FINAL REPORT

The Framework for Calculating the Measure of Resilience for Intermodal Transportation Systems

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The Framework for Calculating the Measure of Resilience for Intermodal Transportation Systems

ABSTRACT

A literature review indicates no conforming approval on the measure of resilience (MOR) for intermodal transportation systems (1, 2, 3). The objective of this report is to develop a framework for calculating the measure of resilience (MOR) to disaster for intermodal transportation systems. TransCAD was used to model the intermodal network and generate transportation data for the MORs calculation procedure. Intermodal Origin-Destination (OD) traffic before and after disaster struck was estimated based on the study area's population and employment data. The pre-disaster and post-disaster population and employment data will be collected at county level and disaggregated to each Traffic Analysis Zone (TAZ) by using linear equations. A series of indicators in terms of mobility, accessibility, and reliability were selected to evaluate the intermodal system performance based on the TransCAD outputs. The report further introduced a Performance Index (PI) combining some indicators to measure the system performance regarding mobility. The Level of Service (LOS) of highway network and intermodal terminals before and after disaster was also determined according to the LOS standards. This report defined MORs as the percentage of system performance degradation due to a disaster. A formula was developed to give the intermodal system MOR a quantitative value with respect to mobility, accessibility, and reliability. The above process was reviewed in a case study along the Mississippi Gulf Coast. Results demonstrated the effectiveness of the proposed MOR calculation procedure.

Keywords: Intermodal Transportation, Resilience, Performance evaluations

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INTRODUCTION

System performance in response to unexpected disruptions or transportation resilience has always been a concern. In recent years, especially after the catastrophe of Hurricane Katrina in August 2005, transportation resilience has emerged as a timely issue. Researchers have paid much attention to resilience studies in an individual mode of transportation such as highway, rail, waterway, and air; however, intermodal transportation resilience has not received wide attention from transportation researchers. Therefore, appropriate methodology has not yet been developed for practicable evaluation of intermodal transportation resilience. Furthermore, regarding the lessons learned from Hurricane Katrina, it is necessary to study the long term effects of disasters to local and regional intermodal transportation and measure of resilience to the system.

In the state of Mississippi, the intermodal system was severely damaged by Hurricane Katrina. For example, the U.S. 90 Bridge between Bay St. Louis and Pass Christian was not repaired until more than two years after the storm. The railroad bridge of CSX Corporation in Bay St. Louis was reconstructed in 156 days after Hurricane Katrina. The port of Gulfport took approximately two and a half months to restore its operation to pre-Katrina levels.

The objective of this research is to develop a framework of calculating the measure of resilience (MOR) for intermodal transportation systems. To accomplish the objective, the following four goals will be achieved:

- Define measures of resilience of intermodal transportation systems
- Recreate the transportation system snapshots before and after Hurricane Katrina
- Propose a framework to calculate the projected MORs, and
- Perform a case study of MORs in the recovery of Mississippi Gulf Coast after Hurricane Katrina

The results from this research will not only provide a specific evaluation to the entire intermodal transportation resiliency of the Mississippi Gulf Coast but will also help the transportation planning agency identify the most vulnerable part of the intermodal network so that resources can be allocated effectively to mitigate the impact of future disasters. The Gulf Regional Planning Commission (GRPC) and Mississippi Department of Transportation (MDOT) are providing various levels of support for this work.

This report contains a relevant background and literature review about state-of-the-art transportation resilience research. The TransCAD modeling procedure used for this research is explained and the proposed MOR calculation framework is discussed in this report. The computational experience and analysis based on the Mississippi Gulf Coast after Hurricane Katrina is presented followed by a conclusion and recommendations for further study related to the scope of this report.

LITERATURE REVIEW

Transportation System Resilience

Resilience has been studied extensively over years. However, intermodal transportation resilience has been addressed to a limited degree (1). Transportation resilience is an inherent value measured by the performance of the transportation system in response to an unexpected situation. Resilience can be evaluated at the individual, community, design, economic, and strategic planning levels (3). Measure of Resilience is tentatively proposed as the percentage of deduction in intermodal transportation system performance indices.

So far, there is no widely accepted MOR in particular for intermodal transportation systems. Li (4) defined resilience as the ratio of recovered system performance resulting from a certain strategy with respect to the system performance reduction without the strategy. Four strategies were proposed to mitigate the road congestion caused by incidents. Four criteria (network performance, average travel speed, Origin-Destination (OD) travel time, and maximum queue length) were employed to evaluate the effectiveness of the proposed strategies. Brabhaharan (5) defined road link resilience as a "combination of its low vulnerability to degradation in a hazard event and the short time within which it can be reinstated after hazard events." The concept of resilience gap was defined as the difference between the expected level of resilience and anticipated level of resilience after a disaster. Several key parameters in terms of road accessibility were considered when measuring the resilience gap.

Dalziell et al. (6) established the concept of resilience as the possibility that a system would continue to function at the expected level in the face of a disaster. A Key Performance Indicator (KPI) - time curve was developed to measure the organizational resilience. Dalziell discussed the relationship between resilience and risk management and how to avoid making the system vulnerable to catastrophic failure.

Bruneau et al. (7) developed a conceptual framework to quantitatively measure the seismic resilience of communities. Seismic resilience was defined as the sustainability and adaptability of a community to a disaster. A set of system wide measures of performance was proposed to evaluate resilience regarding technical, organizational, societal, and economic dimensions.

Wan (8) discussed the resilience of sensor network transportation system to dramatic, physical environment change, during moments of disasters. The sensor network transport resilience was defined as the ability to transit a sufficient number of events to meet the applications' requirements at minimum energy consumption under abrupt changes in the system.

Traffic O-D Pattern before/after Disaster

The interruption of traffic by disasters causes non-recurrent congestion. Li and Murray-Tuite (4) applied a stochastic dynamic assignment, a built-in module of VISSIM to model the driver route choice under non-recurrent congestion so that the demands between nodes in the O-D matrix would have multiple choices in routes.

Dimitriou et al. (9) designed a stochastic road transportation network model. The model was formulated as a stochastic bi-level programming problem where upper-level problems present the objective function of the model and a lower-level problem refers to the demand assignment process. The demand (or capacity) between each O-D pairs was assumed following Gaussian distribution. Genetic Algorithm combined with Monte Carlo simulation was used for calculating system reliability.

Grenzeback and Lukmann (10) discussed the impacts of Hurricane Katrina and Hurricane Rita on the national and regional intermodal transportation facilities. Detailed descriptions about the disruptions and costs of damage in highway, rail, ports, pipelines, and aviation systems were provided. The results showed that the hurricanes caused modest impacts on national freight flows.

