EVALUATION OF TRANSPORTATION NETWORK RESILIENCY WITH CONSIDERATION FOR DISASTER MAGNITUDE

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Infrastructure resiliency, particularly related to transportation networks, is essential to any society, especially when considering natural (and man-made) disasters. Recent events around the globe, including Hurricane Katrina, as well as significant seismic events in Haiti, Chile and Japan, have increased the awareness and importance of this fact. Transportation systems are key to response and recovery. They must be able to withstand stress, maintaining baseline service levels, and be stout in physical design and operational concept in order to provide restoration to the system, thus preventing a destructive event from becoming the catalyst for a degenerative epoch. Analyzing the resiliency of a transportation network will aid decision-makers in identifying specific weaknesses within the network, thus allowing the proper prioritization of investments and improvement projects. This paper expands on previous research in quantifying network resiliency. Through the proposed methodology, properly understanding and applying network resiliency may preclude many of the devastating effects caused by destabilizing events, thus preserving quality of life and economic stability.

The transportation network is critical to a nation’s way of life and economic vitality. The world’s dependence on transportation systems is continually growing as regional, national, and international societal interaction and economic activities become more fully integrated and interdependent. We depend on transportation systems to provide such essentials as food, medicine, and mobility. Disruptions in these systems can have devastating impacts. History has shown how important, and how fragile, the transportation network can be and the long reaching effects that can be felt from network disruption.

In 2005, Hurricane Katrina illustrated this fact as fragility, inadvertently built in to the local and regional transportation networks, was revealed when evacuation and recovery efforts were limited by system performance. In 2010, a magnitude 7.0 earthquake near Haiti devastated its capital, killing hundreds of thousands of people. Perhaps more tragic, however, was that thousands more would perish after the event due to the significant inability to transport much needed goods and services. It was reported that although planes carrying aid began arriving as early as the next day, humanitarian groups struggled to get supplies to victims. This was in large part due to poor roads and debris, causing navigation through the streets to be nearly impossible.

According to the U.S. Geological Survey (USGS), the Modified Mercalli Intensity (MMI) Scale value assigned to a specific site after an earthquake may have a more meaningful measure of severity than the magnitude because intensity refers to the effects actually experienced at that place. The Haitian earthquake just described was consequently assigned an MMI value of IX, meaning severe damage to poorly built structures (i.e. the falling of chimneys, smokestacks, columns, monuments and walls, and the overturning of heavy furniture) as well as considerable damage in specially and well-designed frame structures, as they are thrown out of plumb. Severe damage is also experienced in substantial buildings, with partial collapse as well as buildings shifting off their foundations.

In stark contrast to this Haitian precursor, almost one month later a magnitude 8.8 earthquake rocked the Chilean coast; however, it was assigned an MMI value of only VIII. Despite the significantly stronger event in Chile, the MMI value was lower due to less significant damaging effects. While Haiti suffered for months struggling to recover, Chile was back on its feet within weeks. The key difference between these two examples was resilience.
Resiliency, if properly understood and applied, has the ability to preclude many of the devastating effects resulting from such disasters as previously described. Resilient transportation systems may reduce the probability of failure within the system as well as reduce the consequences of any failure that may occur, thus improving the time for recovery. Previous iterations of the resiliency methodology have focused on evaluation of resiliency after disasters. However, the knowledge of the resiliency of a transportation system after a disaster has occurred does little to mitigate the resulting effects of the event. It is for this purpose that the objective of this paper be to expand on the conceptual framework developed by Heaslip, et al. (3) in assessing the network resiliency of a system before a destabilizing event. This objective will be achieved by the expansion of the methodology to account for metrics that account for pre-disaster resiliency. This process identifies weaknesses within the network and provides decision-makers with a flexible and robust method to quantify resiliency. Those individuals may then use the information obtained to properly prioritize transportation investments in order to enhance network resiliency, thus ensuring the benefits previously described.

