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Ranking Highway Transportation Asset Criticality through Stakeholder Input Using the Analytical Hierarchy Process (AHP)

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Abstract

The transportation system is especially vulnerable to natural and human-made disasters which can have effects on mobility, safety, and the economy. This thesis presents a method to rank transportation assets based on their criticality to the transportation system by uniquely gathering stakeholder input on criticality criteria weights. This serves as a typical first step in vulnerability and resilience assessments. Six criteria were used to estimate asset criticality: Annual Average Daily Traffic (AADT), roadway classification, freight output, tourism output, Social Vulnerability Index (SoVI), and redundancy. Then, the criteria are combined via stakeholder input using a weighted ranking scheme called the Analytical Hierarchy Process (AHP). The AHP produces an average ranking based on the priorities of varied experts (i.e., Analysts, Engineers, Planners, etc.) using a pairwise rating system implemented as an online survey. 30 complete surveys were collected (13.2% response rate) via a national survey conducted in July 2022. While individual rankings vary, the AHP allowed for an average weight to be determined for each criterion and applied to average all criteria into a single metric. Overall, the criteria ranked in the following order (highest to lowest priority): AADT, redundancy, freight output, roadway classification, SoVI, and tourism. Criteria weights derived from AHP are then used to estimate a weighted average criticality for each asset, and finally, all assets can be ranked by their estimated criticality. The stability of the criteria ranking was confirmed after using 15 samples, indicating the minimum number of participants required for robust and reliable results in this AHP study. Using this approach, a statewide vulnerability and/or resiliency assessment can consider multiple, unique stakeholders' perspectives within a single, consistent criticality metric.

Acknowledgment

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Chapter 1. Introduction

Research on the resiliency, connectivity, criticality, vulnerability, and disruption of transportation networks has notably increased over the past few years (García-Palomares et al., 2018; Sullivan et al., 2010), partly as a result of an increased frequency of significant natural and human-made disasters. Notable examples include a series of rockslides on I-40 from Columbia, SC to Knoxville, TN between 2009-2010 resulting in the closure of this critical route for up to several months with an estimated clean-up cost of $2-10 million; Hurricane Katrina in New Orleans in 2008 costing approximately $170 billion in economic damages; Superstorm Sandy in the Northeastern US in 2012 causing nearly $70 billion in damages. Mobility, safety, and the economy are all impacted by these long and short-term disruptions to the transportation system. The transportation system is however one of the most essential US infrastructure sectors since it is critical to the operation of many other key infrastructure segments like emergency services, food and agriculture, healthcare and public health, and manufacturing.

Resiliency, as defined by the National Academy of Sciences, is "*the ability to prepare and plan for, absorb, recover from, and more successfully adapt to adverse events*." Transportation network resilience can be defined as the capability of networks to continue operating during disruptions and recover to a normal state from such disruptions (Pant, 2012). The initial stage in resiliency assessment is determining asset criticality. The likelihood of components of a network (links or nodes) malfunctioning and the effects of that malfunction on the system are both factors in determining the criticality of a given component. The severity of the system's damage when a component is lost increases with the component's criticality (Jenelius et al., 2006). Criticality, therefore, is the measure of an infrastructure asset's importance to the system's resilience, defined by the cost to users, owners, and society resulting from a loss in functionality (Board et al., 2021; Flannery, 2017). Designing reliable and resilient systems requires the identification of critical components of transportation systems (Almotahari & Yazici, 2019). The analysis of the performance of the transportation network under possible disruptions heavily relies on the identification of critical links, which also assist practitioners and policy makers in mitigating and preparing for the disruptions' impacts as well as prioritizing projects such as bridge retrofits, culvert upgrades, and other roadway improvements that enhance system resiliency (Almotahari & Yazici, 2020). This makes this topic an area of interest to federal, state, local, and private transportation authorities.

Numerous studies have explored and implemented different multi-criteria criticality assessment methods. For example, the Connecticut DOT resiliency pilot study quantified criticality in terms of hydraulic, spatial, and social categories that included metrics such as ADT, accident count, flood zone, and flood plain location, as well as subjective stakeholder input for a context-sensitive understanding of the system's criticality. Based on the combined values of each factor, structures were assigned criticality rankings of low, moderate, or critical (United States. Federal Highway Administration, 2016). Similarly, the Colorado DOT I-70 resiliency study estimated criticality using quantitative metrics and ranked assets by six criticality metrics including AADT, Roadway Classification, Freight, Tourism, SoVI and Redundancy using an equal weighting approach (Flannery, 2017). The equal-weighted approach assumes that each criterion is of equal consideration in assessing the criticality of a link and receives the same weight in the analysis. However, this approach may not always reflect the true importance of each criterion in the context of criticality assessment or when different stakeholders collaborate to rank assets by criticality. An unequal weighting approach, on the other hand, assigns different weights to each criterion in computing the criticality of a link. Therefore, it is a more appropriate method in situations where a criterion is considered more indicative, important, and/or representative of a link's criticality to the overall system.

For the criticality assessment proposed in this thesis, a multi-criteria criticality estimation using the unequal weighting approach was adopted. Specifically, we reference the six criticality assessment metrics outlined in the CDOT I-70 resiliency study (Flannery, 2017) to estimate the criticality of statewide highway transportation systems. This study expands the CDOT approach by introducing an Analytical Hierarchy Process (AHP) to estimate a combined criticality metric based on a weighted average of the six criteria with weights informed by stakeholders. It is important to note that although the six-criticality metrics proposed by CDOT are adopted, the AHP method exemplified in this study can be applied to any set of criteria, thus a flexible approach that can be tuned to varied contexts is presented.

AHP is a multi-criteria decision-making approach in which factors (criterion) are arranged in a hierarchical (ranked) structure. AHP has grown in popularity and usage because of its ability to reflect the way people think and make judgments by simplifying a complex decision into a series of pairwise comparisons (Smith & Tighe, 1974).

To facilitate the usage of the AHP in this study, a survey was designed and administered to 227 technical experts (e.g., transportation officials, planners, engineers, etc.) who were asked to compare the relative importance of each criterion. Thus, the aim of this study is (1) to develop a data-driven and repeatable framework for measuring the criticality of statewide transportation system assets based on a set of criticality criteria and stakeholder input and (2) for the set of six criteria explored in this study, to determine the unequal weights and ranking of each criticality assessment metric using the AHP.

The thesis consists of six sections: following the introduction, a literature review on various transportation criticality metrics is presented. Next, the methodological approach, that is the Analytical Hierarchy Process (AHP) is explained in the third section. The fourth section explains the results of the AHP model. A summary of key findings is then discussed in the fifth section. Finally, the conclusion is then presented along with future research directions.

Chapter 2. Literature Review

2.1 Criticality Metrics

Measures of reliability, vulnerability, robustness, resilience, importance, and criticality have been proposed to assess the impact of a transportation asset on system performance (Almotahari & Yazici, 2020). In particular, criticality has seen increasing popularity in research and practice (Almotahari & Yazici, 2020, 2019; Flannery, 2017; Gauthier et al., 2018; ICF International, 2014; Jafino, 2021; Jenelius et al., 2006; Kumar et al., 2019; F. Li et al., 2020; J. Li & Ozbay, 2012; Madar-Vani et al., 2022; Nagurney & Qiang, 2007; Scott et al., 2006; Sullivan et al., 2010; Ukkusuri & Yushimito, 2009; Wang et al., 2016). The more critical the asset, the more severe the impact on the system when that asset is non-operational (Jenelius et al., 2006). Several metrics have been proposed to identify and measure transportation asset criticality. These measures have also been used in networks across sectors, such as telecommunication, biological systems, social networks, and energy.

Criticality metrics are classified into two categories: topological or performance based. Topological methods consider graph theory-based characteristics like connectivity, accessibility, transitivity, maximal flow, etc. which require less data and are computationally more efficient than performance-based measures. Performance-based approach investigates variations in traffic flow (travel time, volume) caused by changes in supply and demand. However, for large networks, this approach can be computationally expensive due to the iterative nature of the calculations (Almotahari & Yazici, 2019).

Examples of topological measures include Betweenness-Centrality (BC), the Link Criticality Index (LCI), the Travel-Time Weighted Betweenness-Centrality (TTWBC), Practice-Friendly Link Criticality Index (PFLCI), and the Efficiency Index (EI). BC is a criticality metric originally created for social network analysis but equally applicable to transportation networks. BC takes into account the number of shortest paths going through a node or link (Almotahari & Yazici, 2019). A weighted version of the BC is known as the TTWBC. Travel times are used as weights for the roadway links when calculating TTWBC (Almotahari & Yazici, 2019). The LCI was introduced as a criticality measure that utilizes the iterations in the Frank–Wolfe solution of the user equilibrium (UE) problem to provide link criticality ranking within a single traffic assignment (Almotahari & Yazici, 2020). It also incorporates network redundancy and connectivity. The PFLCI however, reduces computing requirements present with TTWBC and LCI while considering expert knowledge as input data in a manner consistent with the LCI (Almotahari & Yazici, 2020). Another common approach to evaluate link criticality which is used to assess the performance of a transportation network capturing flows, costs and travel behavior information along with network topology is the EI (Nagurney & Qiang, 2007). EI can be used to establish the importance and ranking of either links, nodes, or both and has been used to evaluate the performance of key infrastructure networks such as electric power generation and distribution networks, supply chain networks, and many more applications in different domains (Nagurney & Qiang, 2007). The key difference between these measures is that TTWBC and LCI require a single traffic assignment for criticality rankings whereas, EI requires multiple traffic assignment to provide criticality rankings (Almotahari & Yazici, 2019).

A common performance-based method for determining link criticality is to run a network scan. This can be done using the Network Robustness Index (NRI), a traffic assignment-based approach that calculates criticality based on changes in the total travel time of the network before and after link failures (Sullivan et al., 2010). In this methodology, all links are removed one at a time from the network, traffic assignment is carried out without the particular link being removed, and a network performance indicator (e.g., total system travel time) is calculated. This comprehensive scan determines the links whose failure has the greatest impact on network performance. However, there is a risk of creating disconnected networks during the omission of the links in the network scan making it impossible to estimate the system-wide impact of that link on travel time. To further address the issues of disconnectivity from NRI, the Important Score (IS) was established (Jenelius et al., 2006). IS is based on two case-specific conditions: one for the case when removing a link does not cause disconnectivity and another one when a link failure causes disconnectivity and unsatisfied demand. The key difference between the above-mentioned measures is that NRI cannot evaluate the impacts when a link failure causes disconnectivity, whereas IS can derive criticality rankings based on failure with and without disconnectivity (Almotahari & Yazici, 2019; Jenelius et al., 2006).

