MISSISSIPPI TRANSPORTATION RESEARCH CENTER

FRAMEWORK OF CALCULATING THE MEASURES OF RESILIENCE (MOR) FOR INTERMODAL TRANSPORTATION SYSTEMS

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Prepared by:

Li Zhang, Ph.D., P.E., FITE
Zhitong Huang
& Yi Wen
Department of Civil and
Environmental Engineering

Mingzhou Jin, Ph.D.
Department of Industrial
and Systems Engineering

Mississippi State University
Mississippi State, MS

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MISSISSIPPI STATE UNIVERSITY
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16. Abstract

Recent catastrophic events, such as Hurricane Katrina, have accentuated the value of measures of resilience (MOR) for the response and restoration of transportation systems following a disaster and have therefore become a topic of great concern for transportation researchers. However, according to a review of current literature, a widely accepted method for evaluating MOR for transportation systems (especially in an intermodal context) has not been established. The objective of this report is to develop a framework for MOR calculation for intermodal transportation systems in response to disaster and to evaluate effectiveness of strategies for improving the MOR. Freight transportation resilience is the main concern in this report; however, to replicate actual traffic conditions, passenger transportation is also considered as a part of an integrated transportation system. For the MOR calculation procedure, TransCAD was used to model the research area network and generate transportation data. Pre-disaster and post-disaster population and employment data was collected at the county level and disaggregated to each Traffic Analysis Zone (TAZ) using linear equations. Then, based on the study area's population and employment data, the network Origin-Destination (OD) traffic before and after the disaster was estimated using TransCAD. A series of resilience indicators in terms of mobility, accessibility, and reliability were selected to evaluate the intermodal system performance based on the TransCAD outputs. A Performance Index (PI) is further introduced which aggregates several resilience indicators to measure system performance regarding mobility. The Level of Service (LOS) of highway networks and intermodal terminals before and after a disaster were also determined according to their respective LOS standards. Based on these resilience indicators, MOR in this report is defined the percentages of system performance measures degraded. A formula was developed to produce quantitative values for intermodal system MOR with respect to mobility, accessibility, and reliability. The above process was reviewed in a case study of the Mississippi Gulf Coast region. The analysis demonstrated the effectiveness of the proposed MOR calculation procedure. In addition, strategies for improving MOR were studied, and because the impact of disaster to MOR was not significant, rerouting was proposed as a method for improvement. To evaluate the effectiveness of rerouting, experiments were explored using DynusT simulation. Results of this experimentation show that, in this case, rerouting is a valid method for MOR enhancement and that diversion delay is significant.

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ABSTRACT

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Keywords: Intermodal Transportation, Resilience, Performance evaluations, Improving measure of resilience, Rerouting, DynusT

FRAMEWORK OF CALCULATING THE MEASURES OF RESILIENCE (MOR) FOR INTERMODAL TRANSPORTATION SYSTEMS

1 INTRODUCTION

Transportation system performance in response to unexpected disruptions is commonly referred to as resilience. Transportation system resilience has always been a major concern because it is vital for response and restoration of transportation systems following a disaster. Transportation researchers have dedicated much attention to resilience studies concerning individual modes of transportation such as highway, rail, waterway, and air. However, in recent years, after the catastrophe of Hurricane Katrina in August 2005, intermodal transportation system resilience has emerged as a timely issue.

In the state of Mississippi, the intermodal system, especially in the Gulf Coast region, was severely damaged by Hurricane Katrina. For example, the U.S. 90 Bridge between Bay St. Louis and Pass Christian was not rebuilt until more than two years after the storm. The railroad bridge of CSX Corporation in Bay St. Louis was repaired 156 days after Hurricane Katrina. The port of Gulfport took approximately two and a half months to restore its operation to pre-Katrina levels. As a result, the Gulf Coast region was selected as a case for this study. Figure 1, from the Mississippi Department of Transportation (MDOT) website (http://gomdot.com/Divisions/IntermodalPlanning/Resources/Maps/StateHighwayMaps.aspx), clearly shows that I-10, I-110, US 90, US 49, MS 67 and MS 63 are major highways in the research area.

Regarding the lessons learned from Hurricane Katrina, several subjects must be incorporated to produce a comprehensive study of intermodal transportation resilience. The long term effects of disasters to local and regional intermodal transportation systems must be evaluated. It is also important to develop a quantifiable measure of resilience (MOR) for the intermodal network following a natural or man-made disaster. Then, based on this information, strategies for resilience enhancement can be explored.

The objective of this research is to develop a framework of calculating the measure of resilience for intermodal transportation systems and to propose, as well as evaluate, strategies for improving the MOR. To accomplish this objective, the following five tasks were achieved:

- Define measures of resilience of intermodal transportation systems
- Recreate the intermodal transportation system snapshots before and after Hurricane Katrina
- Propose a framework to calculate the MORs
- Perform a case study of MORs in the recovery of Mississippi Gulf Coast after Hurricane Katrina
- Propose and evaluate strategies for enhancing MOR based on Mississippi Gulf Coast

The results from this research not only provide specific evaluation to the entire intermodal transportation resiliency of the Mississippi Gulf Coast, but 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 project team also presents an effective strategy to enhance the MOR of the research area.

This report first contains a relevant background and literature review regarding state-of-the-art transportation resilience research. Next, a MOR calculation framework is developed and discussed along with an explanation of the TransCAD modeling procedure used for this research to recreate a snap shot of Mississippi transportation systems before and after Hurricane Katrina. This is followed by a presentation of computational experience and analysis of MOR based on the research area. Finally, different strategies for improving MOR are proposed with an explanation of measuring effectiveness of rerouting, followed by a conclusion and recommendations for further study related to the scope of this report.

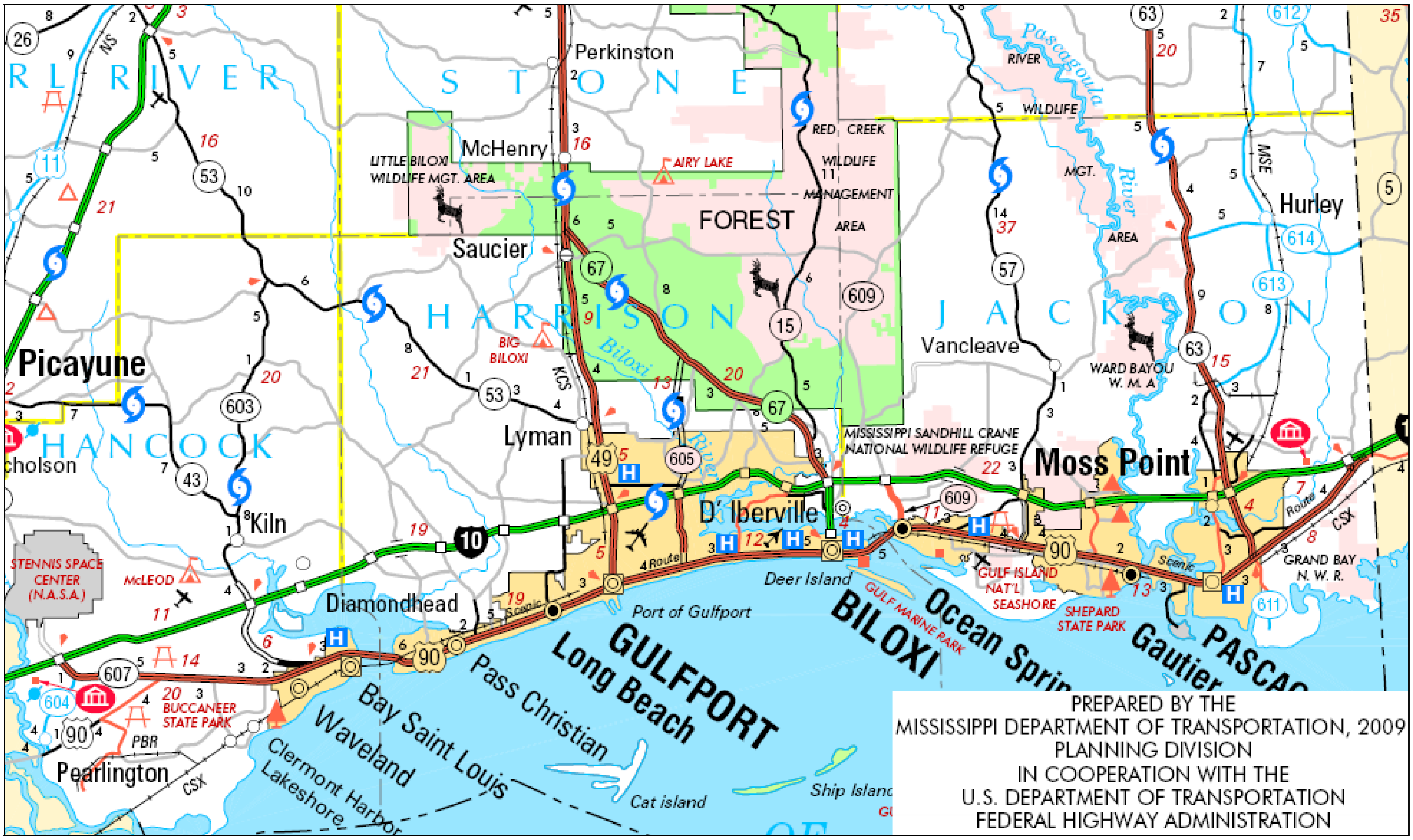

Figure 1 Map of Gulf Coast Region

2 LITERATURE REVIEW

The following section summarizes a literature review for cutting-edge research of transportation resilience. The factors of greatest concern are transportation system resilience, traffic OD pattern before and after disaster, intermodal transportation capacity before and after disaster, measure of resilience and improvement of the MOR.

2.1 Transportation System Resilience

Resilience has been studied extensively over the 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 [2].

So far, there is no widely accepted MOR in particular for intermodal transportation systems. Liu and Murray-Tuite [3] 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 [4] 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. [5] 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. According to his study, organizations are able to track their performance against stated objectives using tangible measures called Key Performance Indicators (KPIs) to reveal the vulnerability of the system. A 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. [6] 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. Three vital measures of resilience: "reduced failure probabilities", "reduced consequences from failures", and "reduced time to recovery" were proposed to evaluate resilience regarding technical, organizational, societal, and economic dimensions.

Wan [7] discussed the resilience of sensor network systems, a form of growing technology that provides wireless communication for the purposes of monitoring and data collection, to dramatic, physical environment change, during moments of disasters. To meet the pressing need for reliable communication and congestion control within these systems, sensor network transport resilience was defined as the ability to transmit a sufficient number of events to meet the applications' requirements at minimum energy consumption under abrupt changes in the system.