Detailed definitions for key variables provided by Heaslip, et al. (3) will be given in this research in order to aid in the quantification of the concept of transportation resiliency. A brief summary of the framework as well as the methodology will be presented, and finally, an application assessment will be completed by providing an illustrative example outlining its use and effectiveness.

DEFINING RESILIENCE

The concept of resilience is broadly applied throughout many different fields of study (e.g., engineering, psychology, sociology, and economics). The definition also can be associated to similar concepts like flexibility, redundancy, reliability, elasticity, and risk management. In economics, the term resilience is related to the ability to recover quickly from a shock (shock-counteraction), to withstand the effect of a shock (shock-absorption), and to avoid the shock altogether (vulnerability) (4). In social science, resilience can be defined as the capacity of a system exposed to hazards, to adapt by resisting or changing, in order to reach and maintain an acceptable level of functioning and structure (5). In earthquake engineering, researchers have defined seismic resilience, particularly, as the ability of social units (e.g., organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways that minimize social disruption and reduce the effects of future earthquakes (6). Community seismic resilience can be acknowledged as the capacity to absorb stress, manage it and recover from it (7). As a more general definition, resilience can be defined as the capacity to absorb shocks gracefully (8).

The concept of resilience has been studied in the field of transportation engineering as well. Conceptual frameworks have been created in order to define and “measure” resilience within the area of transportation. Transportation resilience can be defined in different ways:

- The ability for the system to maintain its demonstrated level of service or to restore itself to that level of service in a specified timeframe (3).
- A characteristic that enables the system to compensate for losses and allows the system to function even when infrastructure is damaged or destroyed (9).
- A system’s ability to accommodate variable and unexpected conditions without catastrophic failure (10).
• The ability for the system to absorb the consequences of disruptions to reduce the impacts of disruptions and maintain freight mobility (11).

Considering these definitions of resiliency, for this paper, the definition used is stated as “the ability for a transportation network to absorb disruptive events gracefully, maintaining its demonstrated level of service, or to return itself to a level of service equal to or greater than the pre-disruption level of service within a reasonable timeframe.”

CONCEPTUAL FRAMEWORK
For the methodology developed by Heaslip, et al. (3), the parameters for resiliency were defined within the context of a ‘resiliency cycle,’ which recognizes the cycle of normalcy, breakdown, annealing, and recovery.

Breakdown is the measure of degradation caused by an event. An event-driven breakdown degrades the system’s performance and often reduces its ability to absorb additional pressure from event-induced demand or a follow-on disaster (such as an aftershock to an earthquake). Annealing and recovery are measures of how quickly the network can regain or exceed the level of service present before the breakdown. Once the damage has been made to the network, the users will optimize their behavior in a way that leads to a new equilibrium on the network in what is called an annealing phase. The annealing process is the progression of the network towards normalcy, but it may be limited by physical damage and loss of capacity. Recovery of the network, if required to offset physical damage, is dependent on the nature of the damage and the access to goods or services needed to repair the network.

It is logical that concerning the annealing and recovery process, time is a critical measure of the success of a resilient system. For a network that is not resilient, delays in beginning those processes, or delays throughout, may cause the effects of the breakdown to spread across wider areas than where the breakdown initially occurred. Consequently, slow recovery times may be devastating to the local, regional, and national economies of the area affected.

In order to enhance the resiliency of a network, then, one must understand the characteristics of a transportation network that affect its overall resilience. When considering critical components of transportation resiliency, Murray-Tuite (12) identifies such characteristics as redundancy, diversity, efficiency, autonomy, strength, adaptability, collaboration, mobility, safety, and recovery. The methodology developed by Heaslip, et al. (3) incorporates a dependency diagram using these, as well as other characteristics relating to transportation network resiliency.

METHODOLOGY
The methodology used in this paper is similar to previous work by Serulle, et al. (13) using a fuzzy inference approach, however differs in that metrics used in previous work by Heaslip, et al. (3) were brought back, and the following methodology was performed. Further, contributions of this new study are found in the specific definitions of each metric used in the calculation of total network resiliency.