While topological and performance-based metrics capture the impact of disruptions on travelers, broader impacts on the economy and/or vulnerable populations are not considered within the above-mentioned metrics. Further, ranking methods using only vehicle-based performance metrics such as Annual Average Daily Traffic (AADT) and volume-to-capacity ratios can be insufficient to capture the broader impacts of network disruptions (Kumar et al., 2019). Thus, multi-criteria metrics are introduced. Multi-criteria metrics are measures that determine link criticality or rankings in a road network based on multiple important factors (Kumar et al., 2019).

Examples of multi-criteria metrics are diverse. One application used three factors, each consisting of sub-criteria (Wang et al., 2016). The first factor uses the link volume based on flow characteristics. The second factor uses the spatial location of the important facilities served by the links. The third factor uses the number of origin-destination pairs served by a link based on network characteristics. This measure was used for prioritization of links and resources for, traffic surveillance cameras installation, location of security personnel and equipment, retrofitting, and maintenance activities (Kumar et al., 2019). Another study considered nine factors to develop a multi-criteria metric for measuring resiliency (J. Li & Ozbay, 2012): road capacity, road density, alternate route proximity, intermodality (availability of other modes), average delay, average speed reduction, transportation cost (user cost), commercial-industrial transportation cost, and network management. This measure helps facilitate decision-making by providing outputs for economic analysis and comparison of alternative investment options to improve the resiliency of the network (Serulle et al., 2011). Another flexible and robust multi-criteria approach consisted of sixteen critical metrics such as food medicine, mobility, goods and material access, fuel and energy access, and emergency response (Freckleton et al., 2012).

As a starting point for this study, the recently implemented multi-criteria analysis developed by the Colorado DOT (CDOT) is adopted. This approach applies a criterion that represents a broad spectrum of system impacts due to a disruptive event (Flannery, 2017). To estimate link criticality, six criteria were defined: Annual Average Daily Traffic (AADT), Roadway Classification, Freight, Tourism, Social Vulnerability Index (SoVI), and Redundancy (**Table 2-1**) (Flannery, 2017). These criteria reflect three pillars of system resilience: environmental, social, and economic impacts and capture impacts across multiple modes (vehicle and truck), sectors of the economy (freight, tourism), and sectors of the population (vulnerable populations) (Flannery, 2017). Since the redundancy metric in the CDOT study was appropriate for corridor-level analysis, a new redundancy metric was developed for this study to suit state-wide analysis. The redundancy metric used is an example of a performance-based metric described above, specifically a modified Network Robustness Index (NRI) (Hernandez & Mitra, 2020).

Table 2-1 Criticality Measures Defined by CDOT Study.

Criteria	Definition	Resolution
Annual Average Daily Traffic (AADT)	Daily traffic volume for each roadway link.	Link
Roadway Classification	Functional class of roadway link: Interstate, Freeways & Expressways, Principal Arterials, Minor Arterials, and Major Collectors.	Link
Freight	Freight value in Millions of US dollars by county for the year.	County
Tourism	Tourism value as expressed as Total County Expenditures in Millions of US dollars by county.	County
Social Vulnerability Index (SoVI)	SoVI measures the social vulnerability of US counties to environmental hazards. It is an indicator comprised of 29 socioeconomic variables that contribute to a county's ability to prepare for, respond to, and recover from hazards.	County
Redundancy	The amount of additional travel time added to the network when a link is non-operational.	Link

AADT is a basic measurement that indicates vehicle traffic load on a road segment. It is the mean traffic volume across all days for a year for a given location along a roadway. It requires volume for every day of the year. It measures how busy a road is and is a critical input parameter in many transportation planning applications as well as for fund allocation to transportation agencies (United States. Federal Highway Administration. Office of Highway Policy Information, 2018). Roadway classification defines the role that a particular roadway segment plays in serving this flow of traffic through the network. Each function class is based on the type of service the road provides to the motoring public with a range of allowable lane widths, shoulder widths, curve radii, etc. (Hernandez & Mitra, 2020). Freight value is expressed as the total value of imports and exports by county estimated by the national freight travel demand model called the Freight Analysis Framework Version 4 (FAF4). FAF4 gathers freight value data from the Commodity Flow Survey. Tourism represents the total expenditure for tourism in the county for that year. SoVI is a computed, comparative index comprised of 29 socio-demographic variables among eight categories and represents a region's level of social vulnerability (Cutter et al., 2003). The eight categories grouped in the model include wealth, race (black) and social status, age, ethnicity and lack of health insurance, special needs populations, service sector employment, race (Native American), and gender (female). SoVI scores greater than 1.5 standard deviations above the mean (positive) are considered the most socially vulnerable, while counties with scores below 1.5 standard deviations of the mean (negative) are the least vulnerable. The redundancy metric captures the increase in overall system-wide travel time as a result of a complete link closure. Links that increase system-wide travel time when closed are more critical than links that cause only a minimal change in system-wide travel time when closed. This is considered a measure of redundancy since a link with many alternate routes of similar distance and travel time would cause minimal impact on the overall system travel time. However, a link with few to no alternate routes or alternate routes that are much longer would have a higher impact on the overall system travel time.

The multiple criteria for the CDOT approach are combined via equal weighting, e.g., unweighted average. In some contexts, certain criteria may be more important. Thus, an unequal weighting approach can be introduced. The AHP approach presented in this study is a commonly used method for estimating weights for choice alternatives.

2.2 Analytical Hierarchy Process

AHP is one of the more powerful and commonly used types of multiple-criteria decision analysis (MCDA) in which conflicting and complex factors are placed in a hierarchical (ranked) structure (R. W. Saaty, 1987). In the context of this study, it is used as an unequal weighting approach to computing the criticality of a link by applying different weights to each criterion such that the weights reflect the priorities of the decision-makers and stakeholders. The different weights also indicate how much more relevant each criterion is in comparison to the others (Zahedi, 1986). Through pairwise comparisons, the AHP generates a reciprocal decision matrix by allowing the evaluator to focus on the comparison of only two criteria at a time. As compared to weighting by ranking (ranking the criteria directly by relative importance), which loses explanatory power as the number of criteria increases, the AHP method provides a consistent and effective approach for prioritizing and ranking criteria. The final output of AHP is a prioritized ranking that shows the relative importance of each alternative.

The AHP has been used in social sciences, environmental sciences, computer science, physics and astronomy, psychology, medicine and dentistry, and engineering, amongst many others. For illustrative purposes, several example applications are discussed in this section. The AHP was employed as a decision-support model in a study for contractor selection (Balubaid & Alamoudi, 2015). In this study, the AHP model was utilized to discover the best contractor capable of delivering satisfactory results in a selection process that is not solely based on the lowest bid. AHP has been used to identify and prioritize a hierarchy of risk factors for the prevention of falls, which is a prevalent cause of injury-related morbidity and mortality in older people (Pecchia et al., 2011). Through the solicitation of judgments from knowledgeable and seasoned healthcare professionals, a hierarchy of risk factors was established with AHP to gain a deeper understanding of experts' assessments of risk factors for falls which can be very helpful in enhancing intervention programs. In this study, the AHP was effective in quantifying qualitative knowledge by measuring intangible dimensions particularly in attempting to understand complex processes and highlight the differences in expert opinions on the relative importance of risk factors for falls. In a comparative study, the AHP was used for the selection of an appropriate intersection design among five design alternatives, including a roundabout, signalization without left turn bay, signalization with left turn bay, and a grade-separated alternative (Ocalir-Akunal, 2016). Eight traffic engineers ranked the five types based on five design criteria: traffic safety, construction cost, average delay, CO emissions, and fuel consumption. In (Abba et al., 2013), AHP was also used to analyze the environmental impacts of solid waste disposal and identify the best ways to manage the problem. The suitable option for waste disposal was further determined in this study through the assessment of the opinions and judgments of stakeholders which included residents and institutional workers. The AHP model provided a framework that easily integrated modeling and usability; it followed the intuitive way stakeholders think and act in a decision-making process.

Chapter 3. Methodology

The main objective of this study is to develop criteria weights for transportation asset criticality metrics based on unequal weights using AHP. While the weights estimated in this study are based on a national sample of experts, they can reasonably be transferred to other studies. The flexibility of the approach is that weights derived from AHP can be tuned based on any particular audience, e.g., state or context specific to demonstrate the use of AHP to estimate criteria weights for transportation asset criticality metrics and to evaluate those criteria weights through a national survey. To apply an AHP model, the following steps were followed:

1. Define the hierarchical structure consisting of the goal and criteria,
2. Collect the input data by pairwise comparisons of criteria through an online survey,
3. Calculate consistency ratios from the individuals' set of judgments and individual priorities for each set of pairwise comparisons, and
4. Compute the overall criteria weights by aggregation of individual priorities (AIP).

3.1 Hierarchical Framework and Definitions

In designing the AHP model, the key steps are to define the decision problem and construct the hierarchy which illustrates the relationship between the overall goal and criteria. The final hierarchy developed for this work defines the goal as "measuring the criticality of highway system assets" and each of the measurements, e.g., AADT, roadway classification, etc., as the criteria (**Figure 3-1**).

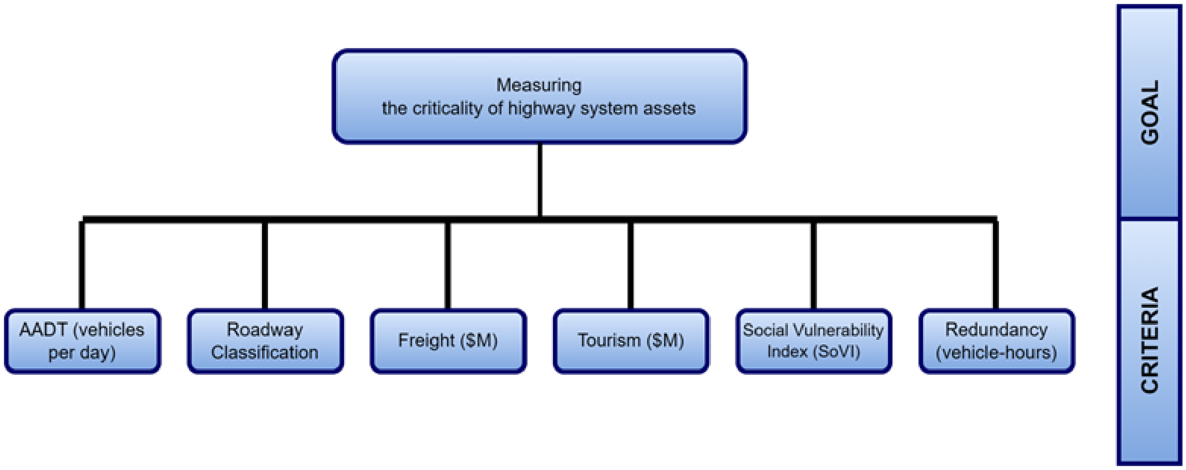


Figure 3-1 Analytic Hierarchy of the Decision.

