FREIGHT RESILIENCY PERFORMANCE MEASURES: BELOIT TO HUDSON CORRIDOR

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Title

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Date

______________________________
Abstract

No one is exempt from emergencies. People, private companies and public agencies, all face the possibility of a sudden event that disrupt their normal functions. Disasters inflict chaos in all aspects of human endeavors and are the source of most disruptions. Recent disasters had raised the need to be able to handle these events.

Resiliency is the capacity of a system to absorb the impacts of a disruption, and the ability to reduce impacts and maintain mobility. A fragile system should be transformed into a resilient one. It should be able to provide service during small interruptions and recover quickly from large disruptions. By examining resiliency measures in transportation systems we can understand vulnerabilities in the networks. Resiliency measures may be used to guide infrastructure investments to protect against disruptions and accelerate recovery after a disaster.

This thesis was focused on the development of a methodology to estimate resiliency measures using data from the American Truck Research Institute (ATRI), collected through the Freight Performance Measurement Initiative, a partnership between FHWA and ATRI, along an interstate corridor to illustrate measures for freight transportation resiliency.

Two resiliency measures, robustness and rapidity, were estimated using freight resiliency triangles during two weather events that affected the Beloit to Hudson corridor in 2008. The corridor was evaluated for seven corridor portions between the cities of Hudson, Eau Claire, Tomah, Mauston, Portage, Madison, Janesville and Beloit, on each direction and each event.

The research presents a set of criteria to qualify the computed resiliency measures. These criteria reflect the corridor’s observed behavior during disruptions. It was developed along with the resiliency triangles, which together are a tool to evaluate resiliency.
Acknowledgements

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1. Introduction

No one is exempt from emergencies. People, private companies and public agencies, all face the possibility of a sudden event that disrupt their normal functions. Disasters inflict chaos in all aspects of human endeavors and are the source of most disruptions. Recent disasters - ranging from the September 11 Terrorist Attacks to events like Hurricane Katrina and the Minneapolis 35W bridge collapse - had raised the need to be able to handle these events.

Nearly all the international cargo arriving to the United States is by ship, which then requires to be transported via surface. This is in addition of freight produced in the United States for domestic and international distribution. Freight demand has been increasing in the past decades and this trend is expected to continue in the near future. Meanwhile, population also increases and highway capacity has expanded little and much infrastructure has aged. A fraction of bridges is structurally deficient or obsolete. These deficiencies make the system fragile and susceptible to fail. This increase leads to challenges for policy makers during a time of economic uncertainty.

Disruptions affect infrastructure and freight transportation systems by constraining free and efficient movement of goods. Therefore, without freight movements the economy will stop. A system can take a long time to reach its normal operation after a disruption. Unfortunately, few states had developed recovery plans for their freight operations.

Past disruptions in freight transportation systems had caused considerable economic losses. The Midwest floods of 1993 disrupted freight movements for months (1). They caused an economic damage of over $12 billion (1). Nowadays, the impact of a similar event could be significantly higher. Examples like this can suggest the need to establish recovery plans that support public infrastructure.
The 2004 National Response Plan requests each state to plan adequate response to incidents that cover all hazards (2). This plan defines two Emergency Support Functions that are relevant to freight movements. One is focused on transportation and the other on long-term community recovery and mitigation. The Emergency Support Functions only provide a general framework for response. It is up to the states to define a detailed response plan for their infrastructure (2).

While the National Response Plan calls for Emergency Support Functions focused on transportation and long-term community recovery, it does not call for plans to address freight movements (2). The absence of such plan represents a deficiency and also an opportunity for improvement.

A fragile system should be transformed into a resilient one. It should be able to provide service during small interruptions and recover quickly from large disruptions. By examining resiliency measures in transportation systems we can understand vulnerabilities in the networks. Resiliency measures may be useful to guide infrastructure investments to protect against disruptions and accelerate recovery after a disaster (2).

1.1 Background Information

1.1.1 Definition of Resiliency

Resiliency is the capacity of a system to absorb the impacts of a disruption, and the ability to reduce impacts and maintain mobility. It is the measurement of how quickly and efficient a system can recover from a disruption. Resiliency is also the capability of a system to sustain an impact and continue to function and the ability to adapt itself and recover quickly.
1.1.2 Disruptions

Disruptions are events that can cause sufficient damage to degrade considerably the performance of a system. Disruptions can be caused by terrorist attacks, natural disasters, infrastructure failure or major accidents (3).

1.1.3 Measuring resiliency

The “resilience triangle” (Figure 1) represents the loss of functionality from damage and disruption (4). It emerges from disaster research (4). It helps visualize the magnitude of the impacts of a disruption on the infrastructure. The depth of the triangle (y-axis) shows the severity of damage and the length (x-axis) shows the time to recovery (4).

At $t_0$ the system experiences a sudden loss of function from damage and disruption. The system slowly returns to the pre-disaster performance level. Full recovery occurs at $t_1$. The depth of the triangle shows the severity of damage and the duration of the recovery period is $t_1 - t_0$.

![Resiliency Triangle](image)

**Figure 1. Resiliency Triangle (4)**

The R4 framework of resiliency, defined by the Multidisciplinary Center for Earthquake Engineering Research, presents four measures of resiliency (4).
✓ **Robustness**: Ability of systems, system elements and other units of analysis to withstand disaster forces without significant degradation or loss of performance.

✓ **Redundancy**: Extent to which systems, system elements, or other units are substitutable if significant degradation or loss of functionality occurs.

✓ **Resourcefulness**: Ability to diagnose and prioritize problems and to initiate solutions by identifying and mobilizing material, monetary, informational, technological and human resources.

✓ **Rapidity**: Capacity to restore functionality in a timely way, containing losses and avoiding disruptions.

### 1.1.4 Freight Resiliency

A research study by Dr. Anne Goodchild et al. at the University of Washington defined several important concepts related with resiliency in the context of freight transportation. The following definitions (Table 2) and concepts are the result of their extensive research on conceptualizing freight resiliency.

#### 1.1.4.1 Definition

Freight transportation system resilience is the ability for the system to absorb the consequences of disruptions, to reduce the impacts of disruptions, and maintain freight mobility (5). Part of the system’s ability to absorb shocks and disruptions is related to both the capacity for resilience in the physical infrastructure as well as the capacity of the managing organization to respond (5).

There is a relationship between the physical infrastructure and the managing organization because the recovery from disasters includes long term planning dependent on the repair or
replacement of debilitated infrastructure and on the ability of the freight transportation infrastructure and system to distribute goods and provide employment (5).

Table 1. Dimensions of Resiliency (5)

<table>
<thead>
<tr>
<th>Concept</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical Infrastructure</td>
<td>System of network of nodes and links, sensors, and information technology infrastructure that support freight transportation and travel</td>
</tr>
<tr>
<td>Managing Organization</td>
<td>Unit that oversees the construction, maintenance, and performance of the freight transportation physical infrastructure.</td>
</tr>
<tr>
<td>System Users</td>
<td>Business enterprises that move goods on the transportation infrastructure and utilize roadway information.</td>
</tr>
</tbody>
</table>

1.1.4.2 Types of Resiliency

Two researchers, Gunderson and Pritchard (2002), categorized two general types of resiliency termed Engineering Resilience and Ecological Resilience (3). Engineering Resilience is the time it takes for a system to recover and Ecological Resilience is the magnitude of the disruption (3).

Furthermore, Gunderson and Pritchard, stated in their research that the properties of vulnerability and adaptive capacity (3). Vulnerability is the ease in which an event may cause a system to deviate from its normal behavior and adaptive capacity is the ability of a system to respond to a disruption. The concept of adaptive capacity is similar to flexibility. According to Morlok and Chang in 2004, flexibility is the ability to accommodate changes in demand or traffic flows without significant declines in performance (3).

1.1.4.3 Infrastructure Dimension

The physical infrastructure is a fundamental piece of the freight transportation system (5). It provides the network on which goods travel and contribute to economic activity. Resilience on this dimension is the ability of the network, given its capacity to supply lane miles, to facilitate
the movement of goods under capacity-constrained conditions due to a disruption (Table 1). The infrastructure itself contains the capacity for resilience in the design and quality of structures of that infrastructure (5).

### 1.1.4.4 Managing Organization Dimension

Infrastructure management occurs within the organizational dimension (5). The managing organization is the unit that oversees the construction, maintenance, and performance of the freight transportation physical infrastructure (Table 1). Awareness of properties of infrastructure resilience provides the managing organization information about the system resources in order to foster the ability to effectively manage, allocate, and deploy resources when preparing and responding to disruptions (5). The ability for the managing organization to prepare for and respond to disruptions in a timely manner is an indirect measure of the freight transportation system’s resilience (5).

One organizational resilience strategy includes effective communication within the managing organization and between the managing organization and other organizations involved in transportation (5). Timely dissemination of information about the system’s status triggers not only the organization’s ability to be responsive, flexible, and adaptable, but also the overall freight transportation system’s resilience (5).

The managing organization’s resilience contributes to the overall resilience of the freight transportation system, which suggests that properties of resilience at the organizational level should promote information sharing, support quality and timeliness of information, and the successful external dissemination of information (5).
A framework for defining freight transportation system resilience offers the opportunity to begin a systematic assessment of system resilience to guide freight transportation systems planning, operations management, infrastructure investments, and program investments (5).

1.1.4.5 User Dimension

Users are not generally responsible for promoting the system’s resilience but individual enterprises can impact system performance, and therefore a system’s ability to move goods and recover after a disruption (5). Government agencies must provide and manage infrastructure and enterprises must behave in a way that supports system function (5).

Interactions between individual enterprises and the system’s managing organization are necessary for either to achieve resilience (5). Governmental policies and the conditions of the physical infrastructure are precursors to the resilience of enterprises. A government’s response to disruptions can have a greater impact on the enterprise than the disruption itself (5). The policies of the federal, state and local governments impact an enterprise’s ability to move goods (5). These policies include federal policies such as the Customs-Trade Partnership against Terrorism and the Container Security Initiative, in addition of local policies (5).

Enterprises that have the ability to disseminate information quickly, make effective and prompt decisions, postpone shipments, and alter the path of the supply chain by calling on alternate suppliers facilitate the resilience of the freight transportation system (5).

Freight transportation system resilience is a product of the dynamic interaction between organizational entities, user enterprises, and the physical infrastructure (5). The effectiveness of resilience at the user dimension contributes to overall resilience to the extent that system users
and the system managers are well connected with dependable and trustworthy channels of communication and fortified relationships prior to the onset of a disruption (5).

**Table 2. Concept Definitions for Freight Resiliency (5)**

<table>
<thead>
<tr>
<th>Concept</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infrastructure Resilience</td>
<td>Ability of the network to move goods in the face of infrastructure failure, either through a reduction in capacity, a complete failure, or a failure in the information infrastructure to provide information.</td>
</tr>
<tr>
<td>Managing Organization Resilience</td>
<td>Capacity to meet priorities and achieve goals in a timely and efficient manner in order to contain losses</td>
</tr>
<tr>
<td>Enterprise Resilience</td>
<td>Ability of an enterprise to move goods in a timely and efficient manner in the face of infrastructure disruption.</td>
</tr>
<tr>
<td>Freight Transportation System Resilience</td>
<td>Ability for the freight transportation system to absorb shocks and reduce the consequences of disruptions. Freight transportation system resilience can be deconstructed along its component dimensions: the infrastructure, the managing organization, and the system users.</td>
</tr>
<tr>
<td>Resilience Strategies</td>
<td>Actions or behaviors of users or managing organizations, that promotes resilience in one or a number of dimensions of the freight transportation system.</td>
</tr>
</tbody>
</table>

1.1.4.6 Resiliency before, during and after disruptive events

Dividing resilience into time periods (before, during and after) allows decision makers to comprehend the impact of strategies on freight resilience (5). Four analytical categories provide the framework in relation to the disruption: mitigation, preparedness, response, and recovery (5). Many actions that enhance resilience are most applicable to mitigation efforts. Mitigation describes actions that are taken prior to any disruption that help control the impact of disruptions.

The actions taken by users and organizations during and after a disruption will also impact freight resilience. Rapid dissemination of information regarding the disruption and mobilization of repair crews to address the disruption are actions that can improve resilience (5).

1.1.4.7 Properties of Resilience

Goodchild’s study defines six properties of freight resilience: redundancy, autonomy of components, collaboration, efficiency, adaptability, and interdependence (Table 3). These properties allow the freight transportation system to be more resilient (5). They can be used by
users, managing organizations, and infrastructure. These properties can contribute to the overall ability of the freight transportation system to recover from disruptions at the infrastructure, organizational, or user dimension (5). Properties of resilience are attributed to users, managing organizations and infrastructure and are not mutually exclusive (5).