At the core of the methodology are four metric groups of interest that have been identified by the research community: metrics related to the individual, metrics related to the community, metrics related to the economy (14), and metrics related to recovery (15). These metric groups are the center of the aggregation schema employed within the proposed methodology.
Individual Resiliency Metrics will show if the transportation network provides options and utility to individual users. In terms of resiliency it means that these options are present to meet their transportation needs even under unusual and unexpected conditions.

Community Resiliency Metrics will show if the transportation system fulfills the needs of the community. In terms of resiliency it means that the network can safely and efficiently accommodate unusual conditions, including construction projects, emergencies, special events, and large gatherings without major impacts.

Economic Resiliency Metrics will show if the transportation network provides services even if a particular resource, such as fuel, becomes scarce and/or expensive [16].

Recovery Metrics will show if the network has the ability to anneal and recover. The recovery metric group examines the resources and qualities necessary to restore resiliency to the network.

Each metric group is supported by a lower tier of measurements of specific attributes, and each contributes to a higher tier that can be used to compare resiliency between assessed areas or that can be used to measure the contribution of specific projects and policies to the improvement of regional resiliency.

The attributes, or variables, are measured on a qualitative scale with input values ranging from low, medium, and high. Numeric values are assigned to each qualitative value as well, such as 1, 2, and 3, respectively. However, sometimes the inverse order is necessary in such cases as transport cost indices and delays. High transportation costs as well as high delays relate to poor conditions in terms of resiliency. Therefore, numeric ranges for such variables are assigned 3, 2, and 1, respectively. Each measurement range definition can be found in TABLE 1.

<table>
<thead>
<tr>
<th>TABLE 1 Variable Input Range Definitions</th>
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<tbody>
<tr>
<td>Variable</td>
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<td>------------------------------------</td>
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<tr>
<td>Mobility Index</td>
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<tr>
<td>Delay Encountered</td>
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<tr>
<td>Food Medicine Index</td>
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<tr>
<td>Personal Transport Cost Index</td>
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<td>Personal Mode Choice</td>
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<td>Network Redundancy</td>
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<td>Infrastructure Alignment</td>
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<td>Goods &amp; Material Access</td>
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<td>Commercial Mode Choice</td>
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<td>Industrial Mode Choice</td>
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<tr>
<td>Network Management</td>
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<td>Fuel &amp; Energy Access</td>
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<td>Commercial Transport Cost Index</td>
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<td>Industrial Transport Cost Index</td>
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<tr>
<td>Emergency Response</td>
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<tr>
<td>Resources Available</td>
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</table>

Each variable is weighted equally according to the number of variables feeding into its related core metric. Therefore, variables determining each core metric group are 1/5 for each individual metric group variable, 1/7 for each community metric group variable, 1/7 for each economic metric group variable, and 1/3 for each recovery metric group variable. It is noted that
the variables considered in more than one metric group will carry a more significant weight concerning the final total network resiliency. This is done by design. For example, mode choice should naturally carry a more significant weight than transport cost due to the fact that, in an extreme case, if no mode choice were available, the cost required to utilize a mode of transport becomes meaningless.

The value for each core metric group is determined by the inputs of each variable supporting it. In order to standardize the metric groups, the numeric value of each variable (1, 2, or 3) is multiplied by its weight, and the summation of each of those values is then divided by three (due to the three input options: low, medium and high). The outputs for each metric group, as well as the total network resiliency, consist of nine parameters and are stratified according to the values shown in TABLE 2.

<table>
<thead>
<tr>
<th>TABLE 2 Output Stratification</th>
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<tbody>
<tr>
<td>0.33 ≤ 0.41</td>
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<tr>
<td>0.48 ≤ 0.56</td>
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<tr>
<td>0.56 ≤ 0.63</td>
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<tr>
<td>0.63 ≤ 0.70</td>
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<tr>
<td>0.70 ≤ 0.78</td>
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<tr>
<td>0.78 ≤ 0.85</td>
</tr>
<tr>
<td>0.85 ≤ 0.93</td>
</tr>
<tr>
<td>0.93 ≤ 1.00</td>
</tr>
</tbody>
</table>

