Transportation Network Data Requirements for Assessing Criticality for Resiliency and Adaptation Planning

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A Research Report from the National Center for Sustainable Transportation

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National Center for Sustainable Transportation

The UNIVERSITY of VERMONT
TRANSPORTATION RESEARCH CENTER

About the National Center for Sustainable Transportation

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EXECUTIVE SUMMARY

This report is one of two NCST Research Report documents produced as part of a project to advance the technical modeling tools for resiliency and adaptation planning, especially those used for criticality rankings. The official final technical report, *Climate Adaptation and Resiliency Planning: Agency Roles and Workforce Development Needs*, summarizes a climate adaptation framework and describes current planning practices and workforce needs of Departments of Transportation and other planning agencies.

This additional technical documentation report looks specifically at the network data challenges of objectively assessing asset criticality, one step in the larger adaptation planning framework and a prerequisite for efficient allocation of limited adaptation resources. Specifically, this report explores the modeling resolution (in terms of the completeness of the road network and the spatial disaggregation of origin and destination matrices) needed to produce accurate criticality ratings. Original modeling work using a well-establish criticality measure, the Network Robustness Index (NRI), on both a small hypothetical network and the road network for Chittenden County, Vermont, demonstrated a need for higher resolution networks for criticality modeling. Since this part of the work was published in the *Transportation Research Record* it is only summarized here.[1] A conceptual discussion of methods explored for creating networks for larger real-world areas that are sufficiently complete for criticality assessment is also included based on exploratory work using the travel demand model for the Greater Sacramento California area.

Our work demonstrated that network resolution has a significant impact on link criticality rankings using both hypothetical and small real-world networks. Resolution reductions that removed 40% of the road mileage and only 25% of road capacity in the hypothetical network resulted in nine of the top 10 most critical links being misidentified in the hypothetical network tests. On the real-world network in Chittenden County, resolution reductions that eliminated 68% of road centerline miles and 57% of network capacity to a typical planning agency model resolution resulted in the misidentification of half of the top 10 most critical links and a quarter of the top 200 most critical links. These results provide strong evidence that lower resolution networks such as those typically used for travel demand models by state and regional planning agencies are inadequate for criticality analysis.

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[1] Dowds, J., K. Sentoff, J. L. Sullivan, and L. Aultman-Hall. Impacts of Model Resolution on Transportation Network Criticality Rankings. *Transportation Research Record: Journal of the Transportation Research Board*, Vol. 2653, 2017, pp. 93–100. https://doi.org/10.3141/2653-11.

Efforts to create a complete road network for the larger Sacramento California area were explored in-depth but proved infeasible within the time constraints of this project. More generally, both data availability and computational constraints may make working with complete networks impractical for large real-world networks. To combat these problems, we consider both "building out" a road network from a core demand model network or "simplifying down" from the full network in map databases to levels that reduce data management and computational burden. Unfortunately, both of these approaches themselves require a functional, complete network model (with codes for capacity, speed, allowable turns, etc.). In other words, our research demonstrates that high resolution road networks are needed to assess criticality and that even to evaluate which links must be included in that network requires a complete network with attributes for traffic routing.

Ultimately, therefore, if objective model-based criticality rankings that account for the spatial distribution of demand and network connectivity are to play a role in adaptation planning, transportation agencies may have to dedicate significant resources to this purpose. This project concludes that criticality assessment cannot simply be appended to the majority of existing travel demand models and assumed to produce accurate results. Doing criticality assessment in a cost-effective manner, therefore, will require resources and collaboration across local, regional and state governments to acquire and maintain accurate, high resolution networks that can be used for the development of criticality specific models. Methods to create more appropriate road networks need development and assessment should include cost benefit analysis in order to consider the merits of purchasing network data. In order to justify this investment, we recommend that future research also assess the cost benefit of improvements based on objective versus subjective prioritizations. Although few published academic papers have addressed the implementation of expert-based judgment such as critical link identification by emergency responders, some agencies have conducted case studies using such methods. Careful review and even detailed development of these techniques may be warranted.

Introduction

The Third National Climate Assessment documents significant sea level rise as well as increases in the frequency and intensity of several types of extreme weather events ranging from heat waves and heavy precipitation to strong hurricanes and severe winter storms (*1*). The damage that these types of extreme weather events inflict on the transportation system is putting a significant strain on transportation agencies' resources (*2*) and the National Climate Assessment predicts that extreme weather trends will intensify as the climate continues to warm (*1*). Faced with this reality, transportation agencies are looking for ways to adapt transportation systems to minimize the recovery costs and disruptive impacts of extreme weather events. Resiliency and adaptation measures can include hardening or relocating infrastructure, improving system redundancy, and adjusting maintenance schedules.

Many resiliency and adaptation planning resources, including guidance documents for practitioners (*2*–*4*) and academic articles (*5*, *6*), recognize the essential role that vulnerability and criticality ratings play in the prioritization of climate adaptation efforts. Vulnerability ratings assess the relative likelihood that a specific road segment (or other transportation network component) will suffer damage as a result of particular types of extreme weather or other threats. Criticality ratings measure the relative impact that the loss or impairment of a specific road segment (or other transportation network component) has on the performance of the entire system in terms of serving travel demand or providing access to important community destinations or services. Since adaptation resources are limited, they should be steered toward system components at significant risk of being compromised in a manner that substantially impacts overall system performance. The relationship between vulnerability, criticality and adaptation prioritization is illustrated in Figure 1. The highest adaptation priorities are those links which are both highly critical and highly vulnerable.