2.2 Traffic O-D Pattern Before/After Disaster

The interruption of traffic by disasters causes non-recurrent congestion. Liu and Murray-Tuite [3] 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. [8] designed a stochastic road transportation network model. The model was formulated as a stochastic bi-level programming problem where the upper-level problem presents the objective function of the model (to optimize enhancement of the network's capacity) and the lower-level problem refers to the demand assignment process. The demand (or capacity) between each O-D pair was assumed following Gaussian distribution. Genetic Algorithm combined with Monte Carlo simulation was used for calculating system reliability as measured in Total Travel Time (TTT).

Grenzeback and Lukmann [9] 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 study concluded that, although transportation facilities located in the New Orleans and the Gulf Coast region heavily influenced by the hurricanes, the hurricanes did not heavily interrupt national freight and passenger networks or cause significant associated costs. The study also indicated that transportation systems and providers performed well in the recover procedure.

Bhamidipati and Demetsky [10] 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) such as hazardous material truck shipment safety, freight shipment security, etc., were combined into a single index in order to rank each project in the case study.

A number of techniques can be applied to disaggregate county-level socioeconomic data into Traffic Analysis Zones (TAZs). Walton et al. [11] introduced the Disaggregated Residential Allocation Model (DRAM) and Employment Allocation Model (EMPAL) (DRAM and EMPAL are the registered trademarks of S.H. Putman Associates). They were used to forecast household and employment location at the Regional Analysis Zone (RAZ) level to reflect changes in socioeconomic characteristics. DRAM/EMPAL applied a modified standard gravity model that incorporates multi-parametric attractiveness function. The duration of the forecasting is 5 years. DRAM plans location of household using income classes and then EMPAL simulate for this 5 years. The Subarea Allocation Model (SAM) developed by Maricopa Association of Governments [11] 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.

2.3 Intermodal Transportation Capacity Before/After Disaster

Chang [12] discussed the impacts of the 1995 earthquake on the Port of Kobe and its long-term impact on the economy of the affected area. Chang categorized the restoration of the port into two groups: restoration of damaged facilities and restoration of cargo shipment. 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 [13] 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 [14] 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 [15] has been widely used in forecasting and modeling transportation demand. TransCAD includes trip generation, distribution, and traffic assignment models that support transportation planning and travel demand forecasting. TransCAD has the feature that integrates geographic information system for transportation (GIS-T). Transportation system network with related geographic data can be built in TransCAD. Therefore, the transportation system capacity before and after disaster can be represented by TransCAD software.

2.4 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 [16] developed a transportation network disruption index and integrated multiple resilience dimensions (redundancy, diversity, and mobility) into one measure. Ballis [17] 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. [18] presented a methodology to quantify the resilience of transportation networks. A series of performance indices were evaluated based on expertise. Fuzzy theory was applied in order to use mathematical relationships to represent experts' preferences using if-then statements.

2.5 Improvement of MOR

Liu and Murray-Tuite [3] used transportation system resilience as a criterion for evaluating effectiveness of strategies for alleviating the impact of incident. Liu proposed four strategies: making HOV lane available for all traffic during incident time, setting "variable speed limits (VSL)" (incident area is designated lower speed limit), diverting vehicles by offering real time traffic conditions though personal and vehicular electronic equipment and using "variable message signs (VMS)" for rerouting. Liu then used a real network for evaluating the four methods in VISSIM simulation. Based on results, the author recommended that the two most effective strategies for improving resilience of transportation system are making HOV lane available for all traffic during incident time and using VMS for rerouting.

Brabhaharan [4] also introduced systematic measures to determine resilience gaps for entire highway network. Based on the gaps, the author recommended three strategies for improving resilience: enhances resistibility to incidents, decreases restore time and plans substitute routes. Brabhaharan suggested these methods should be used altogether.

Victoria Transport Policy Institute [19] developed an online encyclopedia concerning Transportation Demand Management(TDM). The encyclopedia first introduces definitions and related knowledge of resilience. Then, it describes functions of Transportation Demand Management (TDM) for improving transportation system resilience. Next, it illustrates a process of evaluating resilience. The online encyclopedia presented some strategies for enhancement of resilience such as improving diversity, connectivity and redundancy of transportation system, and enhancing resistant ability of the system's infrastructure during extreme events, setting priorities for different transportation resources and their use plan during incidents and so on. In addition, it also introduced many specific TDM methods for improving resilience; for example, building an intermodal transportation system, reserving railway for future emergency use, etc.

RAND Corporation [20] proposed ways for Metropolitan Planning Organizations (MPOs) and Departments of Transportation (DOTs) to enhance resilience of transportation system, primarily for freight transportation, based on their functions and duties. For DOTs, the suggested methods are making a detailed actions plan response to disturbance of transportation system, possessing the ability to control integrated system resources to drastically alleviate impact of disruption and the maximally increase whole system performance. The proposed method is that the minor disruptions are used for exercising reactive activities in order to prepare more serious disruptions. The recommendations are specifically addressed to MPOs. First, MPO should exploit means for evaluating active performance of transportation system by considering dynamic features of the entire system in planning models. In addition, MPOs should infuse resistant ability in planning procedure of transportation system using alternative resources which are not or not seriously impacted by disruption. Furthermore, planning process should specifically consider both freight and passenger traffic, especially freight traffic which may not be widely considered. The article also advised that MPOs and DOTs should match their endeavors in vital areas which demand interaction between two agencies.

3 MOR FRAMEWORK DEVELOPMENT

In this section, a series of resilience indicators (RIs) are developed for MOR. A system-wide performance index (PI) is proposed to evaluate the system mobility based on several RIs. A quantified MOR calculation procedure is proposed in the next subsection using this approach. Another resilience indicator, Level of Service (LOS), is introduced in this section for evaluating MOR. LOS is a method of classification based on operating performance that provides an effective comparison of how traffic conditions change using a qualitative measure, ranging from A to F [21]. However, a range of performance is represented by each LOS classification and therefore cannot reveal MOR change within the same letter score. For this reason, LOS is not included as a quantitative MOR calculation procedure, but simply as a good indication of the resiliency of a system following a disaster.

3.1 Intermodal System Resilience Indicator Measurement

MOR is represented by various resilience indicators. Two categories of performance [22] 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 [23]. 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 for evaluating system mobility. Outcome from an earlier research project performed by Wang et al. [24] were utilized to derive the equation for the calculation of average travel time per mile.

Average travel time per mile is defined as,

$$T = \frac{\sum_{i \in O, j \in D} v_{i,j} t_{i,j}}{\sum_{i \in O, j \in D} v_{i,j} l_{i,j}} \tag{1}$$

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,

$$L = \frac{\sum_{i \in O, j \in D} v_{i,j} l_{i,j}}{n} \tag{2}$$

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 resilience indicator related to accessibility is the percentage of freight vehicles traveling under the acceptable travel speed (T_u). These two indicators pertaining to the connectivity of the network affect the overall travel time and accessibility of an intermodal system. In this report, acceptable travel speed is proposed as the 85th percentile of limited speed. The accessibility relationships described in this paragraph are shown below.

$$L_t = \frac{L_O}{L_T} \times 100\% \tag{3}$$

Where:

L_t : Percentage of total length of highway that is open to freight traffic in the network;

L_O : Total length of highway that is open to freight traffic in the network;

L_T : Total length of highway in the network.

$$I_t = \frac{I_O}{I_T} \times 100\% \tag{4}$$

Where:

I_t : Availability of intermodal terminals;

I_O : Number of intermodal terminals open to freight traffic in the network;

I_T : Total number of intermodal terminals in the network.

$$T_u = \frac{T_U}{T_T} \times 100\% \tag{5}$$

Where:

Acceptable travel speed = 0.85 * speed limit;

T_u : Percentage of freight vehicles traveling under the acceptable travel speed;

T_U : Number of freight vehicles traveling under the acceptable travel speed;

T_T : Total number of freight vehicles in the network.

Reliability: Reliability is usually characterized by the delays caused by system interruptions. Frequency and duration of unanticipated delay are widely used for measuring reliability [25]. Reliability indicates the portion of freight traffic in the network which is able to successfully stay on schedule. It also reflects the ability to timely accommodate variable and unexpected conditions of the intermodal system without catastrophic failure. Within this report, reliability is determined using the average delay per trip equation as follows:

$$d_{i,j} = v_{i,j} \max\left[\frac{l_{i,j}}{s_{i,j}} - \frac{l_{i,j}}{Acceptable\ travel\ speed}, 0 \right] \times 60 \tag{6}$$

$$R = \frac{\sum_{i \in O, j \in D} d_{i,j}}{n} \tag{7}$$

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 (*mph*), $i \in O, j \in D$,

R = average delay time per trip (*min/trip*)

3.2 Intermodal Transportation System Level of Service

The resilience indicators described in the previous section are easily understood by transportation engineers, but they present challenges for the general public. Furthermore, intermodal facilities may possess different numeric numbers and may even be measured by different performance, which makes comparison between modes very difficult. Therefore, a unified term, namely Level of Service (LOS), is introduced to measure MOR of different intermodal transportation facilities.

3.2.1 Highway Network Level of Service

The concept of LOS is commonly used in evaluating intermodal system performance. LOS typically ranks transportation facility performance using a letter score, ranging from A to F (A representing the best traffic condition and F representing the worst condition). The Highway Capacity Manual (HCM) [26] provides a widely accepted methodology to estimate LOS with respect to different types of facilities under different traffic conditions. LOS is one resilience measure chosen for use in this report. In this report, the highway LOS standard, as shown in Table 1, was developed referring to the *Mississippi Gulf Coast Area Transportation Study 2030 Long Range Transportation Plan* [27] and the HCM. Traffic volume and directional volume/capacity ratios were also used as LOS criteria.

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

Note: the maximum volume in this table corresponds to daily traffic in vehicle/day.

3.2.2 Intermodal Terminals Level of Service

In general, the entire intermodal network consists of two components: transportation network and intermodal terminals. The road network may comprise over a thousand miles of highways while the intermodal terminals include seaports, rail terminals and airports. Since the operations between road network and intermodal terminals are not similar, it is necessary to develop a different standard of LOS to evaluate intermodal terminal performances. Considering the data availability, intermodal terminal LOS has been measured by a number of resilience indicators in terms of mobility, reliability, flexibility, security, and accessibility. These measures of criteria, shown in Table 2, are from the Ballis [17] 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	

Note: Incidence rate in departure is defined as percentage of vessel/train delay in departure. Cut-off Time is defined as the “time interval between the latest container delivery at the terminal entrance and the departure time of the vessel/train” [17].

3.3 Performance Index

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

There are several methods to develop a Performance Index (PI) [28]: using an equation that weights each performance indicator (resilience 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. Within this report, PI regarding travel speed has been proposed based on the first method. This PI measures the ratio of travel speed to 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 lower mobility, whereas a PI with a higher value indicates the network mobility is in relatively good status. PI is defined in Table 3 below.