3.2 Input Data Collection via Online Survey

For this study, an online survey was implemented using Qualtrics, a commercial online survey platform to capture the wide range and a substantial number of expert judgments from diverse stakeholder groups. The survey was shared with respondents from private and public sector transportation agencies and companies. An online survey method was preferred in this study over other traditional methods like study, telephone, and mail surveys. The online survey provides a simple and user-friendly visual interface to complete the pairwise comparisons and reduce overall costs related to completing the AHP analysis by providing real-time and continuous accessibility of the results (Barone et al., 2014).

3.3 Survey Sample Frame

Two factors determine the sample size for the survey: consistency of judgments and their validity in practice (T. L. Saaty & Özdemir, 2014). The number of experts (sample size) varies by application: eight traffic engineers participated in a study to select an intersection design type (Balubaid & Alamoudi, 2015); 48 experts from academic institutions, city agencies, and mobility service providers completed the weighting process of different criteria and indicators for social sustainability assessment of mobility services (Gompf et al., 2021); 191 healthcare professionals responded to an investigation of risk factors for preventing falls (Pecchia et al., 2011). To evaluate the criticality of highway transportation assets based on the different criteria, there needs to be a broad representation of experts to provide accurate and consistent results. With the need for diverse backgrounds and knowledge specifically in the field of transportation, the views of these experts provide an accurate and valid reflection of the selected criteria and their relative importance (Wong & Li, 2008). The broad representation is also intended to eliminate bias in the computation of respondent judgments (Ishizaka & Labib, 2011).

Convenience (non-probability) sampling was used to gather participants. A total of 227 experts in the US were invited via email solicitation to complete the online survey. The sample was gathered from professional organization listservs, committee membership rosters, LinkedIn, and public agency directories. The sample was categorized into three demographics based on profession, practice area, and agency. The respondent's profession is the specific role that the respondent plays in his or her agency, institution, or organization (i.e., analysts, engineers, planners, consultants, inspectors, managers, office specialists, operators, project coordinators supervisors, specialists, surveyors, researchers, and technicians). The practice area identifies the respondent's area of expertise or division within the agency, institution, or organization (i.e., asset management, construction, emergency and response, maintenance, operations, planning, engineering, system information and research, policy, and survey). Finally, the respondent's agency refers to the institution or organization in which the respondent is employed (i.e., state, and federal Departments of Transportation (DOTs), state, local, and regional governmental transportation agencies, private engineering consulting firms, and academic institutions).

3.4 Survey Questionnaire

The questions in the survey asked participants to compare the relative importance of the six criteria with respect to the overall goal and report their judgments as pairwise comparisons. Pairwise comparisons are reported using a numerical scale called the Fundamental Scale for Paired Comparisons (R. W. Saaty, 1987) (**Table 3-1**). The level of relative importance of 1, 3, 5, 7, and 9 indicate equal, moderate, strong, very strong, and extreme levels, respectively. The intermediate values of 2, 4, 6, and 8 are found between two adjacent scales. With six criteria to compare, the respondent must make 15 comparisons (15 questions).

Table 3-1 Fundamental Scale for Paired Comparisons.

Scale	Judgment of Preference	Description
1	Equally important	Two factors contribute equally to the objective
3	Moderately important	Experience and judgment slightly favor one over the other
5	Strongly important	Experience and judgment strongly favor one over the other
7	Very strongly important	Experience and judgment very strongly favor one over the other, as demonstrated in practice
9	Extremely important	The evidence favoring one over the other is of the highest possible validity
2,4,6,8	Intermediate preferences between adjacent scales	When compromise is needed

The questions are presented in Qualtrics using a sliding bar scale with the criteria labeled on the rightmost and leftmost edges of the bar and the values of the scale presented in between, centered at zero (**Figure 3-2**). Survey instructions provide definitions for each criterion and a simple example application with pairwise comparisons of oranges, grapes, and mangoes.

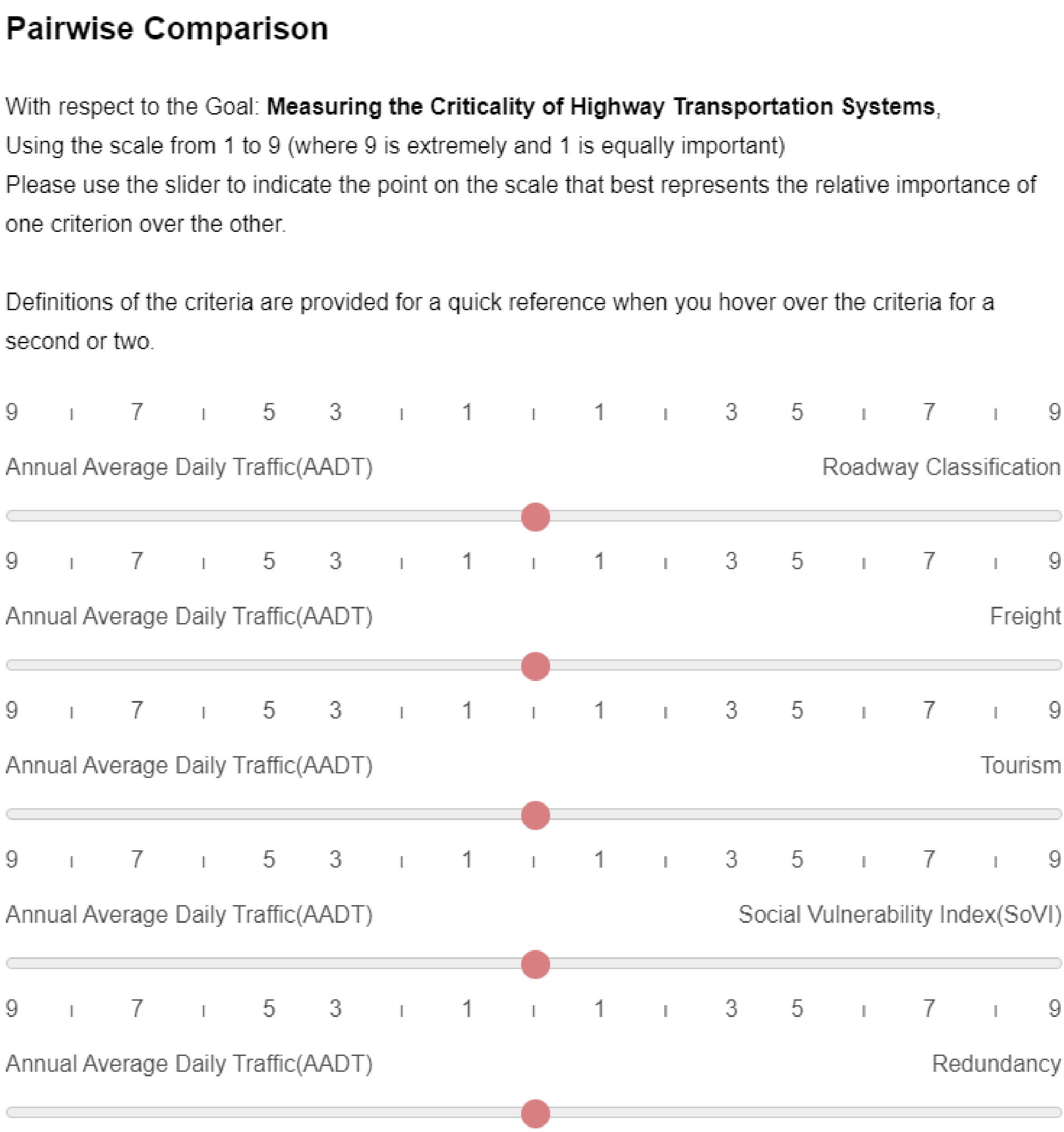


Figure 3-2 Survey Questionnaire in Qualtrics Platform.

3.4 Consistency Ratio Calculations

Due to the nature of the comparisons being pairwise, it is possible that respondents report inconsistent rankings of criteria. This is a common occurrence in decision-making, especially when the criteria under consideration are diverse (Banai, 2006). For example, they may report that AADT is more important than tourism, tourism is more important than freight value, but that freight value is more important than AADT (AADT should be more important than freight value in this example). Thus, the consistency ratio is used to estimate the consistencies of each individual set of judgments to rule out inconsistent logic.

The Consistency Ratio (CR) is the ratio between the Consistency Index (CI) of the decision data and the Random Index (RI). CI is calculated as follows:

$$CI = \frac{\lambda_{max} - n}{n-1} \quad \textbf{(3.1)}$$

Where:

λ_{max} is the largest principal eigenvalue of a positive reciprocal pairwise comparison matrix of size n (number of criteria).

CR is calculated as follows (Wedley, 1993):

$$CR = \frac{CI}{RI} \quad \textbf{(3.2)}$$

Where:

RI is the average CI for randomly generated matrices of the same order (Donegan & Dodd, 1991; Zahedi, 1986).

A CR of less than 0.10 is optimal, while a CR of less than 0.20 is acceptable (Wedley, 1993). Thus, we retain responses (sets of judgments) with CR below 0.20. The resulting reciprocal matrices from the individual pairwise comparisons obtained from the survey and the resulting individual priorities were computed using the AHPy library available in Python (Griffith, 2021).

3.5 Criteria Weights

When a decision-making process involves a group of people, there are several possible ways to aggregate the judgments. These include: (1) synthesizing each of the individual's hierarchies and aggregating the resulting priorities, referred to as Aggregating Individual Priorities (AIP); (2) aggregating the individual judgments for each set of pairwise comparisons into an “aggregate hierarchy”, referred to as Aggregating Individual Judgments (AIJ) and (3) aggregating the individual’s derived priorities in each node in the hierarchy. Although AHP can handle the third method, it is less relevant and is not commonly used. Thus, the AIP and AIJ methods are used in this study. AIP is used when individuals are acting in their own right, with different value systems, and the concern is about the resulting alternative priorities (Forman, 1998). The AIP approach enables us to analyze how each respondent evaluated each of the criteria, illuminating varied ranks, expertise, and priorities across respondents. Finally, the overall criteria weights can be computed via the AIP approach. Following the AIP approach, an individual respondent prioritizing a criterion highly over the other criterion has a substantial effect on the final and overall different weights after the aggregation. AIP is calculated to obtain the final priority vector either with the arithmetic mean, **a** = [a_j], or geometric mean, **g** = [g_j] as follows (Carmo et al., 2013):

$$a_j = \frac{\sum_{i=1}^{n}(w_{ij})}{m} \qquad \textbf{(3.3)}$$

$$g_j = \frac{\prod_{i=1}^{n}(w_{ij})}{m} \qquad \textbf{(3.4)}$$

Where:

a_j is the arithmetic mean of the *j-th* criterion

g_j is the geometric mean of the *j-th* criterion

$w_{i,j}$ is the normalized vector of individual priorities of the *i-th* expert and *j-th* criterion

n is the number of expert individuals

m is the number of criteria

The second method to aggregate the individual responses, called AIJ, is by synthesizing the resulting reciprocal matrix from the individual pairwise comparisons using the geometric mean to form a single judgment matrix. AIJ is used when individuals share common goals and value systems usually within the same group and pool their judgments in such a way that the group becomes a new 'individual' behaving like one (Forman, 1998). This approach highlights the different rankings and priorities of each stakeholder group. In this case, the AIJ generates distinct criterion rankings and weights for each stakeholder and practice area group. AIJ using the geometric mean is calculated as follows (Aragón, 2017; T. Saaty, 1980):

$$w_i = \frac{p_i}{\sum_{i=1}^{N}(p_i)} \tag{3.5}$$

Where:

w_i is a set of normalized eigenvector components

p_i is a set of eigenvector components

3.6 Sensitivity Analysis

A sensitivity analysis is also conducted to determine the extent to which changes in the input data affect the final outcome of the AHP Model (Maletič et al., 2014; Sahin et al., 2013)

Sensitivity analysis is an important technique used in the Analytical Hierarchy Process (AHP) to assess the stability of the ranking or prioritization of criteria and alternatives. In the context of this study, it involves examining the sensitivity of the criteria weights to variations in individual criteria and increases in sample size. Moreover, by increasing the sample size, the study intends to determine the minimum number of participants required for a robust and stable outcome in this AHP study.