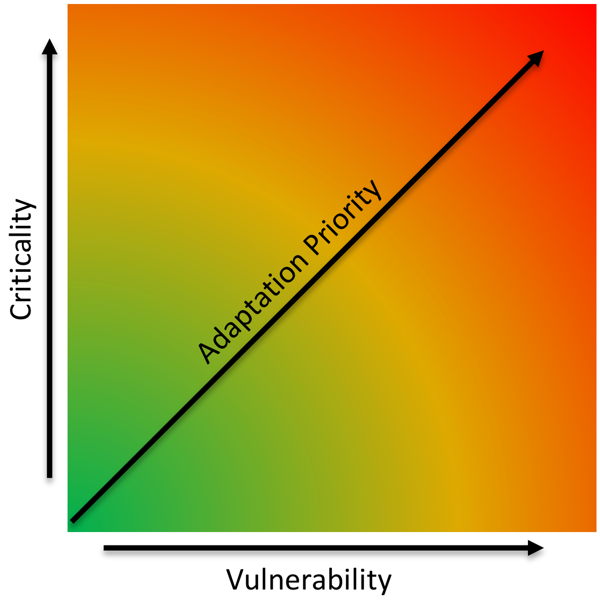

Figure 1. Adaptation prioritization as a function of criticality and vulnerability

A review of adaptation planning literature and interviews with practitioners documented only a moderate level of conceptual understanding of criticality rating as well as poor data and tool availability for developing these types of ratings (*5*). There are also challenges resulting from a lack of consensus on the objective methods to be used for these prioritizations and there is concern for the potential politicization of the rating process (*5*). Modeling the system-wide impacts of disabling (or reducing the capacity of) specific road segments in a transportation system is one approach that has been used to quantify criticality of individual system components (*7*–*10*). These models, like demand forecasting models, typically include only major road links that are often the responsibility of a state agency, not the complete public road network, even though local roads may provide important functional redundancy and alternative routing. Determining the appropriate network resolution for criticality assessment is important, as failure to consider the connectivity provided by both state and local roadways in sufficient detail could result in erroneous prioritizations.

This report summarizes a series of criticality assessment tests conducted using the Network Robustness Index (NRI) (*11*), a criticality rating metric originally developed in 2006 (*7*), and used in several real-world applications. The NRI calculates the total vehicle hours of travel (VHT) with an intact network and then measures the change in VHT caused by capacity reductions to individual links within that network. Our prior work with NRI added a selection of minor roads to the Chittenden County Regional Planning Commission (CCRPC) travel demand model based on expert judgment and clearly indicated that the addition of some of the minor links in the model changed the criticality rankings for at least a subset of minor roads (*12*).

The model assessments undertaken in this NCST project explored the impact of network resolution (that is the proportion of all roads that are included in the model network) and origin-destination (OD) disaggregation or zonal resolution on the NRI criticality rankings. The cases tested included both a small hypothetical network and the network of all public roads in Chittenden County, Vermont. Both the hypothetical and real-world test support the need for highly resolved networks for criticality assessment.

As part of the project, test model runs were conducted for a much larger study area, the region of the Sacramento Area Council of Governments (SACOG), in order to assess the computational feasibility of running criticality-assessment models with an “all-roads” network[2] in a larger urban area. All-road networks are costly to develop and maintain, however, and sufficiently computationally intensive as to be challenging to use at the large metropolitan level and likely infeasible at the state scale for criticality assessments. The reader is directed here to observe the difference between a network file that is sufficient for making a visually accurate map and one that has the connectivity, turning movement allowances, capacities and speed attributes to model traffic flow from origin to destination. Such routable, fully attributed all-road networks are not often within the domain of a public planning agency.

This project investigated two approaches for creating more disaggregate networks that would be sufficient for conducting criticality assessments but that are more cost effective and manageable than all-road networks. One approach systematically eliminates road links from an all-road database by demonstrating that they have no impact on the criticality ratings of the main roads under consideration for prioritization. This simplification only requires traffic attributes for a subset of road links. Based on our Sacramento assessment, this technique still

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[2] Note, we use the term *all-roads network* throughout this report to mean a complete, routable, network that includes all roadways within a given study area coded with allowable turns and with capacity and speed attributes.

results in a larger than ideal network requiring manual attribution for criticality assessment and for repeat model runs. The second approach systematically adds minor roads to an existing, lower-resolution network of major roads until adding additional roads does not impact the criticality ratings of the highest rated links. This approach offers advantages in terms of restricting network size and may be more practical for MPOs and DOTs with limited computational resources and staff time to devote to criticality assessment.

Optimal Network Resolution for Criticality Assessment Based on a Hypothetical Network

A complete description of this portion of the research project is available in a published journal paper and is therefore not repeated here (*11*). The fundamental assessment of the appropriate network resolution and OD aggregation used a hypothetical network, created based on central-place theory by Scott et al. (*7*). The network, which consists of 90 links and 37 nodes and is depicted in Figure 2, was selected after preliminary work in this project with a grid-based hypothetical network that revealed little if any impact of network resolution on criticality rankings. Node placement in Scott's hypothetical network was set in accordance with the central place theory while node populations followed a rank-size distribution, with highest population nodes in the center of the network. Once node placement and population was fixed, an OD matrix was created using a production constrained gravity model. Full details on the non-symmetric network are available in (*7*).