Table 3 Mobility Performance Index

Measure	Calculation	Rating					
		A	B	C	D	E	F
Travel Speed, Truck Miles Traveled	$PI = \frac{\sum_{i \in O, j \in D} \frac{s_{i,j} v_{i,j} l_{i,j}}{FFS_{i,j}}}{\sum_{i \in O, j \in D} v_{i,j} l_{i,j}}$	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

3.4 MOR Definition

In this research, 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 a function of the RIs before and after disaster which were defined earlier, including mobility, accessibility and reliability. LOS is not included in this calculation for reasons discussed at the beginning of this section.

MOR can be calculated by:

$$MOR = \frac{\left(RI_{before} - RI_{after}\right)\left(1 + t^{\alpha}\right)}{RI_{before}} \% \tag{8}$$

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 report, α is tentatively designated as an average value between 0 and 1 of 0.5. Specific calibration will be performed in the future to obtain a more accurate value of α. Since MOR measures the reduction of system performance after disaster, a lower value of MOR means the difference of system performance before and after disaster is lesser and thus, the system is more resilient to the disruption.

4 INTERMODAL OD FLOW ESTIMATION

To calculate the intermodal transportation system RIs changes due to disaster, the first step is to capture OD traffic flow changes. In this section, TransCAD was employed to model the intermodal network and generate data in order to calculate the system's performance. The Mississippi Gulf Coast region is used as a case study to illustrate the process. Detailed discussion about data collection and process methods was provided to develop the model. The TransCAD model was built on the 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 the Gulf Regional Planning Commission (GRPC), was modified to recapture the transportation system both before and after Hurricane Katrina.

4.1 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 engineers. Regional statistics such as county population, employment, road repair and reconstruction progress, etc. were obtained. The research team also communicated with freight companies, such as CSX, Port of Gulfport, Biloxi International Airport, etc. with regard to the freight transportation change after Katrina.

However, a great deal of information would be 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.

4.2 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 performed in this project 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 for 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 [4]. When the TransCAD model was built, census TAZs were divided 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. According to the *Gulf Coast Travel Demand Model User's Guide* [29], external stations are those stations which are located outside the study area but are connected to the internal subarea through a boundary link. The TAZs distribution in the study area can be viewed from Figure 2. The green areas represent TAZs in the Gulf Coast region.

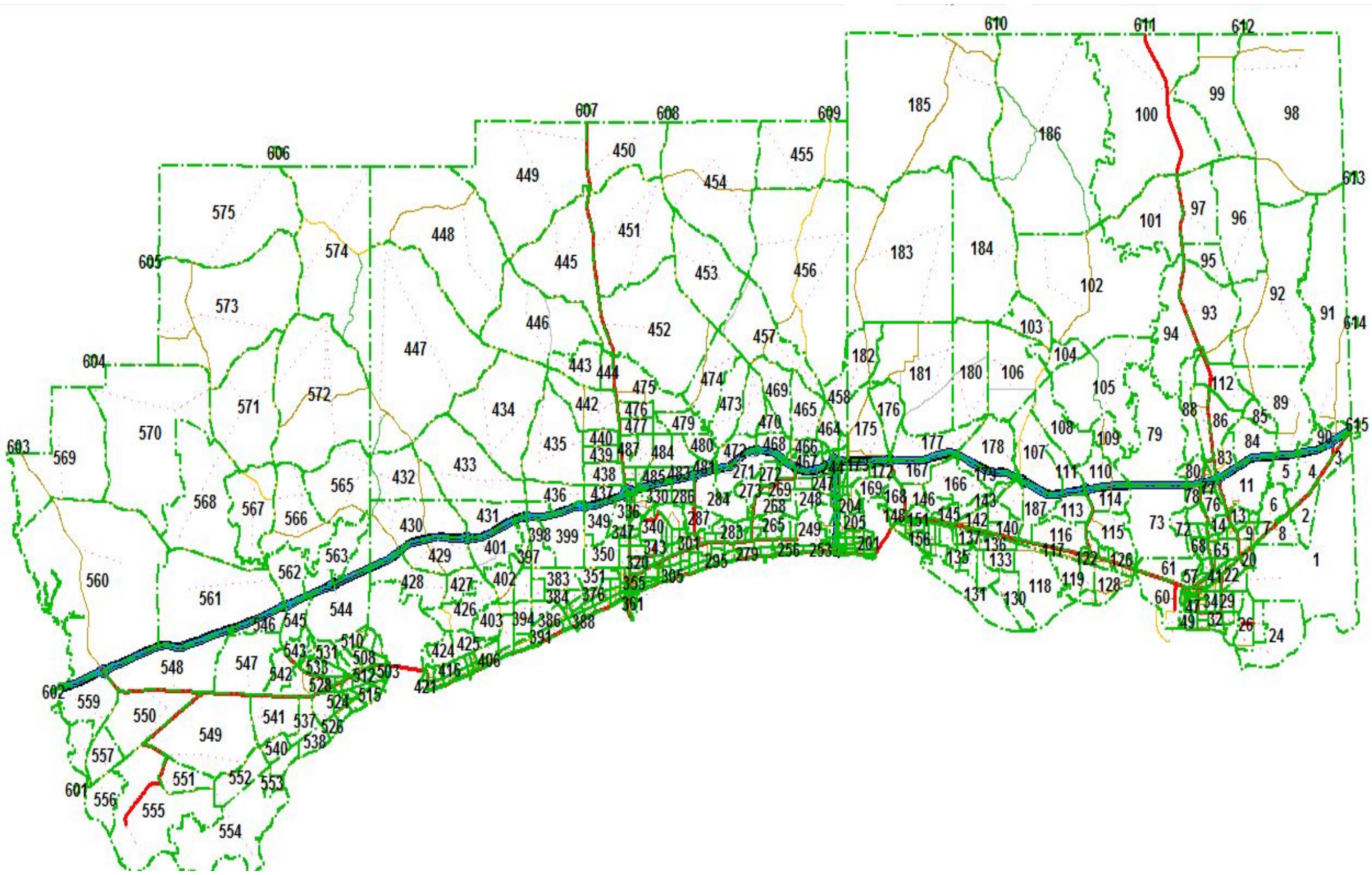

Figure 2 TAZs Distribution Map of TransCAD

Since the base year's (2002) socioeconomic data is available at TAZ level and the target years' (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 years (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. Generate an adjustment factor by calculating the ratio of target year county-level data to base year county-level data.

2. Derive the target year TAZ-level socioeconomic data using the base year TAZ-level socioeconomic data multiplied by the factor in step 1.

The above direct proportional method assumes that all the TAZs have experienced a linear growth at the same ratio as the counties from 2002 to 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.

4.3 Model Outputs Calibration

TransCAD is a Geographic Information System (GIS) based traffic modeling software; therefore its traffic analysis and forecast module only generate vague OD data. For example, TransCAD does not directly 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. This calibration was performed by GRPC in their original models.

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.

4.4 Future Enhancement to Before/After Disaster OD Flow Model

Generally, for resilience study, there are four types of traffic flow in the research area: outside to outside flow (through flow), outside to inside flow (enter flow), inside to outside flow (exit flow) and internal flow. For future resilience flow modeling, the research team suggests that the researchers should concentrate on the last three OD flow changes because these are heavily impacted by natural or man-made incidents. Existing models like TransCAD treat all four types of OD flow all together.

5 CASE STUDY OF GULF COAST INTERMODAL TRANSPORTATION SYSTEM RESILIENCY

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

5.1 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 coastal area, there are 570 TAZs within three counties (Hancock, Harrison, and Jackson) including 4,129 classified roads and other intermodal terminals (Figure 3). 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. The Gulf Coast Region network of TransCAD version has 3,182 nodes, 4,144 links and 570 TAZs.

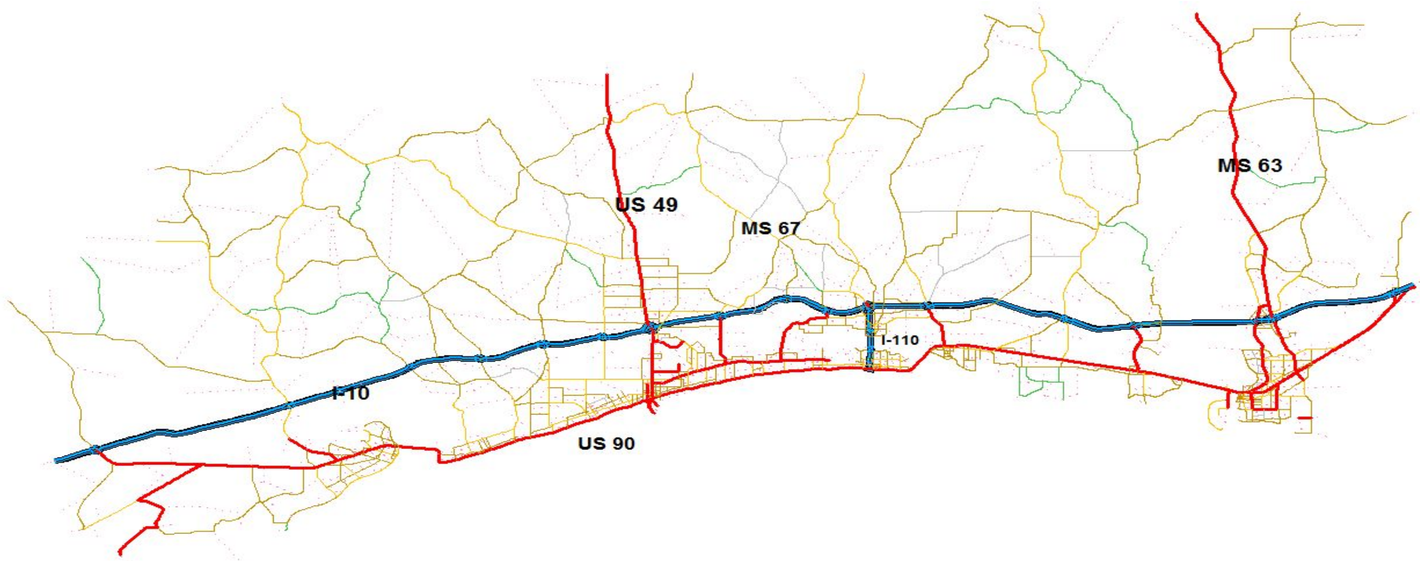

Figure 3 Gulf Coast Intermodal Transportation Network

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

Following the passage of Hurricane Katrina over the central Gulf Coast region, the intermodal transportation network sustained significant damage. For the highway system, although all roads along the Gulf Coast were affected by the hurricane, 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. Two of U.S. 90's vital bridges, the Bay St. Louis Bridge and Biloxi Bay Bridge, remained closed for reconstruction. 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 to traffic in November, 2007 [9].

Additionally, I-10 over the Pascagoula River Basin (eastbound) also experienced damage during the Hurricane 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 on December 23, 2005.

