ODOT Library
555 13th Street NE
Salem, OR 97301
(971) 701-0709
ODOTLibrary@odot.oregon.gov

LITERATURE SEARCH
Road Isolation Index Research

Prepared by: Amanda J. Carter
July 2025

Summary of Results:

While inquiries into other state Department of Transportation projects were unsuccessful, a couple of state projects related to transportation vulnerability are currently underway. Additionally, a few active research projects discovered in TRB's RIP (Transportation Research in Progress) were discovered. All identified projects were initiated or completed within the last two years and are listed and linked below.

Following the active and recently completed projects is the annotated bibliography of 30 journal articles, conference proceedings, book chapters, and reports. Methodologies and models are compared. Existing metrics are analyzed. New metrics are proposed. From a general overview of concepts and definitions discussed as early as 2002, through more recent comparisons of existing metrics and proposals of new metrics, these articles and reports provide comprehensive coverage of current and proposed methodologies in determining and evaluating transportation road vulnerability and link criticality. Some of the articles land between 2010 and 2013, but the vast majority of discussion, comparisons, and proposals are more recent, being published from 2017 to 2025. Geographic coverage spans the globe with most locations existing within the United States or China.

State Projects on Transportation Vulnerability:

Bureau of Transportation Statistics. *Transportation Vulnerability and Resilience (TVAR)*. 2024. https://www.bts.gov/tvar

Washington Coastal Hazards Resilience Network. *Coastal Transportation Vulnerability & Planning Study*. 2025. https://wacoastalnetwork.com/transportation-vulnerability-study/

Research in Progress:

Goldstein, E. (2024). *Evaluation of Road Network Resilience to Natural Hazards using Network Analysis*. NCDOT Research Project Number: 2023-16. https://connect.ncdot.gov/projects/research/Pages/ProjDetails.aspx?ProjectID=2023-16

Roadway vulnerability assessments are often used to predict which routes are currently, or may in the future, be subject to natural hazards. However, these assessments are often conducted for individual roadways and therefore do not assess to what degree road closures affect the connectivity of road networks – i.e., the ability for a user to access other roads in the network. A consequence of this is that future roadway retrofits, such as raising the elevation of roadways, could alter network connectivity in a way that has cascading impacts on community accessibility during extreme events. The principal goal of this project is to improve predictions of roadway vulnerability by using network science and network analysis to understand the connectivity of road networks during extreme events. By treating road intersections as 'nodes' and road segments as 'edges', we can successively remove nodes based on some criteria (such as increasing elevations, akin to flooding or another extreme event) to identify the threshold where the entire network starts to break apart. The network analysis proposed in this project is focused on coastal settings, and specifically flood hazards, but the methodology is broadly applicable to other regions of North Carolina and additional natural hazards (e.g., landslides).

Yin, Y. (2025, October). *End-to-End Learning Framework for Transportation Network Equilibrium Modeling*. Center for Connected and Automated Transportation, University of Michigan. https://ccat.umtri.umich.edu/research/u-m/end-to-end-learning-framework-for-transportation-network-equilibrium-modeling/

This project aims to outline a groundbreaking "end-to-end" transportation demand modeling framework, driven by deep learning techniques and empirical multi-source data. Unlike traditional models, which typically employ a multi-step process, this framework directly associates time-series observations of traffic patterns, urban land use, and socioeconomic features with prediction of future traffic flow distributions. The end-to-end modeling framework is designed to learn travelers travel and route choices while refining link performance functions that estimate travel time based on traffic flow. After calibration against empirical data, the proposed framework can recommend optimal policies or projects for enhancement, thereby facilitating informed decision-making. By utilizing passively collected trajectory data, this framework aims to significantly improve modeling accuracy and the realism of behavioral representation, without additional costs for data collection in the existing modeling system.

Yazici, M. (2025). *Link Disruption Scenario Generation for Transportation Network Criticality Analysis*. Rural Safe, Efficient, and Advanced Transportation Center, Florida A&M University. https://rip.trb.org/View/2509039

Policy makers need the criticality ranking of transportation network links so that they can act to suggest investment/improvement strategies. The criticality of transportation networks links is calculated through utilizing selected criticality metric(s) for various disruption scenarios. The disruption scenarios generally include link failure scenarios that can correspond to one link removal/degradation at a time (the most common) or simultaneous removal/degradation of multiple links. The common approach is to utilize singular component degradation/failure to calculate the individual criticality, i.e., run traffic assignment for each link removal scenario, calculate the difference of the network performance function (e.g., total system travel time) between the unaffected network and the failure scenario, and rank the links based on this functionality loss difference, i.e., the highest the difference, higher the ranking of the link. However, it is more likely that multiple links fail simultaneously, especially when considered within disaster conditions such as hurricanes and snowstorms. As shown in the literature, single link removals do not reveal the actual criticality of link(s) due to network dependencies, e.g., a link that may not create a large network performance change to be deemed critical, yet can cripple the system when fails in conjunction with others. In other words, the network dependencies make it difficult to isolate each link's individual criticality. Multiple simultaneous link removal scenarios can capture the network interactions; however, the calculated criticality scores indicate the criticality ranking of scenarios than individual links, e.g., the links in scenario-1 is more critical than the links in scenario-2. In addition, running multiple link failure scenarios can be computationally infeasible due to the combinatorial nature of scenario creation.