Bhamidipati and Demetsky (11) proposed a framework to qualitatively and quantitatively measure the impacts of an intermodal terminal to the rail-truck intermodal system. ArcGIS software was used to analyze the route diversion within the network. Different measures of effectiveness (MOEs) were combined into a single index in order to rank each project in the case study.

Xu and Hancock (12) developed an analytical model to assign the freight traffic to the highway and railway network. The objective of the model was to optimize the intermodal traffic assignment in order to minimize the overall transportation cost. GIS-T software was used to assign the OD flow to the intermodal network. An iteration procedure integrated a penalty function was applied to find the optimum allocation of the flow considering the interactions between intermodal and single mode transportation.

A number of techniques can be applied to disaggregate county-level socioeconomic data into Traffic Analysis Zones (TAZs). The Disaggregated Residential Allocation Model (DRAM) and Employment Allocation Model (EMPAL), registered trademarks of S.H. Putman Associates, were used to forecast household and employment location at the Regional Analysis Zone (RAZ) level to reflect changes in socioeconomic characteristics. DRAM/EMPAL is a modified standard gravity model that incorporates multi-parametric attractiveness function. The Subarea Allocation Model (SAM) developed by Maricopa Association of Governments (13) has been utilized to forecast population and employment for the Phoenix metropolitan area. SAM is a model set integrated with DRAM/EMPA. The function of SAM is to allocate the population and employment estimates from DRAM/EMPAL to one acre area which is then aggregated to TAZs.

Intermodal Transportation Capacity before and after Disaster

Chang (14) discussed the impacts of the 1995 earthquake on the Port of Kobe and its long-term prospects. Chang categorized the restoration of the port into two groups. One is the restoration of damaged facilities and the other is the restoration of the cargo. Results showed that the restoration of the cargo fell behind the restoration of the facilities. The impacts of the earthquake to the container cargo market were also discussed. Results revealed that the Port of Kobe would suffer a long term loss of market due to the competition among ports.

Kulick and Sawyer (15) used model developed by Automation Associates Inc. (AAI) to support the design, implementation, and operation of an intermodal facility. The model can be used to analyze capacity issues of intermodal facility, such as what improvements are needed to accommodate the increase of intermodal freight transportation and what level of service can be expected if the improvements are implemented etc.

Morlok and Chang (16) studied the flexibility of the transportation network by considering the fluctuation of the demand. Two models, MAXCAP and ADDVOL, were proposed to measure transportation system capacity. The MAXCAP model was used to estimate the maximum capacity of the transportation system based on constant OD flow. Then the ADDVOL model was used to estimate how much more traffic could be accommodated with respect to the MAXCAP model's estimation if the OD flow could deviate from zero up to the capacity of the facility. The results showed that the models could accommodate the freight flow changes well and provide a reasonable method to quantify system flexibility.

TransCAD (17) has been widely used and validated in transportation modeling in the past ten years. TransCAD includes trip generation, distribution, and traffic assignment models that support transportation planning and travel demand forecasting. TransCAD can be applied to model the intermodal network before and after a disaster, imitate the loss of facilities and estimate the system capacity according to the existing facilities' conditions. It can be used for all modes of transportation, at any scale or level of detail.

Measure of Resilience

Murray-Tuite (1) described transportation resilience with ten dimensions: redundancy, diversity, efficiency, autonomous components, strength, collaboration, adaptability, mobility, safety, and the ability to recover quickly. Murray-Tuite proposed several indicators to quantify the system resilience in terms of four of the ten dimensions. Two traffic assignment methods, System Optimum (SO) and User Equilibrium (UE), were evaluated with regard to their impacts on resilience using those indicators.

Some researchers have addressed the importance of introducing a comprehensive matrix for evaluating the resilience. For example, Murray-Tuite and Mahmassani (18) developed a transportation network disruption index and integrated multiple resilience dimensions (redundancy, diversity, and mobility) into one measure. Ballis (19) discussed the necessity and significance of developing Level of Service (LOS) measurements for intermodal terminals. Five principles of developing a set of LOS standards regarding the scale, threshold, and complexity of the standards have been presented in the paper. Based on the adoption of the principles used to develop LOS standards, Ballis proposed a number of quantifiable LOS indicators in terms of mobility, reliability, flexibility, qualification, security, and accessibility of the terminals. Heaslip and Louisell et al. (20) presented a methodology to quantify the resilience of transportation networks. A series of performance indices were evaluated based on the expert advice. Fuzzy theory was applied in order to convert expertise into mathematical relationships.

MOR CALCULATION FRAMEWORK DEVELOPMENT

In this section, a series of performance indicators are developed from the transit agency's point of view. A system-wide performance index is proposed to evaluate the system mobility based on the performance indicators. A quantified MOR calculation procedure is proposed in the next subsection.

Intermodal System Performance Measurement

Two categories of performance (21) were significantly affected during disasters and have been investigated in this report. They are as follows:

Mobility and accessibility: Based on the literature review, mobility is identified as the most basic performance of a transportation system (22). It can be defined as the ability to move goods or people between originations and destinations. Travel time and average trip length are two key indicators to evaluate system mobility. Outcome from an earlier research project performed by Wang and Jin et al (23) were utilized to derive the equation for the calculation of average travel time per mile.

Average travel time per mile is defined as,

$$T = \frac{\sum_{i \in O, j \in D} v_{i,j} \cdot t_{i,j}}{\sum_{i \in O, j \in D} v_{i,j} \cdot l_{i,j}} \qquad (1)$$

Where:
T = average travel time per mile (*min/mi*),
O = set of origin,
D = set of destination,
i,j = origin and destination,
$v_{i,j}$ = average daily truck volume between origin i and destination j (*veh*), $i \in O, j \in D$,
$t_{i,j}$ = average travel time between origin i and destination j (*min*), $i \in O, j \in D$,
$l_{i,j}$ = link length between origin i and destination j (*mi*), $i \in O, j \in D$.

Average truck trip length is defined as,

$$L = \frac{\sum_{i \in O, j \in D} v_{i,j} \cdot l_{i,j}}{n} \qquad (2)$$

Where:
L = average truck trip length (*mi*),
n = total truck trips per day

Accessibility identifies how easily potential freight traffic can use intermodal services. Accessibility can be measured using the percentage of total length of highway (L_t) that is open to freight traffic in the network and the availability of intermodal terminals (I_t). Subscript t signifies that these indicators are time varying parameters along with the recovery process. Another performance indicator related to accessibility is the percentage of freight vehicles traveling under the acceptable travel speed. These two indicators pertaining to the connectivity of the network affect the overall travel time and accessibility of an intermodal system.