**Table 3. Properties of Freight Resiliency (5)**

<table>
<thead>
<tr>
<th>Properties</th>
<th>Physical Infrastructure Dimension</th>
<th>Managing Organization Dimension</th>
<th>User Dimension</th>
<th>Contribution to Freight Systems Resiliency</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Redundancy</strong></td>
<td>Availability of multiple and alternate routing options</td>
<td>Multiple information sources and points of delivery</td>
<td>Multiple parts and materials suppliers; information backed up on distributed servers</td>
<td>Promotes flexibility; supports robustness</td>
</tr>
<tr>
<td><strong>Autonomy of Components</strong></td>
<td>The ability of highway system to function when air space closed; independent signal controls for each intersection</td>
<td>Independence of functional units in an organization, e.g. approvals &amp; decision making can be independent of established hierarchies</td>
<td>Independence of functional units in an enterprise, e.g. procurement, billing, manufacturing, and distribution</td>
<td>Supports system operability despite the failure of individual system components; supports robustness</td>
</tr>
<tr>
<td><strong>Collaboration</strong></td>
<td>Working partnership between federal, state, regional and local public agencies to plan, construct and operate the full freight transportation network to optimize system use</td>
<td>Good internal communication across divisions and external communication with system users; leadership across all levels of the organization</td>
<td>Public-private partnerships to build relationships between organizations</td>
<td>Supports innovative problem solving, reduces miscommunications, spreads risk across groups; Promotes network, versus local, freight system optimization and resiliency.</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>Network designs that reduce travel time between origin and destination</td>
<td>Use of effective mechanisms to prioritize spending within the organization and on infrastructure</td>
<td>Coordination across the supply chain with relationships built across the different parties</td>
<td>Allows resources to be spent on activities or projects that provide most benefit to the users</td>
</tr>
<tr>
<td><strong>Adaptability</strong></td>
<td>Designed with short life-spans and the intent for regular replacement or for</td>
<td>Familiarity of roles and responsibilities across levels of the organization; cross trained employees; leadership can be</td>
<td>Ability to postpone decision making and shipping; build-to order business</td>
<td>Promotes flexibility and system efficiency; supports robustness</td>
</tr>
</tbody>
</table>
the capability to expand capacity without total facility engaged at all levels. model

| Interdependence | Seamless mode transfers; intermodal facilities | Relationships are established across separate, but related agencies and within agencies; mutual understanding of the value & benefit from interaction | Standardization of parts and interchangeability | Exhibits smooth connections and transitions across parts of the system; promotes system efficiency; spreads risk across the system to reduce risk |

2. Objective

The freight transportation system is an important component of economic growth. An important component is a reliable system that delivers goods very close to the time they are needed. A disruption in a system might cause considerable damage that could take long to recover. A freight transportation system should be resilient enough to provide reliable services and return quickly to service after a disruption.

The goal of the study is to design a methodology that provides information of freight resiliency measures by making use of truck traffic data from American Truck Research Institute (ATRI) for the Beloit to Hudson corridor.

3. Literature Review

3.1 Previous Studies on Resiliency

Studies on resiliency had been focused on four different applications (5):

- Infrastructure
- Supply Chains
- Enterprises
- Disaster Research
3.1.1 Development of a Statewide Freight System Resiliency Plan

The Washington State Department of Transportation decided to undertake an analysis of how they could improve their ability to economically recover from disasters by creating a Freight System Resiliency Plan. The plan was developed as a complement to the existing emergency response plans by anticipating how the state department of transportation should control, manage and monitor its network assets and work with the private industry to improve resiliency.

The state DOT worked with the Massachusetts Institute of Technology’s Center for Transportation and Logistics to review all existing state plans for disaster response and recovery. In parallel to the review, several dozen interviews were conducted with representatives of the public and private sectors in the state of Washington. The end result is a process by which any state can create a Freight System Resiliency Plan.

The process of creating a Freight System Resiliency Plan consists of three phases: identification, assessment and implementation (2). Each phase consists of different tasks that may differ state by state. The process should be similar for all plans (2).

The objective of the identification phase is to identify the economic goals and key usage patterns (2). The transportation infrastructure in the region should be analyzed in the context of how it is used by different shippers. It should consider origins, destinations, direction and flow of goods (2). Once key customers segments are identified, the next step is to understand key objectives, priorities and requirements for each of the segments (2).

An important step in the identification phase is quantifying the freight flows for the region (2). The central players in the freight shipping community include the carriers, freight forwarders, and other agents that facilitate the movement of freight and use of the freight transportation
system (2). The following are four user groups that represent the four major types of flows through the corridor (2).

- **Starting and ending outside corridor**: Originates and destines in locations outside the corridor, but travels a portion of the corridor.
- **From corridor, ending outside**: Originates along the corridor but is destined outside the corridor.
- **From outside, ending in corridor**: Originates elsewhere but is destined to a location along the corridor.
- **Starting and ending in corridor**: Starts and ends at locations along the corridor.

The reason for analyzing these flow patterns is to evaluate the effects on the occasion of disruption (2). This also can pave a way to further suggest alternative routes to relevant user groups, minimizing delays and loses in the case of disruptive events (2).

The assessment phase takes the customer segmentation and determines the current state of the network (2). It is important to identify those points that are most vulnerable to disruption. The analysis should include an assignment of magnitude and probability of failure which will lead to a ranking of infrastructure sites that the DOT should focus their immediate attention (2). The first step in this phase is to conduct a vulnerability assessment of the region’s transportation network (2). The second step is to create public/private collaboration mechanisms. The third step is to determine what regulatory and policy procedures need to be put in place and the fourth step is to determine how plans and policies will be enacted (2).

The implementation phase takes the deliverables of the previous phases and tests whether the plan can be implemented (2). The idea is to do an internal test to work out inconsistencies and
procedures. The first step in this phase is to conduct a small scale simulation to analyze how the system can mitigate, recover and restore to the establish metrics (2). The objective is to observe individual effects in order to understand the full impact. The second step is to test the plan with a large scale simulation (2).

The three phase approach can be adopted and customized by any state transportation department (2). The specific tasks per phase may differ.

3.1.2 Pitera’s Interpreting Resiliency

Kelly Pitera’s research explored and evaluated resiliency efforts used by importing enterprises, focusing on goods movement within the supply chain. Information was gathered to understand how enterprises were attempting to improve resiliency with their supply chain in the face of increasing risks (6). Several strategies were identified which result reduced exposure to supply chain disruptions and/or mitigate disruption impacts (6). The research provided a summary of existing strategies but presented a framework for discussing resilience in terms of strategic resiliency and enabler strategies in order to understand the implications of employing various resiliency strategies that can assist companies in making decisions which are in the best interest of a successful supply chain (6). The research also discussed how knowledge of these strategies can assist freight transportation system planners, designers and managers in improving transportation system resilience (6).

Pitera found through interviews that while resiliency was in the field of vision of interviewees, the concept was not a supply chain priority. While resiliency, related to transportation, can impact supply chain costs and efficiency, and enterprises often cites costs and efficiency as
supply chain priorities, there appeared to be a disconnect between the impacts of resilience and enterprise priorities (6).

Pitera identified fifteen resiliency strategies from the interviews. Four were categorized as enabler strategies (6):

- Relationships,
- Use of information and technology,
- Communication, and
- Flexible culture.

Enabler strategies are used to increase the effectiveness of other resiliency efforts and are often an integral part of supply chain operations prior to concerns about resiliency. Eleven strategies were categorized as strategic resiliency strategies (6):

- Flexible transportation.
- C-TPAT certification.
- Distribution center structure.
- Resilient nature of suppliers.
- Expedited freight.
- Use of multiple ports/carriers.
- Employees overseas.
- Extra capacity at distribution centers.
- Off-peak deliveries.
- Domestic sourcing of components.
- Premium transportation.

Pitera states that the strategies are typically part of a long term plan of action but are implemented on a day to day or as needed basis. Both type of strategies result in the reduction of exposure to supply chain disruptions and/or the mitigation of disruption impacts (6). She adds that identifying commonly used strategies can assist those who manage transportation systems in understanding how enterprises continue to operate on disruptions (6).
The research attempted a qualitative assessment of strategies and a ranking of enterprises to give a value to resiliency efforts (6). The amount of information required to assess the value of resiliency strategies within a supply chain make this type of assessment both time consuming and costly (6).

Pitera states that strategies evaluated were drawn from interviews and can be assumed that are commonly used among supply chains in various industries (6). Enterprises in which disruptions are common and the continued flow of goods is crucial to operations are more likely to have a more developed resiliency portfolio (6). That is not often the result of more developed enterprise thinking concerning on transportation resiliency, but response to common occurrences or events within the supply chain (6). Enterprises which have less experience with disruptions or disruption impacts are more likely to have less developed resiliency portfolios, with more focus on enabling strategies than strategic resiliency strategies (6).

Overall, Pitera concludes that enterprises can benefit from the implementation of enabling and strategic resiliency strategies (6). Incorporating the strategies which are best individually suited for a given supply chain can improve resiliency and improve productivity and efficiency, reducing costs and increasing sales (6).

3.1.3 Sheffi’s A Supply Chain View of the Resilient Enterprise

Yossi Sheffi’s research was motivated by the 9/11 attacks and looked at numerous cases of disruption, discovering the common traits between corporations and supply chains that performed well and distinguishing them from those that did not (7). It involved studies of companies and follow-ups with managers who were involved with disrupted operations. The research team examined the security and resiliency strategies of one group of companies and a
second group of companies included companies that experienced disruptions (7). Not all companies agreed to interviews on the subject. In addition to telephone surveys and interviews, the team obtained information from different conferences in which many companies shared their security, resilience and disruption experiences (7).

Sheffi developed a profile which show the effects of a disruption on the performance of a company, whether that performance is measured by sales, production level, profits, customer service or another relevant metric (7). The nature of the disruption was characterized by eight phases (7).

The first phase is preparation. In some cases a company can foresee and prepare for a disruption (7). The second phase is the disruptive event. The third phase is first response aimed at controlling the situation; saving or protecting lives, shutting down affected systems and preventing further damage (7). The fourth phase is initial impact. The full impact of some disruptions can be felt immediately but others can take time to affect a company (7). This depends on factors such as magnitude of the disruption, the available redundancy, and the resilience of the organization and its supply chain (7).

During the time between the disruptive event and full impact, performance deteriorates. The full impact is the fifth phase which can be immediate or delayed (7). The sixth phase is recovery preparations. It typically starts in parallel with first response and sometimes prior to the disruption if it was anticipated. They involve qualifying other suppliers and redirecting supplies (7). The seventh phase is recovery. To get back to normal operation levels, companies make up for lost production with different strategies (7). The final phase is long term impact when the damage is enough to be long standing and difficult to recover from (7).
Besides the disruption profile, Sheffi also developed a vulnerability framework which categorized potential disruptions as a function of their probability and consequences (7). Vulnerability varies considerably from company to company. According to Sheffi, vulnerability is highest when both the likelihood and the impact of disruption are high (7). Rare events or low-consequence events represent the lowest vulnerability levels and require little planning (7). Disruptions that combine high probability and low consequences are part of the scope of daily operations management in the normal flow of business (7). Those characterized by low probability but high impact call for additional planning and response (Figure 2).

![Figure 2. Sheffi’s Vulnerability Chart (7)](image)

Sheffi developed the concept of vulnerability map which categorizes the relative likelihood of potential threats to an organization and the company’s relative resilience to such disruptions (7). Such maps can direct management attention and prioritize the planning (Figure 3).
The assessment of vulnerability is a tool of understanding which is essential when building resilience (7). Sheffi states the resiliency of a company is determined by two variables. One of them is the competitive position of the enterprise and the other is the responsiveness of the supply chain (7). A company must be able to respond quickly or else risk loss of market share. Companies that are very responsive will have the opportunity to gain market share or solidify their position (7).

A company can bolster its resilience by either building redundancy or building flexibility (7). Redundancy in companies is the concept of keeping some resources in reserve to be used in case of a disruption (7). There is more interest in companies to make supply chains more flexible than adding redundancy. Flexibility is building capabilities that can sense threats and respond to them quickly (7).

According to Sheffi, there are five facets of flexibility. The first one is supply and procurement (7). The second one is conversion which measures the company’s ability to respond to a disruption in one of its own manufacturing facilities (7). The third facet is distribution and

**Figure 3. Sheffi’s Vulnerability Map (7)**
costumer-facing activities. Managers need to make a choice about which costumers to serve first in the immediate aftermath of a disruption (7). The fourth facet is control systems which detects disruptions quickly and foster speedy corrective actions (7). The fifth facet is empowering employees to take initiative and actions quickly on the basis of the facts on the ground (7).

Sheffi finalizes by suggesting that companies should increase their flexibility in order to increase their resilience (7). Flexibility would not only increase resilience in times of disruptions but also garners benefits and operational efficiencies in the normal course of business (7).