For the sea ports, the port of Gulfport was heavily damaged by the hurricane and lost almost 700,000 square feet of space [30]. The port's rail system was destroyed completely and seven tenths of berths were demolished. The port's capacity was restored by October 2005 and returned to its pre-Katrina level in November 2005 except for frozen cargo exports. After Katrina hit, the port of Bienville lost rail service and administrative facilities 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 company's truck volume reduced from 37,201 carloads per month before Katrina to 26,968 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 severed.

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 suffer significant damage during Katrina according to a telephone survey.

All the highway system disruptions listed above were modeled on the TransCAD network. The impacts on the network performance due to reduction of the network capacity are discussed in the next subsection.

5.2 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 2005 (before disaster) and 105,213 trips were generated for 2006 (after disaster). The intermodal OD flow was then 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 follows:

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

Scenario 2: September, 2005 – One week after Hurricane Katrina occurred (U.S. 90 was completely 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

As discussed before, there are 2005 and 2006 OD data in TransCAD. OD data of Scenario 1 corresponds to 2005 (before disaster) and OD data of Scenarios 2, 3 and 4 correspond to 2006 (after disaster).

5.2.1 Highway Network

Resilience 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 resilience indicator calculations are shown in Table 5.

Table 5 Results of Performance Measures

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
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^{th} 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

For the calculations 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. Other assumptions were 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. As discussed earlier, US 90 received the greatest impact of all the roadways in the research area. I-10 and US 90 are major highways in the west/east direction, therefore vehicles needed to divert to I-10 after US 90 was interrupted. In the TransCAD network, US 90 and I-10 correspond to principal arterial and interstate highway (freeway) classifications, respectively. Table 6 shows that the percentages of LOS A and B in freeway and principal arterial roads decreased after disaster and the percentage of LOS ranging from D to F notably increased.

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		25	296	76	20	127
Percentage (%)		4.60	54.41	13.97	3.67	23.35
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

Note: Each highway type displays the total number of links corresponding to each category of level of service as well as the percentage that each level of service represents for that particular classification. A link is determined by the transportation engineer who modeled the network. It represents the network size and is a good indicator of labor hours spent in the modeling process.

The table above also shows percentage of LOS F in principal arterial in Scenario 2 is the highest, because it is the most seriously impacted by the disaster in four scenarios and the closure of US 90 roads are considered as the F. Other roads with a value F of LOS is shown in Figure 4. These roads are labeled with blue five-pointed star. The major roads are US 49 from the intersection with Landon Road to the intersection with Airport Road, Pass Road from the intersection with Cowan Road to the intersection with Switzer Road/Debuys Road and Washington Avenue from the intersection with Old Fort Bayou Road to the intersection with US 90.

Figure 4 Roads with a value F of LOS except US 90 in Scenario 2

5.2.2 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 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
	√					

CSX railroad did not return the research team's survey for LOS evaluation and the data is not available in this report. 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 small, 0.00016% of total tonnage [31], compared with other intermodal terminals. Thus, the LOS for air terminals was not discussed in this report.

5.3 MOR Calculation

According to a survey conducted by GRPC, three years after Hurricane Katrina, almost all the population and employment had recovered to pre-Katrina levels [32]. It was feasible to assume that the intermodal transportation 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. 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 (8). 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 85th 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 was only applied to the highway network. Intermodal terminals are measured by LOS using survey data. During our literature review and survey, the highway intermodal terminal MOR would be at least as good as the highway network in the coastal region of Mississippi.

5.4 Case Study

The total truck trips (OD) in 2005 were 135,555 per day and dropped to 105,213 in 2006. This indicates that the total truck trips were 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 before Katrina to 2.275 minutes after Katrina. This indicates 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. On I-10, the interstate highway which runs parallel to U.S.90, the average truck travel time per mile reached 2.470 minutes, which was 116% of the pre-Katrina level. After most trucks were rerouted to I-10, the travel time increased correspondingly. This indicator reduced to 2.257 minutes after U.S. 90 opened one lane and finally reached pre-Katrina levels once U.S. 90 restored full capacity. Another resilience indicator, Percentage of Truck Traveled under 85th Percentile of Limited Speed, also provided evidence to the congestion after Katrina. The percentage of trucks which traveled under 85th percentile of limited speed went up by 5.68% in Scenario 2. All these indicators showed that mobility decreased for the network as a whole.

The mobility PI provided reasonable and consistent results compared with traditional resilience 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'. Although the performance decreased one level, the value of Scenario 2 is very close to the 0.7 boundary. Thus, the mobility decreased after Katrina but not significantly.

Also, it can be seen that, although a certain number of trucks rerouted from US 90 to I-10 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. A further explanation of why the average truck trip length decreased after Katrina is included in the *Traffic Assignment Experience in DynusT* section of this paper. The TransCAD model adjusted the long-distance truck weight factor according to the socioeconomic data change. Herein, Equation (8) 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 5 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.

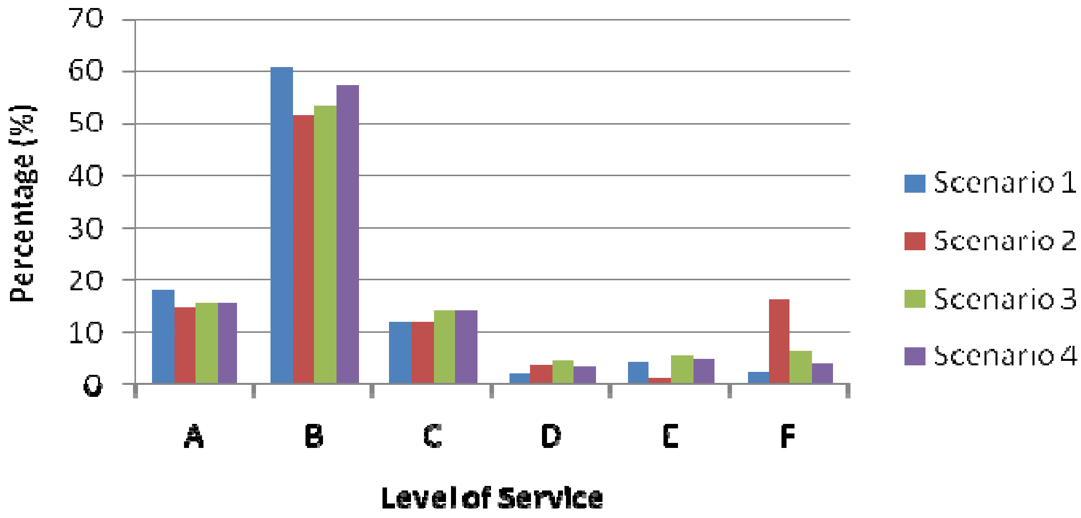

Figure 5 Percentage of LOS for Freeway and Principal Arterial

In Table 7, there was no significant difference in seaport terminals' LOS after Hurricane Katrina. The shipping service recovered very quickly in just 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 tangible 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 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.

6 IMPROVEMENT OF MOR

In this section, with sponsorship from Mississippi Department of Transportation, the research team further explores strategies for improving MOR and evaluates its effectiveness. The research team proposed two methods at first: rerouting and modal shift. Based on the findings of previous sections, the impact of Hurricane Katrina to MORs is not significant enough to cause modal shift and therefore, rerouting is the major focus of MOR improvement for this report.

In addition, the research team chose DynusT, a trail version of dynamic traffic assignment software sponsored by FHWA, for evaluating effectiveness of rerouting. DynusT is software that dynamically assigns and simulates traffic in the field of regional traffic study [33].

The procedure for building the DynusT network is first introduced. Then, a method for evaluating effectiveness of rerouting is described in detail. Finally, simulation experiences in DynusT are presented.

6.1 Building DynusT Network

In previous sections, the Gulf Coast intermodal network was built by using TransCAD obtained from the GRPC. In this section, the TransCAD network is used as a base network. The data from TransCAD network, including node, link (road) and TAZ information, are used for building the DynusT network. The process is tedious and time consuming because a portion of the data was encoded in TransCAD. The research team needed to contact the model developer in order to decode and interpret the data. For example, in TransCAD, a link's number of lanes listed as 31 does not correspond to 31 actual lanes. It means that this link has 3 lanes with one direction of travel (James D. Wilkinson, unpublished data). In addition, DynusT requires different network and traffic formats compared with TransCAD, so that significant manual revision is necessary. Finally, correcting the movement of intersections must be accomplished manually as well intersection by intersection.

In order to replicate actual traffic conditions as much as possible, the research team revised some TransCAD data. The number of lanes for all I-10 links was verified and some of them were revised, according to Google Maps. The speed limit of I-10 and I-110 were increased from 60 mph in TransCAD network to 70 mph which is more consistent with realistic interstate highway.

6.1.1 Network Building

There are three major components of data which require conversion: network, demand and GEO data [33]. Network conversion is a major part of building network. The notable difference between DynusT and TransCAD network is that DynusT is not based on centroids but depends on generation links which generate vehicles into network and destination nodes which vehicles leave network by enter into them, so DynusT requires modifying all centroids and their connectors from TransCAD network and assigns generation links and destination nodes [33]. Thus, the research team manually completed this process through the method suggested by the DynusT online manual [33]. This task is very time consuming since there are 570 TAZs in the Gulf Coast network; each TAZ contains at least one generation link and one destination node.

Based on DynusT requirements [33], node, link, and TAZ data from TransCAD network were inputted into the DynusT network. Because two networks' link types did not correspond they had to be matched. The research team carefully studied the TransCAD data and DynusT online manual [33] supplemented by an inquiry with the DynusT technical support team. By suggestion, the research team decided to implement the mapping information for two different types of networks, shown in Table 9 below, which was provided by the DynusT technical support team (Kris Milster, unpublished data)

Table 9 Mapping information of link types between TransCAD and DynusT

TransCAD	**DynusT**
Local/Unclassified	Arterial
Rural Minor Collector	Arterial
Collector/Rural Major Collector	Arterial
Minor Arterial	Arterial
Principal Arterial	Highway
Interstate Highway	Freeway
Interstate Highway On/Off Ramp	On or Off Ramps

Link is directional in DynusT which means each link has just one direction [33], creating 7,003 links in DynusT after conversion. Thus, after converting the network from TransCAD, there are a total of 3182 nodes, 7003 links and 570 TAZs in the DynusT network.

Regarding the Demand data, the research team used the same OD from TransCAD network and utilized 15 hours' OD for simulation in DynusT. Time of day data were obtained from TransCAD software and are stored in HOURLY.BIN that locates in TransCAD program files (C:\Program Files\TransCAD\tab\HOURLY.BIN) [34]. Table 10 below displays data from HOURLY.BIN [34].