In determining the total network resiliency, the core metric groups are each weighted equally, just as the attributes, according to the number of variables feeding into the next level of the dependency diagram. Therefore, each is weighted 1/4 in determining the total network resiliency. The summation of the values obtained previously for each metric group, multiplied by their weight is used to determine the final qualitative value for total network resiliency. This value is also assigned according to the stratification shown in TABLE 2. This final output produced by the dependency diagram represents the estimated resiliency of the network as a whole. Higher total network resiliency values signify an enhanced likelihood of the system being able to fulfill the definitions of transportation resiliency given previously in this report.

Once this initial network resiliency is determined, one can easily perform a sensitivity analysis on the network by changing the input values of any attribute that a proposed project may change in the network. Comparing the results of this process with the initial resiliency, one can easily see which project(s) will most benefit the network, thus providing valuable information regarding proper prioritization for investments and/or improvement projects.

APPLICATION

In order to illustrate the potential application of the proposed methodology, an illustrative example was developed. The scenario addresses the occurrence of a seismic event along a major fault line on the Wasatch Front near Salt Lake City, Utah. As the MMI Scale gives meaningful measures of the different levels of severity of such events, it is important to understand the classification, or stratification of that scale. The following is an abbreviated description of the 12 levels of intensity, as given by the USGS (2).
I. Not felt except by a very few under especially favorable conditions.

II. Felt only by a few persons at rest, especially on upper floors of buildings.

III. Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.

IV. Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.

VI. Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.

VII. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.

VIII. Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.

IX. Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.

XI. Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.

XII. Damage total. Lines of sight and level are distorted. Objects thrown into the air.

FIGURE 1 represents an estimated curve for the total network resiliency necessary to withstand events of varying intensity, according to the descriptions of the damages given in the MMI Scale.

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**Resiliency vs. Intensity**

- Extremely High
- Very High
- High
- Medium-High
- Medium
- Medium-Low
- Low
- Very Low
- Extremely Low

**FIGURE 1** Resiliency vs. MMI Intensity curve.
A research effort was performed by the University of Utah to assess the possible effects a significant seismic event may have on the local economy of Salt Lake City (17). Information provided by that research was used to build this application, allowing a comprehensive assessment of Salt Lake City’s transportation network resiliency. The area of study contained an area of approximately 520 square kilometers and a population of about 500,000 (18). The region in which most of the damage was expected covered several major roadways including Federal and State Highways, as well as railroads and the Salt Lake International Airport.

Initial Resiliency
The dependency diagram, centered on the Core Metric Groups briefly described previously in the Methodology of this report, was used to determine the initial resiliency of Salt Lake City’s transportation network. The results are given in FIGURE 2. Measures that are considered in more than one Core Metric Group are indicated by dotted lines.

Given the input values determined through the initial assessment of Salt Lake City, a total network resiliency of ‘High’ was obtained through the methodology, as shown. This value represents the approximate resiliency currently instilled within the Salt Lake City network.
Referencing the curve given in FIGURE 1, it is estimated that a ‘High’ resiliency corresponds to Salt Lake City’s transportation network having the capability of being able to withstand a Level VIII event without significant disturbance to the transportation network.

A detailed description of each of the attributes found in the dependency diagram is briefly defined in this section. Data was collected for the study area in relation to those descriptions, and input values were inserted into the dependency diagram according to the range definitions given previously in TABLE 1.

**Mobility Index**

Mobility, referring to the movement of people or goods (19), increases resiliency by fostering annealing. It explains the demand on the infrastructure as well as its performance. Transportation engineers may use standardized methods for calculating mobility in terms of Level of Service (LOS), outlined in the Highway Capacity Manual. LOS values range from high to low, A through F, respectively. From January to August 2010, the average LOS in Salt Lake City during peak hours was found to be LOS B (20).