The sensitivity analysis for this study is conducted in two approaches. Firstly, each criterion under consideration in this study is removed, and the AHP is used to recalculate the weights. Subsequently, the new weights, excluding the removed criterion, are compared to the original weights and rankings. Secondly, the sample sizes are randomly selected and increased from 3 to 18 with the corresponding updated weights and rankings computed accordingly.

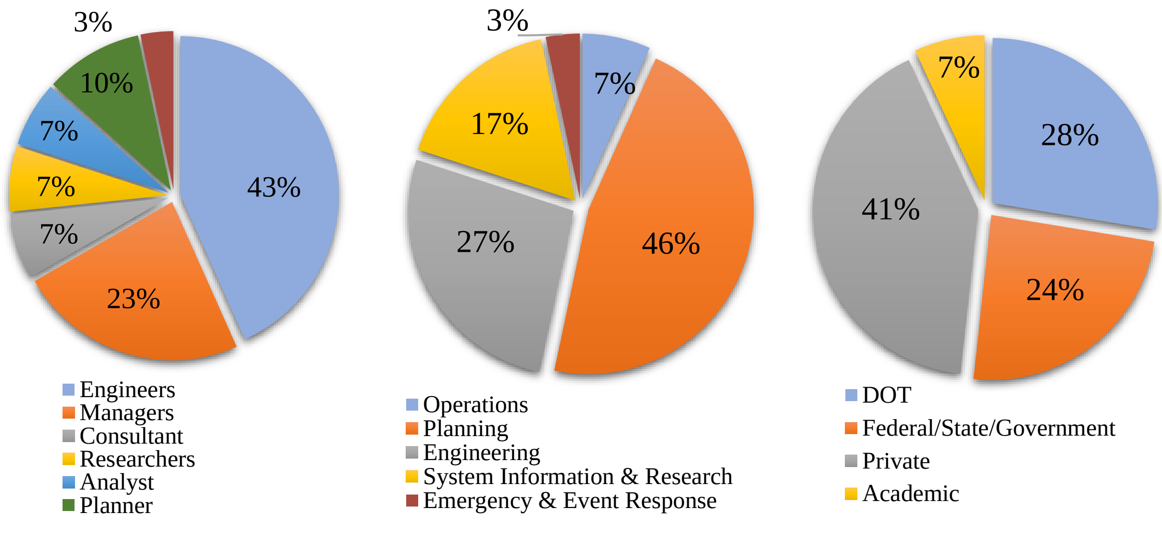
By examining the change in the criteria weights when each criterion is removed from the model, the sensitivity of the weights to changes in individual criteria is assessed. If the weights change significantly when a particular criterion is removed, it may indicate that this criterion is particularly influential in the decision-making process and that careful consideration should be given to its inclusion or exclusion from the model (Keshavarz-Ghorabaee et al., 2021).

Chapter 4. Results

4.1 Response Rates by Sector

The survey was administered between July and November 2022. A total of 30 responses were received from 227 distributed surveys, representing a 13.2% response rate. In addition to the 15 pairwise comparisons, three additional demographic questions were included to indicate the respondents': profession (engineers, planners, consultants, managers, analysts, surveyors, researchers, and technicians), practice area (asset management, construction, emergency and response, maintenance, operations, planning, engineering, system information and research, policy, and survey), agency (state and federal DOTs, state, local, and regional governmental transportation agencies, private engineering consulting firms, and academic institutions. On average, respondents completed the survey in 13 minutes (standard deviation of 8.7 minutes).

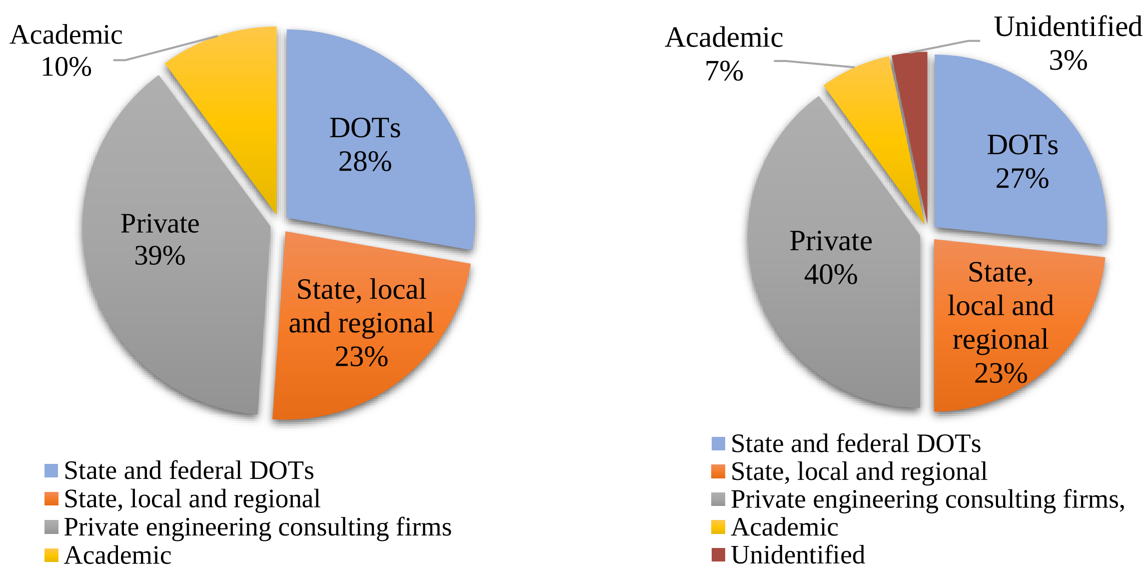
Distributions of respondents by profession (**Figure 4-1a**), practice area (**Figure 4-1b**), and agency (**Figure 4-1c**) show that Engineers (43%), experts from the planning practice area (46%), and from the private industry (41%) made up the majority of respondents, respectively. Response rates by profession and practice area are not available due to the way the sample frame was constructed, e.g., profession and practice area were not known from the contact lists used.



(a) Profession (b) Practice Area (c) Agency

Figure 4-1 Survey Respondents by Profession, Practice Area, and Agency (N = 30).

Most respondents contacted were from private industry (40%) (**Figure 4-1b**). Response rates by organization were 8.7% for academic organizations, 13.6% for private engineering consulting firms, 13.2% for state, local, and regional transportation agencies, and 12.7% for DOTs.



(a) Survey sample frame (N = 30). (b) Survey responses (N = 21).

Figure 4-2 Survey Sample Frame and Respondents by Agency.

4.2 Consistency Ratios of Responses

Twenty-one of the thirty responses passed the consistency ratio test (CR < 0.20) to be included in the overall computation of criteria weights. The average CR of the remaining responses was 0.33 with a standard deviation of 0.068.

Respondents self-reporting a profession as ‘managers’ were the least consistent with an average CR of 0.131, while respondents identifying as ‘planners’ were the most consistent with an average CR of 0.024. Respondents self-reporting as ‘engineers’, ‘analysts’, and ‘consultants’ had average ratios of 0.128, 0.112, and 0.089, respectively. Those reporting as ‘researchers’ had an average CR of 0.062.

Respondents self-reporting a practice area of ‘operations’ were the least consistent with an average ratio of 0.2, while those in the practice area of ‘emergency and event response’ were the most consistent with an average CR of 0.064. Those in the 'planning’ and ‘engineering’ practice areas had average CRs of 0.121 and 0.107, respectively. Those reporting in the practice area of ‘system information and research’ had an average CR of 0.09. Differences can be attributed in part to sample size by practice area.

Comparing across the self-reported agency, respondents from ‘state and federal DOTs’ reported the most inconsistent responses with an average CR of 0.145 while respondents from ‘private engineering consulting firms’ reporting the most consistent responses with an average CR of 0.103.

The consistency ratios were also compared to the survey response time of the respondents in making their judgment in the AHP process. Out of the 21 respondents who achieved an acceptable consistency ratio of less than 0.2, 14 were able to complete the pairwise comparisons within 20 minutes or less, while the remaining 7 required more than 20 minutes to complete the survey. 5 out of the 9 respondents who exhibited inconsistent judgments completed the survey in less than 20 minutes, whereas the remaining 4 required more time to complete the survey. Thus, there is no apparent linkage between CR and response time such that response time can be used in place of or alongside CR when judging the consistency of responses.

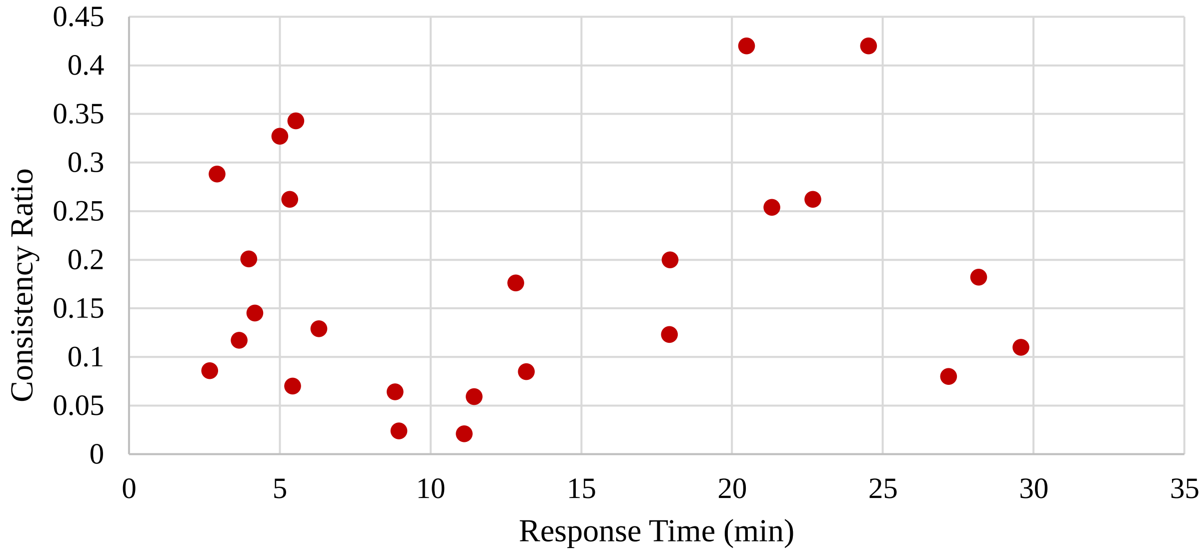


Figure 4-3 Consistency Ratios vs Response Time of Responses.