Table 10 Time of day in TransCAD software

Hour	0	1	2	3	4	5	6	7	8	9	10	11
Percentage (%)	0.70	0.20	0.80	0.10	0.10	1.00	3.20	8.90	4.10	3.20	3.90	4.10
Used in Simulation								√	√	√	√	√
Hour	12	13	14	15	16	17	18	19	20	21	22	23
Percentage (%)	5.20	4.80	4.90	6.70	9.30	8.50	6.40	7.90	5.90	4.80	3.20	2.10
Used in Simulation	√	√	√	√	√	√	√	√	√	√		

According to *Travel Demand Modeling with TransCAD 5.0 User's Guide*, hour 0 corresponds with 12:00 a.m. to 1:00 a.m. [34]. So, based on TransCAD User's Guide, 15 hour simulation lasting between 7:00 a.m. and 22:00 p.m. accounts for 88.6% of daily total OD and includes all daily rush hours [34]. Thus, according to the above table the remaining 9 hours account for a reasonably small percentage of daily traffic, indicating a little chance that congestion will appear during this period.

There are two types of vehicle, “Private Occupancy Vehicles” (POV) and Truck in the TransCAD network [29]. Therefore, it has two corresponding OD tables according to *Gulf Coast Travel Demand Model User’s Guide* [29] and the research team who analyzed information of TransCAD log file by the method suggested by the TransCAD technical support team.

GEO data involves geographic information of nodes, links and TAZs [33]. This data makes link and TAZ’s shape have curvature [33]. The information directly outputted from TransCAD.

6.1.2 Revising Network

After building the network, turning movements of intersections of network are checked manually, according to suggestion by the DynusT technical support team (Eric J. Nava, unpublished data), online manual [33] and research team experience. Incorrect turning movements of intersections may develop during network conversion because intersections with special geometrical shape might be mistakenly identified by software [33]. Figure 6 is an example of such a shape. Although A to C is though movement in reality, software may recognize the movement as left turn movement.

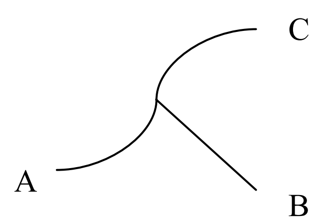

Figure 6 Example of Special Intersection Shape

6.2 Traffic Impact of Rerouting

In this section, traffic impact of rerouting are explored. Scenarios 1 and 4 are chosen for study because traffic volumes were very low during Scenarios 2 and 3 in reality (4 Scenarios are defined previously in the Case Study of Gulf Coast Intermodal Transportation System Resiliency section). During the 1.5 years between Scenario 1 and Scenario 4, the effects of Katrina on daily traffic were shown in Scenario 4. So, effectiveness of rerouting on traffic congestion is demonstrated by comparing Scenario 1 and 4. DynusT was selected to simulate these two Scenarios. Results of different Scenarios of DynusT simulation are shown in the next subsection: Traffic Assignment Experience in DynusT.

Figure 7 was obtained from Google maps. As discussed before, all facilities are opened in Scenario 4 except Bay St. Louis Bridge (icon A) and Biloxi Bay Bridge (icon B). Figure 7 clearly shows that US 90 and I-10 are two major roads in the west/east direction for the research area. Thus, a majority of traffic volume would be forced to divert to I-10 due to two bridges breakdown in Scenario 4.

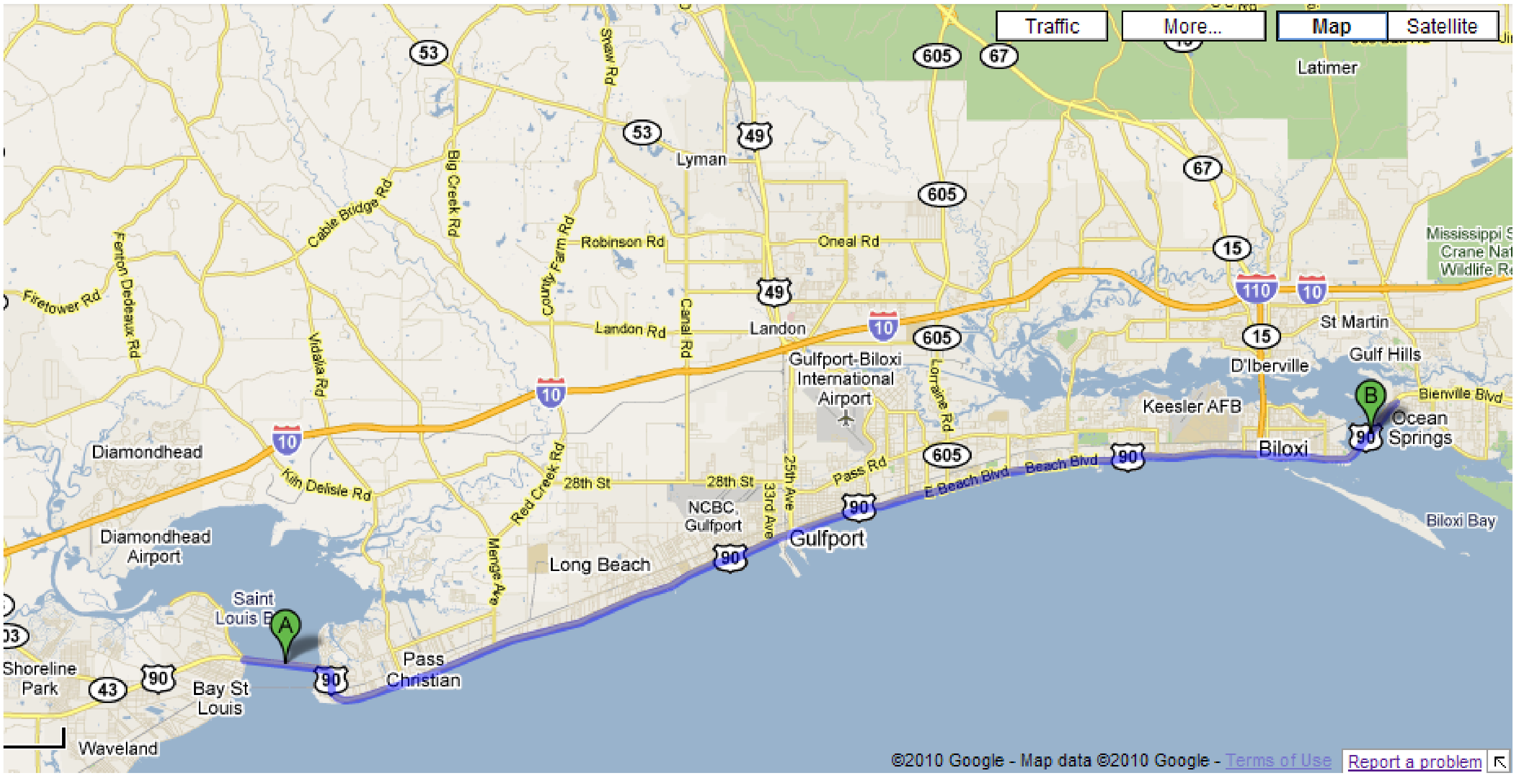

Figure 7 Map of Two Bridges (http://maps.google.com/)

6.2.1 Traffic Assignment Experience in DynusT

6.2.1.1 Briefly introduce Original research plan

As previously discussed, Scenarios 1 and 4 were selected for simulation to evaluate the effectiveness of rerouting. There are three cases required for simulation, including one case for Scenario 1 and two cases for Scenario 4. Of the two cases for Scenario 4, one case is treated as the base case without rerouting and the other case is recognized as an applied diversion strategy. Comparing the Scenario 1 case with the Scenario 4 base case reveals the influence of Katrina for daily traffic after disaster. Then, by comparing both cases for Scenario 4, the effectiveness of rerouting is discovered.

Scenario 1 is simulated by using its network and OD tables then by choosing one of the five “Multiple User Classes” (MUC) [33] in DynusT as a method of traffic assignment. At first, the MUC preferred by the research team was “Class 1 Unresponsive (Historical Data)”, characterized by vehicles that always keep the previous path and ignore all information except compulsory detour [33]. However, the DynusT technical support team explained that this class requires the use of an existing DynusT simulation case as the previous path so that all vehicles generated in the next simulation case would follow the existing case's path (Eric J. Nava, unpublished data). Since there are no previous DynusT simulation cases available, the team implemented "Class 5 Pre-trip Information".

For the base case of Scenario 4, same as Scenario 1, "Class 5 Pre-trip Information" was selected. Then, network and OD tables of Scenario 4 were utilized for simulation. "Class 3 User Equilibrium (UE)" and "Class 2 System Optimal (SO)" were considered for the rerouting case as different strategies in DynusT to determine which strategy was more efficient, but "Class 2 System Optimal (SO)" was currently unavailable within the DynusT software. Therefore, "Class 3 User Equilibrium (UE)" was the only option for analysis of the rerouting case. As discussed earlier, a 15 hour simulation period was selected for daily traffic.

6.2.1.2 Traffic Assignment Experience in DynusT

During the research process, two experiments were conducted using DynusT which caused the research team to explore an alternate method for continuing the project (one of them has been solved partly in the end of this research). As a result, the HCM method was applied for studying the effectiveness of rerouting instead of DynusT. Reasons for this decision are specifically explained in the following section of this report. The two experiences are discussed in detail below.

First of all, when running the DynusT simulation different times under the same simulation files (the same OD tables and network), the total number of vehicles that was generated by DynusT changed between simulations. The DynusT technical support team was inquired about this situation and they explained that the total number of vehicles between simulations should be roughly the same but not identical (Eric J. Nava, unpublished data). However, the DynusT Gulf Coast network appears to be very sensitive to the total number of vehicles. Even an increase of about 5% of total number of vehicles would cause congestion to appear in the network. From Table 11 below, it can be seen that the total number of vehicles in the first simulation was 5.7% more than the second given the exact same OD data. More congestion appeared in the first case than in the second case during simulation. To test whether this situation would appear again, the research team ran a similar simulation using a simple network (6 nodes, 10 links and 2 zones) and OD table (240 trips). The same condition appeared in this network. The problem has been reported to DynusT development teams in both the test cases and original cases.

Table 11 Different Total Number of Vehicles Generated by DynusT Simulation

	Scenario 4(UE) (case 1)	Scenario 4(UE) (case 2)
Total number of Vehicles	984232	931458
Percentage of Truck (%)	8.42	9.74
Total number of Truck	82872	90724

As mentioned before, two types of OD data were inputted into the DynusT network from TransCAD and truck is one type [29]. In this report, the DynusT network's total number of truck is obtained by multiplying the total number of vehicles by the percentage of truck. Since the total number of vehicles and the percentage of truck vary between simulations, the total number of truck changes as a result. This situation seriously impacts the project because truck traffic is the main concern. Table 11 shows that the percentage of truck changed for each case. In the original TransCAD data the percentage of truck in the network was relatively small (12.2% in Scenario 1 and 9.9% in Scenario 4). Therefore, a 1% change in the percentage of truck would result in a significant change in the total number of truck. Moreover, even if the percentage of truck remained the same between simulations, a change in the total number of vehicles would still cause a change in the total number of truck. Unfortunately, DynusT would not generate a stable total number of vehicles as shown in Table 12 below.