For example, for a medium size network with 100 links, the number of scenarios to include all simultaneous two-link removals are 4,950 (combinations of 2 links out of the total 100). For triple link removal, the number of scenarios increase to 485,100, and for quadruple removals, the total number of scenarios is 2,352,735. Considering that simultaneous quadruple link removals in a network size of 100 cannot reveal the network flow interdependencies, such multi-link failure analysis lead to impractical computation times. In this context, there are two main research questions: 1) How to calculate criticality of individual links based on scenarios that include multiple simultaneous failures? and 2) What is the optimal scenario generation approach that reveals the network flow dependencies while it is computationally tractable? For the first problem, PI Yazici has developed an approach that calculates individual link criticality based on a given number of scenarios. The approach utilizes the distribution of the criticality scores for each link, i.e., the criticality score distribution for link #X is composed of the criticality scores of scenarios that include link #X. The criticality ranking for each link is calculated based on its criticality score distribution's mean, coefficient of variation and skewness. The approach was tested on real-life networks and it was shown that it provides robust link criticality rankings that account for network interactions. Hence, this project focuses on the optimal scenario generation strategy that will provide a systematic approach to select a smaller subset of all link failure scenarios that enables transportation criticality analysis that account for network flow interaction patterns with reasonable computation times. The developed procedure will also account for the network size and topology that affect network flow dependencies, thus the criticality of individual links.

Annotated Bibliography:

Links and abstracts are listed with the citations; links open to full-text documents, pages that allow PDF downloads, or abstract pages. Articles and papers not openly available full-text can typically be obtained through interlibrary loans. However, all of the following publications are available for your review upon request.

Almotahari, A. and A. Yazici (2021). A computationally efficient metric for identification of critical links in large transportation networks. *Reliability Engineering & System Safety, 209*: 107458. https://doi.org/10.1016/j.ress.2021.107458

Maintaining safety and resilience in transportation system requires identification of critical components. The existing transportation link criticality metrics typically require multiple traffic assignments to perform a full scan of the network. Link removals create computational burden and can cause network disconnectivity which makes it problematic to run traffic assignment. The authors previously introduced Link Criticality Index (LCI) that identifies the criticality ranking within a single User Equilibrium (UE) traffic assignment using Frank-Wolfe (FW) algorithm. While LCI is shown to provide balanced rankings with respect to connectivity and flow conditions, its computational efficiency diminishes for larger networks due to the need for path enumeration. This paper formulates an adjusted LCI to make it computationally efficient for larger networks. Adjusted LCI utilizes 1) viable routes instead of the complete list of enumerated paths; and, 2) a path-based traffic assignment algorithm (Gradient Projection) to replace FW. The consistency of rankings between original/adjusted LCIs, and other measures from the literature are analyzed and compared for three networks, and through an experimental setup. The proposed method is also applied on a large-scale transportation network, i.e., Chicago network. The results show that both modifications are effective and yield faster results without compromising LCI's advantages.

Almotahari, A., & Yazici, A. (2020). "Practice Friendly Metric for Identification of Critical Links in Road Networks." *Transportation Research Record*, *2674*(8), 219-229. https://doi.org/10.1177/0361198120925475

Despite the important planning value of transportation link criticality, the existing methodologies are mostly in the academic domain, and require in-depth technical skills and extensive data. The most common approach to identify critical links in transportation networks is to remove each link iteratively, conduct traffic assignment, and assess the criticality of each link based on the consequences of its removal. Since conducting multiple traffic assignment is costly for large networks, the authors of this paper recently introduced the link criticality index (LCI). The LCI utilizes the iterations in the Frank–Wolfe solution of the user equilibrium (UE) problem to provide link criticality ranking within a single traffic assignment. The LCI was shown to provide balanced rankings with respect to alternative routes as well as the link flows. However, the LCI is not practice-friendly because of the technical knowledge and data needed to run traffic assignments. Accordingly, this paper introduces a practice friendly link criticality index (PF-LCI). PF-LCI relaxes some of the technical requirements and uses some expert knowledge input data to provide "top" link criticality rankings that are consistent with the LCI. PF-LCI utilizes the network flow instances at different times of day instead of iterations of UE assignment solution. Expert knowledge input is sought for the major origin–destination pairs (ODs) and the viable routes between the selected ODs. The method is implemented on a small sample network and the Sioux Falls network to test PF-LCI's capabilities. Results show that PF-LCI produces accurate rankings for the top critical links that are most relevant to practitioners' concerns.

Almotahari, A., & M. A. Yazici (2019). A link criticality index embedded in the convex combinations solution of user equilibrium traffic assignment. *Transportation Research Part A: Policy and Practice, 126*: 67-82. https://doi.org/10.1016/j.tra.2019.06.005

Identification of critical components in transportation networks is an essential part of designing robust and resilient systems. Topological criticality measures are based on graph theory and are applicable in multiple domains including communication and social networks. However, the non-linearity of link performance functions in transportation systems does not allow a perfect domain transfer of topological measures. Hence, transportation researchers take traffic flow characteristics into account while developing criticality measures. In such approaches, typically, a network performance measure is selected, then links are removed one-by-one, and traffic demand is reassigned to the updated network to calculate the impacts of each link failure. This consecutive link removal procedure requires multiple assignments which create a computational burden, especially for large networks. Overall objectives of this paper are (1) to compare and contrast selected criticality measures, and (2) to develop a new measure to identify critical components of transportation network, considering both traffic characteristics and network topology. For this purpose, the user equilibrium traffic assignment formulation is utilized, and the convex combinations solution algorithm is exploited for identification of link criticality ranking within a single traffic assignment. The developed measure is named Link Criticality Index (LCI). The LCI is compared with the existing measures in the literature through three numerical examples. Pros and cons of the LCI and selected measures are discussed in detail. The results indicate the proposed link criticality measure provides a balanced ranking with respect to connectivity/redundancy as well as the traffic conditions in the network.