4.3 Overall Criteria Weights

From the 21 responses that met the consistency ratio test, priority weights for each criterion were determined using the AIP. The higher the weight of the criteria, the greater its relative importance (**Figure 4-3**). AADT received the largest weight (0.244) followed by redundancy (0.231), freight value (0.198), roadway classification (0.13), SoVI (0.114), and tourism (0.082). AADT and redundancy have a combined weight of 0.475, approximately half of the overall weight and slightly more than the other four criteria combined. This indicates the relative indifference of these metrics.

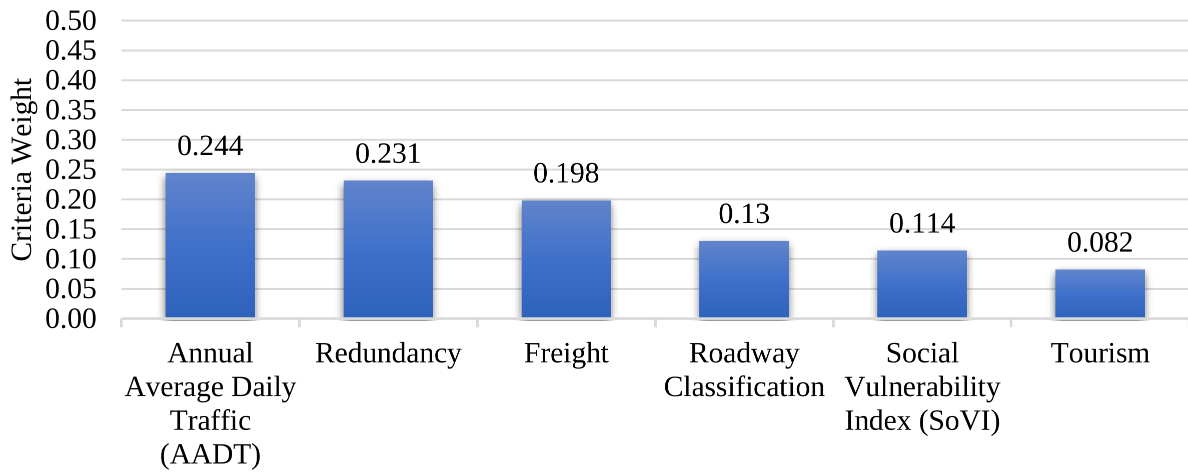


Figure 4-4 Criteria and Weights Derived from the Analytical Hierarchy Process (AHP) Method for All Respondents Meeting the Consistency Ratio Threshold (N=21).

4.4 Criteria Weights by Stakeholder Group

Subsequently, the study analyzes the stakeholder-specific rankings obtained through the AIJ aggregation method. (**Figure 4-4 and Figure 4-5**). These are summarized as follows:

- <u>AADT</u> ranked first by state and federal DOTs, private engineering consulting firms, and state, local, and regional governmental transportation agencies groups while placing fifth in the academic group. AADT ranked first by the respondents from engineering, second by planning and system information and research (SIR) groups, third by operations, and fifth by emergency and event response (EER).
- <u>Redundancy</u> was ranked second by state and federal DOTs, private engineering consulting firms and state, local, and regional governmental transportation agencies groups while placing third in the academic group. Redundancy ranked first by the planning with operations and engineering groups ranking it second. It was ranked third and fourth by EER and SIR, respectively.
- <u>Freight</u> had a varied ranking, ranking second by the academic group, third amongst state and federal DOTs and private engineering consulting firms while ranking fourth by state,

local, and regional governmental transportation agencies group. Experts in the SIR sector ranked freight first, second by EER, third by both planning and engineering and fourth by the operations practice area.

- Roadway classification ranked third by the state, local, and regional governmental transportation agencies group while it ranked fourth by the other stakeholder groups. Roadway classification was the highest-ranked criterion by respondents working in the field of operations with a value of 0.387. It, however, ranked third by SIR, fourth by planning and EER, and finally fifth by engineering.
- SoVI ranked first by respondents from academia with a very high criteria weight of 0.475, placing fourth, fifth, and sixth by the state and federal DOTs, private engineering consulting firms, and state, local and regional governmental transportation agencies respondents, respectively. SoVI ranked first by the respondent from EER with a very high criteria weight of 0.496. It, however, fell to fourth place ranking by the engineering field and fifth across the remaining practice areas.
- Tourism ranked sixth across the state and federal DOTs and private engineering consulting firms' groups in consistency with the overall ranking but was ranked fourth and fifth by the experts from the academia and state, local, and regional governmental transportation agencies, respectively. Tourism was unanimously ranked sixth by all the practice area groups with a value less than 0.1, which is consistent with the overall criteria ranking.

Rankings by both state and federal DOTs and private engineering consulting firm groups were consistent with the overall criteria ranking using the AIP approach with minimal different weights. (e.g., 0.198 vs 0.196 vs 0.183 for the weight assigned to freight). However, the priority weights of roadway classification and SoVI were the same, with a value of 0.089 for the stakeholders from private agencies.

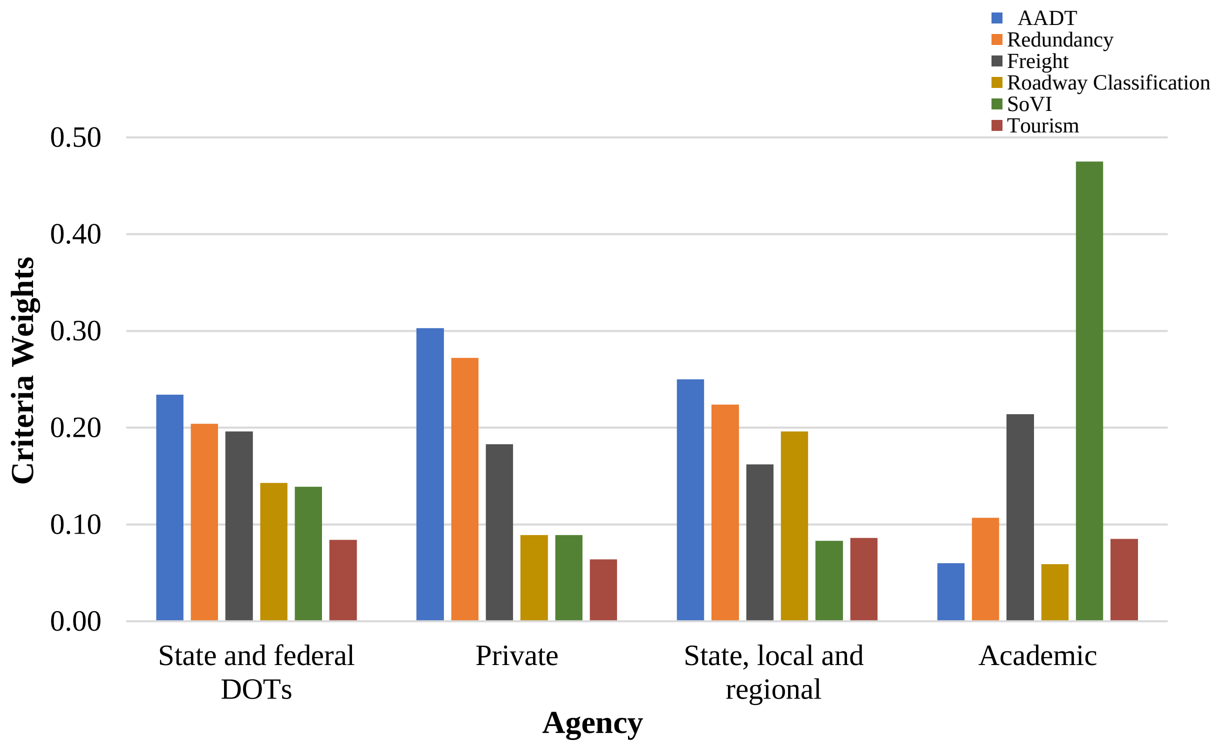


Figure 4-5 Criteria Ranking and Weights by Agency of Respondents.

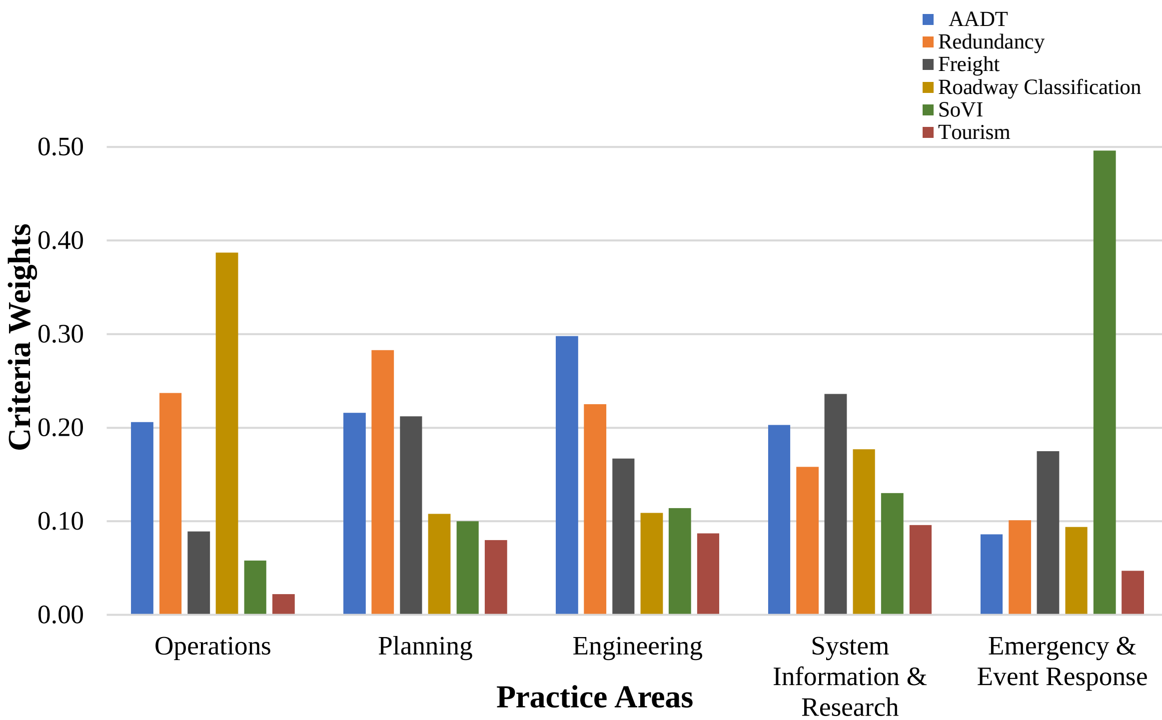
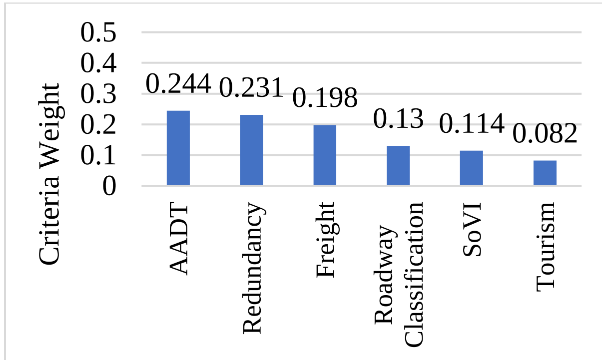


Figure 4-6 Criteria Ranking and Weights of Practice Area of Respondents.