Reliability: Reliability indicates how much freight traffic in the network can keep to the schedule. Reliability reflects the ability to timely accommodate variable and unexpected conditions of the intermodal system without catastrophic failure. Reliability is usually measured by the delays caused by system interruptions. Within this report, reliability is determined using the average delay per trip equation as follows:

$$d_{i,j} = v_{i,j} \cdot \max\left[\frac{l_{i,j}}{s_{i,j}} - \frac{l_{i,j}}{acceptable\ travle\ speed}, 0\right] \qquad (3)$$

$$R = \frac{\sum_{i \in O, j \in D} d_{i,j}}{n} \qquad (4)$$

Where:
$d_{i,j}$ = delay time between origin i and destination j (*min*), $i \in O, j \in D$,
$s_{i,j}$ = actual travel speed between origin i and destination j (*min*), $i \in O, j \in D$,
R = average delay time per trip (*min/trip*)
Acceptable travel speed = 0.85*limited speed (in this report)

The concept of LOS is commonly used in evaluating the intermodal system performance. Usually LOS ranks transportation facility performance with A through F letter scores. The Highway Capacity Manual (HCM) (24) provides a wide accepted methodology to estimate LOS with respect to different types of facilities under different traffic conditions. In this report, LOS standard for the highway was developed referring Mississippi Department of Transportation 2030 Long Range Transportation Plan (25) and HCM. Traffic volume and directional volume/capacity ratio were used as the LOS criteria. See Table 1.

Table 1: LOS Criteria for Intermodal Road Network

Criteria		LOS					
		A	B	C	D	E	F
Local Street and Unclassified Road							
Travel Speed		90%FFS	70%FFS	50%FFS	40%FFS	33%FFS	<33%FFS
Collector							
2 lane	Maximum volume	-	-	10010	16060	17160	>17160
	Maximum v/c	-	-	0.91	1.46	1.56	>1.56
4 lane	Maximum volume	-	-	19620	28510	30160	>30160
	Maximum v/c	-	-	0.89	1.30	1.37	>1.37
Minor Arterial							
2 lane	Maximum volume	-	-	10760	17260	18430	>18430
	Maximum v/c	-	-	0.83	1.33	1.42	>1.42
4 lane	Maximum volume	-	-	19820	28800	30460	>30460
	Maximum v/c	-	-	0.79	1.15	1.22	>1.22
6 lane	Maximum volume	-	-	33400	46800	49300	>49300
	Maximum v/c	-	-	0.86	1.20	1.26	>1. 26
Principal Arterial (Rural)							
2 lane	Maximum volume	-	4960	16310	19380	19970	>19970
	Maximum v/c	-	0.38	1.25	1.49	1.54	>1. 54
4 lane	Maximum volume	4450	27130	32130	33060	-	-
	Maximum v/c	0.18	1.09	1.29	1.32	-	-
6 lane	Maximum volume	7300	44700	52100	53500	-	-
	Maximum v/c	0.19	1.15	1.34	1.37	-	-
8 lane	Maximum volume	9400	58000	66100	67800	-	-
	Maximum v/c	0.18	1.14	1.30	1.33	-	-
Principal Arterial (Urban)							
2 lane	Maximum volume	-	2245	13235	18200	19265	>19265
	Maximum v/c	-	0.17	1.02	1.40	1.48	>1. 48
4 lane	Maximum volume	-	3795	24075	30280	31945	>31945
	Maximum v/c	-	0.15	0.96	1.21	1.28	>1. 28
6 lane	Maximum volume	-	6500	40300	49200	51800	>51800
	Maximum v/c	-	0.17	1.03	1.26	1.33	>1. 33
8 lane	Maximum volume	-	8500	53300	63800	67000	>67000
	Maximum v/c	-	0.17	1.05	1.25	1.31	>1. 31
Freeway (Rural)							
4 lane	Maximum volume	23800	39600	55200	67100	74600	>74600
	Maximum v/c	0.35	0.58	0.81	0.99	1.11	>1.11
6lane	Maximum volume	36900	61100	85300	103600	115300	>115300
	Maximum v/c	0.36	0.60	0.84	1.02	1.13	>1.13
8 lane	Maximum volume	49900	82700	115300	140200	156000	>156000
	Maximum v/c	0.37	0.61	0.85	1.03	1.15	>1.15
Freeway (Urban)							
4 lane	Maximum volume	22000	36000	52000	67200	76500	>76500
	Maximum v/c	0.32	0.53	0.76	0.99	1.13	>1.13
6lane	Maximum volume	34800	56500	81700	105800	120200	>120200
	Maximum v/c	0.34	0.55	0.8	1.04	1.18	>1.18
8 lane	Maximum volume	47500	77000	111400	144300	163900	>163900
	Maximum v/c	0.35	0.57	0.82	1.06	1.21	>1.21

In the study area, the entire intermodal network consists of two components: road network and intermodal terminals. The road network comprises over four thousand highways while the intermodal terminals include seaports, rail stations, and airports. Since the operations between road network and intermodal terminals are different, it is necessary to develop a specific set of indicators to evaluate intermodal terminal performances. Considering the data availability, intermodal terminal LOS has been measured by a number of performance indicators in terms of mobility, reliability, flexibility, security, and accessibility. These measures of criteria shown in Table 2 are from the Ballis (19) proposed set of LOS standards for intermodal terminals.

Table 2: Level of Service Criteria for Intermodal Terminals

		A	B	C	D	E	F
Mobility							System Breakdown
Average Truck Waiting Time (minutes)		<= 20	21 - 30	31 - 40	41- 60	61 - 120	
Reliability							
Delay in Departure (minutes)	Rail Station	<= 10	11 - 20	21 - 30	31 - 40	41 - 60	
	Sea Port	<= 30	31 - 45	46 - 60	61 - 90	91 - 180	
Incidents Rate in Departure (%)		<= 2	3 - 5	6 - 10	11 - 20	21 - 40	
Flexibility							
Cut-off Time (hours)	Rail Station	<= 0.5	0.5 - 2	2 - 4	4 - 6	6 – 8	
	Sea Port	<= 2	2 - 4	4 - 6	6 - 8	8 - 24	
Security							
Loss of Goods (%)		0	0	0 - 0.5	0.5 - 1	1 – 2	
Accessibility							
Working Hours per Day (hours)		24	24	16	16	8	

Performance Index

Some aspects of system performance outcomes, such as mobility and reliability, are connected with a number of performance indicators. In order to perform simple notations of potentially complex measures, a performance index has been proposed by combining results from other performance indicators in an equation to generate a single output measure.

Usually, there are several methods to develop a performance index (26): using an equation that weights each performance indicator based on their importance, using a regression model to make quantitative predictions of one measure from the values of other measures, or using results from customer satisfaction surveys by providing customers with the related system performance results. Within this report, the Performance Index (PI) regarding travel speed has been proposed based on the first method. This PI attempts to measure the ratio of the travel speed with respect to the Free Flow Speed (FFS) weighted by truck miles traveled. The value of the PI ranges from 0 to 1. A PI with a lower value means the network has worse performance in terms of mobility whereas a PI with a higher value indicates the network mobility is in relatively good status.