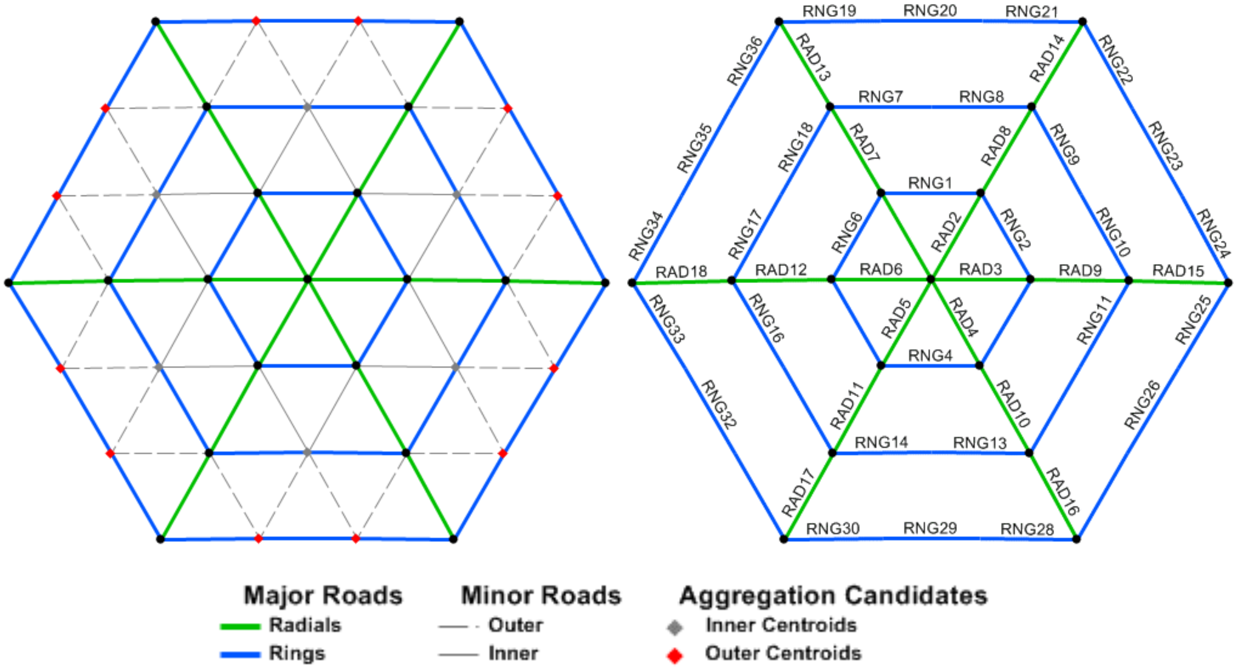

Figure 2. Complete network and B. Major roads network

Use of the hypothetical network allowed for comparison of the criticality rankings produced using the *high-resolution network* that included all road links with the criticality rankings calculated using *lower resolution networks* that included only “major roads.” We were also able to test the impact of aggregating the OD matrix to a smaller subset of the nodes and the combined effect of reducing network resolution while aggregating the OD matrix. Baseline NRI rankings were calculated for the 54 major roads in the hypothetical network using the full, 90-link network, the most disaggregate, 37X37 node OD. These criticality rankings represent the “true” criticality of the 54 major links. A series of five link-exclusion scenarios, four demand-aggregation scenarios, and three combined link-exclusion and demand-aggregation scenarios then provide the basis for comparing NRI rankings produced at lower network resolutions and greater demand aggregation to the baseline measures. The results of these scenarios are summarized below.

Network Resolution Reduction

To test the impact of network resolution on criticality rankings, the NRI was calculated for each major link for five link-exclusion scenarios (designated LE1 – LE5) that reduced the full network by excluding an increasing number of minor links towards a major road only network (like those used by most agencies for modeling). Each link exclusion scenario eliminated between 12 and 36 minor links from the full hypothetical network. Three of the five scenarios removed random subsets of the minor roads and in these cases each scenario was modeled five times, excluding different, randomly selected minor links. In the lowest resolution scenario with only major roads where all minor roads were removed from the hypothetical model, network road miles were limited to 40% of the total and network capacity was 24.5% of total.

As shown in Table 1, reducing the network resolution had a substantial impact on criticality rankings. No more than two of the top 10 most critical links were correctly identified in any of the reduced resolution scenarios. The change in the criticality ranking of the 54 major roads averaged 12 to 25 positions depending on the resolution scenario.

Table 1. Top 10 highest-ranked links by NRI for network resolution reduction scenarios

Rank	Baseline Links	LE1 Links (Initial Rank)	LE2 Links (Initial Rank)	LE3 Links (Initial Rank)	LE4 Links (Initial Rank)	LE5 Links (Initial Rank)
1	RAD6	RNG25 (52)	RAD18 (9)	RAD17 (29)	RAD17 (29)	RAD17 (29)
2	RAD4	RNG27 (38)	RNG31 (37)	RAD18 (9)	RAD18 (9)	RAD18 (9)
3	RAD5	RAD16 (32)	RAD17 (29)	RAD16 (32)	RAD16 (32)	RAD16 (32)
4	RAD3	RAD13 (13)	RNG33 (34)	RAD13 (13)	RAD13 (13)	RAD13 (13)
5	RAD1	RAD18 (9)	RNG32 (28)	RAD15 (50)	RAD15 (50)	RAD15 (50)
6	RAD2	RNG29 (26)	RAD13 (13)	RAD14 (43)	RAD14 (43)	RAD14 (43)
7	RAD10	RAD15 (50)	RAD16 (32)	RNG33 (34)	RNG33 (34)	RNG33 (34)
8	RAD12	RNG26 (36)	RNG29 (26)	RNG28 (31)	RNG25 (52)	RNG28 (31)
9	RAD18	RNG30 (33)	RAD6 (1)	RNG25 (52)	RNG18 (31)	RNG25 (52)
10	RAD11	RAD14 (43)	RNG30 (33)	RNG31 (37)	RNG31 (37)	RNG30 (33)

The Wilcoxon Signed-Rank Test reveals significant differences in NRI rankings at the p = 0.01 level for all scenarios relative to the baseline scenario

Demand Aggregation

To test the impact of origin-destination analysis zone aggregation on criticality rankings, the NRI was calculated for each major link for four OD demand aggregation scenarios (designated DA1 – DA4) that aggregated demand location from all nodes to a smaller subset of network nodes. The baseline, disaggregated OD included 37 nodes while the aggregation scenarios included between 19 and 31 nodes. As with the network scenarios, this most disaggregate case was considered to produce the most accurate results. In the most aggregate scenario, the origins and destinations for a total of 53% of trips were aggregated to adjacent nodes.