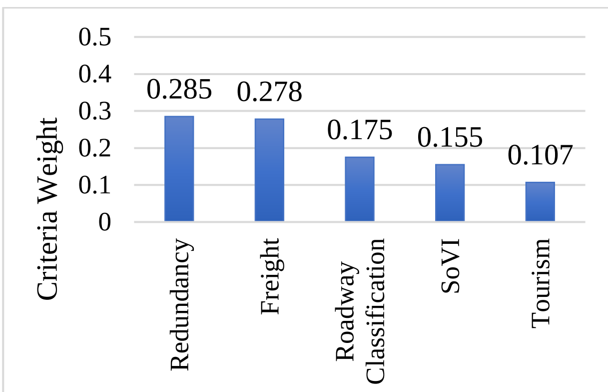
4.5 Sensitivity Analysis of Criteria

In this study, each criterion is removed one at a time and the criteria weights are recalculated to evaluate their impact on the overall results. Thus, the impact of removing each criterion is examined individually to evaluate its individual contribution to the overall ranking of the criteria.

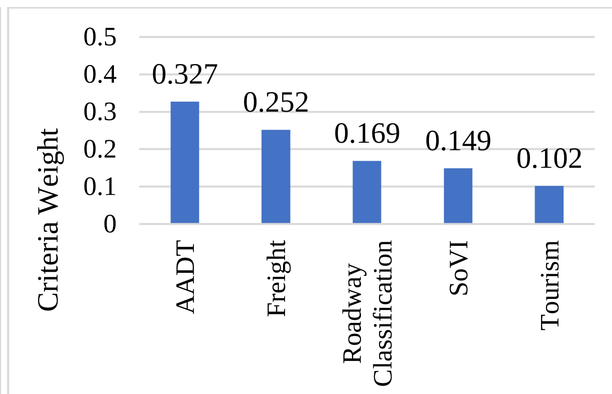
Based on the observations from **Figure 4-6**, it can be noted that the revised criteria ranking is consistent with the original (**Figure 4-6a)**, except for the removal of the criteria in **Figures 4-6b, 4-6c, 4-6e, 4-6f, 4-6g.** However, there was a minor change in the weights and ranking shown in **Figure 4-6d** due to the exclusion of Freight, with Redundancy ranked first with a weight of 0.298. AADT followed closely in second, with a weight of 0.293. The remaining criteria showed consistency with the initial findings. The exclusion of various criteria led to a significant increase in the weights of the remaining criteria with the decreasing number of criteria. However, it is important to note that the extent of this increase varies depending on the specific criteria being removed.



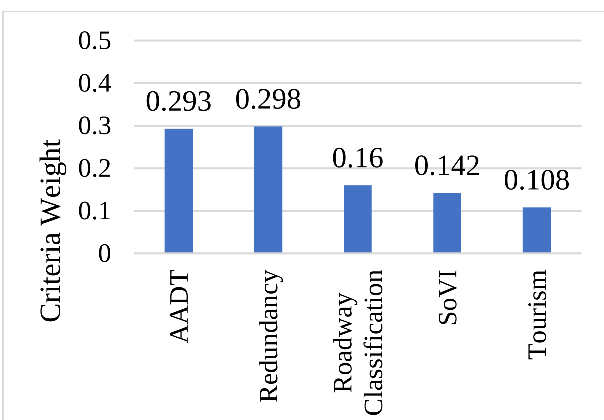
(a) Original Criteria Rankings and Weights



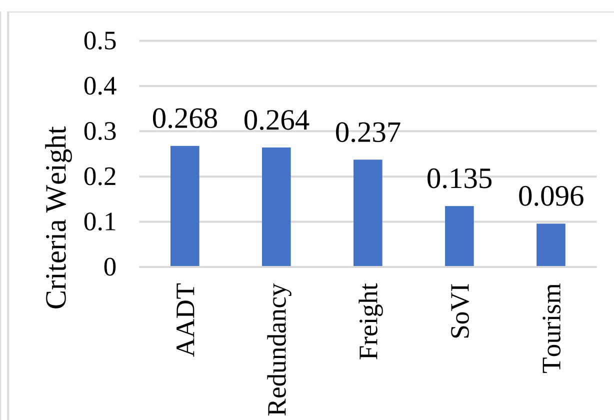
(b) Exclusion of AADT



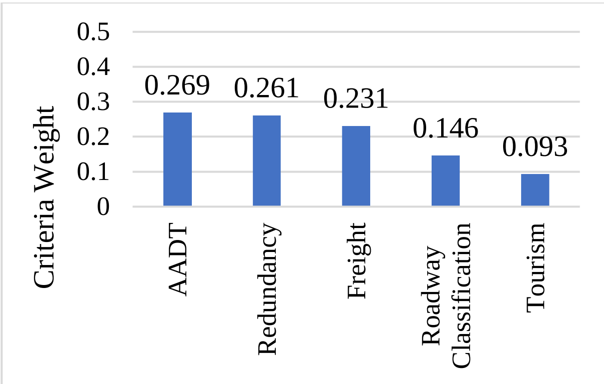
(c) Exclusion of Redundancy



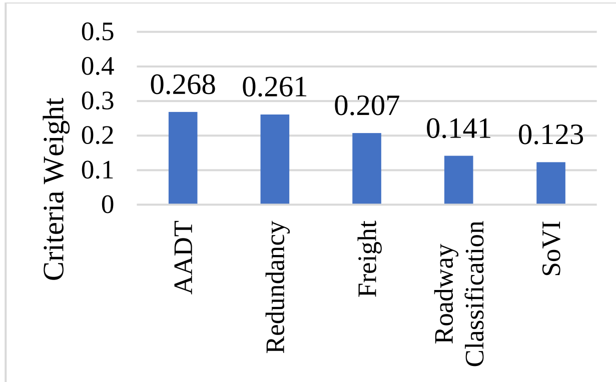
(d) Exclusion of Freight



(e) Exclusion of Roadway Classification



(f) Exclusion of SoVI



(g) Exclusion of Tourism

Figure 4-7 Criteria and Weights with Inclusion of All Criteria and Exclusion of Individual Criterion.

The rankings of the criteria were also assessed under varying sample sizes, which were increased from 3 to 21 through random selection. The rankings of the criteria varied as the sample size increased from 3 to 12, but they remained consistent with the original rankings after using 15 samples in the final computation **(Table 4-1)**. The most frequent ranking of each criterion is also presented in the last row of **Table 4-1.**

Table 4-1 Criteria Rankings under Varying Sample Sizes.

Sample Size	Rankings					
	AADT	Redundancy	Freight	Roadway Classification	SoVI	Tourism
3	3	1	2	4	6	5
6	2	1	3	4	5	6
9	3	2	1	6	4	5
12	1	3	2	5	4	6
15*	1	2	3	4	5	6
18	1	2	3	4	5	6
21	1	2	3	4	5	6
Mode	**1**	**2**	**3**	**4**	**5**	**6**

* Stability in ranking achieved at 15 responses.

4.6 Application

The following is an example of how the weights can be applied to estimate the criticality of a link in a transportation network. Each criticality metric is divided into levels that can be adjusted to the application context (**Table 4-1**). The values shown in **Table 4-1**, for example, are relative to the statewide ranges (Arkansas) of each criterion. Each criterion is given a numerical level (center columns in **Table 4-1**). The numerical levels can then be combined or averaged to estimate a link's overall criticality. Each criterion is weighted based on the weights obtained from the AHP method using the geometric mean. In this example, the criteria weights utilized are derived from the responses of participants from Arkansas.

Table 4-2 Criteria Levels and Weights Derived from the Analytical Hierarchy Process (AHP) Method Applied to the State of Arkansas.

Criteria	Criticality Score					
	1 Very Low Impact	**2 Low Impact**	**3 Moderate Impact**	**4 High Impact**	**5 Very High Impact**	**Weight**
Redundancy	<=200	201-788	789-1870	1871-7500	>7500	**0.333**
Freight	<=800	801-2085	2086-3898	3899-12250	>12250	**0.235**
Annual Average Daily Traffic (AADT)	<=720	721-1900	1901-4600	4601-15000	>15000	**0.177**
Roadway Classification	Major Collector	Minor Arterial	Principal Arterial	Freeway Expressway	Interstate	**0.146**
Social Vulnerability Index (SoVI)	-4.49–2.93	-2.92–1.24	-1.23–0.67	0.68–2.51	2.52-5.40	**0.060**
Tourism	<=85	86–270	271–567	568–928	>928	**0.049**

For this example, consider the following levels of the criteria that are estimated for a single link:

1. Redundancy is estimated to be 1600 vehicle-hours and is assigned Level 3
2. Freight value is $1000M and is assigned Level 2
3. AADT is 500 vehicles per day and assigned Level 1
4. Roadway class is a minor arterial and is assigned Level 2
5. SoVI is estimated to be 1.55 and is assigned Level 4
6. Tourism value is $2M and is assigned Level 1

The unequally weighted average is calculated as follows:

$$\boldsymbol{Criticality_i = \sum_{n=1}^{N}(w_i) \times c_{i,n}} \tag{4.1}$$

Where;

$Criticality_i$ is the combined criticality score for each link *i*

$w_{i,n}$ is the weight assigned to each criterion, n, e.g., AHP deduced weights

$c_{i,n}$ is the score of the criterion, n, for each link *i*

N is the number of criteria, e.g., *N=6.*

The weighted average is calculated as:

Criticality = (0.333×3) + (0.235×2) + (0.177×1) + (0.146×2) + (0.06×2) + (0.049×1) = **2.23**

The estimated criticality of the link used in the example, which is 2.23 would be more critical than a link with a criticality score of 1.50 and less critical than a link with a criticality score of 3.00. Subsequently, all other links in the transportation network can be estimated as such.