PI is defined as:

Table 3: Mobility Performance Index

Measure	Calculation	Rating					
		A	B	C	D	E	F
Travel Speed, Truck Miles Traveled	$PI = \frac{\sum_{i \in O, j \in D} \frac{s_{i,j} v_{i,j} \cdot l_{i,j}}{FFS_{i,j}}}{\sum_{i \in O, j \in D} v_{i,j} \cdot l_{i,j}}$	1.00 – 0.95	0.95 – 0.85	0.85 – 0.70	0.70 – 0.60	0.60 – 0.50	< 0.50
		Excellent	Good	Fair	Poor	Very Poor	Failing

MOR Definition

In this document, the intermodal network resilience is defined as the ratio of the reduction of the intermodal system performance after a disaster with respect to the system performance before a disaster. The proposed methodology for MOR is based on the calculation of the performance indicators.

MOR can be calculated by:

$$MOR = \frac{\left(PI_{Before} - PI_{after}\right)\left(1 + t^{\alpha}\right)}{PI_{Before}}\% \tag{5}$$

Where:
t = total time required to restore the capacity (year), and
α = system parameter, used $\alpha = 0.5$ in case study

The parameter α is related with network size, socioeconomic status, government policy, etc. In this piece, α is designated as an average value of 0.5. Specific calibration will be performed in the future to obtain a more accurate value of α. It is important to note that resilience comes with a specific system disruption. The lower value of MOR means the system is more resilient to the disruption.

INTERMODAL OD FLOW ESTIMATION

TransCAD was employed to model the intermodal network and generate data in order to calculate the system's performance. Detailed discussion about data collection and process methods was provided to develop the model. The TransCAD model was built on TAZ-level. A disaggregation method was developed in order to break down the socioeconomic data from County-level to TAZ-level. Finally, based on updated information in each TAZ, the TransCAD model, created and calibrated by GRPC was modified to recapture the transportation system both before and after Katrina.

Data Collection and Process

In this study, great efforts were spent on field data collection and survey on the intermodal transportation system in the study area. The research team deployed radar detectors and NC200 detectors at I-110, I-10, and Highway 49 along the Mississippi Gulf Coast in order to collect real time freight transportation data. Moreover, several meetings were conducted with GRPC and MDOT officers. Regional statistics such as county population, employment, road repair and reconstruction progress, etc. were obtained from the meeting. Additionally, the research team communicated with transportation companies, such as CSX, Port of Gulfport, Biloxi International Airport, etc. with regard to the freight transportation change after Katrina.

However, there would be a large number of information needed in order to perform the system resilience measurement. Parts of the data needed for resilience measurements are still unavailable for various reasons. For example, there are two complications with collecting field data before and after a disaster: 1) usually it is not reasonable to conduct a survey to collect the dynamic traffic data since the scenario has been past for years and impacts from the disaster are wearing off, and 2) limited research resources do not allow for field data collection at all TAZs. Thus, it is necessary to generate some dynamic traffic data using transportation planning software. TransCAD was selected for modeling the intermodal network and generating traffic data for the MOR calculation.

TransCAD Modeling

TransCAD was used for generating the intermodal OD flow to support MOR calculation procedure. MDOT and the Gulf Coast Metropolitan Planning Organization have built and maintained the up-to-date State Wide and Gulfport Coast Regional TransCAD models which have been accessible to the project team. The TransCAD model used in this research was provided by GRPC. The task is to recapture the 2005 (before Katrina) and 2006 (after Katrina) social economic dynamics at the TAZ level.

The spatial units of the TransCAD network are TAZ. In the study area, there are actually 473 census TAZs according to the 2000 Census Transportation Planning Package. TAZ ranges from large areas in the suburbs to city blocks in the urban area by US census division. The criteria of defining a TAZ border is usually considered as utilizing the administrative borderline such as census tracts, county boundary or geographic separators such as roads, mountains, and rivers (5). When the TransCAD model was built, census TAZs were divided up into more homogenous zones with respect to the social economic characteristics in some outlying rural area. Moreover, parts of census TAZs inside the urbanized area boundary were also split in order to achieve a more realistic and accurate distribution of traffic. Therefore, the total 473 census TAZs in the study area have been divided up to 570 TAZs including 16 external stations in the TransCAD model. The TAZs distribution in the study area can be viewed from Figure 1.

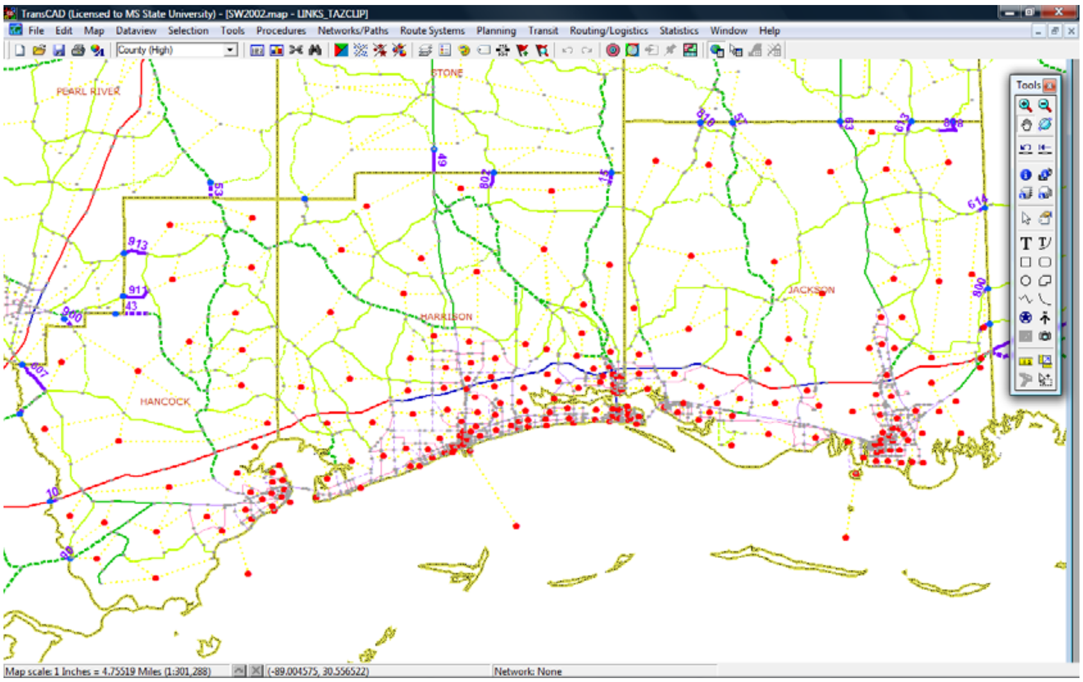

Figure 1: TAZs Distribution Map

Since the base year (2002) socioeconomic data is available at TAZ level and the target year (2005 and 2006) socioeconomic data can be obtained at the county level from the US census website, a disaggregation procedure has been applied to estimate the socioeconomic data associated with the TAZs using the county-level data. In this report, because there is insufficient socioeconomic data from the base year (2002) to the target year (2005 and 2006), a simplified and innovative method has been applied to disaggregate the county-level socioeconomic data to TAZs. The main points of the procedure are as follows:

1. Calculate the ratio of target year county-level data to base year county-level data.
2. Derive the target year socioeconomic data using the base year socioeconomic data multiplied by the ratio in step 1.