3.1.4 Tierney and Bruneau’s Conceptualizing and Measuring Resilience, A Key to Disaster Loss Reduction

Kathleen Tierney and Michel Bruneau from the Multidisciplinary Center for Earthquake Engineering Research have collaborated on studies to conceptualize and measure disaster resilience. According to them, disaster resistance emphasizes the importance of pre-disaster mitigation measures that enhance the performance of structures, infrastructure elements, and institutions in reducing losses from a disaster (4). Resilience reflects a concern for improving the capacity of physical and human systems to respond to and recover from extreme events (4).

The goals of their research were to define disaster resilience, develop measures appropriate for assessing resilience, and then demonstrate the utility of the concept through empirical research. To develop a framework, the research team drew on various literatures and research traditions focused on resilience (4). The literature revealed consistent treatments in which resilience was viewed as both strength and the ability to be adaptable after disruptive events (4).

Tierney and Bruneau developed the R4 framework and the resilience triangle (already defined in the background section). In addition they identified four dimensions or domains of resilience: the
technical, organizational, social, and economic (4). The technical domain refers to the physical properties of systems, including the ability to resist damage and loss of function. It includes the physical components that add redundancy (4). Organizational resilience relates to the institutions that manage the physical components of the systems. This includes measures of organizational capacity, planning, training, leadership, experience, and information management that improve disaster-related organizational performance and problem solving (4). The resilience of an emergency management system is based on both the physical components of the system—such as emergency operations centers and emergency vehicles—and on the properties of the emergency management organization itself—such as the quality of the disaster plans—(4). The social dimension encompasses population characteristics—such as poverty, education level—that render social groups either more vulnerable or more adaptable to hazards and disasters (4). Economic resilience has been analyzed in terms of the properties of local economies—such as the ability of firms to make adjustments during non-disaster times—and in terms of their capacity for post-disaster improvisation, innovation, and resource substitution (4).

According to Tierney and Bruneau, understanding the attributes and dimensions of resilience provides guidance for defining and achieving acceptable levels of loss, disruption, and system performance (4). The team suggests a range of approaches to enhance resilience, including mitigation-based strategies, the development of a robust organizational and community capacity to respond to disasters, and improving the coping capabilities of households and businesses (4).
3.1.5 Ortiz, Ecola and Willis’ Freight Transportation Resilience: How a system wide perspective can help Metropolitan Planning Organizations and Departments of Transportation

Ortiz, Ecola and Willis’ research of resiliency on a transportation context begins by stating that advances in supply chain management have resulted in significant economic gains to corporations and consumers (3). These advances depend on a reliable transportation system to facilitate goods movement. According to the authors, the infrastructure that supports these movements, especially in urban areas is operating at or above capacity and is aging (3). There is concern in the business community that the result of increased flows of freight and other traffic, when combined with the limited capacity and age of the system, are making the transportation system brittle in the sense that a small event could have far reaching adverse effects (3). If the transportation system were instead resilient, it would be able to recover quickly from large disasters (3).

The authors continue by defining another set of properties of resilience. These properties include: connectivity supporting multiple alternative paths among origins and destinations, and sufficient capacity and flexibility to use fully the alternative paths, possibly including alternative modes of travel (3).

The authors identified factors that enhance resilience of the transportation system which are improve responsiveness of operations (directing freight traffic to alternate routes), quick infrastructure repairs after a disaster to limit the effect of a disruption, and add capacity and provide flexibility (additional lanes) in the transportation system in response to a disruption (3). The authors also identified factors that degrade resilience which are system congestion and obsolete infrastructure (3).
Ortiz, Ecola and Willis state that DOTs and MPOs may improve resilience by focusing investments and planning to address those factors that improve the resilience of the system (3). DOTs, in particular, can plan for disruptions, using experience from small disturbances and exercises to practice rerouting traffic and repairing quickly damaged infrastructure (3). The ability of DOTs to manage actively transportation system resources to meet demand and key needs is critical (3). Given their role in system planning, MPOs can improve resilience through building, maintaining, and applying transportation planning models that consider the dynamism of a system (3). Incorporating additional system capacity into planning and direct engagement with the freight community to understand particular needs can also enhance resilience (3). They add that DOTs and MPOs must coordinate their efforts to improve resiliency in the transportation corridors under their jurisdictions (3).

4. Scope of the Study

The objective of the study is to develop a methodology to measure freight resiliency in order to understand how the corridor performed during two disruptive events. The study does not provide exact reasons of why the Beloit to Hudson corridor performed in a certain way, instead probable reasons will be given in cases that merit it. The methodology was applied to the corridor to show how it works.

4.1 Study Area: Beloit to Hudson Corridor

The Beloit to Hudson Corridor runs approximately 290 miles along Interstate 94 from Hudson to Tomah, Wisconsin and continues along Interstate 90 to Beloit. The corridor supports high volumes of freight and passenger travel and has a unique role as the critical backbone in Wisconsin to freight and passenger mobility and accessibility.
Research to know the performance of the corridor is important to prepare and respond to unanticipated events. Two weather events in 2008, a winter storm and major floods, had shown how fragile some sections of the corridor can be. This study is entirely focused on the corridor. Figure 4 shows the corridor with all interchanges and the number of segments that comprise it. Table 4 provides information of each of the 58 segments shown in the map.

4.2 Disruptive Events

4.2.1 February 2008 Winter Storm

On February 6, 2008 a severe winter storm hit Wisconsin and resulted in over 13 inches of snow and ice. Difficult travel conditions caused tractor-trailers to lose traction and block the road (8). As weather deteriorated, directions experienced stand still conditions for over 8 hours (8, 9).
Figure 5 shows the snowfall amounts during the event from February 5 to February 7. Over 18 inches of snow fell in Rock County and portions of Dane, Green, Walworth and Jefferson counties between February 5 and February 7 (10). 21 inches of snow fell in Beloit and 13 inches in Madison on the same time period (10).

4.2.2 June 2008 Midwest Floods

On June 7, 2008 at least six confirmed tornadoes touched down in Wisconsin. Governor Jim Doyle declared a state of emergency in 30 counties on June 9 due to the flooding. The event began in June 7 and lasted until June 28. Heavy rains in Wisconsin Dells led to the Dell creek bypassing the dam holding Lake Delton. On June 9 water rushing out of the lake eroded a section of County Highway A and washed away three homes and tore apart several others. This event led to lane closures on the corridor.

The Wisconsin Department of Transportation shut down one of the eastbound lanes of the corridor starting at Mauston and closed the section from Portage to Madison at 10 pm Thursday June 12 (11). The lanes remained closed until June 15. The westbound lanes from Portage to Madison were also closed but re-opened on Friday, June 14 (12).

Figure 6 shows the rainfall amounts during a portion of the event from June 5 to June 13, 2008. The highest rainfall amounts were registered in Columbia County with over 14 inches of rain (13). The counties of Sauk and Dodge received near 12 inches of rain. A portion of the corridor, near the cities of Portage and Mauston, received over 10 inches of rain (13).
Figure 5. National Oceanic and Atmospheric Administration (NOAA) Image of February 2008 snow storm with the corridor highlighted (10).
Figure 6. NWS map of Wisconsin rainfall totals for June 5 to June 13 2008 with the corridor highlighted (13)

5. Type of Research

This research is an exploratory project using data from the American Truck Research Institute (ATRI), collected through the Freight Performance Measurement Initiative, a partnership
between FHWA and ATRI, along an interstate corridor to illustrate measures for freight transportation resiliency (14).

6. Methodology

ATRI data was obtained for selective dates before, during and after the February 2008 winter storm and the June 2008 Midwest floods. In the first step of the process, the corridor was segmented. Each segment was bounded by two interchanges. In the second step, truck counts and speeds were calculated per segment, per direction, per event. The third step consisted in understanding the corridor by observing trends in truck counts and truck speeds on a daily basis before, during and after the two weather events. The fourth step consisted in evaluating freight resiliency performance measures for the entire corridor during the disruptive events.

6.1 Creation of Segments

The Beloit to Hudson Corridor was segmented using the intersections as limits. There are a total of 59 intersections to trace the truck entry and exits from the corridor. The segment limits were established with the intersections and a total of 58 segments made up the Beloit to Hudson Corridor.

Segments numbering started with 1 in Hudson, increasing to the east. The 58th segment is at the Wisconsin-Illinois border near Beloit. The corridor segments are presented in table 4.

Table 4. Segments in the Beloit to Hudson Corridor

<table>
<thead>
<tr>
<th>Segment</th>
<th>Start</th>
<th>End</th>
<th>Length (Miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>I-94 and Route 35</td>
<td>I-94 and Carmichael Road</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>I-94 and Carmichael Road</td>
<td>I-94 and Route 35</td>
<td>1.3</td>
</tr>
<tr>
<td>3</td>
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<td>I-94 and Route 12</td>
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</tr>
<tr>
<td>4</td>
<td>I-94 and Route 12</td>
<td>I-94 and Route 65</td>
<td>5.9</td>
</tr>
<tr>
<td>5</td>
<td>I-94 and Route 65</td>
<td>I-94 and Route T</td>
<td>6.5</td>
</tr>
<tr>
<td>6</td>
<td>I-94 and Route T</td>
<td>I-94 and Route 63</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Route 1</td>
<td>Route 2</td>
<td>Distance</td>
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<td>7</td>
<td>I-94 and Route 63</td>
<td>I-94 and Route B</td>
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</tbody>
</table>
The data set provided by ATRI provided unique truck IDs, date and time, latitudes, and longitudes. A total of 9,608 unique truck IDs were available for February 5 to 7 and 30,633 for June 1 to 16. The number of unique truck IDs available for both weather events are a sample and not the total amount of trucks that traversed the corridor.

A VBA script was developed by Ravi Pavuluri to calculate truck speeds considering time differences and distances obtained from latitudes and longitudes. Appendix B provides charts that illustrate speeds variations among segments. Another script was developed to obtain origin-destination data to quantify the four flow types mentioned in the literature review. The origin-destination calculations only considered those truck trips which traversed at least two segments on the corridor, due to data reliability issues. Truck counts were calculated for each segment using Microsoft Excel. Appendix A provides charts that illustrate truck count variations among segments. This would give a general overview of how the freight system is performing during these months.

6.3 Understanding the Corridor

Data was obtained for February 5, 6 and 7 and for June 1 to 16 in 2008 to evaluate freight performance before, during and after disruptive events. Data for the entire month of March 2009
(no disruption) was obtained to observe the trend in the travel patterns with flow types, average speeds and counts in each direction per segment.

6.3.1 Corridor performance on March 2009

Truck counts and average speeds per direction were obtained for each segment. There was a gradual increase in truck counts along the corridor from Hudson (segment 1) towards Madison (segments 40 to 45). Most of the segments, regardless of direction, had counts of over 10,000 trucks (Table 5). Speeds were not rounded up to notice the differences between segments. Multiple segments had speeds over 54 mph. The segments with lowest speeds were located near Hudson and Beloit (Table 6).

Table 5. Segments with highest truck counts at the Beloit to Hudson corridor on March 2009

<table>
<thead>
<tr>
<th>Segment</th>
<th>EB Count</th>
<th>Segment</th>
<th>WB Count</th>
<th>Segment</th>
<th>Total Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>18472</td>
<td>40</td>
<td>20636</td>
<td>40</td>
<td>39041</td>
</tr>
<tr>
<td>40</td>
<td>18405</td>
<td>42</td>
<td>20500</td>
<td>42</td>
<td>38972</td>
</tr>
<tr>
<td>41</td>
<td>18121</td>
<td>38</td>
<td>20402</td>
<td>41</td>
<td>38323</td>
</tr>
<tr>
<td>38</td>
<td>17914</td>
<td>33</td>
<td>20216</td>
<td>38</td>
<td>38316</td>
</tr>
<tr>
<td>43</td>
<td>17882</td>
<td>41</td>
<td>20202</td>
<td>33</td>
<td>37844</td>
</tr>
<tr>
<td>33</td>
<td>17628</td>
<td>34</td>
<td>20026</td>
<td>34</td>
<td>37565</td>
</tr>
<tr>
<td>34</td>
<td>17539</td>
<td>37</td>
<td>19841</td>
<td>43</td>
<td>37503</td>
</tr>
<tr>
<td>37</td>
<td>17406</td>
<td>36</td>
<td>19814</td>
<td>37</td>
<td>37247</td>
</tr>
<tr>
<td>36</td>
<td>17368</td>
<td>35</td>
<td>19801</td>
<td>36</td>
<td>37182</td>
</tr>
<tr>
<td>45</td>
<td>17362</td>
<td>39</td>
<td>19715</td>
<td>35</td>
<td>37115</td>
</tr>
</tbody>
</table>

Table 6. Segments with lowest truck speeds at the Beloit to Hudson corridor on March 2009

<table>
<thead>
<tr>
<th>Segment</th>
<th>EB Speed (mph)</th>
<th>Segment</th>
<th>WB Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td>58</td>
<td>46.1</td>
<td>58</td>
<td>46.4</td>
</tr>
<tr>
<td>1</td>
<td>46.9</td>
<td>57</td>
<td>48.6</td>
</tr>
<tr>
<td>57</td>
<td>48.0</td>
<td>27</td>
<td>50.1</td>
</tr>
<tr>
<td>2</td>
<td>48.1</td>
<td>26</td>
<td>50.2</td>
</tr>
<tr>
<td>3</td>
<td>48.8</td>
<td>56</td>
<td>50.2</td>
</tr>
<tr>
<td>4</td>
<td>49.1</td>
<td>28</td>
<td>50.2</td>
</tr>
</tbody>
</table>
The majority of truck trips were those that started and ended within the corridor. Trucks starting outside the corridor and ending outside the corridor had the smallest share of all (Table 7).