**Delay Encountered**

Delay represents an average additional amount of time that a traveler will likely experience due to network disruption (19). It lengthens the time it may take for annealing to begin, particularly in the case of sudden events. It should be noted that as delay increases, one’s ability, as well as motivation to travel becomes weakened. The Texas Transportation Institute has defined a travel time index as a measure of congestion that focuses on individual trips and each mile of travel. It is a ratio of travel time in the peak period to travel time in free-flow. For example, an index value of 1.20 would indicate that a 30-minute free flow trip would take approximately 36 minutes during peak hours (21). In 2007, Salt Lake City was found to have a travel time index value of 1.19, which was considered much higher than average in a comparison of several urban areas throughout the country containing populations between 500,000 and 1 million (21).

**Food Medicine Index**

This variable represents the availability of food and/or medicine within the network. Increased access to food and medicine throughout the network will provide resiliency in and of itself, as well as a buffer for annealing to begin without major disruption to the network. The Food Medicine Index is measured in terms of the number of locations per capita. Examples of such locations are hospitals and grocery stores containing pharmacies. Roughly 200 of these locations were located within the study area, therefore Salt Lake City was found to contain approximately 4 locations per 10,000 people.

**Personal Transport Cost Index**

This variable represents the cost incurred by individuals to utilize the network for transportation purposes. It is logical that as transportation costs increase, budgets are increasingly strained (22). Therefore, high costs for transport will limit options when individuals react to destabilizing events. As the price of fuel and other supporting commodities and services increase, one’s ability as well as motivation to travel decreases. Measurements for this variable are given in units of cost per distance traveled. Values may be computed using typical cost of travel “calculator wizards” and planning program components available to Metropolitan Planning...
Organizations (MPOs). According to the IRS (23), the current standard mileage rate for the use of a car, van, or pickup truck is $0.31/kilometer.

**Personal Mode Choice**

Mode choice represents the ability to utilize alternative modes of transportation throughout the network. Increased transportation mode choices will enhance options when individuals react to destabilizing events. If only one mode of transport remained usable after an event, many other aspects of the network (i.e. mobility, delay, and cost) would be significantly affected as individuals scrambled for necessary goods and services. On the other hand, if more than one mode of transport were usable, those parameters would likely be alleviated to some extent. Therefore, Personal Mode Choice is measured in terms of the total number of mode choices available to individuals. Currently, Salt Lake City is able to utilize personal automobile transportation as well as various modes of public transportation, including bus and railway.

**Network Redundancy**

Redundancy, representing backup organization built in to a system in order to prevent total system failure, is a major component of network resiliency (24). Redundancy within the network reduces choke points that could limit the options for annealing to begin. It represents the ability for a traveler to adjust routes as necessary to detour around an affected section of the network. Research has shown that higher values of road density result in better developed networks due to their inherent redundancy (25). However, despite the road density local roads may offer, it is unlikely that they will provide significant relief (i.e. cul-de-sacs). Thus, this variable is measured in terms of freeway and arterial road density, or the amount of arterial lane-kilometers within a specified area. Roughly 1,950 lane-kilometers of freeway and arterial road were measured within the study area.

**Infrastructure Alignment**

This variable represents the availability of secondary infrastructures within a network (i.e. alternative routes). A well-aligned secondary infrastructure will decrease the impact of the destabilizing event on the network. The variable is measured in terms of proximity, or the distance between primary and secondary infrastructures. It is noted that at closer distances, the event that destabilizes the primary infrastructure will likely affect the secondary infrastructure as well. Also, at further distances, the ability for travelers to utilize the secondary infrastructure becomes limited. Therefore, intermediate distances are most desired when considering this variable. The average distance between infrastructures in Salt Lake City was found to be approximately 6 kilometers, resulting in an intermediate distance, and therefore a high rating, according to TABLE 1.

**Goods & Material Access**

This variable represents the availability of goods and materials within the network specific to transportation needs. Access to these supplies will provide the means for the annealing of the network. Goods and materials access is measured in terms of density, or the number of locations that can provide transportation-related goods and materials within a specified area. Examples of such locations are warehouses, lumber yards, and concrete suppliers as well as airports and train stations, due to the fact that goods and materials may be transported to those locations, assuming they are functioning after the destabilizing event. Approximately 50 of these locations were
identified within the study area; therefore Salt Lake City was found to contain less than 1 location per 10 square kilometers.