Table 12 Example of Different Total Number of Truck

	Scenario 4 (Class 5)	Scenario 4 (UE)
Total number of Vehicles	936403	931458
Percentage of Truck (%)	9.74	9.74
Total number of Truck	91206	90724

At the end of this study, the first experience was partly corrected by persistent endeavors of the research team. To determine why the total number of vehicles varied between different simulations, the research team spent much time analyzing data of completed simulation cases. Using previous experience, the research team decided to check the random number seed setting within the program. There are two options for random number seed when setting up the scenario data in DynusT. Selecting the "system" option enables DynusT to generate a new seed for each simulation, while selecting the "user-specified" option assigns a fixed value designated by the user for different simulations [33]. Thus, the research team performed two simulations with the same fixed random number seed using the "user-specified" option. OD tables and network were the same and both simulations chose class 5 as the traffic assignment method. The total number of vehicles for the first and second run was almost identical, 978,244 and 979,261, representing a mere difference between them of 0.1 %. However, the percentage of truck changed from 6.75% to 8.30%, which causes the total number of truck to change based on reasons discussed earlier.

Secondly, there are three choices for "Vehicle Generation Mode": veh files, OD matrix and veh+path files (output_vehicle.dat and output_path.dat) in DynusT [33]. In order to fix the fact that the total number of vehicles is not the same in different simulation cases, DynusT technical support team (Eric J. Nava, unpublished data) suggests the use of the output_vehicle.dat and output_path.dat files from a previous simulation case instead of OD data to run the simulation a second time. DynusT technical support team indicated this produces the exact same total number of vehicles in the whole network between two simulation cases. For the issue that output_path.dat is also need for simulation, DynusT technical support team explained the path file would update during simulation. The research team completed two simulation cases for Scenario 4 following this approach. Scenario 4 (Class 5) was simulated by using OD data of Scenario 4 and Class 5 as the traffic assignment method. Scenario 4 (UE) was then simulated using output_vehicle.dat and output_path.dat from the previous case and utilizing the Class 3 traffic assignment method.

However, following this method resulted in vehicles lost in the OD pair for the second simulation. The research team then utilized a tool called "Vehicle Path Analysis" [33] in DynusT software to study vehicle paths after rerouting. It was found that, in one case, one OD pair from 203 to 159 having 37 vehicles (5 Trucks) in the first simulation case lost all vehicles in the second simulation case. According to the DynusT technical support team (Eric J. Nava, unpublished data) and the online manual [33], the function of the AltPah.dat file is to record all DynusT generated vehicles' path information during simulation, but even in the AltPah.dat file, there is no vehicle path information recorded from zone 203 to 159 in the second simulation case. As a result, the MOR resilience indicators generated by DynusT can only be accurate to a certain degree, but might be still calculated for a rough analysis. Performance for the scenarios was computed according to the previously proposed calculation method for resilience indicators. The results of such analysis are shown in Table 13.

Table 13 Results of MOR Performance of Lost Vehicles Pair Cases

	Scenario 1	Scenario 4 (Class5) input OD	Scenario 4 (UE)
Mobility			
Average Truck Trip Length (mile)	15.975	15.274	10.111
Average Travel Time per Mile (min)	1.238	1.229	1.390
Mobility Performance Index	0.989	0.989	0.986
Accessibility			
Percentage of Truck Traveled under 85th Percentile of Limited Speed (%)	3.36	3.44	3
Reliability			
Average Delay Per Truck Trip (min)	0.049	0.059	0.055
Network			
Total number of Vehicles	978370	936403	936403
Percentage of Truck (%)	12.12	9.74	9.98
Total number of Truck	118578	91206	93453

Percentage of Open Highway (Equation 3) was not calculated because the Gulf Coast network's condition did not change between DynusT and TransCAD and thus the percentage remained the same. From Table 13 it can be seen that average truck trip length dropped considerably in the second simulation of Scenario 4.

To confirm this situation and test whether it might be caused by choosing to first simulate Scenario 4 by using Class 5 and then applying UE for the second simulation, the research team decided to use reverse ordering for testing. Scenario 4 (UE) was simulated with the inputted OD tables of Scenario 4 and then its output_vehicle.dat and output_path.dat files were used to run a Scenario 4 (Class 5) simulation. The "Vehicle Path Analysis" tool [33] was also utilized to check the same OD pair from zone 203 to 159 which lost all vehicles before. In the first case, there were 26 vehicles (7 Trucks) from zone 203 to 159 but the second case produced a similar situation with only one vehicle (no Truck) from zone 203 to 159. Calculation for MOR resilience indicators is also performed for this analysis and results are summarized in Table 14.

Table 14 Results of MOR Performance of Lost Vehicles Pair Cases (reverse order)

	Scenario 1	Scenario 4 (Class5)	Scenario 4 (UE) Input OD
Mobility			
Average Truck Trip Length (mile)	15.975	10.203	15.488
Average Travel Time per Mile (min)	1.238	1.485	1.317
Mobility Performance Index	0.989	0.930	0.944
Accessibility			
Percentage of Truck Traveled under 85th Percentile of Limited Speed (%)	3.36	16.8	16.77
Reliability			
Average Delay Per Truck Trip (min)	0.049	0.245	0.272
Network			
Total number of Vehicles	978370	984232	984232
Percentage of Truck (%)	12.12	9.01	8.42
Total number of Truck	118578	88679	82872

The research team reported this problem to FHWA's DynusT developer for further investigation. There are 570 TAZs in the network so checking every OD pair for one case would require checking 570*570 possibilities, which is impossible due to time constraints. Also, the research team anticipates that a situation similar to the one in the first experience involving the random number seed setting could also be responsible for the loss of vehicles in the simulation.

Based on above discussions, the research team ran the simulation multiple times using the same OD data and network in order to find two cases in which the total number of vehicles and percentage of truck are approximately equal. Table 15 displays the results of calculation for MOR resilience indicators for two qualified cases.

Table 15 Results of MOR Performance (all input OD tables)

	Scenario 1	Scenario 4 (Class5)	Scenario 4 (UE)
Mobility			
Average Truck Trip Length (mile)	15.975	15.274	15.241
Average Travel Time per Mile (min)	1.238	1.229	1.229
Mobility Performance Index	0.989	0.989	0.989
Accessibility			
Percentage of Truck Traveled under 85^{th} Percentile of Limited Speed (%)	3.36	3.44	3.37
Reliability			
Average Delay Per Truck Trip (min)	0.049	0.059	0.058
Network			
Total number of Vehicles	978370	936403	931458
Percentage of Truck (%)	12.12	9.74	9.74
Total number of Truck	118578	91206	90724

As explained before in the original research plan, Scenario 4 (Class 5) was applied as a base case and Scenario 4 (UE) was used as a rerouting case for Scenario 4. From Table 15 above, comparing Scenario 1 and Scenario 4 base or rerouting cases, it can be seen that average truck trip length dropped slightly after disaster. There are three types of truck, "long distance truck", "special generators truck" and "local truck" in the TransCAD model [35] which were inputted into the DynusT network. Compared with Scenario 1, Scenario 4's TransCAD data concerning OD data of total truck, "long distance truck", "special generators truck", and "local truck" decreased 22.38%, 23.71%, 41.90% and 21.92%, respectively. Even though the percentage drop of "long distance truck" is not notable compared to others, it has a significant impact on average truck trip length since this type of truck travels a longer distances than other types of trucks. For example, the white links in the east/west direction shown in Figure 8 are I-10 segments in DynusT network. Trucks belong to "long distance truck" from one OD pair, TAZ 189 and 492, travel the whole I-10 segments in research area. Thus, the number of "long distance truck" in Scenario 4 decreased, resulting in a decrease in average truck trip length, even considering diversion of some trucks due to the interruption of two bridges.

Figure 8 Location of TAZ 189 and 492

Furthermore, average travel time per mile decreased only slightly which indicates that closure of the two bridges did not have a serious influence on the whole network. On the contrary, it slightly improved traffic conditions for the network due to a decrease in traffic volume. On the other hand, the percentage of truck traveling under 85th percentile of limiting speed and average delay per truck trip rose which shows that the diversion of vehicles deteriorated traffic conditions of specific areas and created congestion. Combined with the results of the HCM method in the next subsection, congestion would appear around ramps from west to east direction of I-10 affected by disruption of the Biloxi Bay Bridge.

Comparing Scenario 4 (Class 5) with Scenario 4 (UE), it can be seen that the two cases' performance parameters are approximately the same. With respect to mobility, the performance index of two cases ranked A (Excellent) according to Table 3. Both cases' average travel time per mile was 1.229 min. which corresponds to an average speed of 48.8 mph. With respect to accessibility and reliability, resilience variables were also found to represent good conditions. As shown in Table 16, based on the standard of Table 1, LOS of arterial, highway and freeway were calculated between A and D which means that traffic conditions are acceptable for the two cases. Performances concerning average truck trip length, percentage of truck traveled under 85th percentile of limited speed and average delay per truck trip in the rerouting case of Scenario 4 are slightly better than the base case. This indicates that rerouting can improve traffic conditions and MOR to a certain degree.

Table 16 Highway Network LOS of DynusT network

Gulf Coast Highway Network Level of Service						
Scenario 1	A	B	C	D	E	F
Arterial	---	---	4602	---	---	---
Percentage (%)	---	---	100	---	---	---
Highway	---	458	628	---	---	---
Percentage (%)	---	42.17	57.83	---	---	---
Freeway	37	47	22	---	---	---
Percentage (%)	34.91	44.34	20.75	---	---	---
Scenario 4 (class5)	A	B	C	D	E	F
Arterial	---	---	4602	---	---	---
Percentage (%)	---	---	100	---	---	---
Highway	---	484	598	---	---	---
Percentage (%)	---	44.73	55.27	---	---	---
Freeway	42	46	17	1	---	---
Percentage (%)	39.62	43.40	16.04	0.94	---	---
Scenario 4 (UE)	A	B	C	D	E	F
Arterial	---	---	4602	---	---	---
Percentage (%)	---	---	100	---	---	---
Highway	---	485	597	---	---	---
Percentage (%)	---	44.82	55.18	---	---	---
Freeway	39	50	16	1	---	---
Percentage (%)	36.79	47.17	15.09	0.94	---	---

Note: See Note in Table 6

6.2.2 HCM Method

Due to the two situations in DynusT, the research team explored another method to evaluate effectiveness of rerouting. Below is a detailed description of the method used by the research team to assess the traffic impact of diversion, according to the Highway Capacity Manual (HCM) [26]. For the remainder of this report it is referred to as the HCM method. As discussed before, Scenario 4 is the only post-disaster scenario chosen for study. The method focuses on evaluating traffic conditions of Scenario 4 which shows daily traffic after disaster. To analyze the influence of two bridges broken down on traffic congestion in Scenario 4, the research team used the network with all facilities opened, including the two bridges and the OD tables of Scenario 4 for simulation. The assumption was made that only vehicles which passed the two bridges needed to divert to I-10 after interruption; other vehicles would follow original paths. Based on this assumption, the volume of both bridges of Scenario 4 in DynusT simulation cases is manually assigned to I-10 to simulate traffic impact of rerouting. Because the analysis is for each direction, the volume of a specific I-10 link, affected by one of two damaged bridges after diversion, is obtained by summing the volume of the I-10 link before diversion and the volume of the bridge in the same direction before diversion at the same time stamp. In this section, two terms are frequently used to describe the state of analysis; *before diversion* describes the traffic conditions preceding bridge closure and *after diversion* describes the traffic conditions following bridge closure that results in the rerouting of vehicles from US 90 bridges to I-10.