The above direct proportional method assumes that all the TAZs have experienced a linear growth at a same ratio as the counties have during 2002 – 2005. The acquired socioeconomic data is a rough estimation and more accurate data could be expected after the census releases the socioeconomic statistical data of target years in the future.

Model Outputs Calibration

TransCAD is a Global Information System (GIS) based traffic modeling software; therefore its traffic analysis and forecast module only generates vague OD data. For example, TransCAD does not provide split traffic flow at an intersection. Thereby, the outputs of the model need to be calibrated and refined in order to minimize the network analysis error.

To compensate for this disadvantage, GRPC utilized the Annual Average Daily Traffic (AADT) data to calibrate the TransCAD model. The base year and target years' AADT data has been divided into two sets. One is used for calibration and the other one is utilized for feasibility analysis.

CASE STUDY OF GULF COAST INTERMODAL TRANSPORTATION SYSTEM RESILIENCY

In this section, a case study is conducted for the Gulf Coast intermodal network which suffered severe damage during the 2005 Hurricane Katrina. The application of the proposed resilience measurement methodology on the intermodal network using results of the TransCAD model is illustrated as well.

Network Description

The TransCAD intermodal network of the Gulf Coast was obtained from the GRPC. The network was built on the base year 2002 and modified to imitate the damaged network after Katrina. In the coast area, there are 570 TAZs within three counties (Hancock, Harrison, and Jackson) including 4129 classified roads and other intermodal terminals (Figure 2). I-10, I-110, U.S.90, U.S.49, Highway 63, and Highway 67 are major roads in the Gulf Coast area. The network also contains information about the road length, classification, design speed, capacity and other details.

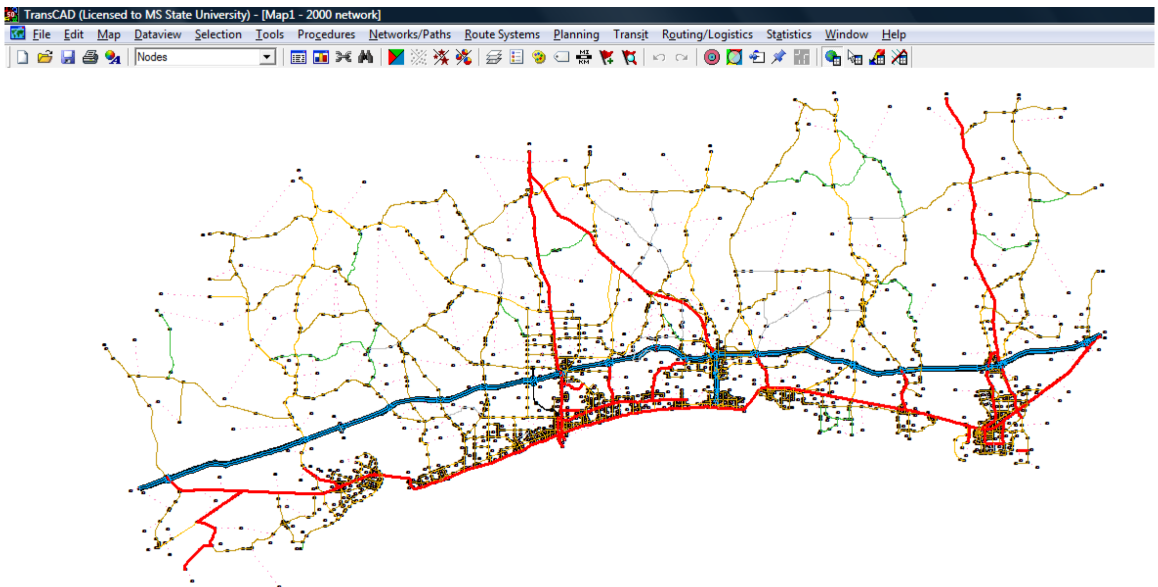

Figure 2: Gulf Coast Intermodal Transportation Network

The target year socioeconomic data associated with TAZs is disaggregated based on the collected county-level socioeconomic data (See Table 4). This data is used to estimate the target years (2005 and 2006) OD flow at TAZ-level in TransCAD. The detailed disaggregation procedure was previously discussed.

Table 4: Socioeconomic Data for the Gulf Coast Area

County	2002		2005		2006	
	Population	Employment	Population	Employment	Population	Employment
Hancock	42960	13860	46121	21190	38892	19060
Harrison	189599	91971	195969	93440	173218	84570
Jackson	133922	57698	134381	62740	128109	59510

After Hurricane Katrina destroyed the central Gulf Coast, the intermodal network was damaged significantly. For the highway system, although all roads along the Gulf Coast were affected by Hurricane Katrina, most of the state highways in the area were opened one week after the storm. Much of U.S. 90 along the coast was destroyed and it was the only major highway closed after Katrina. It opened in

February 2006 with at least one lane operating (eastbound) and in December 2006 with all lanes opened, minus the bridges.

Other disruptions include the bridge between Bay St. Louis and Pass Christian and the Biloxi-Ocean Springs Bridge. The U.S. 90 Bridge between Bay St. Louis and Pass Christian reopened to two lanes of traffic on May 17, 2007 and four lanes in January, 2008. The Biloxi-Ocean Springs Bridge opened two lanes traffic in November, 2007. There is no estimated opening date for the new bridge (10).

Additionally, I-10 over the Pascagoula River Basin (eastbound) also underwent damage during the height of Katrina. MDOT restored one lane of traffic in each direction of Interstate 10 by using the undamaged westbound span for a distance of three miles. By October 1st 2005, MDOT reopened the bridge and restored four-lane traffic on I-10. Some spans of the Popps Ferry Bridge were damaged by Katrina. The repair work was completed at December 23, 2005.