As shown in Table 2, increasing OD aggregation also had an impact on criticality rankings, but a less pronounced impact than reducing network resolution. Depending on the scenario, between eight and nine of the top 10 most critical links were correctly identified as being among the top ten links and the top five most critical links were ranked in the top five for all scenarios, though not necessarily in the same order. The change in the criticality ranking of the 54 major roads averaged only 1.2 to 1.8 positions, depending on the demand aggregation scenario.

Table 2. Top 10 highest-ranked links by NRI for demand aggregation scenarios

Rank	Baseline Links	DA1 (Initial Rank)	DA2 (Initial Rank)	DA3 (Initial Rank)	DA4 (Initial Rank)
1	RAD6	RAD6 (1)	RAD6 (1)	RAD6 (1)	RAD6 (1)
2	RAD4	RAD4 (2)	RAD4 (2)	RAD4 (2)	RAD4 (2)
3	RAD5	RAD1 (5)	RAD5 (3)	RAD1 (5)	RAD1 (5)
4	RAD3	RAD3 (4)	RAD3 (4)	RAD3 (4)	RAD3 (4)
5	RAD1	RAD5 (3)	RAD1 (5)	RAD5 (3)	RAD5 (3)
6	RAD2	RAD10 (7)	RAD10 (7)	RAD7 (12)	RAD10 (7)
7	RAD10	RAD12 (8)	RAD12 (8)	RAD10 (7)	RAD12 (8)
8	RAD12	RAD2 (6)	RAD7 (12)	RAD12 (8)	RAD7 (12)
9	RAD18	RAD7 (12)	RAD11 (10)	RAD2 (6)	RAD11 (10)
10	RAD11	RAD9 (22)	RAD2 (6)	RAD9 (22)	RAD2 (6)

The Wilcoxon Signed-Rank Test reveals significant differences in NRI rankings at the p = 0.01 level for all scenarios relative to the baseline scenario

Simultaneous Network Resolution Reduction and Demand Aggregation

To test the simultaneous impact of reducing network resolution and aggregating demand OD zones on criticality rankings, the NRI was calculated for each major link for three combined network reduction and demand aggregation scenarios (designated CRA1 – CRA3). These scenarios excluded an increasing number of minor links from the modeling process while simultaneously aggregating the OD matrix. As shown in Table 3, these scenarios had a less pronounced impact on criticality rankings than reducing network resolution alone, but a more pronounced impact than aggregating while maintaining the full network. This pattern is related to the radial road network layout and may not be generalizable to all networks.

Table 3. Top 10 highest-ranked links by NRI by for combined reduction/aggregation scenarios

Rank	Baseline	CRA1 (Initial Rank)	CRA2 (Initial Rank)	CRA3 (Initial Rank)
1	RAD6	RAD18 (9)	RAD18 (9)	RAD18 (9)
2	RAD4	RNG32 (28)	RAD13 (13)	RAD13 (13)
3	RAD5	RAD13 (13)	RAD14 (43)	RAD14 (43)
4	RAD3	RAD6 (1)	RAD17 (29)	RAD17 (29)
5	RAD1	RNG31 (37)	RAD6 (1)	RAD10 (7)
6	RAD2	RAD17 (29)	RAD4 (2)	RAD6 (1)
7	RAD10	RAD7 (12)	RAD16 (32)	RAD12 (8)
8	RAD12	RAD4 (2)	RAD15 (50)	RAD7 (12)
9	RAD18	RAD10 (7)	RAD3 (4)	RAD4 (2)
10	RAD11	RAD12 (8)	RAD1 (5)	RAD11 (10)

The Wilcoxon Signed-Rank Test reveals significant differences in NRI rankings at the p = 0.01 level for all scenarios relative to the baseline scenario

Criticality Assessment and Network Resolution for a Real-world Road Network

In order to validate the hypothetical network results we were able to replicate the network resolution experiment using the road network in Chittenden County, Vermont. This work was feasible because a graduate student undertook the labor-intensive tasks of constructing a complete, all-roads network for the county. By adding all roads to the major road network used in the travel demand model of the Chittenden County Regional Planning Commission (CCPRC), a complete network with full connectivity and traffic operation parameters was produced. The network size for the alternative networks of the county are summarized in Table 4. This effort was aided by the study area being relatively small (618 square miles with a population of 158,000). A similar effort to add all links to the master highway network used by the Sacramento Area Council of Governments (SACOG) for its SACSIM travel demand model (*13*) proved too labor intensive to be fully completed within the scope of this project. The SACOG area covers 6,560 square miles. Table 4 lists the number of links in the MPO demand models as well as the estimated number of links and nodes from a GIS road database. The large number of roads excluded from the demand model is clearly evident in Figure 3, which shows the roads in SACOG demand model in black and the additional road links that are not included in the model in gray for western El Dorado County.

