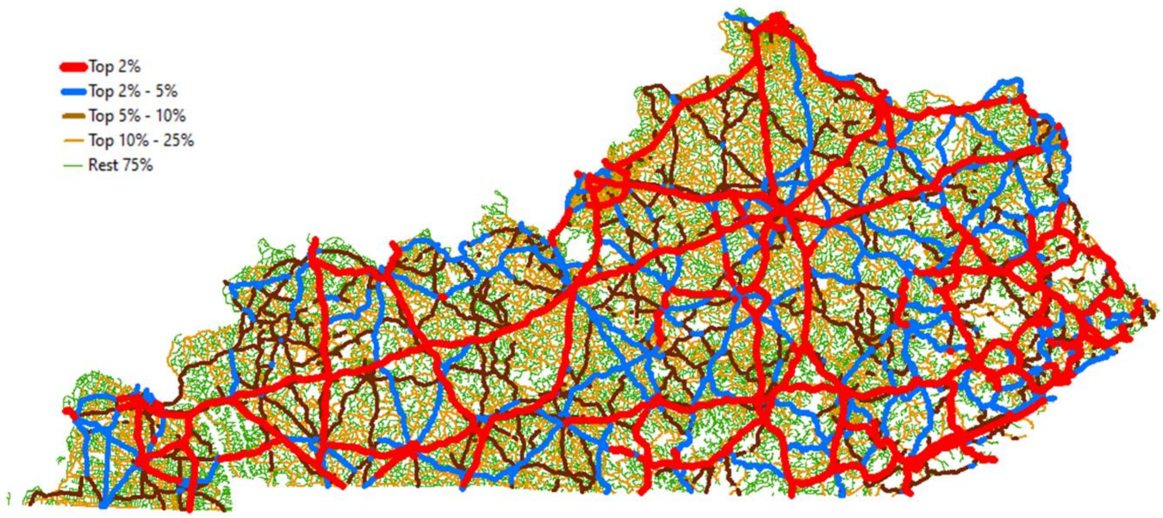

Figure 3.5 Statewide Ranking of Overall Highway Criticality Score

Alternatively, if a raw-score approach were adopted by the SHIFT Umbrella Project, the scaling method described above can be adjusted. Rather than scaling BC and DT scores using percentile ranks, the maximum value of the metric from all projects is used as the baseline to determine the percentage of BC and DT points each project receives. Based on the results of this study Figure 3.6 shows the proposed System Resilience formula for SHIFT 2024.

Resilience

Criticality Formula

Criticality Score = [(BC)†$_{Scaled}$ + (DT)†$_{Scaled}$]†$_{Scaled}$

Measure	Description	Data Source
BC	The centrality of a road, calculated as the percentage of OD pairs using the road within its 1-hour travel time neighborhood.	HIS, HERE data, KYSTDM TAZ, Census block group
DT	The importance of the road as detour to other highways with top 5% BC values. $$DT_a = \sum_{i=1}^{k} BC_i \times p_i \times w_i$$ where DT_a is the detour score of link a; BC_i is the BC value of the segment i whose detour will include link a; p_i is the percent trips originally using segment i that rerouted through link a when segment i is disrupted; w_i value varies by functional classification: 1 for FC1, 0.95 for FC2, 0.8 for FC3, 0.7 for FC4, 0.5 for FC5, 0.4 for FC6, and 0.2 for FC7.	HIS, HERE data, KYSTDM TAZ, Census block group

†Scaled - Converts value to a score of 0 to 100 by dividing the value with the maximum value of all projects.

Figure 3.6 Proposed System Resilience formula for SHIFT 2024

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