For the sea ports, the port of Gulfport bore the brunt of the hit to a ruinous degree and lost almost 700,000 square feet of space (27). The port's rail system was destroyed in whole and seven tenths of berths were demolished. The port's capacity was returned by October 2005 and returned to its pre-Katrina level in November 2005 except for frozen cargo exports. The port of Bienville lost the rail service and administrative facilities after Katrina hit but recovered very quickly, resuming operations in December 2005.

For the rail system, the CSX rail line sustained devastation under the storm surge. The company's rail line along the coast was almost closed for the first few months and was then rerouted due to the destruction of the railroad bridge across the Bay of Saint Louis. The truck volume reduced from 37201 carloads per month before Katrina to 26968 carloads per month after Katrina. The Port of Bienville Railroad closed approximately 80% of its 14.5 mile track after Katrina; its connection with CSX was completely destroyed.

For the airports, Gulfport-Biloxi airport reported that the current air cargo building suffered extensive damage during Hurricane Katrina and was in need of substantial repair and renovation. It was expected to move all air cargo activity into a new facility by the end of August 2008. Another airport, Stennis International airport, did not suffered significant damage during Katrina according to a telephone survey.

All the disruptions listed above will be revealed on the TransCAD network. The impacts on the network performance due to reduction of the network capacity will be discussed in the next subsection.

Performance Measure Calculation

Based on the forecasted socioeconomic data for each TAZ, the intermodal OD flow before and after Katrina among TAZs was generated by TransCAD. A total of 135,555 truck trips were generated for year 2005 and 105,213 trips were generated for year 2006. Then, the intermodal OD flow was divided and distributed to the intermodal network using the TransCAD Trip Assignment Module.

In order to present the case study more clearly, four scenarios were defined as follow:

Scenario 1: August, 2005 – Right before Hurricane Katrina occurred,

Scenario 2: September, 2005 – One week after Hurricane Katrina occurred (U.S. 90 was closed. Bay St. Louis Bridge and Biloxi Bay Bridge were destroyed.)

Scenario 3: February 2006 – U.S. 90 had one lane open except the bridges

Scenario 4: December, 2006 – All lanes of U.S. 90 are opened except the bridges

The total average daily truck flow for these four scenarios was shown in Figure 3.

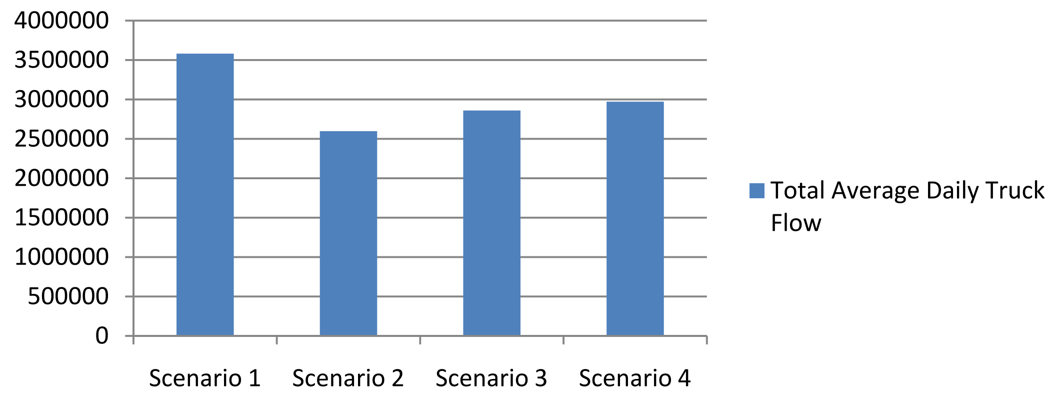

Figure 3: Total Average Daily Truck Flow for all Scenarios in Gulf Coast

Highway Network

Performance indicators were calculated regarding network mobility, accessibility, and reliability. Because the truck tonnage data was not available, Truck Miles Traveled (TMT) was used as a basic parameter to evaluate truck mobility instead of Ton Miles Traveled. The total trip length per day was obtained by summing TMT on each road. In 2005, TMT was 2,219,150 miles but it reduced to 1,614,380 miles right after Katrina in 2006. The results of the performance indicator calculations are shown in Table 5.

Table 5: Results of Performance Measures

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Average Daily Truck Flow	3581421	2595761	2858859	2870996
Mobility				
Average Truck Trip Length (mile)	16.371	15.344	15.795	15.814
Average Travel Time per Mile (min)	2.129	2.275	2.257	2.185
Mobility Performance Index	0.727	0.693	0.712	0.725
Accessibility				
Percentage of Open Highway (%)	100.0%	91.12%	98.39%	98.88%
Percentage of Truck Traveled under 85 Percentile of Limited Speed (%)	33.08%	38.76%	36.79%	36.03%
Reliability				
Average Delay Per Truck Trip (hour)	0.150	0.166	0.157	0.154

In Table 5, it was assumed that half of U.S. 90's capacity was restored since there was only one lane open in Scenario 3. Another assumption was that the acceptable travel speed on each link was the 85^{th} percentile of limited speed, and the trucks that traveled under this speed would suffer delay.

The level of service for each road in the network was estimated; the results are summarized in Table 6.

Table 6: Highway Network Level of Service

Gulf Coast Highway Network Level of Service						
Scenario 1	A	B	C	D	E	F
Local Street and Unclassified Road	1074	5	0	0	0	0
Percentage (%)	99.54	0.46	0	0	0	0
Collector	-	-	1412	24	1	0

Percentage (%)	-	-	98.26	1.67	0.07	0.00
Minor Arterial	-	-	628	69	3	1
Percentage (%)	-	-	89.59	9.84	0.43	0.14
Principal Arterial	35	400	48	9	36	17
Percentage (%)	6.42	73.39	8.81	1.65	6.61	3.12
Freeway	118	113	53	11	2	6
Percentage (%)	38.94	37.29	17.49	3.63	0.66	1.98
Scenario 2	A	B	C	D	E	F
Local Street and Unclassified Road	1010	69	0	0	0	0
Percentage (%)	93.61	6.39	0.00	0.00	0.00	0.00
Collector	-	-	1382	48	0	5
Percentage (%)	-	-	96.31	3.34	0.00	0.35
Minor Arterial	-	-	604	74	12	10
Percentage (%)	-	-	86.29	10.57	1.71	1.43
Principal Arterial	26	346	49	2	5	117
Percentage (%)	4.77	63.49	8.99	0.37	0.92	21.47
Freeway	101	91	52	30	8	21
Percentage (%)	33.33	30.03	17.16	9.90	2.64	6.93
Scenario 3	A	B	C	D	E	F
Local Street and Unclassified Road	1064	15	0	0	0	0
Percentage (%)	98.61	1.39	0.00	0.00	0.00	0.00
Collector	-	-	1389	41	4	1
Percentage (%)	-	-	96.79	2.86	0.28	0.07
Minor Arterial	-	-	603	86	7	4
Percentage (%)	-	-	86.14	12.29	1.00	0.57
Principal Arterial	32	349	74	9	38	43
Percentage (%)	5.87	64.04	13.58	1.65	6.97	7.89
Freeway	101	104	46	31	9	12
Percentage (%)	33.33	34.32	15.18	10.23	2.97	3.96
Scenario 4	A	B	C	D	E	F
Local Street and Unclassified Road	1071	8	0	0	0	0
Percentage (%)	99.26	0.74	0.00	0.00	0.00	0.00
Collector	-	-	1400	34	1	0
Percentage (%)	-	-	97.56	2.37	0.07	0.00
Minor Arterial	-	-	632	63	2	3
Percentage (%)	-	-	90.29	9.00	0.29	0.43
Principal Arterial	33	382	74	4	36	16
Percentage (%)	6.06	70.09	13.58	0.73	6.61	2.94
Freeway	101	105	46	25	7	19
Percentage (%)	33.33	34.65	15.18	8.25	2.31	6.27