*Commercial Mode Choice*
Increased mode choice for commercial transport will enhance options when commercial interests react to destabilizing events. If only one mode of commercial transport remained usable after an event, the ability to transport goods to their necessary locations may be limited. However, if more than one mode of transport were available, the ability to transport goods to their necessary locations would increase. Therefore, Commercial Mode Choice is measured in terms of the total number of mode choices available to commercial entities. Truck, rail, and air modes of transport are currently available for commercial use within the area of study.

*Industrial Mode Choice*
Increased mode choice for industrial transport will enhance options when industrial interests react to the destabilizing event and the ability to transport industrial items in order to begin annealing. If only one mode of industrial transport remained usable after an event, the ability to transport the necessary items to specific locations may be significantly restricted. If more modes of transport are available, the ability to transport items to affected areas would increase. Therefore, Industrial Mode Choice is measured in terms of the total number of mode choices available to industrial entities. Truck and railway transportation is currently available for industrial transport in the Salt Lake City area.

*Network Management*
Network management refers to the activities, methods, procedures, and tools that pertain to the operation, administration, maintenance, and provision of network systems (26). Its goal is to ensure effective, efficient, and standardized operations within and among transportation modes (1). Advanced network management provides real-time shifting of resources and demands on the network which enables annealing to begin and dulls the impact of destabilizing events. The following are some examples of network management used for the measurements shown in TABLE 1.

- **Level I** – Police officers directing traffic
- **Level II** – Traffic signals
- **Level III** – Dynamic traffic signal timing and ramp metering
- **Level IV** – Traffic cameras and variable message signs
- **Level V** – Intelligent transportation systems and advanced traveler information systems

Salt Lake City currently has the highest number of traffic cameras per capita as well as per roadway mile than any other transportation network in the country. Considering that fact, as well as its traffic management center, Salt Lake City’s network management is considered to be performing at a Level V.
**Fuel & Energy Access**
This variable represents the availability of fuel and energy within the network. Limitations of fuel and energy access would weaken the ability of the network to anneal and would increase the impact of the destabilizing event. Fuel and energy access is measured in terms of density, or the number of locations that provide fuel and energy within a specified area. Roughly 235 locations are situated within the study area that provide fuel and energy, leading to a value of about 4.5 locations per 10 square kilometers.

**Commercial Transport Cost Index**
This variable represents the cost for commercial entities to utilize the network for transportation purposes. High costs for commercial transport will limit options when commercial interests react to the destabilizing event. This variable reacts similarly to the Personal Transport Cost Index, as significantly high costs for fuel and other supporting commodities and services may make commercial transport unlikely. This variable is measured in terms of cost per distance. Commercial transport in Salt Lake City was found to be approximately $0.90 per kilometer.

**Industrial Transport Cost Index**
This variable represents the cost for industrial entities to utilize the network for transportation purposes. High costs for industrial transport will limit options when industrial interests react to the destabilizing event and the ability to transport industrial items to begin annealing. As with the Personal and Commercial Transport Cost Indexes, significantly high transportation costs may make industrial transport unlikely. Likewise, this variable is also measured in terms of cost per distance and is currently approximated to be equal to commercial transport cost ($0.90 per kilometer).

**Emergency Response**
Emergency response represents the ability for a region to mobilize response efforts without the help of other areas. According to the Federal Emergency Management Agency (27), the first 48 hours can make the difference in allaying the effects of a disaster. As such, rapid response times will increase resiliency. This variable goes slightly beyond that timeframe and assumes that, considering first response, the first two hours may be the most critical. It is therefore measured in terms of the time it takes for first responders to react to an event. In Salt Lake City, it was found that first response times average an impressive five minutes.