According to online manual [33], in DynusT, there are five classes: "Class 1 Unresponsive (Historical Data)", "Class 2 System Optimal (SO)", "Class 3 User Equilibrium (UE)", "Class 4 En-Route Information" and "Class 5 Pre-trip Information", which are called "Multiple User Classes (MUC)". The five class are used to differentiate driver's action to response information and user could set percentage allocation for each class [33]. "Class 5 Pre-trip Information", drivers are already aware of network situation and choose a minimum travel time path before departure and DynusT assign the path when vehicle create [33], and "Class 3 User Equilibrium" are selected respectively as methods of traffic assignment in two simulation cases for study. In this report, all classes chosen had been set a 100% distribution in order to utilize one class for simulation. To better study the influence of diversion vehicles to I-10, basic segments and ramps of I-10 will be analyzed for each direction.

6.2.2.1 Analysis of Bay St. Louis Bridge

Basic Segment of I-10

Figure 9 is a map of the Bay St. Louis Bridge (icon A) obtained from Google maps. It can be clearly seen that after damage of the Bay St. Louis Bridge, vehicles needed to divert to segments of I-10 between MS 43 and Kiln Delisle Road.

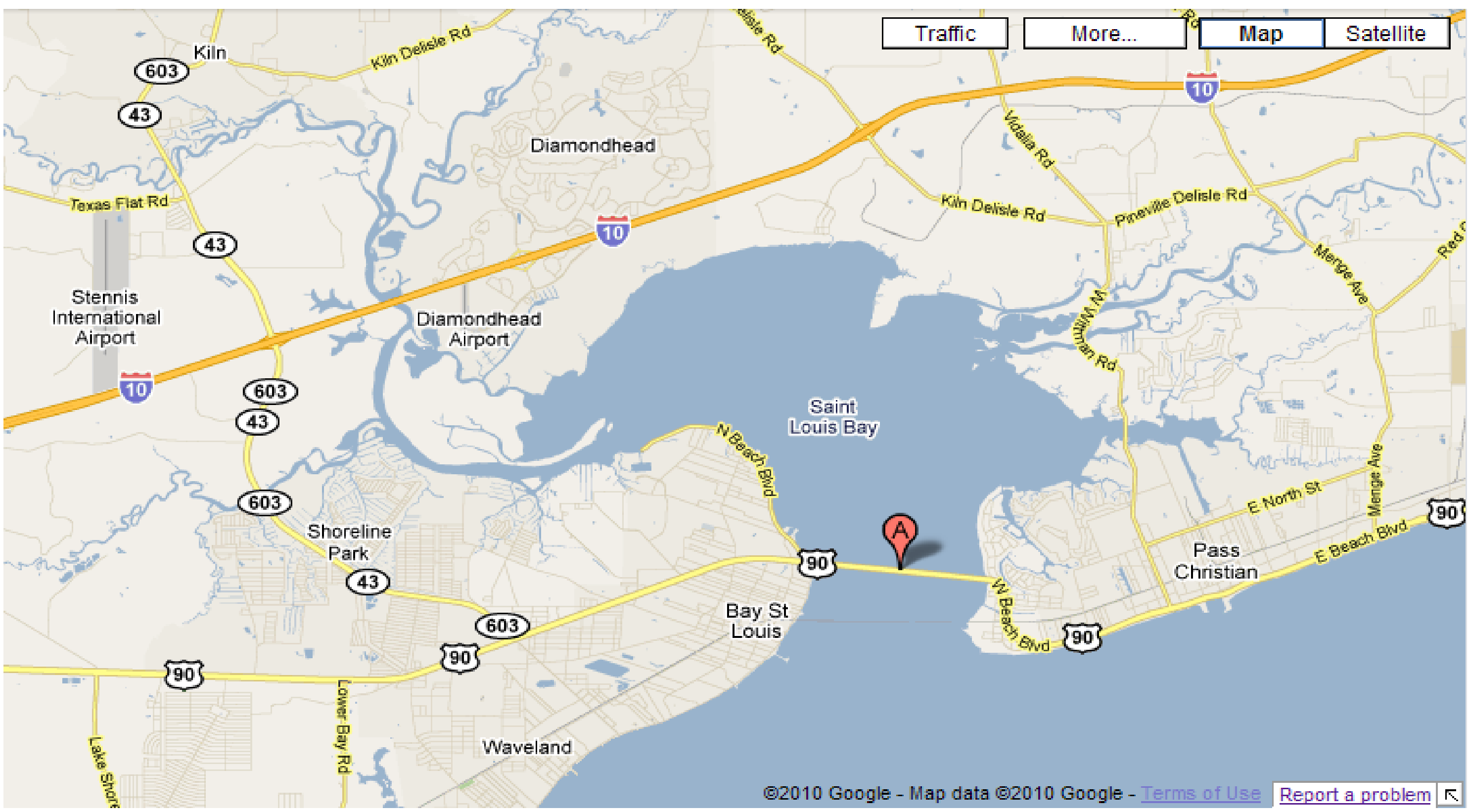

Figure 9 Map of Bay St. Louis Bridge (http://maps.google.com/)

Because the bridge's direction from west to east is broken down, vehicles divert to this section of I-10 basic segments which corresponds to three links in DynusT network. In accordance with the HCM method, maximum flow rate of these I-10 links before and after diversion during 15 hours are calculated and links' LOS are obtained according to Table 1. Results are illustrated in Table 17 below. The links' maximum flow rate and maximum v/c ratio increased slightly after diversion. Only link 2207's LOS decreased in the case of class 5; thus, the effects of the bridge breakdown in this direction are marginal for I-10 basic segments.

During simulation time, maximum flow rate of an I-10 link after diversion (in this table and other tables in this section) was calculated as the first obtained maximum value of the sum of the fifteen minute flow rate of the I-10 link and the same fifteen minute flow rate of the bridge in the same direction before diversion. Multiplying by a factor of four can then convert this value to an hourly maximum flow rate.

It should be noted that during simulation time, maximum fifteen minute flow rate of the I-10 link after diversion and the I-10 link and bridge in the same direction before diversion may occur at different time frames. Let (*c)* represent the fifteen minute flow rate of an I-10 link after diversion and (*a*) and (*b*) represent the corresponding fifteen minute flow rates of I-10 and the bridge before diversion, respectively, which together add up to (c). Flow rates (*a*) and (*b*) do not necessarily represent individual maximum values when (c) produces a maximum value. This is clearly shown in Table 17 below, where (A), (B) and (C) represent the converted hourly maximum flow rates of the I-10 link before diversion, the bridge before diversion and the same I-10 link after diversion.

For the class 5 case, the maximum flow rate of the I-10 link after diversion nearly equals the sum of the maximum flow rate of the same I-10 link and the bridge in west to east direction before diversion. However, for the class 3 case, the sum of the maximum flow rate of the I-10 link and the bridge in west to east direction before diversion is larger than the maximum flow rate of the same I-10 link after diversion. Additionally, the difference in the I-10 link before and after diversion is much less than the maximum flow rate of bridge in this direction which means the volume of the I-10 links has a greater impact than the volume of the bridge before diversion on the volume of the same I-10 link after diversion.

Table 17 Results of Bay St. Louis Bridge Breakdown for I-10 Basic Segments from West to East

Class Type		"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"
I-10 Links	Link ID	2225		2173		2207	
	Number of lanes	3		2		2	
	Capacity (veh/hr)	6000		4000		4000	
	Before diversion						
	Maximum$^{(A)}$ flow rate (veh/hr)	3044	2944	2716	2632	2904	2828
	Maximum v/c ratio	0.51	0.49	0.68	0.66	0.73	0.71
	LOS	B	B	C	C	C	C
	After diversion						
	Maximum$^{(C)}$ flow rate (veh/hr)	3212	3128	2900	2876	3076	3044
	Maximum v/c ratio	0.54	0.52	0.73	0.72	0.77	0.76
	LOS	B	B	C	C	D	C
Bay St. Louis Bridge	Before diversion						
	Link ID	1286					
	Maximum$^{(B)}$ flow rate (veh/hr)	200	636	200	636	200	636

Similarly, when Bay St. Louis Bridge's direction from east to west is interrupted, the same part of I-10 segments is influenced in the reverse direction. This segment also corresponds to three links in the DynusT network. Using the same method used for analysis in the opposite direction, an analysis was performed and the results are shown in Table 18 below.

Table 18 Results of Bay St. Louis Bridge Breakdown for I-10 basic Segments from East to West

Class Type		"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"
I-10 links	Link ID	2195		2205		2398	
	Number of lanes	3		2		2	
	Capacity (veh/hr)	6000		4000		4000	
	Before diversion						
	Maximum flow rate (veh/hr)	3180	2912	2784	2636	2904	2828
	Maximum v/c ratio	0.53	0.49	0.70	0.66	0.73	0.71
	LOS	B	B	C	C	C	C
	After diversion						
	Maximum flow rate (veh/hr)	3368	3140	2980	2836	3088	3032
	Maximum v/c ratio	0.56	0.52	0.75	0.71	0.77	0.76
	LOS	C	B	C	C	D	C
Bay St.Louis Bridge	Before diversion						
	Link ID	3422					
	Maximum flow rate (veh/hr)	256	248	256	248	256	248

The results from the east to west direction are similar to those from the opposite direction. Maximum flow rate and maximum v/c ratio rose but not significantly. LOS of link 2195 and 2398 declined in the case of class 5. And the maximum flow rate of the bridge before damage is nearly same in class 3 and 5 cases. Based on these two tables, it can be concluded that interruption of the Bay St. Louis Bridge has a minor effect on I-10 basic segments. Even if all traffic volume of the bridge is rerouted to I-10 after it is damaged, LOS for the basic segments of I-10 in both directions is between B and D which is acceptable. Differences of maximum flow rate, maximum v/c ratio and LOS for both directions before and after diversion are small.

Ramps of I-10

Another transportation facility which should be considered is ramps. In reality, the appearance of congestion on a ramp is more probable than in basic segments of a freeway. DynusT was selected as the first method of analysis. To evaluate the effectiveness of DynusT, the class 5 simulation case was selected involving an on ramp (link 2309) and the corresponding downstream basic segment of I-10 (link 2225) affected by the Bay St. Louis Bridge in the west to east direction.