Barati, H., Yazici, A., & Almotahari, A. (2024). A methodology for ranking of critical links in transportation networks based on criticality score distributions. *Reliability Engineering & System Safety, 251*, 110332. https://doi.org/10.1016/j.ress.2024.110332

Criticality of transportation networks links is calculated through utilizing criticality metric(s) for various disruption scenarios that generally include one link removal/degradation at a time or simultaneous removal/degradation of multiple links. As also shown in this paper, single link removals do not reveal the actual criticality of link(s) due to network dependencies. Multiple simultaneous link removal scenarios can capture the network interactions; however, the results relate to the criticality ranking of scenarios than the links, e.g., the links in scenario-1 are more critical than the links in scenario-2. This paper addressed the need for a methodology that provides individual link criticality rankings based on failure scenarios. The proposed approach utilizes the distribution of the criticality scores for each link based on running traffic assignment for each failure scenario, e.g., the distribution for link #X is composed of the criticality scores of all link failure combinations that include link #X. The criticality ranking for each link is identified based on its criticality distribution's mean, coefficient of variation and skewness. The use of the proposed approach is illustrated on test networks to show that it provides robust link criticality rankings that accounts for network interactions across varying scales of link failure scenarios.

Berdica, K. (2002). An introduction to road vulnerability: what has been done, is done and should be done. *Transport Policy, 9*(2): 117-127. https://doi.org/10.1016/S0967-070X(02)00011-2

Vulnerability in the road transportation system, studied not only from a safety point of view but also as a problem of an insufficient level of service, is proposed as a setting for future transport studies. This relatively new notion is conceptualised by discussing a number of definitions and related concepts, reviewing especially the concept of reliability as a feasible theoretical approach. The paper relates how vulnerability related problems have been addressed so far, current developments and finally what the future should hold in order to provide us with the comprehensive network analysis tool that our complex society calls for.

Çalışkan, B., Atahan, A.O., & Kesten, A.S. (2022). *GIS Aided Vulnerability Assessment for Roads*. In: Akhnoukh, A., et al. Advances in Road Infrastructure and Mobility, IRF 2021. Sustainable Civil Infrastructures. Springer, Cham. https://doi.org/10.1007/978-3-030-79801-7_80

Road networks are vulnerable to natural disasters such as floods, earthquakes and forest fires which can adversely affect the travel on the network. However, not all road links equally affect the travel conditions in a given network; typically some links are more critical to the network functioning than the others. The first stage of study involves the investigation of geological conditions. Image classification used for extracting information classes from 'Geological Map of Istanbul area' image file. The resulting raster layer used to create thematic map. A reclassification was performed for lithologic types. The second stage involves analyzing topological situation. A slope map prepared and classified according to percentage of slope values. The third phase is the analysis and interpretation of the accumulated data to establish suitable and applicable road vulnerability scores. The information in the source data for each vulnerability factor are classified into three different vulnerability scores: +2 (considerably increases vulnerability), +1 (increases vulnerability) and 0 (does not increase vulnerability) by using a vulnerability score table. The study area was categorized into three different traffic analysis zones as: (1) least favorable area; (2) favorable area; (3) most favorable area. Vulnerability values obtained to measure serviceability of critical links in dense urban road networks and applies them to the case of 'Beyoğlu' region. Thematic layers were prepared using the Geographic Information System (GIS), and they were then combined to produce the serviceability of road links in the 'Beyoğlu' region.

Consequently, A site specific vulnerability index is proposed, considering the serviceability of road links. A conceptual flowchart of the GIS processing steps taken to obtain the vulnerability index is illustrated.

Chung, S., Sardak, D., Cegan, J., & Linkov, I. (2025). Assessing the Robustness and Resilience of U.S. Strategic Highways: A Network Science Perspective. *Transportation Research Record*, *0*(0). https://doi.org/10.1177/03611981251348445

Network science is a powerful tool for analyzing transportation networks, offering insights into their structures and enabling the quantification of resilience and robustness. Understanding the underlying structures of transportation networks is crucial for effective infrastructure planning and maintenance. In military contexts, network science is valuable for analyzing logistics networks, critical for the movement and supply of troops and equipment. The U.S. Army's logistical success, particularly in the "fort-to-port" phase, relies heavily on the Strategic Highway Network (STRAHNET) in the U.S., which is a system of public highways crucial for military deployments. However, the shared nature of these networks with civilian users introduces unique challenges, including vulnerabilities to cyberattacks and physical sabotage, which is highlighted by the concept of contested logistics. This paper proposes a method that uses network science and geographic information systems (GIS) to assess the robustness and resilience of transportation networks, specifically applied to military logistics. Our findings indicate that, while the STRAHNET is robust against targeted disruptions, it is more resilient to random disruptions.

Dowds, J., Sentoff, K., Sullivan, J. L., & Aultman-Hall, L. (2017). Impacts of Model Resolution on Transportation Network Criticality Rankings. *Transportation Research Record*, *2653*(1), 93-100. https://doi.org/10.3141/2653-11

Objective rankings of the criticality of transportation network infrastructure are essential for efficiently allocating limited adaptation resources and must account for network connectivity and travel demand. Road link criticality can be quantified by the total travel delay caused when the capacity of a road segment or link is disrupted or removed. These methods can use standard travel demand models, but the exclusion of lower-volume roads and the aggregate nature of traffic analysis zones may distort resulting criticality rankings. To test the impact of link exclusion and demand aggregation, the authors applied the network robustness index, a well-established link criticality measure, to a hypothetical network with varying levels of network resolution and demand aggregation. The results show a statistically significant change in criticality rankings when demand is aggregated and especially when links are excluded from the network, suggesting that criticality rankings may be distorted when estimated with typical demand models. Application to a road network in Vermont supports the finding on the impact of network resolution on criticality rankings.