The application of the methodology was extended to estimate the criticality metrics of the roadway network that is maintained by the state of Arkansas.

To provide a clearer visualization of the criticality map, the combined criteria were categorized into three levels of criticality: low, moderate, and high (as shown in **Figure 4-8**). This stratification was based on the distribution of criticality values, with around 72% of links classified as low criticality, 19% as moderate criticality, and 9% as high criticality.

The following locations rank among the 10 most critical sites with criticality scores greater than 4.2.

1. US 67/167 from AR 440 to South Redmond Road, *Pulaski County*, score: 4.401
2. Garrison Avenue, *Sebastian County*, score: 4.315
3. I-55 from US 70 to the I-55 Memphis-Arkansas Bridge, *Crittenden County*, score: 4.225
4. I-430 from S. Shackleford Road to Stagecoach Road and from the I-40 to Crystal Hill Road (AR 100) interchange, *Pulaski County*, score: 4.214
5. I-40 from Crystal Hill Road to West Military Drive, *Pulaski County*, score: 4.214
6. I-40 from AR 440 to AR 391, *Pulaski County*, criticality score: 4.214
7. I-30 from AR 365 to I-530/I-440 interchange, *Pulaski County*, score: 4.214
8. I-530 from 145th/Pratt Road to E. Bingham Road, *Pulaski County*, score: 4.214
9. I-440 from Fourche Dam Pike to US 165, *Pulaski County*, score: 4.214
10. I-40 from AR 440 to AR 391, *Pulaski County*, score: 4.214

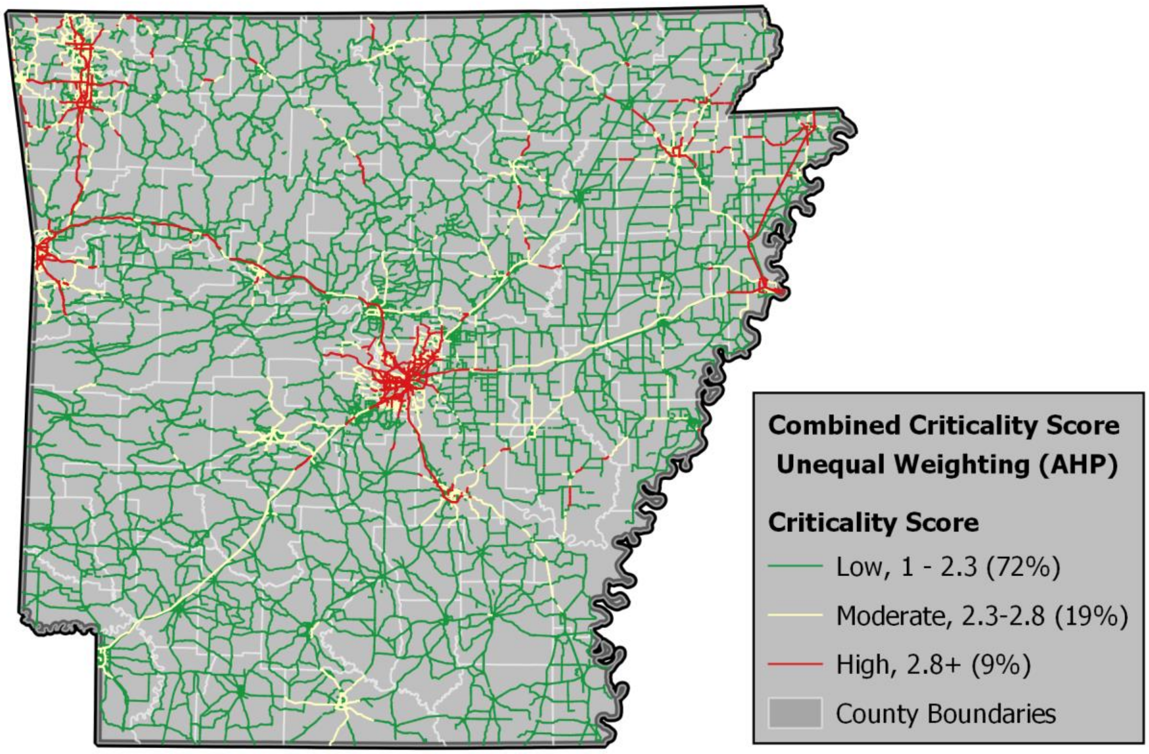


Figure 4-8 Combined Criticality Score for Arkansas' Statewide Road Network.

Chapter 5. Discussion

In this study, the AHP derived weights are sensitive to decreases in sample size, the make-up of the respondent's professions, practice areas, and organizations, and the aggregation approach, e.g., AIJ or AIP. In this section, the challenges and suggestions for assessing the sensitivity of the approach to these factors are discussed.

Although a response rate of 13.2% was achieved in this study, a non-probability sampling approach was used. Thus, it is not possible to weigh the sample across all respondent demographics. With a final usable sample of 21 responses, it is not advisable to draw strong conclusions about the priorities of minority respondent groups. For example, a limited sample of one respondent (**Figure 4-1b**) was gathered from those representing EER. However, because the AHP is a subjective method rather than a statistical technique, a smaller sample size is acceptable for implementing the AHP model as long as the responses reflect the logical and analytical opinions of experts from various stakeholders (T. L. Saaty & Özdemir, 2014; Wong & Li, 2008).

The AIP and AIJ methods are used when the relative importance of the decision-makers is assumed to be equal. The AIP produces the overall criteria weights. Using the AIP method produced an overall weight of 0.244 for AADT which ranked first and 0.231 for redundancy which ranked second. Freight, roadway classification, and SoVI followed in rankings with closer weights of 0.198, 0.13, and 0.114, respectively. Tourism had a lower weight of 0.082, ranking sixth. From the AIP of the individual responses, it is established that an individual respondent prioritizing a criterion highly over the other criterion has a substantial effect on the final and overall different weights after the aggregation. This can be explained by differences in priorities across the various stakeholder groups (i.e., by agency or practice area), and varying interpretations of the criteria in the various responses. When the rankings by a stakeholder group were the same, the AIJ method showed slight weight differences when compared to AIP. The respondents from the state and federal DOTs had the same ranking as the overall criteria ranking. When comparing both weights, for example, AADT has a weight of 0.244 for AIP and 0.234 for AIJ. Overall, utilizing the AIJ over the AIP aggregation approach demonstrates the sensitivity of the weights to the interpretation of the group's (practice area or agency) decision-making process. When the group shares a common goal then the AIJ is more appropriate compared to the AIP which is applied when the individuals act according to their own priorities.

Consistency is an important requirement of the AHP method (Wong & Li, 2008). The acceptable CR values for different matrices sizes are: 0.05 for a 3 by 3 matrix, 0.08 for a 4 by 4 matrix, and, 0.10 and a tolerable ratio of 0.2 for larger matrices (Wedley, 1993; Wong & Li, 2008), where the size of the matrix represents the number of criteria being compared. This indicates that using more criteria results in a higher number of inconsistencies. 21 responses passed the consistency ratio test ($CR < 0.20$) with an average of 0.115. The CR values varied differently among the various stakeholder groups with respondents self-reporting a practice area of 'operations' having the highest CR value of 0.2 while respondents identifying as 'researchers' had the lowest CR value of 0.062. The differences in consistency, in part, can be attributed to the different sample sizes across the various stakeholder groups. A least consistent individual respondent with a high CR value has a significant effect on the average CR of the specific stakeholder group. The area of expertise required to make the pairwise comparisons must be known to engage respondents who have both knowledge and practical experience with the subject matter to ensure consistent responses (T. L. Saaty & Özdemir, 2014). Despite the lack of a significant correlation between the consistency ratio (CR) and the response time, it is noteworthy that almost half of the survey respondents who achieved consistency in their pairwise comparisons did so within 20 minutes. The variation in response time could be attributed to the diverse criteria being considered, as well as the varying levels of expertise and experience among the decision-makers.

To also ensure that the ranking of the criteria is stable and robust, a sensitivity analysis was conducted. Based on the results presented in **Figure 4-6**, it can be inferred that some criteria have a greater impact on the final outcome. For example, AADT and Roadway Classification are selected to evaluate their impacts on the overall results. These two criteria are selected because they are often correlated, in that, typically a more heavily trafficked roadway is a highway or interstate roadway. Thus, the impact of removing each criterion is examined individually to evaluate its contribution to the overall ranking of the criteria. From **Figures 4-6b** and **4-6e,** it can be concluded that AADT has a greater impact on the final outcome compared to Roadway Classification. This is evident from the increase in the weight of AADT and ranking first in the overall model when Roadway Classification was removed from the criteria in **Figure 4-6e**. Additionally, the stability of sample size is accessed in this study to determine the minimum number of participants needed for this AHP study that generates reliable and consistent results. A stable sample size means that the results are not significantly affected by small variations in the number of participants, and the findings are reliable and robust. Employing a sample size of 15 responses, stable and consistent criteria rankings were achieved for this study. Overall, the sensitivity analysis indicated that the criteria rankings were relatively stable across different scenarios, with only a slight reduction in stability observed when the sample size decreased.

Chapter 6. Conclusion

This study presents an application of an Analytical Hierarchy Process (AHP) to the ranking and weighting of criteria to measure the criticality of roadway segments across a statewide network. The AHP method uniquely allows for the aggregation of diverse stakeholder rankings of multiple criteria using a pairwise rating system. The AHP model was well-suited to determine weights and ranking of the six-criticality assessment metrics, i.e., AADT, roadway classification, freight value, tourism expenditures, Social Vulnerability Index, and redundancy. The model's hierarchical structure allows experts and stakeholders in the transportation sector to easily identify and evaluate the metrics by considering the multiple criteria that are relevant to their priorities. Furthermore, the AHP model provides fast and efficient results to explain the criticality of road links in a transportation system.

The AHP process was carried out using an online survey resulting in 30 complete responses, representing a 13.2% response rate. Respondents represented public transportation agencies, private consulting firms and academic intuitions across the US. After applying a threshold for consistency in individual responses, an aggregate weighting approach called the AIP was used to estimate the criteria weights. The weights across the whole sample (21 responses) and by stakeholder group were compared.

Each metric receives a weight that is proportional to its rank, e.g., larger weights indicate a higher ranking. The key finding from the metric ranking is that AADT is consistently ranked most important among the six criteria with a weight of 0.244. Redundancy was the second-ranked criteria with an average weight of 0.231. Combined, AADT and redundancy account for 0.475 of the total weight, representing almost half the weight of the other four criteria combined. The experts surveyed agreed that tourism is the least important of the six-criticality metrics weighing of 0.082. Tourism was ranked as the least important criterion by the majority, if not all, stakeholders, and practice area groups.