**Table 7. Flow Type Distribution on March 2009**

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>March 2009 Truck Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EB</td>
</tr>
<tr>
<td>Starting and Ending Outside Corridor</td>
<td>85</td>
</tr>
<tr>
<td>Starting Inside Corridor, Ending Outside Corridor</td>
<td>2858</td>
</tr>
<tr>
<td>Starting Outside Corridor, Ending Inside Corridor</td>
<td>871</td>
</tr>
<tr>
<td>Starting and Ending Inside Corridor</td>
<td>25898</td>
</tr>
</tbody>
</table>

Additional origin-destination data was obtained for pairs of cities along the corridor: Madison, Hudson, Beloit, Eau Claire and Janesville. The truck counts on Table 8 are trips between the intersections located in the origin city and the intersections located in the destination city for the entire month of March. It is not necessarily one intersection per city, there can be more than one depending on the city.

**Table 8. Origin to Destination Counts between Cities along Corridor on March 2009**

<table>
<thead>
<tr>
<th>From Origin</th>
<th>Hudson &amp; Beyond</th>
<th>Eau Claire</th>
<th>Madison</th>
<th>Janesville</th>
<th>Beloit &amp; Beyond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hudson &amp; Beyond</td>
<td>-</td>
<td>27</td>
<td>82</td>
<td>144</td>
<td>250</td>
</tr>
<tr>
<td>Eau Claire</td>
<td>21</td>
<td>-</td>
<td>13</td>
<td>17</td>
<td>20</td>
</tr>
<tr>
<td>Madison</td>
<td>96</td>
<td>14</td>
<td>-</td>
<td>171</td>
<td>264</td>
</tr>
<tr>
<td>Janesville</td>
<td>138</td>
<td>23</td>
<td>136</td>
<td>-</td>
<td>284</td>
</tr>
<tr>
<td>Beloit &amp; Beyond</td>
<td>363</td>
<td>33</td>
<td>327</td>
<td>353</td>
<td>-</td>
</tr>
</tbody>
</table>
Segments #30 to #49 had total truck counts higher than 30,000 and also had the highest counts in both directions. The segments with the highest truck counts (total, eastbound, westbound) were between Tomah and Madison.

Most of the segments in the eastbound direction operated at average speeds near or over 54 mph. In the westbound direction, the corridor mostly operated with average speeds between 52 and 53 mph. Overall, the speeds are similar in all segments, except in the ends of the corridor at Hudson and Beloit where the speeds were lower than the rest of the corridor.

**6.3.2 Corridor performance from February 5th to 7th in 2008**

From February 5 to 7 there was a gradual increase in truck counts along the corridor from Hudson (segment 1) towards Madison (segment 49). The highest truck counts were on a portion from the intersection of Interstates 94/90 with Route 80 near New Lisbon to the intersection of Interstates 94/90/39 and Route 151 near Madison (Table 9).

The ten segments with the highest truck counts in March 2009 also had the highest counts in February 5, 6 and 7. Truck counts increased eastward until reaching a peak point between segments #40 and #50 and then they started to decrease. Westbound counts were slightly higher than eastbound counts in almost all segments. More than half of the segments had speeds over 53 mph. Ten segments had speeds over 48 mph. The segments with the lowest speeds were located near Beloit (Table 10). Overall, the segments had lower speeds than March 2009 especially in the westbound direction.

<table>
<thead>
<tr>
<th>Segment</th>
<th>EB Count</th>
<th>Segment</th>
<th>WB Count</th>
<th>Segment</th>
<th>Total Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>2751</td>
<td>40</td>
<td>2889</td>
<td>42</td>
<td>5631</td>
</tr>
<tr>
<td>40</td>
<td>2676</td>
<td>42</td>
<td>2880</td>
<td>40</td>
<td>5565</td>
</tr>
</tbody>
</table>
Table 10. Segments with lowest truck speeds at the Beloit to Hudson corridor from February 5-7

<table>
<thead>
<tr>
<th>Segment</th>
<th>EB Speed</th>
<th>Segment</th>
<th>WB Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>58</td>
<td>45.2</td>
<td>58</td>
<td>39.1</td>
</tr>
<tr>
<td>56</td>
<td>45.6</td>
<td>56</td>
<td>38.0</td>
</tr>
<tr>
<td>57</td>
<td>45.9</td>
<td>57</td>
<td>39.5</td>
</tr>
<tr>
<td>55</td>
<td>46.3</td>
<td>55</td>
<td>37.2</td>
</tr>
<tr>
<td>54</td>
<td>46.8</td>
<td>54</td>
<td>37.3</td>
</tr>
<tr>
<td>52</td>
<td>47.0</td>
<td>52</td>
<td>37.3</td>
</tr>
<tr>
<td>51</td>
<td>47.0</td>
<td>51</td>
<td>37.9</td>
</tr>
<tr>
<td>53</td>
<td>47.1</td>
<td>53</td>
<td>37.5</td>
</tr>
<tr>
<td>50</td>
<td>47.3</td>
<td>50</td>
<td>38.4</td>
</tr>
<tr>
<td>49</td>
<td>47.6</td>
<td>49</td>
<td>38.6</td>
</tr>
</tbody>
</table>

The majority of truck trips started and ended within the corridor (Table 11). Truck trips that started and ended outside the corridor had the smallest share. This was observed in March 2009 as well.

Table 11. Flow Type Distribution from February 5 to 7, 2008

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>February 5 Truck Counts</th>
<th>February 6 Truck Counts</th>
<th>February 7 Truck Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EB</td>
<td>WB</td>
<td>Total</td>
</tr>
<tr>
<td>Starting and Ending Outside Corridor</td>
<td>4</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Starting Inside Corridor, Ending Outside Corridor</td>
<td>196</td>
<td>52</td>
<td>248</td>
</tr>
<tr>
<td>Starting Outside Corridor, Ending Inside Corridor</td>
<td>46</td>
<td>230</td>
<td>276</td>
</tr>
<tr>
<td>Starting and Ending Inside Corridor</td>
<td>1577</td>
<td>1323</td>
<td>2900</td>
</tr>
</tbody>
</table>
Origin destination data on Table 12 have the total truck counts from different pairs of intersections located in several cities for February 5, 6 and 7.

**Table 12. Origin to Destination Counts between Cities along Corridor from February 5 to 7, 2008**

<table>
<thead>
<tr>
<th>From Origin</th>
<th>Truck Counts to Destination of February 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hudson &amp; Beyond</td>
</tr>
<tr>
<td>Hudson &amp; Beyond</td>
<td>-</td>
</tr>
<tr>
<td>Eau Claire</td>
<td>1</td>
</tr>
<tr>
<td>Madison</td>
<td>4</td>
</tr>
<tr>
<td>Janesville</td>
<td>6</td>
</tr>
<tr>
<td>Beloit &amp; Beyond</td>
<td>15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>From Origin</th>
<th>Truck Counts to Destination on February 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hudson &amp; Beyond</td>
</tr>
<tr>
<td>Hudson &amp; Beyond</td>
<td>-</td>
</tr>
<tr>
<td>Eau Claire</td>
<td>3</td>
</tr>
<tr>
<td>Madison</td>
<td>2</td>
</tr>
<tr>
<td>Janesville</td>
<td>2</td>
</tr>
<tr>
<td>Beloit &amp; Beyond</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>From Origin</th>
<th>Truck Counts to Destination on February 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hudson &amp; Beyond</td>
</tr>
<tr>
<td>Hudson &amp; Beyond</td>
<td>-</td>
</tr>
<tr>
<td>Eau Claire</td>
<td>0</td>
</tr>
<tr>
<td>Madison</td>
<td>4</td>
</tr>
<tr>
<td>Janesville</td>
<td>5</td>
</tr>
<tr>
<td>Beloit &amp; Beyond</td>
<td>15</td>
</tr>
</tbody>
</table>

From February 5 (before storm) and February 6 (during storm) all segments in the eastbound direction had 10% to 20% reductions in truck counts. The westbound direction suffered the most with reductions between 20% and 40%. Speeds on the eastbound direction also had reductions in all segments. From segment #1 to #31 the reductions were below 10%. The remaining segments had reductions between 10% and 25%. On the westbound direction, all segments of the corridor had reductions. Many of them had reductions from 20% up to 45%.

All counts and speeds in February 6 (during storm) were compared with February 7 (after storm). Segments #1 to #40 had reductions in truck counts in the eastbound direction. The westbound direction had considerable truck count increases in all segments. There were increases of over
50% after segment #17. Most segments had speed increases in the eastbound direction and speed decreases in the westbound direction.

### 6.3.3 Corridor performance from June 1st to 16th 2008

From June 1 to June 16 the corridor portion from the intersection of Interstates 94/90 with Route 80 near New Lisbon to the intersection of Interstates 94/90/39 and Route 151 near Madison had the highest truck counts (Table 13). This happened in March 2009 and in February 2008 as well.

**Table 13. Segments with highest truck counts at the Beloit to Hudson corridor from June 1-16**

<table>
<thead>
<tr>
<th>Segment</th>
<th>EB Counts</th>
<th>Segment</th>
<th>WB Counts</th>
<th>Segment</th>
<th>Total Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>11289</td>
<td>40</td>
<td>13613</td>
<td>40</td>
<td>24891</td>
</tr>
<tr>
<td>40</td>
<td>11278</td>
<td>42</td>
<td>13457</td>
<td>42</td>
<td>24746</td>
</tr>
<tr>
<td>41</td>
<td>11147</td>
<td>33</td>
<td>13453</td>
<td>41</td>
<td>24476</td>
</tr>
<tr>
<td>33</td>
<td>11010</td>
<td>38</td>
<td>13442</td>
<td>33</td>
<td>24463</td>
</tr>
<tr>
<td>43</td>
<td>10951</td>
<td>41</td>
<td>13329</td>
<td>38</td>
<td>24323</td>
</tr>
<tr>
<td>34</td>
<td>10898</td>
<td>34</td>
<td>13223</td>
<td>34</td>
<td>24121</td>
</tr>
<tr>
<td>38</td>
<td>10881</td>
<td>37</td>
<td>13087</td>
<td>36</td>
<td>23893</td>
</tr>
<tr>
<td>36</td>
<td>10820</td>
<td>39</td>
<td>13087</td>
<td>43</td>
<td>23886</td>
</tr>
<tr>
<td>37</td>
<td>10798</td>
<td>36</td>
<td>13073</td>
<td>37</td>
<td>23885</td>
</tr>
<tr>
<td>35</td>
<td>10785</td>
<td>35</td>
<td>13055</td>
<td>35</td>
<td>23840</td>
</tr>
</tbody>
</table>

**Table 14. Segments with lowest truck speeds at the Beloit to Hudson corridor from June 1-16**

<table>
<thead>
<tr>
<th>Segment</th>
<th>EB Speeds</th>
<th>Segment</th>
<th>WB Speeds</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>48.7</td>
<td>58</td>
<td>48.3</td>
</tr>
<tr>
<td>3</td>
<td>48.8</td>
<td>57</td>
<td>50.3</td>
</tr>
<tr>
<td>2</td>
<td>48.8</td>
<td>27</td>
<td>51.8</td>
</tr>
<tr>
<td>58</td>
<td>49.4</td>
<td>28</td>
<td>51.8</td>
</tr>
<tr>
<td>4</td>
<td>50.1</td>
<td>26</td>
<td>51.9</td>
</tr>
<tr>
<td>11</td>
<td>50.8</td>
<td>56</td>
<td>51.9</td>
</tr>
<tr>
<td>57</td>
<td>50.8</td>
<td>55</td>
<td>52.3</td>
</tr>
<tr>
<td>12</td>
<td>51.0</td>
<td>54</td>
<td>52.5</td>
</tr>
<tr>
<td>13</td>
<td>51.1</td>
<td>25</td>
<td>52.5</td>
</tr>
<tr>
<td>15</td>
<td>51.1</td>
<td>53</td>
<td>52.5</td>
</tr>
</tbody>
</table>
Eastbound truck counts varied from 1062 trucks in segment #1 to 10,762 trucks in segment #40. Westbound counts varied from 744 trucks in segment #1 to 12,765 trucks in segment #40. Speeds were not rounded up to notice the differences between segments. Differences were slight. Segment #58 had the lowest average eastbound speed with 49 mph. Approximately 10 segments had speeds near 52 mph. In the westbound direction, segment #58 had the lowest speed with an average of 47 mph. Nearly half of the segments had speeds over 53 mph (Table 14).