Gerges, F., et al. (2022). A GIS-based approach for estimating community transportation exposure and capacity in the context of disaster resilience. *Sustainable Horizons, 3*: 100030. https://doi.org/10.1016/j.horiz.2022.100030

Transportation is a critical sector for communities. It is, however, particularly vulnerable to climate change, and a disruption in its infrastructure impacts the whole community. Enhancing the resilience of transportation infrastructure is vital for reliable and sustainable functionalities, and subsequently, to more resilient communities. There are indices and frameworks that assess and evaluate transportation resilience and performance, ranging from component-based, to network and system metrics. The existing approaches, however, usually overlook location and capacity of critical transportation components. These two characteristics possess significant effects on the resilience and performance of the transportation sector. Moreover, the stress type and its magnitude should be incorporated in the resilience assessment. In this work, we leverage a recent resilience quantification framework to compute the Exposure and Capacity-based Transportation Resilience Index (EC-TRI), describing the resilience of the transportation infrastructure, focusing on the location and capacity of certain assets. We argue for the adoption of this index as a complement to existing frameworks, and we develop a web-based GIS framework to evaluate EC-TRI for communities within New Jersey (NJ). The novelty of EC-TRI lies in its consideration for the stress level, the exposure and capacity characteristics of transportation assets, as well as in its practicality and scalability. Users can leverage EC-TRI to locate the weak and vulnerable components within the transportation network, and to provide a community-based assessment of the resilience level of the transportation infrastructure. In addition, we provide EC-TRI as a highly scalable GIS framework, providing users with the ability to adjust the quantification components as per local needs and priorities.

Hernandez, S., Mitra, S., Amankwah-Nkyi, K., Tasnim, F., Mahmud, S., & Rothwell, S. (2023). *Data-Driven Methods to Assess Transportation System Resilience in Arkansas*. Department of Civil Engineering, University of Arkansas. https://rosap.ntl.bts.gov/view/dot/75150

The work described in this report proposes a foundational and repeatable resiliency assessment methodology to identify the most critical and vulnerable highway infrastructure assets. This study developed resiliency metrics that measure the overall network resiliency as a combination of the probability of disruptions in one or more of the network links (threats) and the importance of the link to mobility (criticality). The research team synthesized existing studies and practices to (a) define resiliency assessment methods, (b) define resiliency indices, and (c) evaluate the current state of practices within ARDOT. The method developed by the Colorado Department of Transportation (CDOT) was adopted in this study. Briefly, the CDOT method estimates the criticality and vulnerability of each transportation network segment. Six criteria were used to estimate system criticality: traffic volume (annual average daily traffic [AADT]), roadway classification, freight output, tourism output, Social Vulnerability Index (SoVI), and redundancy. Three threat types were used to estimate system vulnerability: floods, landslides, and earthquakes. The criticality and vulnerability values were converted into intensity scores and then combined so that the highest-scoring links were considered the most critical and most vulnerable based on the underlying data and assumptions used. Crittenden, Mississippi, and Craighead counties ranked highest in terms of combined criticality and vulnerability. Across all roadway segments, five segments had the highest combined criticality and vulnerability score. For these segments, we performed a detailed benefit-cost analysis of the existing (baseline) asset conditions and possible mitigation alternatives.

Hyun, K. K., Mattingly, S. P., & Arabi, M. (2021). *Network Analysis to Identify Critical Links for Relief Activities during Extreme Weather Events*. Transportation Consortium of South-Central States (Tran-SET), University Transportation Cetner for Region 6. https://rosap.ntl.bts.gov/view/dot/61730

As one of the principal lifeline systems, transportation networks are crucial for evacuation and delivering essential resources and services during the response and recovery phases of extreme weather events and must remain intact to enhance regional resiliency. The conventional evaluation measures that estimate the vulnerability or criticality of road network based on travel time or link volumes do not capture the community impacts due to disruptions. This study seeks to develop a framework to evaluate road network infrastructure criticality during extreme weather events by introducing measures

that evaluate the vulnerability of roads users, rather than the physical aspects of link importance. The research develops an innovative approach that integrates three important concepts including hurricane evacuation behavior, community impacts, and road criticality to identify the critical links. Results show that the critical links for vulnerable populations during evacuation do not always align with conventional link-based measures. This highlights the importance of using a performance measure that takes the social vulnerability of road users into consideration when identifying the criticality of a road network and planning for fortification of links to avoid irreversible consequences for vulnerable population groups. Furthermore, decision-making that considers the risks to different communities may lead to a more effective distribution of resources and help support a timely and safe evacuation from disaster events by strengthening the preservation of critical infrastructure links.