**Resources Available**
This variable represents the availability of people/organizations and equipment. Having resources available to a region to procure the materials necessary to anneal increases network resiliency. The U.S. Army Corps of Engineers (28) has developed a contractor registry to assist with disaster response. They use their engineering and contracting capabilities to support FEMA and other Federal, State and local government agencies in a wide variety of missions during natural and man-made disasters. Information in this registry may be used by Corps of Engineers offices searching for specific goods or services during emergencies. Therefore, this variable is measured by the number of licensed and registered disaster response contractors within the boundaries of the area under assessment. A total of 55 disaster response contractors were found within this registry’s records that would have the capability of rapidly responding to an emergency situation in Salt Lake City (29).
SUGGESTIONS FOR IMPROVEMENT

When considering the costs and benefits of improvement projects, it is obviously desirable to obtain the most benefits at the lowest cost. However, an inverse relationship typically exists between these two elements. Lower costs usually only result from the sacrifice of certain benefits, and vice versa. It is for this purpose that it becomes important to choose specific projects that will essentially provide “the biggest bang for your buck.” Also, as resiliency is bolstered, the cost to rise to the next level becomes increasingly expensive, often with little change in overall resiliency. Therefore, decision-makers should prioritize projects according to the perceived results provided by their implementation and weigh them against their overall benefit.

As previously stated, some variables in the dependency diagram are taken into account in more than one of the core metric groups. As such, those variables naturally carry a more significant weight when considering the final outcome of the results. Also, variables contributing to core metric groups with fewer numbers of attributes supporting them will carry heavier weights when considering the final results. For example, each variable contributing to the recovery metric group has a weight of 1/3, whereas each variable contributing to the economic metric group has a weight of 1/7. Hence in this case, improving variables contributing to the recovery metric group will generally have a greater impact on the final results. Given this information, it is therefore suggested that in performing a sensitivity analysis in order to determine the proper prioritization of improvement projects, specific attention be paid to attributes which carry more significant weight.

RESULTS

Considering the suggestions described, attributes related to mode choice and access to goods and materials were considered first for improvement. Taking into account the fact that building an entirely new mode choice in Salt Lake City would be highly expensive, goods and materials access was chosen as the first improvement project. The improvement of this attribute consequently raised the total network resiliency of the system. Subsequent to those improvements, other attributes were tested, but with little or no improvement in total outcome. Therefore, boosting goods and materials access became the highest priority for improvements, assuming limitations to funding for improvement projects. This provided the best results for the least cost.

Assuming that change to the network, the new qualitative value for goods and materials access was input into the dependency diagram, and a new total network resiliency value of “Very High” was obtained. The impact this change had on the dependency diagram is given in TABLE 3.

<table>
<thead>
<tr>
<th>Improvement</th>
<th>Initial Value</th>
<th>Improved Value</th>
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<tbody>
<tr>
<td>Goods &amp; Material Access</td>
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<td>High</td>
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<table>
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<tr>
<th>Result</th>
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</tbody>
</table>
The improved value of “Very High” represents the approximate resiliency of Salt Lake City after the suggested improvements have been implemented. According to FIGURE 1, it is estimated that this “Very High” resiliency corresponds to Salt Lake City’s transportation network now having the capability of being able to withstand a Level IX event without experiencing significant disturbance to the transportation network.

CONCLUSION
Along with an ever-growing dependence on transportation systems to provide life essentials, societies also develop a continual need to maintain the serviceability of that system, especially in the face of unpredictable disasters. Resilience must be a key focus in developing new transportation systems, as well as improving existing ones. The application of the proposed methodology has shown that specific weaknesses may be pin-pointed within a transportation network. Then, given that information, continuation of the network assessment has shown that it also provides a practical means of properly prioritizing improvement projects in order to enhance the system’s total network resiliency. Due to the nature of disastrous events, it is difficult to predict what damage may be incurred throughout a system. In that light, perhaps the best one can do is prepare, so as to mitigate negative results. Successfully building the resilience of a transportation network will help stabilize the economy and well-being of communities, regions, and nations. The methodology proposed in this report has been proven through analysis to provide the means to prioritize transportation infrastructure projects to successfully increase network resiliency.

REFERENCES