Table 4. Full Network and Demand Model Network Size

Network	Links	Nodes	Daily Capacity (vehicle-miles)
CCRPC	2,322	2,500	4,577,250
Chittenden County All Roads	7,942	6,385	10,642,000
SACOG	17,285	10,043	NA
SACOG Area All Roads	191,816	158,888	NA

All values exclude centroids and centroid connectors

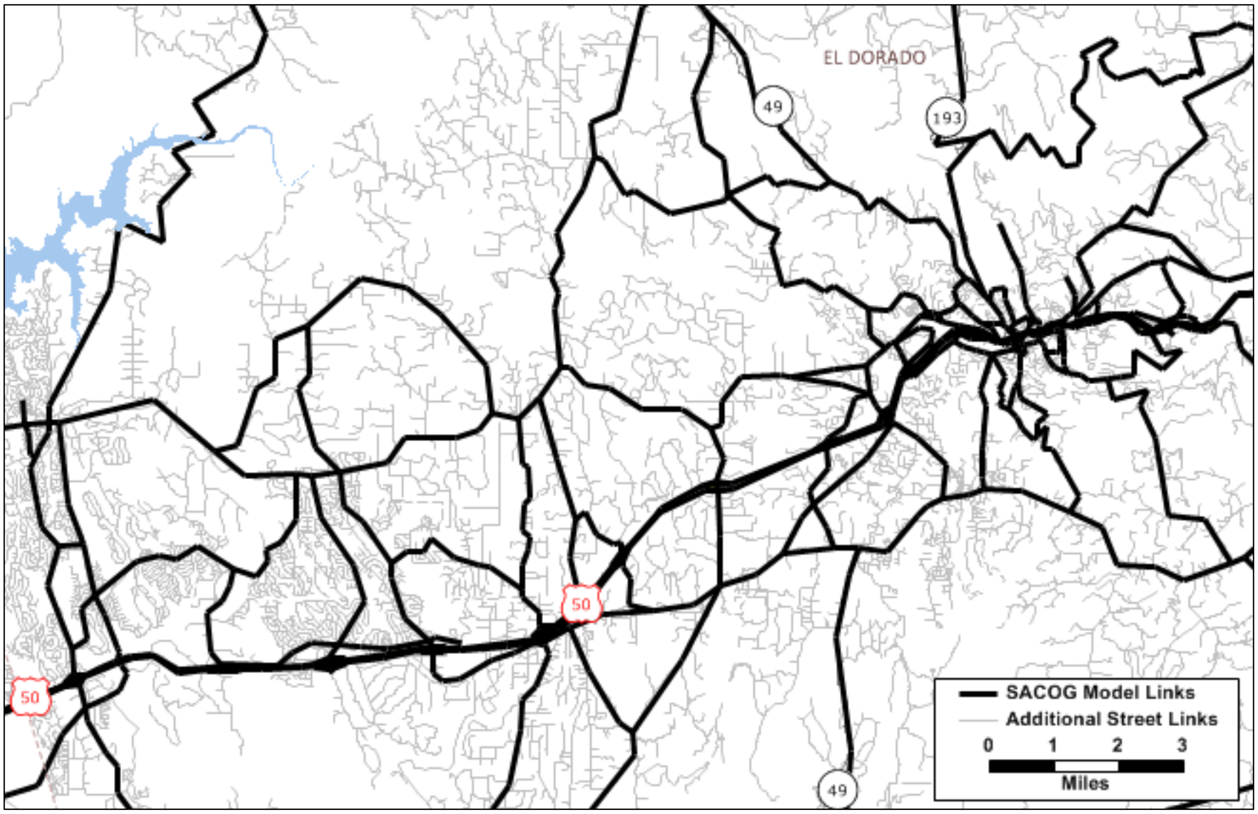

Figure 3. The SACOG demand model network and all-roads network for western El Dorado County.

As with the hypothetical network, the lower resolution CCRPC network of only major roads failed to replicate the true criticality rankings produced with the full network. Table 5 shows the substantial degree of misalignment between travel-model and complete network criticality rankings.

Table 5. Ranking disparities using complete and travel-model networks for Chittenden County

Criticality Rank Category	% of Links within Category Misidentified Using Travel-Model Network	Average Baseline NRI Rank of Misidentified Links
Top 10 Links	50%	720.4 (n=5)
Top 25 Links	40%	971.1 (n=10)
Top 50 Links	30%	971.9 (n=15)
Top 100 Links	26%	755.7 (n=26)
Top 200 Links	27%	1198.7 (n=54)

Moving toward Large Real-World Networks

Both the hypothetical and limited real-world network tests in (*11*) provide strong evidence that the completeness of the road network used for criticality assessment has substantial impacts on criticality modeling outputs. Therefore, the most accurate criticality assessment and prioritization results would be produced using a complete transportation network that includes all roadways regardless of size, ownership or location. Ideally, all passenger modes would also be included as different modes may provide redundancy for one another.

Several factors make creation of all-road, all-mode model networks impractical, however. First, the cost and effort of acquiring, conducting quality control and data maintenance on a complete network can be considerable. Second, in cases where OD demand is not available at the parcel level (as is the case for most jurisdictions), road segments that are part of an isolated sub-network (that is connected to the larger network by only a single link) frequently increase computational burden and computing time without improving accuracy of major road criticality ratings. Finally, given typically available computing resources, conducting criticality assessments on all-road networks is likely to be time-consuming or even impossible at large metropolitan and state levels. These contradicting constraints point to the need to determine a “criticality assessment sufficient” network resolution that is capable of producing accurate criticality ratings for major roads with lower time and computational burden than the all-road network. Such a network would include all of the main roads but only those minor roads that provide meaningful redundancy for demand and routing for those main roads. A technique is needed to determine which road links to add without having all road links added. Methods to create such a network were pursued within this project using the SACOG travel demand model.