Jafino, B. A., et al. (2020). Transport network criticality metrics: a comparative analysis and a guideline for selection. *Transport Reviews, 40*(2): 241-264. https://doi.org/10.1080/01441647.2019.1703843

Transport network criticality analysis aims at ranking transport infrastructure elements based on their contribution to the performance of the overall infrastructure network. Despite the wide variety of transport network criticality metrics, little guidance is available on selecting metrics that are fit for the specific purpose of a study. To address this gap, this study reviews, evaluates and compares seventeen criticality metrics. First, we conceptually evaluate these metrics in terms of the functionality of the transport system that the metrics try to represent (either maintaining connectivity, reducing travel cost, or improving accessibility), the underlying ethical principles (either utilitarianism or egalitarianism), and the spatial aggregation considered by the metrics (either network-wide or localised). Next, we empirically compare the metrics by calculating them for eight transport networks. We define the empirical similarity between two metrics as the degree to which they yield similar rankings of infrastructure elements. Pairs of metrics that have high empirical similarity highlight the same set of transport infrastructure elements as critical. We find that empirical similarity is partly dependent on the network's topology. We also observe that metrics that are conceptually similar do not necessarily have high empirical similarity. Based on the insights from the conceptual and empirical comparison, we propose a five-step guideline for transport authorities and analysts to identify the set of criticality metrics to use which best aligns with the nature of their policy questions.

Jia, G., & Bui, K. (2023). *Development of Improved Redundancy Measure for the Colorado State Highway System*. Colorado Department of Transportation. https://rosap.ntl.bts.gov/view/dot/83835

The Colorado Department of Transportation (CDOT) has been working to improve the resiliency of its transportation system and facilities. A vital attribute of a resilient transportation system is whether the system has redundancies built into it. For example, if a roadway is closed to traffic, but there are alternative routes for the drivers to take, then the closed roadway could be considered to have redundancy. The current redundancy measure that CDOT uses is based on the number of other state highways that connect to a particular highway. The redundancy measure needs refinement because it does not consider the additional travel time and distance from the alternative routes. This research developed an improved method for measuring the redundancy of state highway facilities in Colorado. To establish information on the number of detours (i.e., alternative routes) for a specific road segment and the additional travel time and distance on each of the detours, detour analyses are carried out to identify (if any) the first, second, and third best alternative detours for all the highway segments in the state highway system. This is realized by closing the corresponding segment or alternative routes, updating the transportation network, and rerunning the traffic analysis on the updated transportation

network. For more accurate analysis, the combined distribution and assignment model is used to consider the effects of congestion on the traffic flow. Because the full transportation network in CDOT's statewide model has large number of nodes and links, to reduce the computational effort for the detour analysis (which needs to be repeated for all road segments), an aggregated network based on the full network is developed and used for detour analysis for cars. Separate detour analyses are also carried out for the freight vehicles since they use a separate freight network, which is a subnetwork of the aggregated network. In the end, using the information from the detour analyses, a new improved redundancy metric is developed that considers not only the number of alternative routes for a road segment but also the additional time and distance on the alternative routes. The new redundancy metric also incorporates a weight for each best detour (e.g., the first, second, and third best detours are weighted differently). The detour information will be used to update the existing CDOT Detour Identification Tool. The redundancy metric can be further used to calculate and update CDOT's criticality score to determine resiliency of the Colorado State Highway System and guide activities to enhance its resilience.

Jin L, Wang H, Xie B, Yu L, & Liu L (2017) A user exposure based approach for non-structural road network vulnerability analysis. *PLOS ONE 12*(11): e0188790. https://doi.org/10.1371/journal.pone.0188790

Aiming at the dense urban road network vulnerability without structural negative consequences, this paper proposes a novel non-structural road network vulnerability analysis framework. Three aspects of the framework are mainly described: (i) the rationality of non-structural road network vulnerability, (ii) the metrics for negative consequences accounting for variant road conditions, and (iii) the introduction of a new vulnerability index based on user exposure. Based on the proposed methodology, a case study in the Sioux Falls network which was usually threatened by regular heavy snow during wintertime is detailedly discussed. The vulnerability ranking of links of Sioux Falls network with respect to heavy snow scenario is identified. As a result of non-structural consequences accompanied by conceivable degeneration of network, there are significant increases in generalized travel time costs which are measurements for "emotionally hurt" of topological road network.

Kurmankhojayev, D., et al. (2025). A methodological foundation for proactive disruption mitigation in transport networks: Integrating route similarity and elastic demand in stochastic user equilibrium-based link criticality analysis. *Reliability Engineering & System Safety, 261*: 111084. https://doi.org/10.1016/j.ress.2025.111084

Assessing link criticality in transport networks requires accounting for route similarity (due to shared links) and elastic demand (ED) (due to travelers' responses to congestion). Route similarity induces correlated route choices, diverting traffic from overlapping routes, while ED adjusts travel volumes as travelers may switch modes, change their departure times, or forego trips altogether in response to congestion. Current methods often ignore both factors, oversimplifying their joint impact on traffic flows and link criticality rankings. Addressing this gap can enhance assessment reliability, supporting strategies for mitigating medium- to long-term network disruptions such as infrastructure deterioration or collapse. This study suggests an approach to advance the link criticality index (LCI), a state-of-the-art method for link criticality analysis, via the integration of route similarity. Specifically, we present an advanced LCI method based on the cross-nested logit (CNL) stochastic user equilibrium (SUE) assignment model, which can flexibly and realistically capture the effect of route similarity on both individuals' route choices and network flows. Numerical experiments on toy and real-size networks show and quantify how route similarity can affect link criticality values under the assumption of fixed demand (FD) and elastic demand (ED). The results demonstrate that the criticality ranking of links may be significantly altered if route similarity and demand elasticity are overlooked.