Intermodal Terminals

In this study, interviews were conducted with the Deputy Director of Trade Development at the Port of Gulfport, CSX Railroad Company, and GRPC to gather information with regard to the freight transportation statistics before and after Hurricane Katrina. The results are summarized in the Table 7.

Table 7: Intermodal Terminals Level of Service

Port of Gulfport LOS Survey - Before Katrina						
	A	B	C	D	E	F
Average waiting time of users (min)	UP to 19	20 – 30	31 – 40	41 – 60	61 – 120	> 120
			√			
Incidents of delay in departure (%)	UP to 2%	(3 – 5)%	(6 – 15)%	(16 – 30)%	(31 – 60)%	> 60%
		√				
Duration of delay in departure (min)	UP to 30	31 – 45	46 – 60	61 – 90	91 – 180	> 180
	√					
Cut-off time (hour)	UP to 2	3 – 4	5 – 6	7 – 8	9 – 24	> 24
	√					
Loss of goods (%)	UP to 0	0 – 0.2%	0.2 – 0.5%	0.5 – 1%	1 – 2%	> 2%
		√				
Working hour per day (hours)		24		16 -24		< 16
		√				
Port of Gulfport LOS Survey - After Katrina						
Average waiting time of users (min)	UP to 19	20 – 30	31 – 40	41 – 60	61 – 120	> 120
		√				
Incidents of delay in departure (%)	UP to 2%	(3 – 5)%	(6 – 15)%	(16 – 30)%	(31 – 60)%	> 60%
		√				
Duration of delay in departure (min)	UP to 30	31 – 45	46 – 60	61 – 90	91 – 180	> 180
	√					
Cut-off time (hour)	UP to 2	3 – 4	5 – 6	7 – 8	9 – 24	> 24
	√					
Loss of goods (%)	UP to 0	0 – 0.2%	0.2 – 0.5%	0.5 – 1%	1 – 2%	> 2%
			√			
Working hour per day (hours)		24		16 -24		< 16
		√				

By far, CSX railroad is collecting the base information for LOS evaluation. Once the data is available it will be added to the calculation.

Since the Gulfport-Biloxi airport lost most of the facilities for cargo transportation during Katrina, it would not generate much cargo activity until the new facilities were built. Furthermore, the daily air cargo tonnage at Gulfport-Biloxi airport before Katrina was relatively weak, 0.00016% of total tonnage (28), compared with other intermodal terminals. Thus, the level of service for air terminals was not discussed in this report.

MOR Calculation

According to a survey conducted by GRPC, three years after Hurricane Katrina, almost all the population and employment had been recovered to pre-Katrina level (29). It was feasible to assume that the intermodal system had recovered from the disaster after three years of reconstruction, especially after U.S. 90, Bay St. Louis Bridge, and Biloxi Bay Bridge restored their capacity, although the repair work was still far from completion. Therefore, t – the total time required to restore the capacity is valued at 3 in the following MOR calculation.

In this analysis, MOR was calculated by comparing the performance between Scenario 1 and Scenario 2 using Formula (5). The results are listed in Table 8.

Table 8: MOR Calculation

	Scenario 1	Scenario 2	MOR
Mobility			
Average Travel Time per Mile (min)	2.129	2.275	18.7%
Mobility Performance Index	0.727	0.693	12.8%
Accessibility			
Percentage of Open Highway (%)	100.0%	91.12%	24.3%
Percentage of Truck Traveled under 85 Percentile of Limited Speed (%)	33.08%	38.76%	46.9%
Reliability			
Average Delay Per Truck Trip (hour)	0.150	0.166	29.1%

In this report, the MOR calculation for intermodal terminals was not provided for lack of information. That MOR calculation will proceed in the consecutive research.

Analysis of Case Study

The total truck trips in 2005 were 135,555 per day and truck volume was 3,581,421 per day. These numbers dropped to 105,213 and 2,596,761 respectively in 2006. The total truck trips and truck volume was seriously affected by the reduction of the population and employment.

In Table 5, the average truck travel time per mile raised from 2.129 minutes to 2.275 minutes after Katrina. It indicated that congestion was spreading in the highway network because some major roads, such as U.S. 90, Biloxi Bay Bridge, Popps Ferry Bridge, etc., were closed. Especially on I-10, which is the interstate highway paralleled with U.S.90, the average truck travel time reached 2.470 minutes, which was 116% of the pre-Katrina level. With most trucks choosing to reroute to I-10, the travel time increased correspondingly. This indicator reduced to 2.257 minutes after U.S. 90 opened one lane and went back to the pre-Katrina level once U.S. 90 restored full capacity. Another performance indicator, Percentage of Truck Traveled under 85 Percentile of Limited Speed, also provided evidence to the extensive congestion after Katrina. The percentage of trucks which traveled under 85^{th} percentile of limited speed went up by 5.68% in Scenario 2. All these indicators showed that the overall network performance on mobility had decreased.

The mobility PI provided reasonable and consistent results compared with traditional performance indicators. In Scenario 2, the value of PI was $0.693 < 0.7$, evaluated as ‘Poor’, while the value of PI in other scenarios were more than 0.7 matched ‘Fair’.

It also can be seen that, though a certain number of trucks rerouted after Katrina, the average truck trip length dropped from 16.371 miles before Katrina to 15.344 miles after Katrina. Then, the number increased to 15.814 with the recovery of the network capacity. The reason the average truck trip length decreased after Katrina was that the proportion of long-distance truck trips to the total truck trips was reduced. The TransCAD model adjusted the long-distance truck weight factor according to the socioeconomic data change. Herein, Equation (5) was not applicable to calculate MOR in terms of the average truck trip length since the intermodal system had a better average truck trip length performance after Katrina.