The majority of truck trips were those that started and ended within the corridor (Table 15). The same happened in February 2008 and in March 2009.

Table 15. Flow Type Distribution from June 1 to 16, 2008

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>June 1 to June 16 Truck Counts</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EB</td>
<td>WB</td>
<td>Total</td>
<td></td>
</tr>
<tr>
<td>Starting and Ending Outside Corridor</td>
<td>50</td>
<td>79</td>
<td>129</td>
<td></td>
</tr>
<tr>
<td>Starting Inside Corridor, Ending Outside Corridor</td>
<td>2247</td>
<td>635</td>
<td>2882</td>
<td></td>
</tr>
<tr>
<td>Starting Outside Corridor, Ending Inside Corridor</td>
<td>619</td>
<td>3436</td>
<td>4055</td>
<td></td>
</tr>
<tr>
<td>Starting and Ending Inside Corridor</td>
<td>17130</td>
<td>18012</td>
<td>35142</td>
<td></td>
</tr>
</tbody>
</table>

Data on Table16 has the total truck counts from the intersections located in the origin city to the intersections located in the destination city for June 1 to 16.

Table 16. Origin to Destination Counts between Cities along Corridor from June 1 to 16, 2008

<table>
<thead>
<tr>
<th>Origin</th>
<th>Hudson &amp; Beyond</th>
<th>Eau Claire</th>
<th>Madison</th>
<th>Janesville</th>
<th>Beloit &amp; Beyond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hudson &amp; Beyond</td>
<td>-</td>
<td>22</td>
<td>67</td>
<td>107</td>
<td>171</td>
</tr>
<tr>
<td>Eau Claire</td>
<td>18</td>
<td>-</td>
<td>6</td>
<td>17</td>
<td>18</td>
</tr>
<tr>
<td>Madison</td>
<td>79</td>
<td>14</td>
<td>-</td>
<td>72</td>
<td>131</td>
</tr>
<tr>
<td>Janesville</td>
<td>110</td>
<td>16</td>
<td>68</td>
<td>-</td>
<td>206</td>
</tr>
<tr>
<td>Beloit &amp; Beyond</td>
<td>250</td>
<td>36</td>
<td>206</td>
<td>267</td>
<td>-</td>
</tr>
</tbody>
</table>

From June 2 (before event) to June 6 (before event) the eastbound direction had slight increases in all segments with some having considerable increases. In the westbound direction the
increases were larger. Both directions had speed fluctuations of no more than 5% in most segments. A few had decreases between 5% and 10%.

From June 6 (before event) to June 7 (during event) truck counts decreased in the eastbound direction. Many of the segments had very high decreases. There were major decreases in all segments in the westbound direction. Both directions had minor speed decreases in almost all segments.

The next pair was June 7 and June 8, both during the event. Truck counts decreased in all segments in the eastbound direction. Some segments had 50% drops. The westbound direction truck counts remained pretty stable with some slight variations. Both directions experienced speed increases as compared to June 7.

From June 8 to June 9, both during the event, all segments in the eastbound direction had truck counts increases of over 50%. Many of them had increases of 70%. There were considerable increases in all segments in the westbound direction. Some of the segments had increases of over 30%.

Most of the segments had slight speed increases in the eastbound direction. There were decreases in the first 10 segments of the corridor. More than three fourths of the corridor had speed increases of more than 10% in the westbound direction. The segments with westbound speed decreases were those located near Hudson.

Between June 9 to June 11 (also during the event) truck counts increased in all segments in the eastbound direction. More than half of the segments had increases of more than 20%. There were considerable increases in all segments in the westbound direction. Nearly three fourths of the segments had increases of over 40%.
Almost all the segments had speed decreases in the eastbound direction. The westbound direction had speed decreases from segment #15 to segment #50.

From June 11 to June 13 truck counts decreased in most of the segments in the eastbound direction. All segments after segment #20 had decreases of more than 25%. Some decreases were over 50%. There were considerable decreases in all segments in the westbound direction. Nearly one third of the segments had decreases of over 30%.

Almost all segments had speed decreases in the eastbound direction. Many had decreases greater than 20%. The westbound direction had speed decreases in all segments. Several segments had more than 15% decreases.

From June 13 to June 16 the majority of segments after segment #17 had truck count increases in the eastbound direction. The increases were greater than 20% after segment #29. Nearly half of the segments had truck counts decreases in the westbound direction. Both directions had speed increases in most of the corridor.

The corridor’s truck counts variations show the normal traffic patterns of a week instead of being a direct consequence of the disruptive events. Reductions in truck counts happened on weekends and increases on weekdays. On the other hand, speeds were more sensitive. There were speed reductions as a result of the effects of both disruptive events. The highest truck counts in the corridor were at a portion from New Lisbon to Madison in all cases.

6.4 Resiliency Performance Measures

The availability of travel speeds and relative truck counts prior to, during, and after two significant weather events were useful to compute and illustrate two resiliency performance measures: robustness and rapidity. The concept of a resiliency triangle, which helps to visualize
the magnitude of the impact of a disruption on the infrastructure served as a base to design a new methodology to evaluate these performance measures.

The resiliency triangle concept that emerged from disaster research (as shown before) served as base to create the freight resiliency triangle. The resiliency triangles derived using the ATRI geospatial truck location data differ from the concept shown in Figure 1. Rather than a sudden abrupt loss of function, the impact was more gradual as conceptualized in Figure 7. The shape and areas of the resiliency triangle provide information about two measures of resiliency.

Robustness is the ability of the highway system network and system elements to withstand disaster forces without significant degradation or loss of performance. Rapidity is the capacity to restore functionality in a timely way by containing losses and avoiding disruptions. Two other measures, redundancy and resourcefulness, deal with the infrastructure network and policy. Those measures could not be represented with the data set provided by ATRI and therefore could not be quantified.

Current research on this topic does not present ways to numerically quantify the conceptual measures associated with the resiliency triangle.

This set of criteria was developed to qualify the computed resiliency measures. These criteria are useful to reflect the corridor’s observed behavior during the disruptive events. The criteria has estimated threshold values, they are not theoretical or empirical values. More research would be required to determine the threshold values.
The resiliency triangle is created by:

- **Performance at the start of the event or disruption.**
- **Lowest Performance during full impact.**
- **Full recovery.**

The resiliency triangles show:

- **How much loss the system had.**
- **How much time the system took to reach its lowest performance.**
- **How much time the system took to recover.**

Robustness is the left half of the triangle. It starts at the beginning of the event and continues to the lowest performance point. The average deceleration rate is the downward slope of the resiliency triangle and a measure of robustness. Rapidity is the right half of the triangle. It starts at the lowest performance point up point of full recovery. The average acceleration rate is the upward slope of the resiliency triangle and a measure of rapidity.
Robustness was categorized as high, moderate or low depending on the adjacent and opposite sides of the triangle. If the opposite side is less than 10 mph, there is high robustness (Figure 8).

**Figure 8. High Robustness Diagram**

If the ratio of $\Delta S$ over $T_1$ is less than 0.50 (i.e. the adjacent side of the triangle is long) and the opposite side is equal or greater than 10 mph, there is moderate robustness (Figure 9).

**Figure 9. Moderate Robustness Diagram**

If the ratio of $\Delta S$ over $T_1$ is greater or equal than 0.50 (i.e. the adjacent side of the triangle is short) and the opposite side is equal or greater than 10 mph, there is low robustness (Figure 10).
Rapidity was categorized as high, moderate or low depending on the adjacent and opposite sides of the triangle as well.

If the ratio of $\Delta S$ over $T_2$ is greater or equal than 0.50 (i.e. the adjacent side of the triangle is short), there is high rapidity (Figure 11).

If the ratio of $\Delta S$ over $T_2$ is less than 0.50 and greater than 0.20 (i.e. the adjacent side of the triangle is middle sized or moderate), there is moderate rapidity (Figure 12).
Figure 12. Moderate Rapidity Diagram

If the ratio of $\Delta S$ over $T_2$ is equal or less than 0.20 (i.e. the adjacent side of the triangle is long), there is low rapidity (Figure 13).

Figure 13. Low Rapidity Diagram

With these criteria the Beloit to Hudson corridor resiliency was evaluated, specifically the concepts of robustness and rapidity.

7. Results and Discussion

To evaluate the applicable resiliency measures, the concept of the resiliency triangle that represents the loss of performance from damage and disruption as shown before was used.
Truck count and speed charts were created for the February 2008 winter storm and the June 2008 Midwest floods to observe the behavior of the corridor between Hudson and Beloit before, during and after the event. Charts were created for the following segments:

- Beloit to Janesville
- Janesville to Madison
- Madison to Portage
- Portage to Mauston
- Mauston to Tomah
- Tomah to Eau Claire
- Eau Claire to Hudson

In all charts, the red triangle corresponds to the westbound direction and the black triangle corresponds to the eastbound direction. Triangles were created only on the speed charts since the truck count variations may not necessarily represent the effects of the event but rather the normal traffic pattern.

### 7.1 February 2008 Winter Storm

The three day period (February 5 to February 7) was divided into 6 hour intervals per direction for all segments. Truck count and speed charts were created for each segment. Resiliency triangles are included in the truck speed charts.

#### 7.1.1 Hudson to Eau Claire

During the February 2008 snow storm, the Hudson to Eau Claire portion (Figure 14) of the corridor received between 0 and 0.1 inches of snow. The portion has a length of 58.2 miles and encompasses segments 1 to 13. Truck counts followed a normal pattern, peaking at nighttime.
There was a slight decrease in truck counts in both directions on February 7th after 12am. The decrease is more evident on the westbound direction. One reason for the drop in truck traffic on the section is that those trucks were otherwise stranded on the Janesville to Beloit section.

There is a noticeable increase in truck counts after 6am on February 7 (Figure 15). The interstate was closed near Beloit stranding vehicles and blocking incoming traffic. This sudden increase might be as a result of those trucks that were either stranded or blocked now moving to their destinations after the interstate was reopened.

![Figure 14. Hudson to Eau Claire Portion](image)

Travel speeds remained fairly constant in the eastbound direction (Figure 16). However, the westbound direction speeds started to decline after 12am on February 6th reaching full impact after 12am of February 8 more than 48 hours after the event started. The impact on this portion was delayed.
Figure 15. Truck counts for Hudson-Eau Claire on February 2008 winter storm

Figure 16. Truck speeds for Hudson-Eau Claire on February 2008 winter storm
There was a speed reduction of 18 mph in 45 hours in the westbound direction, dropping from 55 mph to 37 mph.

For this portion between Hudson and Eau Claire, the only applicable resiliency measure is robustness on the westbound direction (Figure 17). There is not enough data to evaluate rapidity. The eastbound direction did not experience major speed losses. The deceleration rate (measure of robustness) for the westbound direction is 0.4 mph/hr.

### 7.1.2 Eau Claire to Tomah

During the February 2008 snow storm, the Eau Claire to Tomah portion (Figure 18) of the corridor received between 0 and 0.2 inches of snow. The corridor portion has a length of 76 miles and encompasses segments 14 to 25. Truck counts followed a normal pattern, peaking on nighttime.
There was a decrease in truck counts after 12pm on February 6 on the westbound direction (Figure 19). The eastbound direction remained stable. The same reasoning applies. The drop in truck traffic on the section is that those trucks were otherwise stranded on the Janesville to Beloit section.

There is a noticeable increase in truck counts after 6am on February 7 on this portion of the corridor as well. The same reasoning applies. This sudden increase might be as a result of those trucks that were either stranded or blocked at Beloit now moving to their destinations after the interstate was reopened.

Travel speeds remained fairly constant in the eastbound direction. However, the westbound direction speeds started to decline after 12am on February 6 reaching full impact between 12pm and 6pm on February 7, 36 hours after the start of the event (Figure 20).

**Figure 18. Eau Claire to Tomah Portion**
Figure 19. Truck counts for Eau Claire-Tomah on February 2008 winter storm

Figure 20. Truck speeds for Eau Claire-Tomah on February 2008 winter storm
There was a speed reduction of 24 mph in 39 hours in the westbound direction, dropping from 55 mph to 31 mph.

For this portion between Eau Claire and Tomah, the applicable resiliency measures are robustness and rapidity on the westbound direction (Figures 21 and 22). There was not enough data for rapidity but in this case was estimated. The eastbound direction did not suffer major losses. The deceleration rate (measure of robustness) for the westbound direction is 0.61 mph/hr and the acceleration rate (measure of rapidity) is 0.96 mph/hr.