Li, J., & Ozbay, K. (2012). Evaluation of Link Criticality for Day-to-Day Degradable Transportation Networks. *Transportation Research Record*, *2284*(1), 117-124. https://doi.org/10.3141/2284-14

The evaluation of link criticality is an important step for public officials to apply when planning hazard mitigation. However, this type of analysis presents numerous challenges for capturing the impact of highly stochastic hazard events accurately. An analytical framework and an efficient solution procedure for the evaluation of link criticality are proposed: those tools consider the impact of day-to-day degradable conditions in transportation networks. Link capacity was examined as a multistatus variable, and a sampling technique was used to generate realizations of capacity value for transportation networks. With different capacity realizations, traffic demand was repeatedly assigned on the regional planning model network. The assignment results were measured with multiple criteria and analyzed with several statistical indices. A case study based on a section of the New Jersey roadway network verified the proposed approach.

Luathep, P., et al. (2011). Large-scale road network vulnerability analysis: A sensitivity analysis based approach. *Transportation*, *38*(5): 799-817. https://doi.org/10.1007/s11116-011-9350-0

Traditionally, an assessment of transport network vulnerability is a computationally intensive operation. This article proposes a sensitivity analysis-based approach to improve computational efficiency and allow for large-scale applications of road network vulnerability analysis. Various vulnerability measures can be used with the proposed method. For illustrative purposes, this article adopts the relative accessibility index (AI), which follows the Hansen integral index, as the network vulnerability measure for evaluating the socio-economic effects of link (or road segment) capacity degradation or closure. Critical links are ranked according to the differences in the AIs between normal and degraded networks. The proposed method only requires a single computation of the network equilibrium problem. The proposed technique significantly reduces computational burden and memory storage requirements compared with the traditional approach. The road networks of the Sioux Falls city and the Bangkok metropolitan area are used to demonstrate the applicability and efficiency of the proposed method. Network manager(s) or transport planner(s) can use this approach as a decision support tool for identifying critical links in road networks. By improving these critical links or constructing new bypass roads (or parallel paths) to increase capacity redundancy, the overall vulnerability of the networks can be reduced.

National Academies of Sciences, Engineering, and Medicine. (2021). *Investing in Transportation Resilience: A Framework for Informed Choices*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26292.

Significant progress has been made over the last decade in integrating resilience criteria into transportation decision-making. A compelling case remains for investing in making transportation projects more resilient in the face of increasing and intensifying storms, floods, droughts, and other natural hazards that are combining with sea-level rise, new temperature and precipitation norms, and other effects from climate change. This report reviews current practices by transportation agencies for evaluating resilience and conducting investment analysis for the purpose of restoring and adding resilience. These practices require methods for measuring the resilience of the existing transportation

system and for evaluating and prioritizing options to improve resilience by strengthening, adding redundancy to, and relocating vulnerable assets.

Pucci, A., Puppio, M. L., Sousa, H. S., Giresini, L., Matos, J. C., & Sassu, M. (2021). Detour-Impact Index Method and Traffic Gathering Algorithm for Assessing Alternative Paths of Disrupted Roads. *Transportation Research Record, 2675*(12), 717-729. https://doi.org/10.1177/03611981211031237

Infrastructure plays a key role in society. Recent collapses of bridges have underlined their importance for road functionality, causing disruptions to commuters and emergency vehicles. Major issues arise on rural roads, where the lack of redundancy leads to the isolation of entire communities. Actual approaches to assess the resilience of countryside roads rely on the availability of specific datasets, limiting their practical application; this issue is typically related to traffic data. This research aims to propose innovative algorithms to assess the road network's vulnerability in rural areas, including a novel traffic data collection process and its calibration. The aggregate metric is called Detour-Impact Index (DII) and compares user costs before and after a disruptive event. The method uses traditional network-impact metrics in combination with a new algorithm that allows us to gather quantitative traffic data starting from qualitative information. User travel time showed good agreement between the proposed procedure and traditional web-based methods. Furthermore, the paper provides user delay costs functions accounting for traffic composition, trip purposes, vehicle operative costs, nonlinear volume–capacity relation, and average daily traffic. A significant aspect is the adaptability of this framework, as it is designed to be coupled with existing approaches. The method is demonstrated on a case study in Tuscany (Italy).

Reynaud, F., et al. (2018). Extending the Network Robustness Index to include emissions: a holistic framework for link criticality analysis for Montreal transportation system. *Transportation Letters, 10*(6): 302-315. https://doi.org/10.1080/19427867.2016.1262980

The Network Robustness Index (NRI) was one of the first tools to successfully assess network-wide congestion effects due to single-link closures. This paper investigates the use of systemwide metrics in the context of Montreal's urban road network, and provides a new mechanism to evaluate the importance of individual links while internalizing the environmental perspective. Specifically, the NRI is expanded to include road emissions in the link criticality analysis process, resulting in the creation of an Emissions-based NRI (ENRI), to be used in conjunction with the NRI. The results of this new Emissions-based NRI (ENRI) are compared with the NRI results and we observe that both tools provide similar results for major scenarios (such as capacity reduction on major bridges) while for minor scenarios (such as capacity reduction on arterial roads) the results are quite different. The results suggest that new holistic frameworks are needed to assess link criticality in urban areas.

Sugiura, S., & Kurauchi, F. (2023). Isolation vulnerability analysis in road network: Edge connectivity and critical link sets. *Transportation Research Part D: Transport and Environment, 119*, 103768. https://doi.org/10.1016/j.trd.2023.103768

This article focuses on vulnerability in transportation systems because of large-scale disasters. We proposes an index of isolation vulnerability as a new metric for network vulnerability analysis. Isolation vulnerability covers the situation in which supporting bases and receiving bases in a network cannot connect when some links are degraded due to external forces imposed on the network. Isolation vulnerability is derived as a solution of the maximum flow problem for a one-to-one network extended

for supporting bases and receiving bases. A single set of link combinations does not necessarily exist that defines an isolation vulnerability, i.e., a set that is isolation-critical. A method of enumerating all of these critical link sets is provided and applied to the road network in Sapporo city, Japan, to identify highly vulnerable public shelters and analyze their characteristics.