In order to be useable for criticality ratings, a network must be routable, must have speed and capacity data for all road segments, and accurate turning restriction data for all intersections (overpasses and underpasses for example must be coded). Capacity may be estimated based on road functional class when the number of road lanes is known. Many network files are available free of cost from federal and open source entities or can be purchased from for-profit companies such as ESRI, Caliper and others. For example, the U.S. Census Bureau creates the TIGER/Line Shapefiles, a publicly available GIS product that includes a road network that covers the fifty states, the District of Columbia, Puerto Rico, and the Island areas. The TIGER/Line network includes all roads downloadable in county-based files. Each road segment is coded with a MAF/TIGER Feature Class Code that identifies the segment as one of 15 road or path features (e.g. as a primary, secondary road, city street, or pedestrian walkway). Speed, capacity and number of lanes are not included in this dataset, however. OpenStreetMap is another freely available source of road network data that is maintained by the OpenStreetMap Foundation, a nonprofit dedicated to promoting the distribution of free geospatial data. OpenStreetMap data is generated by a community of users and includes a wide range of street characteristics including roadway classification, speed limit and lane data. Data completeness varies considerably from region to region and street to street, however, and these variables are not available for many roadways. Commercially available road networks are likely to offer greater data completeness but regardless of sources, some data errors are to be anticipated. Caliper, for example, provides travel time and speed data for “major roads” only.[3]

Comprehensive review of street databases, especially at the regional or state level is likely to be too highly labor intensive to be practical for public sector agencies. In addition, using all-roads networks in large areas is also computationally intensive and would not be feasible with the computing resources that are readily available to most planning agencies. Two approaches to developing networks that are sufficiently detailed for criticality assessment, but small enough to be practically manageable, are discussed here. The first approach is to simplify a complete network by eliminating roads that can be identified as having no impact on criticality ratings. The second approach is to build out a core road network by systematically adding minor roads until the addition of new road segments no longer impacts the criticality rankings of the core roads.

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[3] *Geographic and Demographic Data Included with TransCAD* available at http://www.caliper.com/tcdata.htm.

Simplification of an All-Roads Network

One method to reduce both the burden of reviewing network data accuracy and computational intensity without losing criticality ranking accuracy is to eliminate isolated sub-networks that do not provide access to centroids. These segments are not on the path between centroids and do not provide functional route redundancy. For example, in the Sacramento region, Oak Ave, San Juanita Ave, Central Ave, and Main Ave in Orangevale, CA, form the boundaries of a traffic analysis zone (TAZ). In the SACOG travel demand model, trips originating or terminating within this TAZ are connected with “dummy” connectors to the road network at the intersection of Oak Ave and San Juanita Ave and the intersection of Main Ave and Central Ave. In Figure 3, the SACOG travel model for this TAZ, consisting of centroid connectors (in black) and main road roads (in red) is overlaid on an all-road network from ESRI (gray, blue and yellow). Road segments within the TAZ that only connect to the larger road network via a single road segment (shown in blue in Figure 4) are referred to as isolated sub-networks (*14*). Because they do not provide access to another part of the road network, these road segments will never be used in a traffic assignment, and their inclusion or exclusion from the model will not affect overall system performance in a disruption-based criticality assessment of major roads using a model such as the NRI. Note that while the horseshoe defined by Wiltshire Way and Rotherfield Way (yellow links) would not be on the shortest path between centroids, it does provide redundancy for the parallel segment of Main Ave. From a criticality perspective, this means that these road segments impact the criticality of this segment of Main Ave (it would have a lower criticality rating than the segment of Main Ave between Elm and Wiltshire which lacks a comparably close alternative route), though the impact may be marginal.