![Figure 21. Westbound robustness for Eau Claire-Tomah on February 2008 winter storm](image)

![Figure 22. Westbound rapidity for Eau Claire-Tomah on February 2008 winter storm](image)
7.1.3 Tomah to Mauston

During the February 2008 snow storm, the Tomah to Mauston (Figure 23) portion of the corridor received between 0.2 and 6 inches of snow. The corridor portion has a length of 24 miles and encompasses segments 26 to 32. Truck counts followed a normal pattern, peaking on nighttime.

![Map of Tomah to Mauston Portion]

**Figure 23. Tomah to Mauston Portion**

There was a decrease in truck counts after 12pm on February 6 on the westbound direction (Figure 24). The eastbound direction remained stable. This happened in the previous sections of the corridor and therefore the same reasoning applies. The drop in truck traffic on the section is that those trucks were otherwise stranded on the Janesville to Beloit section.

There is a noticeable increase in truck counts after 6am on February 7th on this portion of the corridor as in the previous two portions of the corridor. The same reasoning applies. This sudden increase might be as a result of those trucks that were either stranded or blocked at Beloit now moving to their destinations after the interstate was reopened.
Travel speeds remained fairly constant in the eastbound direction (Figure 25). However, the westbound direction speeds started to decline after 12am on February 6\textsuperscript{th} reaching full impact between 12pm and 6pm on February 7\textsuperscript{th}. As we move closer to Beloit, the full impact delay is reducing.

\textbf{Figure 24.} Truck counts for Tomah to Mauston on February 2008 winter storm
There was a speed reduction of 26 mph in 39 hours in the westbound direction, dropping from 53 mph to 27 mph.

For this portion between Tomah and Mauston, the applicable resiliency measures are robustness and rapidity on the westbound direction (Figure 26 and 27). The eastbound direction did not suffer major losses as with the previous sections. The deceleration rate (measure of robustness) for the westbound direction is 0.67 mph/hr and the acceleration rate (measure of rapidity) is 2 mph/hr.

**Figure 25.** Truck speeds for Tomah to Mauston on February 2008 winter storm
7.1.4 Mauston to Portage

During the February 2008 snow storm, the Mauston to Portage portion (Figure 28) of the corridor received between 6 and 12 inches of snow. The corridor portion has a length of 39 miles and encompasses segments 33 to 39. Truck counts followed a normal pattern, peaking on nighttime.

Westbound Robustness

\[ \frac{\Delta S}{T_1} = \frac{26}{39} = 0.67 \text{ mph/hr} \]

Figure 26. Westbound robustness for Tomah-Mauston on February 2008 winter storm

Westbound Rapidity

\[ \frac{\Delta S}{T_2} = \frac{26}{13} = 2.00 \text{ mph/hr} \]

Figure 27. Westbound rapidity for Tomah-Mauston on February 2008 winter storm
There was a decrease in truck counts on February 6 after 12pm in the westbound direction followed by a considerable increase after 12am on February 7 (Figure 29). The same reasons apply as with the previous sections of the corridor.

Travel speeds remained fairly constant in the eastbound direction. However, the westbound direction speeds started to decline after 12am on February 6 reaching full impact after 12pm of February 7 (Figure 30).

**Figure 28. Mauston to Portage Portion**
**Figure 29.** Truck counts for Mauston to Portage on February 2008 winter storm

**Figure 30.** Truck speeds for Mauston to Portage on February 2008 winter storm
There was a speed reduction of 22 mph in 39 hours in the westbound direction, dropping from 50 mph to 28 mph.

For this portion between Mauston and Portage the applicable resiliency measures are robustness and rapidity on the westbound direction (Figure 31 and 32). The eastbound direction did not suffer major losses. The deceleration rate (measure of robustness) for the westbound direction is 0.56 mph/hr and the acceleration rate (measure of rapidity) is 1.83 mph/hr.

Westbound Robustness
\[
\frac{\Delta S}{T_1} = \frac{22}{39} = 0.56 \text{ mph/hr}
\]

Figure 31. Westbound robustness for Mauston-Portage on February 2008 winter storm

Westbound Rapidity
\[
\frac{\Delta S}{T_2} = \frac{22}{12} = 1.83 \text{ mph/hr}
\]

Figure 32. Westbound rapidity for Mauston-Portage on February 2008 winter storm
7.1.5 Portage to Madison

During the February 2008 snow storm, the Portage to Madison (Figure 33) portion of the corridor received between 9 and 16 inches of snow. The corridor portion has a length of 22 miles and encompasses segments 40 to 43. Truck counts followed a normal pattern, peaking on nighttime.

![Map of Portage to Madison Portion](image)

**Figure 33. Portage to Madison Portion**

There was a decrease in truck counts on February 6 after 12pm in the westbound direction followed by a rapid increase in truck counts after 6am on February 7 (Figure 34). Same reasons apply as with the previous sections of the corridor.

Travel speeds started to decline in the eastbound and westbound directions after 12am on February 6. The westbound direction reached full impact after 12pm of February 7 and the eastbound direction after 6pm on February 6 (Figure 35).
Figure 34. Truck counts for Portage to Madison on February 2008 winter storm

Figure 35. Truck speeds for Portage to Madison on February 2008 winter storm
There was a speed reduction of 31 mph in 39 hours in the westbound direction, dropping from 53 mph to 22 mph. The eastbound direction suffered a 15 mph reduction in 21 hours, dropping from 49 mph to 34 mph.

For this portion between Portage to Madison the applicable resiliency measures are robustness and rapidity on the westbound direction and the eastbound direction (Figures 36 to 39). The deceleration rate for the westbound direction is 0.79 mph/hr and 0.71 mph/hr for eastbound. The acceleration rate for the westbound direction is 2.58 mph/hr and 0.63 mph/hr for eastbound.

**Eastbound Robustness**

\[
\frac{\Delta S}{T_1} = \frac{15}{21} = 0.71 \text{ mph/hr}
\]

*Figure 36. Eastbound robustness for Portage-Madison on February 2008 winter storm.*

**Westbound Robustness**

\[
\frac{\Delta S}{T_1} = \frac{31}{39} = 0.79 \text{ mph/hr}
\]

*Figure 37. Westbound robustness for Portage-Madison on February 2008 winter storm.*
7.1.6 Madison to Janesville

During the February 2008 snow storm, the Madison to Janesville portion (Figure 40) of the corridor received between 16 and 21 inches of snow. The corridor portion has a length of 41 miles and encompasses segments 44 to 53. Truck counts followed a normal pattern, peaking on nighttime.
After 12 pm on February 6, truck traffic was stranded in the corridor for around 18 hours in both directions as a direct effect of the weather event. After 6am on February 7, truck counts started to increase in both directions. The westbound direction had a greater increase than the eastbound direction. This probably is a result of those trucks that were either stranded or blocked at the corridor now moving to their destinations after the interstate was reopened (Figure 41).

Travel speeds started to decline in the eastbound and westbound directions after 12am on February 6. The westbound direction reached full impact after 12am of February 7 and the eastbound direction around the same time as well (Figure 42). To be consistent with stand-still condition on the highway, the average speed should be zero. The data set includes moving trucks on adjoining segments and results may also be affected by moving trucks on very nearby access roads and crossings that were included when the spatial buffer was applied along the highway to select the data set.
Figure 41. Truck counts for Madison to Janesville on February 2008 winter storm

Figure 42. Truck speeds for Madison to Janesville on February 2008 winter storm
There was a speed reduction of 31 mph in 27 hours in the westbound direction, dropping from 46 mph to 15 mph. The eastbound direction suffered a 16 mph reduction in 25 hours, dropping from 48 mph to 32 mph.

For this portion between Madison and Janesville the applicable resiliency measures are robustness and rapidity on the westbound and eastbound directions (Figures 43 to 46). The deceleration rate for the westbound direction is 1.15 mph/hr and 0.64 mph/hr for eastbound. The acceleration rate for the westbound direction is 1.34 mph/hr and 0.67 mph/hr for eastbound.
7.1.7 Janesville to Beloit

During the February 2008 snow storm, the Janesville to Beloit portion (Figure 47) of the corridor received between 18 and 21 inches of snow. The corridor portion has a length of 16 miles and encompasses segments 54 to 58. Truck counts followed a normal pattern, peaking on nighttime.

After 12 pm on February 6, truck traffic was stranded in the corridor for around 18 hours in the westbound direction and in a lesser extent in the eastbound direction as a direct effect of the weather event. After 6am on February 7, truck counts started to increase in both directions. The

Eastbound Rapidity

\[
\frac{\Delta S}{T_2} = \frac{16}{24} = 0.67 \text{ mph/hr}
\]

Figure 45. Eastbound rapidity for Madison-Janesville on February 2008 winter storm

Westbound Rapidity

\[
\frac{\Delta S}{T_2} = \frac{31}{23} = 1.34 \text{ mph/hr}
\]

Figure 46. Westbound rapidity for Madison-Janesville on February 2008 winter storm
westbound direction had a greater increase than the eastbound direction. This probably is a result of those trucks that were either stranded or blocked at the corridor now moving to their destinations after the interstate was reopened (Figure 48).

![Figure 47. Janesville to Beloit Portion](image)

Travel speeds started to decline in the eastbound and westbound directions after 12am on February 6. The westbound direction reached full impact after 12am of February 7 and the eastbound direction around the same time as well (Figure 49). To be consistent with stand-still condition on the highway, the average speed should be zero. The data set includes moving trucks on adjoining segments and results may also be affected by moving trucks on very nearby access roads and crossings that were included when the spatial buffer was applied along the highway to select the data set.
**Figure 48.** Truck counts for Janesville to Beloit on February 2008 winter storm

**Figure 49.** Truck speeds for Janesville to Beloit on February 2008 winter storm
There was a speed reduction of 31 mph in 27 hours in the westbound direction, dropping from 46 mph to 15 mph. The eastbound direction suffered a 17 mph reduction in 27 hours, dropping from 48 mph to 31 mph.

For this portion between Janesville and Beloit the applicable resiliency measures are robustness and rapidity on the westbound and eastbound directions (Figures 50 to 53). The deceleration rate for the westbound direction is 1.15 mph/hr and 0.63 mph/hr for eastbound. The acceleration rate for the westbound direction is 1.72 mph/hr and 0.74 mph/hr for eastbound.

**Eastbound Robustness**

\[
\frac{\Delta S}{T1} = \frac{17}{27} = 0.63 \frac{mph}{hr}
\]

**Figure 50.** Eastbound robustness for Janesville-Beloit on February 2008 winter storm

**Westbound Robustness**

\[
\frac{\Delta S}{T1} = \frac{31}{27} = 1.15 \frac{mph}{hr}
\]

**Figure 51.** Westbound robustness for Janesville-Beloit on February 2008 winter storm
7.1.8 Summary of February 2008 winter storm

The following table is a summary of all freight resiliency performance measures for the February 2008 winter storm. The deceleration and acceleration rates were converted to angles in degrees.

**Table 17. Freight Resiliency Performance Measures for February 2008 winter storm**

<table>
<thead>
<tr>
<th>Corridor Section</th>
<th>Direction</th>
<th>Initial speed</th>
<th>Minimum speed</th>
<th>ΔS</th>
<th>T1</th>
<th>Robustness (ΔS/T1)</th>
<th>T2</th>
<th>Rapidity (ΔS/T2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mph</td>
<td>mph</td>
<td>hrs</td>
<td>mph/hr</td>
<td>α</td>
<td>hrs</td>
<td>mph/hr</td>
</tr>
<tr>
<td>Hudson to Eau Claire</td>
<td>West</td>
<td>55</td>
<td>37</td>
<td>18</td>
<td>45</td>
<td>0.40</td>
<td>21.8</td>
<td>-</td>
</tr>
<tr>
<td>Eau Claire to Tomah</td>
<td>West</td>
<td>55</td>
<td>31</td>
<td>24</td>
<td>39</td>
<td>0.62</td>
<td>31.6</td>
<td>25</td>
</tr>
</tbody>
</table>

**Eastbound Rapidity**

\[
\frac{\Delta S}{T_2} = \frac{17}{23} = 0.74 \ \text{mph/hr}
\]

**Figure 52. Eastbound rapidity for Janesville-Beloit on February 2008 winter storm**

**Westbound Rapidity**

\[
\frac{\Delta S}{T_2} = \frac{31}{18} = 1.72 \ \text{mph/hr}
\]

**Figure 53. Westbound rapidity for Janesville-Beloit on February 2008 winter storm**
7.2 June 2008 Midwest Floods

The period was divided into 24 hour intervals per direction for all segments. Truck count and speed charts were created for each segment. Resiliency triangles are included in the truck speed charts as in the February 2008 winter storm.

7.2.1 Hudson to Eau Claire

During the June 2008 Midwest floods, the Hudson to Eau Claire portion of the corridor received between 2 and 4 inches of rain.