Sullivan, J. L., et al. (2010). Identifying critical road segments and measuring system-wide robustness in transportation networks with isolating links: A link-based capacity-reduction approach. *Transportation Research Part A: Policy and Practice, 44*(5): 323-336. https://doi.org/10.1016/j.tra.2010.02.003

A wide range of relatively short-term disruptive events such as partial flooding, visibility reductions, traction hazards due to weather, and pavement deterioration occur on transportation networks on a daily basis. Despite being relatively minor when compared to catastrophes, these events still have profound impacts on traffic flow. To date there has been very little distinction drawn between different types of network-disruption studies and how the methodological approaches used in those studies differ depending on the specific research objectives and on the disruption scenarios being modeled. In this paper, we advance a methodological approach that employs different link-based capacity-disruption values for identifying and ranking the most critical links and quantifying network robustness in a transportation network. We demonstrate how an ideal capacity-disruption range can be objectively determined for a particular network and introduce a scalable system-wide performance measure, called the Network Trip Robustness (NTR) that can be used to directly compare networks of different sizes, topologies, and connectivity levels. Our approach yields results that are independent of the degree of connectivity and can be used to evaluate robustness on networks with isolating links. We show that system-wide travel-times and the rank-ordering of the most critical links in a network can vary dramatically based on both the capacity-disruption level and on the overall connectivity of the network. We further show that the relationships between network robustness, the capacity-disruption level used for modeling, and network connectivity are non-linear and not necessarily intuitive. We discuss our findings with respect to Braess' Paradox.

Sullivan, J., Novak, D., & Scot, D. (2013). *Travel Importance and Strategic Investment in Vermont's Transportation Assets.* University of Vermont Transportation Research Center. https://rosap.ntl.bts.gov/view/dot/27393

This project advances a new type of system-wide measurement of link criticality that will provide the tools needed for strategic disinvestment in roads that are not critical to the health and welfare of Vermonters. This new approach requires a paradigm shift in our current planning function and in the methods used to measure the importance of transportation system components. In this research, the Network Robustness Index (NRI) methodology is modified to include a process for considering the reason for travel in valuing roadways in Vermont. In addition, a new planning metric based on critical accessibility to emergency services is introduced, and combined with the NRI to yield a new measure, the access-based NRI (aNRI), that is uniquely suited to disinvestment planning.

Sullivan, J. L., Sentoff, K., Segale, J., Marshall, N. L., Fitzgerald, E., & Schiff, R. (2024). A new risk-based measure of link criticality for flood risk planning. *Transportation, 51*(6), 2051-2071. https://doi.org/10.1007/s11116-023-10396-y

The importance of a reliable transportation system is often taken for granted but its value becomes undeniable when the system is severely disrupted with little warning, the area of impact is extensive, and the amount of time required to restore system connectivity is prolonged. For many states, the largest single cost of flood damage comes from damage to transportation infrastructure and the ensuing disruption of personal, commercial, and emergency-response travel. The goal of transportation risk planning at the state or provincial level is to consider the risks imposed by the vulnerability of network elements to strengthen the system's ability to withstand a disruptive impact. Although separate measures of vulnerability and criticality are useful, a true risk-based measure would use the vulnerability of links in the network to calculate criticality, so links that are unlikely to be disrupted by a given hazard are left intact in the calculations. This paper details the development and application of the Network Criticality Index (NCI), a new link-specific, risk-based performance measure that uses flood-risk vulnerability scores and a Monte Carlo simulation process for simulating disruptive impacts and measuring link criticality. The paper includes an application of the NCI for flood risk planning to the Deerfield River basin in Vermont. Highly critical segments can be identified as those with the highest NCI values, and mitigation projects can be designed to mitigate the risk. The application finds that relatively high traffic flows can make highly vulnerable links critical due to a lack of redundant routes with adequate capacity to handle flows when they are disrupted by floods. Reducing risk to the highway system from flooding means either (1) improving the segment or crossing and thereby reducing its vulnerability score, or (2) influencing regional traffic flows to prevent disruptive effects on travelers when a disruption occurs. Addressing the vulnerability of the segment or crossing can be done with an engineering design that is sensitive to the project context and the need to improve its ability to withstand higher stream flows in the future.

Susilawati, S. and N. S. T. Yaw (2017). Dynamic Traffic Assignment for Road Network Vulnerability Analysis. *Journal of the Eastern Asia Society for Transportation Studies, 12*: 130-145. https://doi.org/10.11175/easts.12.130

The purpose of the research is to compare results of Dynamic Traffic Assignment models to traditional Static Models during Road Vulnerability Analyses. It is hypothesized that Dynamic Assignment models will improve vulnerability analyses results compared to Static Assignment models as it is able to consider temporal effects of traffic. Vulnerability Analyses are conducted for area disruption cases (multiple links affected) with 99% link capacity reductions. Disruption areas are assigned randomly and are the same size for all cases. NEXTA software issued for both assignment models int eh case study area of West Jordan, Utah. A total of 256 cases during the AM peak and PM peak periods are simulated using four different queue models. Results showed an insignificant difference of average travel time increase and overall demand during disruptions between Dynamic and Static assignment models for most cases.