Individual responses reveal the sensitivity of the AHP model to stakeholder roles and traits. For example, there were few academic respondents, one happening to be the sole response associated with the field of EER. SoVI was ranked by this respondent as the most vital criterion, with a very high weight of 0.496, which is nearly equal to the combined weights of the remaining criteria. This suggests that the results are sensitive to the sample sizes from both stakeholder and practice groups. However, with an overall sample size of 15 and an allotted time of 20 minutes, the final AHP model produced a reliable and robust outcome that is consistent and stable. Future research will need to solicit more respondents with particular attention to the respondents' knowledge level and practical experience from across the various stakeholder groups. A pilot study can be conducted to identify and select respondents who have a high level of expertise, and knowledge on the subject matter to participate in the AHP survey and also gather general feedback on the important criteria metric required for measuring the criticality of transportation highway assets (Cheng & Li, 2002). The suggested metrics from the survey can be considered to reduce the criteria and the inconsistencies with more robust results. In addition, the results of excluding Roadway Classification from the criteria indicate that AADT plays a more vital role in measuring the criticality of transportation highway assets. This finding also suggests that by removing likely correlated criteria, it is possible to streamline the criteria and increase the efficiency of the decision-making process.

Other metrics considered important for measuring the criticality of statewide highway transportation assets were asked of the participants. Respondents proposed metrics such as safety, volume/capacity, supply chain vulnerability, and the inclusion of other types of transportation facilities such as seaports, airports, and so on. These metrics can be incorporated into future criticality and resiliency assessments using this framework.

Despite these limitations, this method is demonstrated to be an important first step in identifying transportation link criticality rankings within a transportation system. The proposed methodology provides a framework that is easily implementable in practice. This framework can be used by practitioners and decision-makers for prioritization and ranking of project and investment decisions, maintenance projects, planning decisions, and infrastructure mitigation actions.

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Appendix

Online Survey

Research Title: Criticality Assessment Metrics of Highway Transportation Systems using the Analytical Hierarchy Process (AHP) Model.

You are invited to participate in an online survey for a research study: "Criticality Assessment Metrics of Highway Systems using the Analytical Hierarchy Process (AHP) Model." The objective of this survey is to determine the most important criteria to measure the importance (or criticality) of highway transportation systems components like roadway links. This data will be used to inform statewide transportation system resiliency metrics. The 15-minute survey contains three sections covering: (i) details of the respondent, (ii) guidelines and instructions, and (iii) pairwise comparison. We realize your time is valuable, and we truly appreciate your contribution to this research. If you are willing to participate, please complete the survey by **December 31st, 2022.**

Explanation of Research

Investigator: Kwadwo Amankwah-Nkyi, University of Arkansas, kwadwoa@uark.edu
Faculty Supervisors: Sarah Hernandez, Ph.D., PE, University of Arkansas, sarahvh@uark.edu and Suman Kumar Mitra, Ph.D., University of Arkansas, skmitra@uark.edu
Purpose: You are being asked to take part in a research study. The purpose of this research study is to determine the most important criteria to measure the importance (or criticality) of highway transportation systems components like roadway links.
Activities: The study activities include the administration of an online survey designed to understand the relative importance of the six criteria determined for measuring the criticality of highway transportation systems in various states within the United States.
Time: Your participation in this study will last about 10-20 minutes to complete and includes 18 questions.
Confidentiality: It is possible that others could learn that you participated in this study but the information you provide will be kept confidential to the extent permitted by law. The data will be shared with the research team at the University of Arkansas.
Risks: The security and confidentiality of the information collected from participants online cannot be guaranteed. Confidentiality will be kept to the extent permitted by the technology being used. Information collected from online can be intercepted, corrupted, lost, destroyed, arrive late or incomplete, or contain viruses.
Benefits: There are no direct benefits to participants, however, the research has the potential to improve transportation system resiliency planning in the United States to mitigate the impacts of future events.
Voluntary Participation: Your participation in this research is completely voluntary and refusing to participate will not adversely affect any other relationship with the University or the researchers.
Study contacts: If you have any questions about this research project, please contact: Kwadwo Amankwah-Nkyi at kwadwoa@uark.edu

Statement of Consent

Before you begin this survey, please read the series of statements regarding your consent for the survey. However, personal information will remain anonymous for the answers to the survey questions.

- I confirm that I have had the opportunity to ask questions.
- I confirm that I have had the opportunity to receive information regarding the purpose of this research and that I recognize what I am being asked to do to contribute to the study.
- I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason and without there being any negative consequences. In addition, should I not wish to answer any particular question or questions, I am free to decline.
- I understand that my responses will be kept confidential to the extent allowed by law and University policy. I understand that my name will not be linked with the research materials and will not be identified or identifiable in the report or reports that result from the research.
- I agree that my anonymized data will be kept for future research purposes such as publications related to this study after the completion of the study.
- I confirm that I have the contact information for both the Principal Investigator and the University of Arkansas IRB Coordinator for future concerns after the day of this survey.
- I agree to take part in this survey.

If you are not satisfied with the manner in which this study is being conducted, you may report (anonymously if you so choose) any complaints to the University of Arkansas Internal Review Board (IRB) Coordinator Ro Windwalker, irb@uark.edu at 109 MLKG, Fayetteville, AR, 72701 or 479-575-2208.

- If you wish to participate, please click the **"I Agree"** button and you will be taken to the survey.
- If you do not wish to participate in this study, please select **"I Disagree".**

If you want a copy of this consent for your records, you can print it from the screen.

General Information

Agency/Institution/Company

Practice Area

- Asset management
- Construction
- Emergency and event response
- Engineering
- Maintenance
- Operations
- Planning
- Policy
- System Information and Research
- Survey
- Other, please describe in your words in the space provided.

Job Title

- ○ Analyst
- ○ Engineer
- ○ Consultant
- ○ Inspector
- ○ Manager
- ○ Office Specialist
- ○ Operator
- ○ Planner
- ○ Project coordinator
- ○ Supervisor
- ○ Specialist
- ○ Surveyor
- ○ Technician
- ○ Other, please describe in your words in the space provided.

Guidelines

Goal: Develop and implement a framework for measuring the criticality of a statewide highway transportation system component like a roadway or bridge asset.

Criteria: Six criteria (criticality assessment metrics) were chosen to determine the importance (or criticality) of a highway network link. The six criteria (described below) can be taken as individual metrics or combined through averaging and ranking to estimate the overall criticality of a segment.

These are;

1. **Annual Average Daily Traffic (AADT):** This is the daily traffic volume in vehicles per day for each roadway link. This data is typically collected for federal reporting purposes, e.g., the Highway Performance Monitoring System (HPMS) and is gathered from tube or video cameras.
2. **Roadway Classification:** This refers to the functional class of roadway link: Interstate, Freeways & Expressways, Principal Arterials, Minor Arterials, and Major Collectors.
3. **Freight:** This measure refers to the freight value originating or destined to the county in which the roadway segment or transportation asset is located. It is measured in Millions of US dollars. Unlike AADT and classification, this measure is at a county level, rather than at the segment or asset level.
4. **Tourism:** This measure refers to the tourism value as expressed as Total County Expenditures in Millions of US dollars by county**.** Like Freight, it is expressed at a county level due to the availability of data.
5. **Social Vulnerability Index (SoVI):** SoVI measures the social vulnerability of US counties to environmental hazards. It is an indicator comprised of 29 socioeconomic variables that contribute to a county's ability to prepare for, respond to, and recover from hazards**.** Examples of sociodemographic variables include income, gender, ethnicity, etc. Like Tourism and Freight, it is measured at the county level.
6. **Redundancy:** It is the amount of additional travel time added to the network when a link is non-operational, e.g., closed due to flooding or other damage. The additional time added to the network results from drivers having to detour around the closed asset and related congestion effects.

Instructions

In this survey, we would like your professional opinion on how to compare each of the six criteria described above. We propose that preferences among the six criteria are dependent on the state context, your role within your institution/company, and your knowledge and experience. Rather than asking you to rank each of the six criteria as a set, we ask you to make pairwise comparisons. Through these pairwise comparisons, we will apply an averaging and ranking method to better understand the ranking and prioritization of each of the criteria.

Table 1. The Saaty scale of AHP.

Scale	Judgement of preference	Description
1	Equally important	Two factors contribute equally to the objective
3	Moderately important	Experience and judgment slightly favor one over the other
5	Strongly important	Experience and judgment strongly favor one over the other
7	Very strongly important	Experience and judgment very strongly favor one over the other, as demonstrated in practice
9	Extremely important	The evidence favoring one over the other is of the highest possible validity
2,4,6,8	Intermediate preferences between adjacent scales	When compromise is needed

It is important that you try to make the following comparisons in a consistent manner.
For example, you are asked to express your preferences by comparing three different fruits:

While ranking, you express that you strongly prefer oranges over mangoes, but only slightly prefer grapes over mangoes. Meaning that the order of your ranking would be oranges first, followed by grapes second, followed by mangoes third in terms of preference.
Logically, you could not prefer grapes over oranges, because you prefer grapes only slightly more than mangoes and you prefer oranges strongly more than mangoes.

Pairwise Comparisons

With respect to the Goal: **Measuring the Criticality of Highway Transportation Systems**,
Using the scale from 1 to 9 (where 9 is extremely and 1 is equally important)
Please use the slider to indicate the point on the scale that best represents the relative importance of one criterion over the other.

Definitions of the criteria are provided for a quick reference when you hover over the criteria for a second or two.

	-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9
Annual Average Daily Traffic (AADT) Roadway Classification ()	
Annual Average Daily Traffic (AADT) Freight ()	
Annual Average Daily Traffic (AADT) Tourism ()	
Annual Average Daily Traffic (AADT) Social Vulnerability Index (SoVI) ()	
Annual Average Daily Traffic (AADT) Redundancy ()	
Roadway Classification Freight ()	
Roadway Classification Tourism ()	
Roadway Classification Social Vulnerability Index (SoVI) ()	
Roadway Classification Redundancy ()	
Freight Tourism ()	
Freight Social Vulnerability Index (SoVI) ()	
Freight Redundancy ()	
Tourism Social Vulnerability Index (SoVI) ()	
Tourism Redundancy ()	
Social Vulnerability Index (SoVI)Redundancy ()	

IRB Approval

UNIVERSITY OF ARKANSAS

To:	Kwadwo Amankwah-Nkyi
From:	Douglas J Adams, Chair IRB Expedited Review
Date:	07/01/2022
Action:	**Exemption Granted**
Action Date:	07/01/2022
Protocol #:	2206406049
Study Title:	Criticality Assessment Metrics of Highway Transportation Systems using the Analytical Hierarchy Process (AHP) Model

The above-referenced protocol has been determined to be exempt.

If you wish to make any modifications in the approved protocol that may affect the level of risk to your participants, you must seek approval prior to implementing those changes. All modifications must provide sufficient detail to assess the impact of the change.

If you have any questions or need any assistance from the IRB, please contact the IRB Coordinator at 109 MLKG Building, 5-2208, or irb@uark.edu.

cc: Sarah V Hernandez, Investigator
Suman Mitra, Investigator