The truck traffic pattern seems to follow what is expected. That is decreasing counts on weekends and increasing counts on weekdays. The lowest counts were on June 8 and June 15 which were Sundays. The same happened in both directions (Figure 54).

Travel speeds remained stable during the whole period without major variations in both directions. The weather event did not have an effect on the performance of this portion of the corridor (Figure 55).

For this portion between Hudson and Eau Claire there are no applicable resiliency measures to evaluate.
Figure 54. Truck counts for Hudson to Eau Claire on June 2008 Midwest floods

Figure 55. Truck speeds for Hudson to Eau Claire on June 2008 Midwest floods
7.2.2 Eau Claire to Tomah

During the June 2008 Midwest floods, the Eau Claire to Tomah portion of the corridor received between 2 and 8 inches of rain.

As with the previous section, the truck traffic pattern seems to follow what is expected. That is decreasing counts on weekends and increasing counts on weekdays. The same happened in both directions. The westbound direction had higher truck counts than the eastbound direction like the previous section (Figure 56).

Travel speeds remained stable during the whole period without major variations in both directions (Figure 57). The weather event did not have an effect on the performance of this portion of the corridor. Therefore, for this portion between Eau Claire and Tomah there are no applicable resiliency measures to evaluate.

Figure 56. Truck counts for Eau Claire to Tomah on June 2008 Midwest floods
7.2.3 Tomah to Mauston

During the June 2008 Midwest floods, the Tomah to Mauston portion of the corridor received between 2 and 8 inches of rain.

As with the previous two sections, the truck traffic pattern seems to follow what is expected. That is decreasing counts on weekends and increasing counts on weekdays (Figure 58). The same happened in both directions. The westbound direction had higher truck counts than the eastbound direction like the previous sections.

Travel speeds began to decrease on June 12 in the eastbound direction and on June 13 in the westbound direction. The westbound direction reached full impact on June 15 and the eastbound direction on June 13 (Figure 59).
Figure 58. Truck counts for Tomah to Mauston on June 2008 Midwest floods

Figure 59. Truck speeds for Tomah to Mauston on June 2008 Midwest floods
There was a speed reduction of 14 mph in 42 hours in the westbound direction, dropping from 49 mph to 35 mph. The eastbound direction suffered an 11 mph reduction in 24 hours, dropping from 44 mph to 33 mph.

For this portion between Tomah and Mauston the applicable resiliency measures are robustness and rapidity on the westbound and eastbound directions (Figures 60 to 63). The deceleration rate for the westbound direction is 0.33 mph/hr and 0.46 mph/hr for eastbound. The acceleration rate for the westbound direction is 0.39 mph/hr and 0.17 mph/hr for eastbound.

**Eastbound Robustness**

\[
\frac{\Delta S}{T1} = \frac{11}{24} = 0.46 \text{ mph/hr}
\]

*Figure 60. Eastbound robustness for Tomah-Mauston on June 2008 Midwest floods*

**Westbound Robustness**

\[
\frac{\Delta S}{T1} = \frac{14}{42} = 0.33 \text{ mph/hr}
\]

*Figure 61. Westbound robustness for Tomah-Mauston on June 2008 Midwest floods*
### 7.2.4 Mauston to Portage

During the June 2008 Midwest floods, the Mauston to Portage portion of the corridor received between 10 and 14 inches of rain.

The truck traffic pattern seems to follow what is expected as with the previous sections. That is decreasing counts on weekends and increasing counts on weekdays. The same happened in both directions. The westbound direction had higher truck counts than the eastbound direction like the previous sections (Figure 64).

**Eastbound Rapidity**

\[
\frac{\Delta S}{T_2} = \frac{11}{68} = 0.17 \, \text{mph/hr}
\]

*Figure 62. Eastbound rapidity for Tomah-Mauston on June 2008 Midwest floods*

**Westbound Rapidity**

\[
\frac{\Delta S}{T_2} = \frac{14}{36} = 0.39 \, \text{mph/hr}
\]

*Figure 63. Westbound rapidity for Tomah to Mauston on June 2008 Midwest floods*
Travel speeds were over 50 mph on average in both directions. They began to decrease in the eastbound direction on June 12 reaching full impact on June 13 (Figure 65).

There was a speed reduction of 10 mph in 24 hours in the eastbound direction, dropping from 49 mph to 39 mph. The westbound direction did not suffer speed reductions. To be consistent with highway closures, the average speed should be zero. The data set includes moving trucks on adjoining segments and results may also be affected by moving trucks on very nearby access roads and crossings that were included when the spatial buffer was applied along the highway to select the data set.

Figure 64. Truck counts for Mauston to Portage on June 2008 Midwest floods
Figure 65. Truck speeds for Mauston to Portage on June 2008 Midwest floods

For this portion between Mauston and Portage the applicable resiliency measures are robustness and rapidity on the eastbound direction (Figures 66 and 67). The deceleration rate (measure of robustness) is 0.42 mph/hr and the acceleration rate (measure of rapidity) is 0.17 mph/hr.

Eastbound Robustness

\[
\frac{\Delta S}{T_1} = \frac{10}{24} = 0.42 \text{ mph/hr}
\]

Figure 66. Eastbound robustness for Mauston-Portage on June 2008 Midwest floods
7.2.5 Portage to Madison

During the June 2008 Midwest floods, the Portage to Madison portion of the corridor received between 8 and 14 inches of rain. In this portion of the corridor we can see the most severe effects of the weather event. After June 12, truck counts had a severe and rapid decrease in a 48 hour period in both directions (Figure 68).

Travel speeds were around 50 mph on average in both directions. They began to decrease in the eastbound direction on June 12 reaching full impact on June 15 (Figure 69).

There was a speed reduction of 25 mph in 70 hours in the eastbound direction, dropping from 50 mph to 25 mph. The westbound direction had a reduction of less than 10 mph, which is not major. To be consistent with highway closures, the average speed should be zero. The data set includes moving trucks on adjoining segments and results may also be affected by moving trucks on very nearby access roads and crossings that were included when the spatial buffer was applied along the highway to select the data set.

**Eastbound Rapidity**

\[
\frac{\Delta S}{T} = \frac{10}{60} = 0.17 \text{ mph/hr}
\]

**Figure 67. Eastbound rapidity for Mauston-Portage on June 2008 Midwest floods**
Figure 68. Truck counts for Portage to Madison on June 2008 Midwest floods

Figure 69. Truck speeds for Portage to Madison on June 2008 Midwest floods
For this portion between Portage and Madison the applicable resiliency measures are robustness and rapidity on the eastbound direction (Figures 70 and 71). The deceleration rate (measure of robustness) is 0.42 mph/hr and the acceleration rate (measure of rapidity) is 0.17 mph/hr.

**Eastbound Robustness**

\[
\frac{\Delta S}{T_1} = \frac{25}{70} = 0.36 \frac{mph}{hr}
\]

**Figure 70. Eastbound robustness for Portage-Madison on June 2008 Midwest floods**

**Eastbound Rapidity**

\[
\frac{\Delta S}{T_2} = \frac{25}{24} = 1.04 \frac{mph}{hr}
\]

**Figure 71. Eastbound rapidity for Portage-Madison on June 2008 Midwest floods**

### 7.2.6 Madison to Janesville

During the June 2008 Midwest floods, the Madison to Janesville portion of the corridor received between 6 and 10 inches of rain.
As with most of the previous sections, the truck traffic pattern seems to follow what is expected. That is decreasing counts on weekends and increasing counts on weekdays. The same happened in both directions. The westbound direction had higher truck counts than the eastbound direction like the previous sections (Figure 72).

Travel speeds were around 50 mph in both directions until June 12. After June 12, both directions experienced speed decreases. The eastbound direction reached full impact on June 14 and the westbound direction on June 15 (Figure 73).

There was a speed reduction of 12 mph in 44 hours in the eastbound direction, dropping from 50 mph to 38 mph. The westbound direction had a reduction of 12 mph in 24 hours, dropping from 50 mph to 38 mph as well.

Figure 72. Truck counts for Madison to Janesville on June 2008 Midwest floods
Figure 73. Truck speeds for Madison to Janesville on June 2008 Midwest floods

For robustness, the deceleration rate is 0.5 mph/hr for the westbound direction and 0.25 mph/hr for the eastbound direction. For rapidity, the acceleration rate is 0.5 mph/hr for the eastbound direction and 0.17 mph/hr for the westbound direction (Figures 74 to 77).

Eastbound Robustness

\[ \frac{\Delta S}{T1} = \frac{12}{48} = 0.25 \text{ mph/hr} \]

Figure 74. Eastbound robustness for Madison-Janesville on June 2008 Midwest floods
**Westbound Robustness**

\[
\frac{\Delta S}{T1} = \frac{12}{24} = 0.5 \text{ mph/hr}
\]

*Figure 75. Westbound robustness for Madison-Janesville on June 2008 Midwest floods*

**Eastbound Rapidity**

\[
\frac{\Delta S}{T2} = \frac{12}{24} = 0.5 \text{ mph/hr}
\]

*Figure 76. Eastbound rapidity for Madison-Janesville on June 2008 Midwest floods*

**Westbound Rapidity**

\[
\frac{\Delta S}{T2} = \frac{12}{72} = 0.17 \text{ mph/hr}
\]

*Figure 77. Westbound rapidity for Madison-Janesville on June 2008 Midwest floods*
7.2.7 Janesville to Beloit

During the June 2008 Midwest floods, the Janesville to Beloit portion of the corridor received between 6 and 8 inches of rain.

As with most of the previous sections, the truck traffic pattern seems to follow what is expected. That is decreasing counts on weekends and increasing counts on weekdays. The same happened in both directions. The westbound direction had higher truck counts than the eastbound direction like the previous sections (Figure 78).

Travel speeds were between 45 and 50 mph in both directions. After June 10, the speeds on the eastbound direction started to decrease reaching full impact on June 13. The speeds in the westbound direction started to decrease after June 12 and reached full impact on June 14 (Figure 79).

There was a speed reduction of 11 mph in 68 hours in the eastbound direction, dropping from 49 mph to 38 mph. The westbound direction had a reduction of 10 mph in 56 hours, dropping from 49 mph to 39 mph.

For this portion between Janesville and Beloit the applicable resiliency measures are robustness and rapidity in both directions (Figures 80 to 83). The deceleration rate (measure of robustness) is 0.18 mph/hr for the westbound direction and 0.16 mph/hr for the eastbound direction. The acceleration rate (measure of rapidity) is 0.16 mph/hr for the eastbound direction and 0.24 mph/hr for the westbound direction.
Figure 78. Truck counts for Janesville to Beloit on June 2008 Midwest floods

Figure 79. Truck speeds for Janesville to Beloit on June 2008 Midwest floods
Eastbound Robustness

\[ \frac{\Delta S}{T_1} = \frac{11}{68} = 0.16 \frac{mph}{hr} \]

*Figure 80. Eastbound robustness for Janesville-Beloit on June 2008 Midwest floods*

Westbound Robustness

\[ \frac{\Delta S}{T_1} = \frac{10}{56} = 0.18 \frac{mph}{hr} \]

*Figure 81. Westbound robustness for Janesville-Beloit on June 2008 Midwest floods*

Eastbound Rapidity

\[ \frac{\Delta S}{T_2} = \frac{11}{80} = 0.14 \frac{mph}{hr} \]

*Figure 82. Eastbound rapidity for Janesville-Beloit on June 2008 Midwest floods*
7.2.8 Summary for June 2008 Midwest floods

The following table is a summary of all freight resiliency performance measures for the June 2008 Midwest floods. The deceleration and acceleration rates were converted to angles.

Table 18. Freight Resiliency Performance Measures for June 2008 Midwest floods.