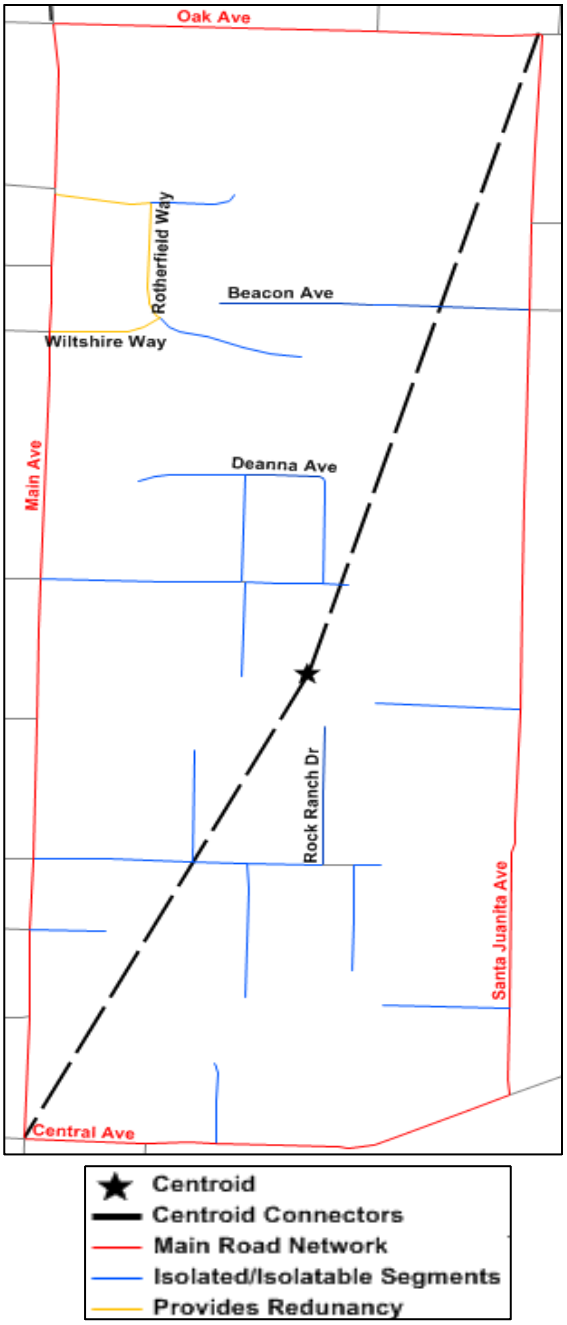

Figure 4. Network resolution considerations

Assuming the network file data are fully connected with the correct topology (link directionality and node turn restrictions), isolating links can be identified and eliminated programmatically, without manual review. Simple isolating links such as Beacon Ave that do not provide access to a centroid can be identified automatically and removed in many GIS software packages by creating a program that counts the number of links connected to each node. Any non-centroid node that is only connected to a single link can then be deleted along with the link that attaches to it. More complicated isolating links, such as the loop that includes Deanna Ave and connects to the larger road network via Elm Ave, can be identified using minimum path algorithms while sequentially removing road segments. Segments that create multiple, disconnected territories (i.e. where one subset of nodes cannot reach the remainder of the nodes in the network) can be used to identify and then delete isolating links and the isolated sub-networks they provide access to, provided that the sub-network does not contain any centroids. Eliminating the isolating links off of San Juanita Ave in 4, for example, would reduce the number of road segments comprising Central Ave from five to three. In aggregate, eliminating road segments that are known to have no impact on criticality rankings can greatly reduce network size thus reducing the ultimate model computing times as well as the effort required to add speed, capacity and turning information to the network database. The number of road links in the SACOG area can be reduced by approximately 50% by eliminating isolating links.

Depending on the size of the network, however, identifying and eliminating isolated sub-networks may present a computational challenge in and of itself. In addition, the remaining network may still be too large for meaningful manual review or addition of speed, capacity and allowable turn behavior. For these reasons, we deem the reduction of a full network as insufficient to create manageable networks over large areas.

Building out Travel Model Networks

A second approach to creating a manageably sized network that produces accurate criticality rankings is to start with a core demand model network of major roads and then add in additional minor roads until the addition of minor roads no longer impacts the ranking of the most critical roads in the core network. A comprehensive and systematic approach to road link additions is needed to have confidence that the appropriate roads have been added. A systematic link addition method could be undertaken programmatically.

The first step to building out a core network to include an optimal set of minor road segments would be to run the criticality assessment on the core demand model network. Once these baseline criticality rankings are established and an “actionable” criticality ranking threshold is selected, e.g. the most critical 1% of road links, an iterative road addition process could be implemented. This process would begin with the single most critical road segment, and use a user-equilibrium traffic assignment to identify the most desirable alternative to the critical road segment. The alternative route would then be included in the network and the criticality assessment repeated with all roads in the core network being assessed. Once again, the user-equilibrium algorithm would be used to identify the alternative paths to the most critical link (regardless of whether or not this link is the same link as in the previous iteration or a new link). In the event that this process does not produce a viable alternative to the road segments already included in the network (that is if the detour distance is sufficiently great for a particular level of demand that the next minimum travel time path exceeds the travel time for existing roads as determined by user-equilibrium travel times) then the procedure for determining alternative routes for inclusion would be repeated for the second most critical link in the road network. By iterating this process until the addition of alternative links did not impact the criticality rankings for the major road network segments above the criticality threshold, a sufficiently resolved network could be achieved.

SACOG was an ideal test area in that it includes areas of both grid road networks, especially in the flatter Central Valley, and non-grid roads in suburban, rural and hillier areas to the east of the city. Our preliminary run of the NRI tool using the SACOG travel demand model (with only major roads) are shown in Figure 5 with the most critical links colored red. These results indicate differences in criticality patterns in grid versus non-grid areas. In the more western part of the region, critical links are associated with the most heavily traveled freeway corridors including the highway accessing the airport. The bridge over the River in Yuba City is also among the top ranked links. However, in the eastern portion of the region, while river crossings are also critical, the ability to understand redundant routes becomes too complex to understand visually. Note that these results were generated with an aggregate demand model network and given the discussion in this report cannot yet be considered accurate. The proportion of the total road network that will be required for criticality assessment may depend on the pattern of roads in the network. Grid networks, which have relatively high redundancy, may not be as significantly impacted by reduced network resolution as non-grid network areas that have lower redundancy.