Takhtfiroozeh, H., Golias, M., & Mishra, S. (2021). Topological-Based Measures with Flow Attributes to Identify Critical Links in a Transportation Network. *Transportation Research Record, 2675*(10), 863-875. https://doi.org/10.1177/03611981211013039

An important part of transportation network vulnerability analysis is identifying critical links where failure may lead to severe consequences, and the potential of such incidents cannot be considered negligible. Existing transportation network vulnerability assessment can be categorized as topological, or traffic based. Topological-based assessment identifies the most critical components in the network by considering network structure and connectivity. Traffic-based assessment identifies the most critical components in the network by full-scan analysis and takes into consideration effects of link failures to traffic flow assignment. The former approach does not consider traffic flow dynamics and fails to capture the non-linearity performance function of transport systems while the latter, even though accurate and robust, requires significant computational power and time and may not always be feasible for real life size networks. The primary objective of this paper is to propose new link criticality measures and evaluate their accuracy for transportation network vulnerability assessment. These measures combine characteristics of traffic equilibrium and network topology to balance accuracy and computational complexity. Nine measures are proposed, and their accuracy is compared with three existing traffic-based measures using three case study transportation networks from the literature. Results indicate that three of the proposed measures show strong correlation to the three traffic-based measures while requiring significantly less computational power and time.

Wandelt, S., et al. (2021). Estimation and improvement of transportation network robustness by exploiting communities. *Reliability Engineering & System Safety, 206*: 107307. https://doi.org/10.1016/j.ress.2020.107307

Throughout the past years, researchers increasingly study the resilience of transportation systems through the lens of complex networks. This model simplification has helped to identify bottlenecks for all kinds of systems, e.g., subway, railway, and road networks. Nevertheless, for large networks, with ten thousand and more nodes, standard complex network-based robustness analysis methods do not scale up well. In this study, we propose to estimate and improve the robustness of transportation systems by exploiting the presence of communities in complex network representations. A community, by definition, is densely connected inside, but loosely connected to other components in the system. Accordingly, the community structure and the induced edges connecting communities can help to orchestrate a framework for better analysis and protection of our transportation systems. Experiments on twelve real-world transportation systems demonstrate the efficiency and scalability of our novel community-based framework.

Zhang, N. H., Hong; Su, Boni; Zhao, Junlong (2014). Analysis of Road Vulnerability for Population Evacuation Using Complex Network. In M. Beer, S.K. Au, & J. W. Hall (Eds.), *Vulnerability, Uncertainty, and Risk: Quantification, Mitigation, and Management* (pp. 772 – 781). American Society of Civil Engineers. https://doi.org/10.1061/9780784413609.079

Population evacuation in an area with high population density is a very serious problem which should be paid more attention. Knowing the road vulnerability for population evacuation and having efficient reconstruction plans of roads, buildings and emergency shelters play a very important role in emergency response. In this paper, a complex network was used to analyze the road vulnerability for population evacuation in an objective way instead of the traditional subjective methods like the expert evaluation approach. Through the data analysis, road-load vulnerability, accessibility and safe distance to emergency shelter of each road and intersection in population evacuation are studied in detail. Furthermore, the improvement plans of each road, intersection and emergency shelter are put forward. The process and the results that were obtained are essential for improving the efficiency of evacuations and reducing the potential risk in population evacuation, which should considerably reduce the possible injury, deaths and other losses in disasters.

Zhao, L., et al. (2022). Impacts of Land Use on Urban Road Network Vulnerability. *Journal of Urban Planning and Development*, *148*(3): 04022032. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000862

Growth in travel demand exacerbates the road network vulnerability. This study aims to explore how the source of travel demand, that is, the land-use spatial layout, impacts road network vulnerability. Based on the interaction between land use and transportation, this study develops a new raster-based road network vulnerability assessment model and employs a logistic model to quantify the correlation between land use and vulnerability. To assess the raster-based vulnerability, this study uses the change in the total travel time for all O-D pairs before and after the disruption of all intersecting links and nodes within the geographical extent of a grid. The central city in Wuhan, China was selected as the case study which was divided into 2,096 grids of uniformly shaped and sized cells. Highly vulnerable areas showed a centripetal distribution trend and were mainly concentrated in the areas around the bridges, expressways, and arterial roads. The logistic model revealed the statistical results that the closer to residential land, public service land, and water area, the higher the vulnerability. Intensive density and land-use mix increase the vulnerability of road networks. High-risk road links were identified for adapting strategies by overlapping the congested road maps with the vulnerability results. Police implications were summarized to mitigate road vulnerability. This method provided technical support for prioritizing the improvement of road network resilience.

Zhou, D., C. Qixiu, Q. An, B. Lu, & L. Zhiyuan (2018). *Link Criticality Analysis Based on Reliable Shortest Path in Network with Correlated Link Travel Times*. CICTP 2018: Intelligence, Connectivity, and Mobility. https://ascelibrary.org/doi/10.1061/9780784481523.250

Link criticality assessment in a transportation network is of significance to traffic operators in that it can provide guidance on road maintenance scheduling and reconstruction prioritizing under failure. Also, link criticality can help improve a network's resilience, providing more efficient services. This paper proposes a reliable-shortest-path-based analyzing procedure to study edge betweenness centrality. A Lagrangian-relaxation subgradient-projection (LR-SP) algorithm for finding the most reliable path in a network is described. More specifically, a covariance matrix in the network is first decomposed, then the problem is reformulated to a convex minimization program. With dualization, the problem is further simplified and solved using a subgradient projection method. Link criticality analysis is then conveyed followed by experiments on a real transportation network that validate the effectiveness of the proposed procedure. With validated link importance, we can then prioritize maintenance and restoration activities, thus improving the network's performance.