<table>
<thead>
<tr>
<th>Corridor Section</th>
<th>Direction</th>
<th>Initial speed</th>
<th>Minimum speed</th>
<th>ΔS</th>
<th>T1</th>
<th>Robustness (ΔS/T1)</th>
<th>T2</th>
<th>Rapidity (ΔS/T2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>mph</td>
<td>mph</td>
<td>hrs</td>
<td>mph/hr</td>
<td>hrs</td>
<td>mph/hr</td>
<td></td>
</tr>
<tr>
<td>Tomah to Mauston</td>
<td>East</td>
<td>44</td>
<td>33</td>
<td>11</td>
<td>24</td>
<td>0.46</td>
<td>24.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>49</td>
<td>35</td>
<td>14</td>
<td>42</td>
<td>0.33</td>
<td>18.4</td>
<td></td>
</tr>
<tr>
<td>Mauston to Portage</td>
<td>East</td>
<td>49</td>
<td>39</td>
<td>10</td>
<td>24</td>
<td>0.42</td>
<td>22.6</td>
<td></td>
</tr>
<tr>
<td>Portage to Madison</td>
<td>East</td>
<td>50</td>
<td>25</td>
<td>25</td>
<td>70</td>
<td>0.36</td>
<td>19.7</td>
<td></td>
</tr>
<tr>
<td>Madison to Janesville</td>
<td>East</td>
<td>50</td>
<td>38</td>
<td>12</td>
<td>48</td>
<td>0.25</td>
<td>14.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>50</td>
<td>38</td>
<td>12</td>
<td>24</td>
<td>0.50</td>
<td>26.6</td>
<td></td>
</tr>
<tr>
<td>Janesville to Beloit</td>
<td>East</td>
<td>49</td>
<td>38</td>
<td>11</td>
<td>68</td>
<td>0.16</td>
<td>10.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>49</td>
<td>39</td>
<td>10</td>
<td>56</td>
<td>0.18</td>
<td>10.1</td>
<td></td>
</tr>
</tbody>
</table>

8. Conclusion and Findings

This thesis was focused on the development of a methodology to estimate resiliency measures. The research used data from the American Truck Research Institute (ATRI), collected through...
the Freight Performance Measurement Initiative, a partnership between FHWA and ATRI, along an interstate corridor to illustrate measures for freight transportation resiliency. Current research on this topic does not present ways to numerically quantify the conceptual measures associated with the resiliency triangle. This research used the ATRI data to attempt to fill the gap.

After understanding the corridor by evaluating its performance in terms of truck counts and speeds during the events, resiliency measures were estimated to comply with the main objective of this study. Of the four resiliency measures: robustness, redundancy, resourcefulness and rapidity, the first and the last were evaluated with the data provided by ATRI.

Freight resiliency triangles were created for all truck speed charts per segment per direction during the February and June 2008 weather events. The triangles are formed by three distinct points that represent the performance at the start of the disruption, lowest performance during full impact and full recovery. The triangles show how much loss the system had, how much time the system took to reach its lowest performance, and how much time the system took to recover.

Robustness was seen as the first portion of the resiliency triangle, from the point where performance starts to deteriorate due to an event to the lowest performance point. If the triangle has a gentle downward slope then the system performance is deteriorating slowly because the system has the robustness to withstand the disaster forces. Conversely, rapid loss in performance indicates low robustness since the disaster forces deteriorate the system quickly. For the more robust sections of the Hudson to Beloit interstate corridor, we may posit alternate routes provided redundancy for those sections. This research could not evaluate use of alternate routes.

Rapidity was seen as the second portion of the resiliency triangle, from the lowest performance point to the point where performance returns to the same level before the event. If this closure
angle has a steep slope, the system recovered quickly. If the slope is gradual, then the system did not recover quickly.

The following set of criteria is proposed to qualify the computed resiliency measures. These criteria reflect the corridor’s observed behavior during disruptions. Table 19 summarizes the criteria with estimated threshold values. These threshold values are not empirical or theoretical values. They were chosen by the researcher after observing and comparing performance patterns before, during and after the two disruptive weather events. Therefore, more research will be required to determine the threshold values. The set of criteria was developed along with the resiliency triangles, which together are a tool to evaluate resiliency.

**Table 19. Proposed methodology to measure freight resiliency and performance.**

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Figure</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High Robustness:</strong> No loss or minor loss of truck speed (ΔS) over time period (T1).</td>
<td><img src="image1.png" alt="Figure" /></td>
</tr>
<tr>
<td>$\Delta S &lt; 10 \text{ mph}$</td>
<td>$\alpha &lt; 26.6^\circ$</td>
</tr>
<tr>
<td><strong>Moderate Robustness:</strong> Significant loss in truck speed (ΔS) occurs over long period of time (T1)</td>
<td><img src="image2.png" alt="Figure" /></td>
</tr>
<tr>
<td>$\Delta S/T1 &lt; 0.50 \text{ mph/hr}, \Delta S \geq 10 \text{ mph}$</td>
<td>$\alpha &lt; 26.6^\circ$</td>
</tr>
<tr>
<td><strong>Low Robustness:</strong> Rapid loss in truck speed (ΔS) occurs over short time period (T1).</td>
<td><img src="image3.png" alt="Figure" /></td>
</tr>
<tr>
<td>$\Delta S/T1 \geq 0.50 \text{ mph/hr}, \Delta S \geq 10 \text{ mph}$</td>
<td>$\alpha \geq 26.6^\circ$</td>
</tr>
<tr>
<td><strong>High Rapidity:</strong> Rapid increase in truck speed (ΔS) occurs over short time period (T2).</td>
<td><img src="image4.png" alt="Figure" /></td>
</tr>
<tr>
<td>$\Delta S/T2 \geq 0.50 \text{ mph/hr}$</td>
<td>$\beta \geq 26.6^\circ$</td>
</tr>
<tr>
<td><strong>Moderate Rapidity:</strong> Significant increase in truck speed (ΔS) occurs over moderate period of time (T2)</td>
<td><img src="image5.png" alt="Figure" /></td>
</tr>
<tr>
<td>$0.20 \text{ mph/hr} &lt; \Delta S/T2 &lt; 0.50 \text{ mph/hr}$</td>
<td>$11.3^\circ &lt; \beta &lt; 26.6^\circ$</td>
</tr>
<tr>
<td><strong>Low Rapidity:</strong> Gradual increase in truck speed (ΔS) over a long time period (T2).</td>
<td><img src="image6.png" alt="Figure" /></td>
</tr>
<tr>
<td>$\Delta S/T2 \leq 0.20 \text{ mph/hr}$</td>
<td>$\beta \leq 11.3^\circ$</td>
</tr>
</tbody>
</table>
All portions of the corridor were evaluated in two distinct weather events. The corridor was not impacted equally as a whole during both events. During the February 2008 winter storm, the Hudson to Eau Claire portion was the least affected, but the portion had an impact on average speeds. This means that even though the direct impact of the storm was near Beloit, the event produced a delayed reaction in the farthest portions of the corridor. The Hudson to Tomah segments reached full impact in the westbound direction almost 24 hours after the Madison to Beloit segments had the poorest performance. The effects of the weather event were more notable in the westbound direction of the entire corridor with low robustness in most of the corridor. On the other hand, even though the corridor robustness was low, it recovered quickly with high rapidity in most of the segments. The eastbound direction was affected from Portage to Beloit with low robustness in the entire portion. Rapidity was high as well.

The effects of the June 2008 Midwest floods were more localized than the winter storm. Almost none of the segments had low robustness. The portion from Hudson to Tomah had high robustness in both directions; the rest up to Beloit had moderate robustness. The segment from Tomah to Portage was the most affected with moderate robustness and low rapidity.

The westbound direction, in general, seemed to be less robust than the eastbound direction. The reason must be differences in physical infrastructure such as vertical and horizontal alignments since both directions experienced the same event.

Considering both directions together, the portion from Portage to Beloit, which coincidentally had high truck counts, seemed to be the most vulnerable in both events. The rest of the corridor, although not completely exempt from the effects of both weather events, was more resistant.
Table 20 summarizes the findings for all portions of the Beloit to Hudson corridor using the Freight Resiliency Performance Measure criteria developed to evaluate resiliency.

Table 20. Classification according to Freight Resiliency Performance Measures criteria

<table>
<thead>
<tr>
<th>Corridor Portion</th>
<th>Period</th>
<th>Robustness</th>
<th>Rapidity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Eastbound</td>
<td>Westbound</td>
</tr>
<tr>
<td>Hudson to Eau Claire</td>
<td>February</td>
<td>High</td>
<td>0.4 Moderate</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Eau Claire to Tomah</td>
<td>February</td>
<td>High</td>
<td>0.61 Low</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Tomah to Mauston</td>
<td>February</td>
<td>High</td>
<td>0.67 Low</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>0.46 Moderate</td>
<td>0.33 Moderate</td>
</tr>
<tr>
<td>Mauston to Portage</td>
<td>February</td>
<td>High</td>
<td>0.56 Low</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>0.42 Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Portage to Madison</td>
<td>February</td>
<td>0.71 Low</td>
<td>0.79 Low</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>0.36 Moderate</td>
<td>High</td>
</tr>
<tr>
<td>Madison to Janesville</td>
<td>February</td>
<td>0.64 Low</td>
<td>1.15 Low</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>0.25 Moderate</td>
<td>0.5 Low</td>
</tr>
<tr>
<td>Janesville to Beloit</td>
<td>February</td>
<td>0.63 Low</td>
<td>1.15 Low</td>
</tr>
<tr>
<td></td>
<td>June</td>
<td>0.16 Moderate</td>
<td>0.18 Moderate</td>
</tr>
</tbody>
</table>

High robustness or a combination of moderate robustness and high rapidity is the ideal performance for a corridor. The best case is no losses. If there are losses, it is important to reach full impact gradually than suddenly. This gradual loss is indicative that the system is resisting the impacts of the disruptions as a possible result of redundancy because of the presence of alternate routes. Increasing redundancy or flexibility, which are similar concepts, should be a focus area.
for the transportation authorities in order to increase resiliency. Reducing the area of the resiliency triangle could be an indication of improvements in the corridor’s resilience.
Figure 84. Map with classifications according to Freight Resiliency Performance Measures criteria

By plotting the resiliency triangles and being able to analyze the system performance during the disruptions we can conclude that the ATRI data is useful for measuring the robustness and rapidity of truck routes. These are important measures for evaluating overall freight route resiliency.

9. Future Study

Additional supplementary research would be required to determine the threshold values for the different categories of robustness and rapidity. Corridors operate differently across the nation, so probably these threshold values could differ from state to state.

The concepts of resourcefulness and redundancy could not be studied because of data limitations. Although we can make assumptions on redundancy depending on robustness, it would be important to assess the availability of alternate routes that would define the degree of redundancy.
that the corridor have. Neither redundancy nor resourcefulness could be computed with the data provided by ATRI.

Research on freight infrastructure resiliency have not been extensive, it is an emerging concept. Additional studies focused on policy and infrastructure improvements would be useful because all together can serve as a tool to direct funding to those road segments that are more vulnerable.

10. References


Appendix A: Truck Count Variations

The following two charts show the truck count variations among segments in the Beloit to Hudson Corridor. The first chart shows truck counts from February 5 to 7. The second chart shows truck counts from June 1 to 16.

![February 5-7 Directional Truck Counts per Segment](image)

**Figure A.1 Truck count variations among segments in February 5-7, 2008.**

Figure A.1 shows that eastbound truck counts are fairly low on the first three segments. The truck count in segment #4 has a sharp increase. A steep increase continues until segment #11. In segment #12 we see a slight drop but the counts slowly increases until segment #29. After segment #29 the truck counts starts to steeply increase until reaching the highest values after segment #40. After segment #49 truck counts starts to decrease.
In the westbound direction, there are low truck counts in the first three segments. There is a sudden increase in segment #4. After segment #4, there is a steep increase until segment #12 when it becomes more gradual. The highest truck counts are from segment #33 to segment #49. After segment #52 truck counts start to decline. Counts on the westbound direction are higher in almost all segments.

![Directional Truck Counts per Segment](image)

**Figure A.2** Truck count variations among segments in June 1-16, 2008.

In Figure A.2 we can see that as we move east, the truck counts on each direction increase until a point in segment #40 where the truck counts start to decrease. The same happened in February 2008.

The figure also shows that eastbound truck counts are fairly low on the first three segments. The truck count in segment #4 has a sudden increase. A steep increase continues until segment #11.
From segment #12 to #16 we see a slight drop. Then the truck counts slowly increase again and reach the highest values after segment #33. After segment #49 truck counts starts to decrease with a steep decrease after segment #52.

In the westbound direction, there are low truck counts in the first three segments. There is a sudden increase in segment #4. From segment #4, there is steep increase until segment #14 when the increase becomes more gradual. The highest truck counts are from segment #33 to segment #42. After segment #49 truck counts start to decline.
Appendix B: Truck Speed Variations

The following two charts show the truck speed variations among segments in the Beloit to Hudson Corridor. The first chart shows truck counts from February 5 to 7. The second chart shows truck counts from June 1 to 16.

Figure B.1 Truck speed variations among segments in February 5-7, 2008.

An interesting pattern is seen on the speed chart on Figure B.1. The average speeds decline as we move eastward and closer to the segments that received the highest amounts of snow. The February 2008 data set takes into consideration days 5, 6 and 7 which are during the snowfall event. The chart shows how performance starts to deteriorate as we move east. The segments after Portage (segment #39 to #58) had the lowest speeds.
Figure B.2 shows that westbound average speeds are around 51 mph and eastbound average speeds are around 53 mph. Westbound speeds are higher in almost all segments. The charts include data from June 1 to 16. A considerable portion of data is from days before the disruptive flooding event that led to road closures. That is why we cannot notice the reductions in speeds during the road closures that happened from June 12 to June 15.

Figure B.2 Truck speed variations among segments in June 1-16, 2008.