In the Gulf Coast area, freeways and principal arterials were the major two classes of roads where congestion occurred quite often after Katrina. Figure 4 shows the percentage of each level of service regarding freeway and principal arterial. For each scenario, freeways and principal arterials with LOS B exceeded 50 percent. The percentage of LOS A and LOS B for Scenario 1 are more than other scenarios. Additionally, the percentage of LOS F for Scenario 2 is much more than the other scenarios since the LOS for the roads of U.S. 90, closed in Scenario 2, were evaluated as LOS F.

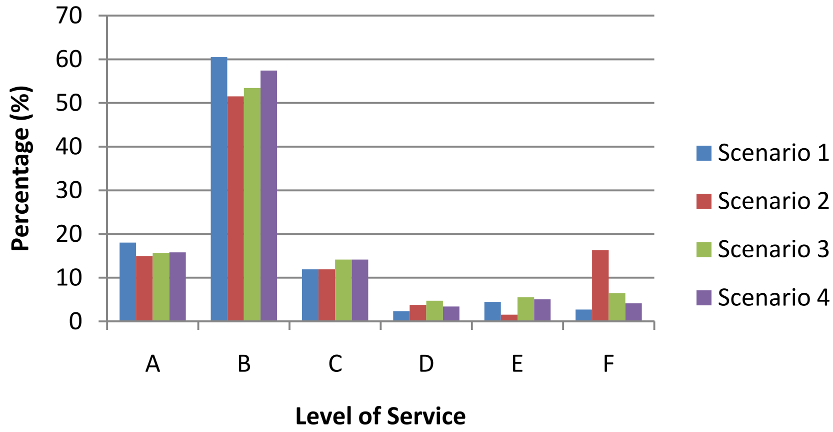

Figure 4: Percentage of LOS for Freeway and Principal Arterial

In Table 7, there was no significant difference in seaport terminals' LOS after Hurricane Katrina. The shipping service recovered very quickly in almost half a month after Katrina. The reduction of capacity did not affect the LOS severely. The only two minor differences lay on the aspects of "Average Waiting Time of Users" and "Loss of Goods". The LOS in terms of Average Waiting Time of Users was improved from C to B after Katrina. This phenomenon indicated that the port of Gulfport suffered a dramatic drop in demand after Katrina due to the reduction of total truck trips. Thus, the waiting time of trucks at the port were slightly reduced though the capacity of the port had not restored to the pre-Katrina level. Another LOS on Loss of Goods experienced declined from B to C after Katrina. This could result from lack of experience in response to emergencies. Loss of goods also dealt with certain capabilities of the ports such as large freezer storage being destroyed in the storm.

In Table 8, the results of MOR calculation showed a fair resilience ranging from 15% to 30% with respect to Average Travel Time per Mile, Mobility Performance Index, and Percentage of Open Highway. The MOR of Percentage of Truck Traveled under 85 Percentile of Limited Speed reached 46.9% and proclaimed a poor resilience level on this indicator.

CONCLUSIONS AND RECOMMENDATIONS

A framework of MOR assessment for intermodal network was presented in this report. To create the intermodal transportation system snapshots, TransCAD was employed to model the intermodal network before and after Katrina and generate traffic data for the MOR calculation. A disaggregation procedure was developed to estimate the population and employment at TAZ-level. The population and employment data was then used in TransCAD for generating the intermodal OD flow. A series of indicators were introduced to measure the intermodal system performance with respect to mobility, accessibility, and reliability. Then, a system-wide performance index integrated by some indicators was designed to evaluate the system's mobility. Based on the indicators, the intermodal system's resilience was measured as a performance reduction rate in the proposed calculation. Finally, result analysis of a case study on the Mississippi Gulf Coast showed that the truck speed was the most vulnerable performance due to the loss of capacity in major roads.

This report focuses on evaluating intermodal transportation resilience to the disasters which is a subject that is largely absent from existing research literature. The results of the calculation will facilitate the transportation agency to make a decision on the location of the most vulnerable part of the intermodal system, which facility has the most significant impacts to the intermodal system performance if broken down, which transportation mode plays the most important role in the intermodal network, and what strategies should be applied to mitigate the system congestion. The introduced socioeconomic data disaggregation procedure is easy to implement and offers flexibility to researchers who are faced with a lack of socioeconomic data. The proposed PI and MOR calculation method is proved to be intuitive and effective in order to quantify the system resilience. Although MOR calculation method was developed for system-level evaluation, it can still be applied to a specified individual facility.

In this report, the calculated system-wide resilience is corresponding to a specified disaster. With this lack of information, the level of intensity of the disaster was not accounted for in the MOR calculation; therefore, one cannot expect that the intermodal system will perform with the same resilience in another disaster. In the future, factors related to the level of intensity of the disaster should be considered in the framework. Another perspective of future activity is to work on strategies to enhance MOR. After Katrina, some strategies, such as route diversion, shifting goods to another mode, were applied to alleviate the impacts of facilities destruction. In order to measure the effectiveness of these strategies and identify strategies to enhance MOR, a second phase study will be conducted with the sponsorship of the Mississippi Department of Transportation. With the continued funding support from MDOT, the research team will use a manual process of re-routing and/or modal changes to identify and show potential MOR enhancement. A showcase will be used to demonstrate effectiveness of the infrastructure improvement strategy to the MOR enhancement.

PROJECT DISSEMINATION

This project has received additional funding of $25,862 from Mississippi Department of transportation to support a case study in the Gulf Coast of Mississippi. The proposed case study area was hit hard by hurricane Katrina and the extra task and fund fit the proposed framework perfect well. Additionally, an award by NCIT has been made to a continue research project "Modeling Economic Benefits Resilience Enhancement Strategies for Intermodal Transportation Systems", which deals with the follow-up issues (economic impact) on this research (transportation system resilience) by NCIT. Additional funding request has been made to Mississippi Department of Transportation as well.

Project results have been disseminated by submitting a paper for TRB presentation and TRR publication: "The Framework for Calculating the Measure of Resilience for Intermodal Transportation Systems"

1. Would you consider your project to be basic research, advanced research, or applied research?	Applied Research
2. Number of transportation research reports/papers published	0 (not include this one)
3. Number of transportation research papers presented at academic/professional meetings*	0
4. Number of students participating in transportation research projects	1 graduate 1 undergraduate**
5. Number of transportation seminars, symposia, distance learning classes, etc. conducted for transportation professionals	0
6. Number of transportation professionals participating in those events	0

*: A paper has been submitted for TRB presentation and TRR for publication.
**: Sponsored by MDOT fund

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