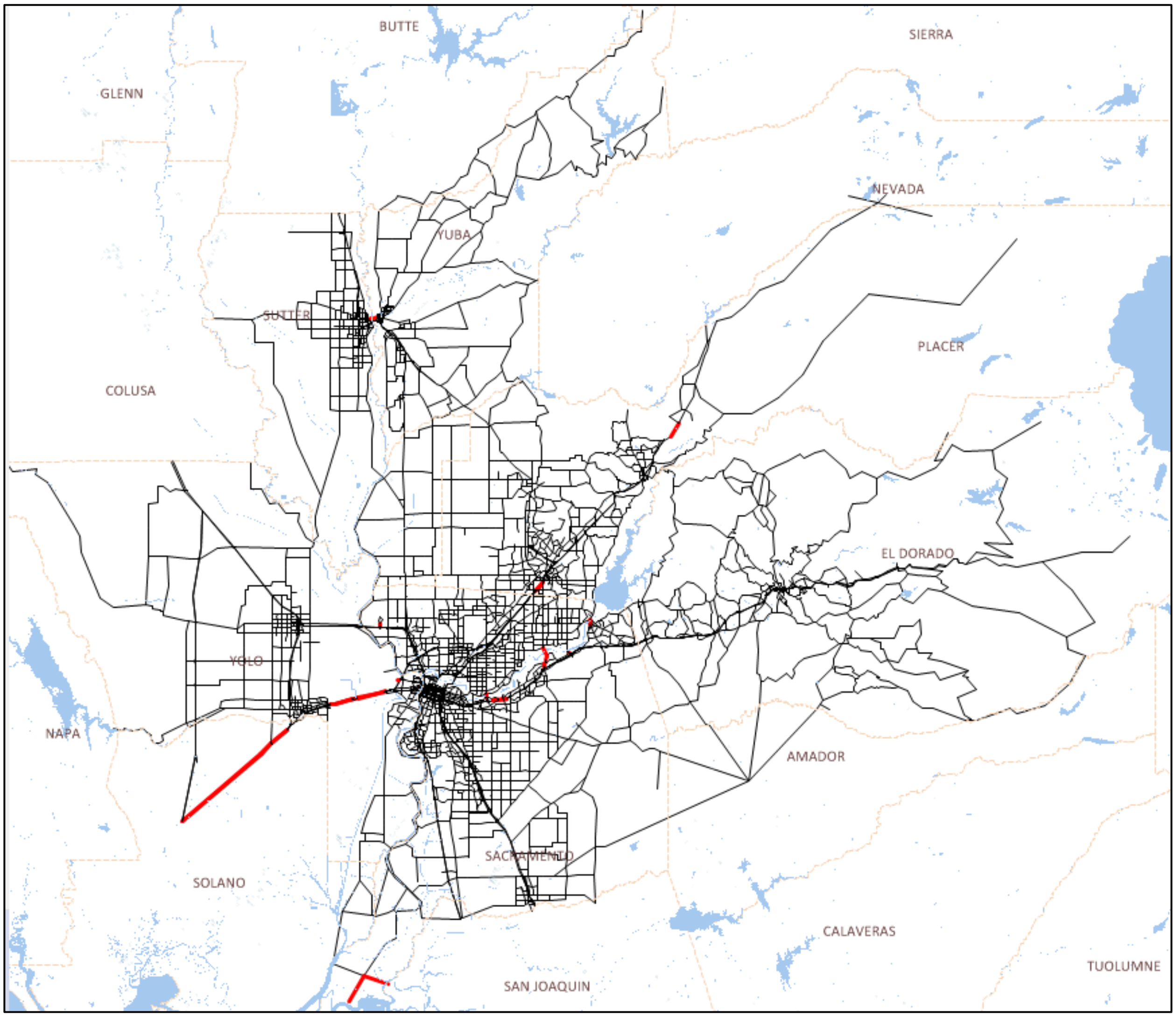

Figure 5. NRI-based most critical link - SACOG (n=36)

Conclusions

Network resolution has been demonstrated to have a significant impact on criticality rankings using both hypothetical and small real-world networks. Network resolution reductions that removed 40% of the road mileage and only 25% of road capacity in the hypothetical network resulted in nine of the top 10 most critical links being misidentified in the hypothetical network tests. OD aggregation also impacted criticality rankings, though the impact was less pronounced. On the real-world network in Chittenden County, network resolution reductions that eliminated 68% of road centerline miles and 57% of network capacity resulted in the misidentification of half of the top 10 most critical links and a quarter of the top 200 most critical links. Most travel demand models today use a very limited percentage of the full road network (approximately 29% in Chittenden County and 9% in Greater Sacramento). These results provide strong evidence that lower resolution networks such as those typically used for travel demand models are inadequate for criticality analysis. We postulate that because this is true for the NRI that it is also true for any of the several methods that use link disruption or link elimination to measure criticality.

Running criticality assessments on complete, all-roads networks, while theoretically desirable, presents significant practical challenges. The first challenge is simply one of data availability; freely available road networks suffer from significant data quality and completeness issues. Commercially available data sources may offer better data quality and completeness but come at a financial cost to agencies and may still require considerable quality control and maintenance. The second challenge is that complete, all-roads networks are computationally intensive to work with and are likely to exceed the readily available computing capacity of many transportation agencies. The challenges described here would be exacerbated when conducting criticality analysis for multi-modal networks since these are yet larger in size. Nonetheless, different modes can provide redundancy for one another, and there have been numerous calls to consider all passenger modes in criticality assessment (*5*, *11*). This would place even greater cost on network creation as multimodal travel demand networks are not typical. Moreover, additional links would no doubt add complexity to finding an optimal network resolution that balances accuracy of criticality rankings with manageability in data needs.

The two approaches outlined here and explored using the SACOG network can in theory create suitable compromise networks but both require a full, all-roads network to implement. Ultimately, therefore, if objective criticality rankings that account for the spatial distribution of demand and network connectivity are to play a role in the criticality assessment of adaptation planning, transportation agencies will have to dedicate significant resources to this purpose. This project concludes that criticality assessment cannot simply be appended to the majority of existing travel demand models and assumed to produce accurate results. Doing criticality assessments in a cost-effective manner, therefore, will require resources and collaboration across local, regional and state governments to acquire and maintain accurate, high resolution networks that can be used for the development of criticality specific models.

In order to move forward with objective model-based criticality assessments this research project has resulted in the following recommendations:

- Methods to create routable road networks at appropriate levels of resolution for criticality must be developed for public agency use.
- Assessment including cost benefit analysis and accuracy must be conducted in order to consider level of network resolution and the merits of purchasing full network data;
- Comparison of the accuracy of objective model-based rankings to more subjective expert-based prioritizations is merited. Although few published academic papers have addressed the implementation of expert-based judgment such as critical link identification by emergency responders, some agencies have conducted case studies using such methods. Careful review and even detailed development of these techniques may be warranted. The agreement between objective models and subjective expert prioritizations should be assessed.

Based on prior related research on these methods, the next steps of criticality model development for real world study areas should also include the following methodological developments:

- Incorporation of measures of link-specific vulnerability to extreme weather/other threats;
- Implementation of heuristic procedures to allow for efficient assessment of multi-link disruption scenarios including cross-link correlation of disruption likelihood;
- Improvement of the OD matrices used as model input from the typical daily demand used in existing models to emergency and disruption scenarios that account for disadvantaged communities, freight and supply logistics, and alternative spatial demand that represents evacuation patterns, not daily commuting.

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