Figure 10 displays the density, speed and volume relationships of link 2309 (red line) and link 2225 (green line) for this simulation case. The values displayed on the graphs are hourly measurements displayed for every minute, according to DynusT technical support team explanation (Eric J. Nava, unpublished data). The DynusT program evaluates the relationships at one minute intervals. The speed limit of the ramp is 45 mph, but according to the figure, around the end of the first hour, the density exceeds 80 vhc/ml/ln, the volume is about 1200 veh/hr and its speed is less than 20 mph. These situations indicate that congestion occurred and many vehicles passed this ramp to I-10. Also, according to these graphs, the downstream freeway link has a density less than 20 vhc/ml/ln and maintained a speed of 70 mph. This indicates excellent traffic conditions for the I-10 segment, despite the congestion of the on ramp. Based on this situation, it could be concluded that the ramp does not influence the I-10 basic segment which contradicts actual conditions. Since it appears that DynusT cannot perform a direct analysis, the data was used in conjunction with the HCM method to measure ramp performance.

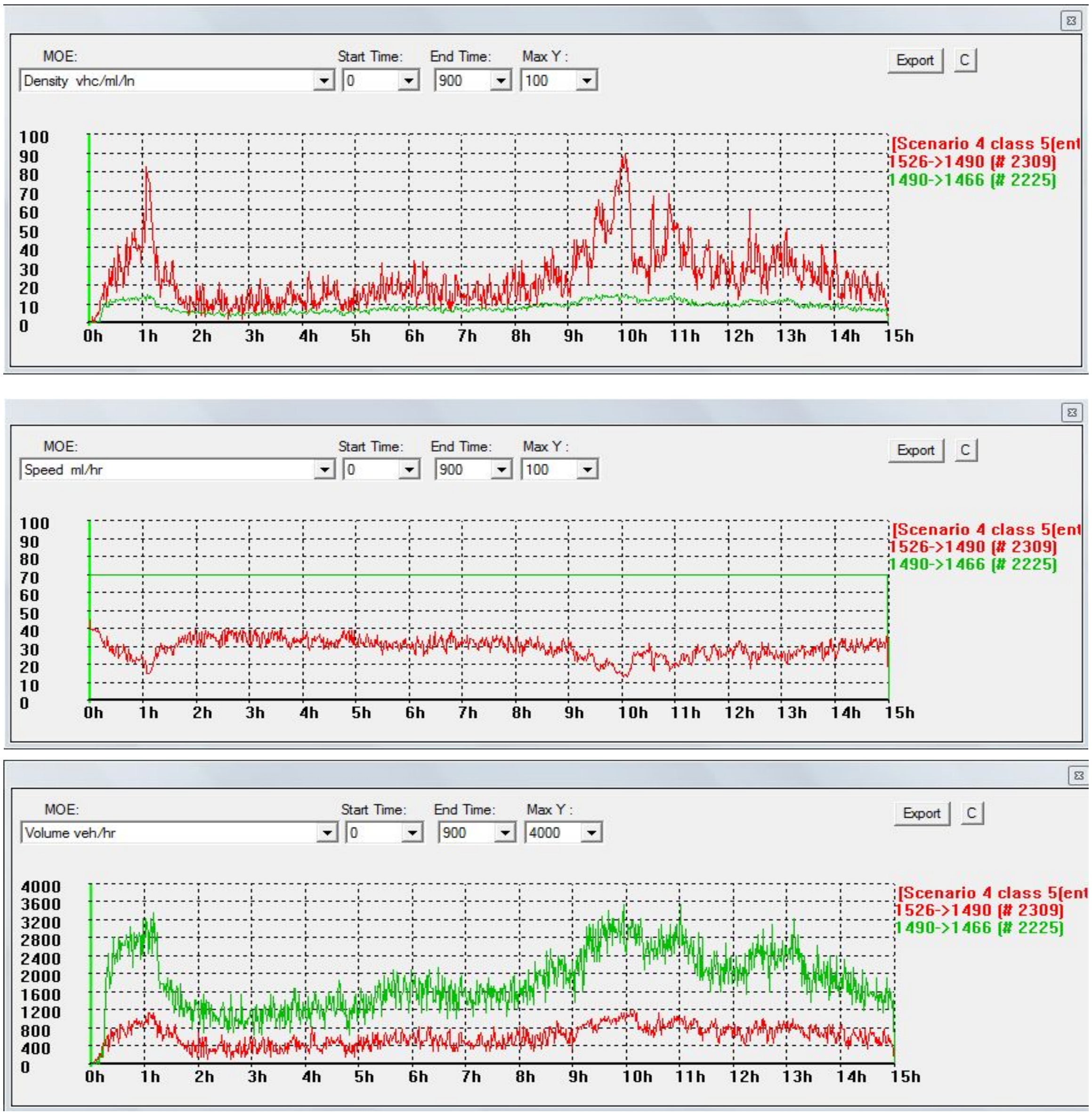

Figure 10 Density, Speed and Volume Graphs in DynusT

Highway Capacity Software (HCS2000) based on Highway Capacity Manual 2000 [26], exploited by the McTrans Center in University of Florida, is selected for calculating LOS of ramps. Because descriptive data concerning ramps' acceleration or deceleration lane were not available, respective lengths were measured using tools within the Google Earth program.

Four ramps are connected with the segments of I-10 affected by the Bay St. Louis Bridge: two on ramps and two off ramps. To better analyze each ramp, two conditions after diversion are considered. The first one represents normal conditions in which, after diversion, the maximum flow rate of the ramps and the upstream freeway of the off ramp are computed using the same method as described for the I-10 segments. Maximum flow rate of adjacent ramps and upstream freeway of the on ramp are not influenced by diverting vehicles, so their values are the same as before diversion. The second one represents the worst condition in which the maximum flow rate of the ramps and the upstream freeway of the off ramp after diversion are obtained by the sum of the maximum flow rate of the same facilities and the bridge in this direction before diversion, even though they may have occurred in different time frames. Maximum flow rate of adjacent ramps and upstream freeway of the on ramp are also obtained by converting the highest fifteen minutes flow rate during simulation time.

In addition, the same manner as the basic segment of I-10, ramps are also analyzed directionally. First, the direction from west to east is studied. There are two ramps affected by the bridge in this direction: one on ramp and one off ramp.

The results for the ramps in the west to east direction are summarized in Table 19 below. According to the results, for the on ramp, LOS in Class 5 case is B before and after diversion (normal and worst condition) ; and LOS in Class 3 case is B in before diversion and normal condition of after diversion, but LOS decreased to C in worst condition. For the off ramp, LOS in Class 3 and 5 cases dropped from C to D and B to D, respectively after diversion (normal condition) and keeps the same in the worst condition of after diversion. It can be seen that maximum flow rate and density continually increased in before diversion, after diversion (normal condition) and after diversion (worst condition). And space mean speed constantly decreased except in class 5 case of off ramp. Besides, more vehicles passed ramp of this direction in Class 3 case.

Table 19 LOS of Ramps Affected by Bay St. Louis Bridge from West to East

Class Type	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"
Link ID	2309		2328	
Ramp type	On ramp		Off ramp	
Length of acceleration or deceleration lane (ft)	2000		360	
Before diversion				
V_R (pcph)	1155	1491	197	399
V_{12} (pcph)	1945	903	2957	2045
V_{R12} (pcph)	3100	2394	---	---
D_R (pc/mi/ln)	16.6	10.9	26.4	18.6
S_R (mph)	64	65	61	61
LOS	B	B	C	B
After diversion				
V_R (pcph)	1352	1861	370	748
V_{12} (pcph)	1949	1247	3175	3196
V_{R12} (pcph)	3301	3108	---	---
D_R (pc/mi/ln)	18.1	16.3	28.3	28.5
S_R (mph)	63	64	61	60
LOS	B	B	D	D

Worst case condition				
V_R (pcph)	1365	2159	407	1067
V_{12} (pcph)	2159	2092	3259	3637
V_{R12} (pcph)	3524	4251	---	---
D_R (pc/mi/ln)	19.8	25.1	29.0	32.3
S_R (mph)	62	58	61	59
LOS	B	C	D	D

Similarly, the direction from east to west is analyzed as reverse direction, using an on ramp and an off ramp influenced by the bridge. Table 20 displays the results which were developed. The traffic condition before and after diversion (normal and worst condition) are acceptable for two influenced ramps in both two cases. The LOS for on ramp before and after rerouting (normal condition) is B and dropped to C after diversion (worst condition) in Class 5 and Class 3 cases. The LOS for off ramp is A in all conditions and both cases. On and off ramp density increased slightly from before diversion to after diversion (normal condition), but density rose notably in after diversion (worst condition). With respect to average speed, the change is sight in all conditions and both cases. Thus, based on results of two directions, the traffic impact of Bay St. Louis Bridge closure is also insignificant for ramps. Combined with analysis for the basic segment of freeway, it can be concluded that I-10 is fully capable of diverting vehicles from the US 90 Bay St. Louis Bridge without significant impact on traffic congestion.

Table 20 LOS of Ramps Affected by Bay St. Louis Bridge from East to West

Class Type	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"
Link ID	1230		1197	
Ramp type	On ramp		Off ramp	
Length of acceleration or deceleration lane (ft)	930		2000	
Before diversion				
V_R (pcph)	155	151	1197	1113
V_{12} (pcph)	1768	2276	2476	2294
V_{R12} (pcph)	1923	2427	---	---
D_R (pc/mi/ln)	14.6	18.5	7.5	6.0
S_R (mph)	63	62	59	59
LOS	B	B	A	A
After diversion				
V_R (pcph)	382	399	1411	1340
V_{12} (pcph)	1768	2150	2628	2490
V_{R12} (pcph)	2150	2549	---	---
D_R (pc/mi/ln)	16.2	19.3	8.9	7.7
S_R (mph)	62	62	58	58
LOS	B	B	A	A

Worst case condition				
V_R (pcph)	424	412	1466	1373
V_{12} (pcph)	2936	2835	2756	2567
V_{R12} (pcph)	3360	3247	---	---
D_R (pc/mi/ln)	25.7	24.8	10.0	8.3
S_R (mph)	60	61	58	58
LOS	C	C	A	A

Diversion Delay

Although congestion is not likely for this bridge after diversion, an increase in travel time is generated due to the rerouting delay. Rerouting travel time from the east to west direction is larger than the reverse direction because vehicles must overpass or underpass I-10 to approach the on ramp. As shown in Table 21, diversion delay of every vehicle from west to east and from east to west is 15.7 min. and 16.2 min., respectively. The total delay of one direction is notable and ranges from 25,465.4 vehicle min. (424.4 vehicle hours) to 30,650.4 vehicle min. (vehicle 510.8 hours). Thus, damage to the Bay St. Louis Bridge would influence economic activity and increase vehicle operation cost, both of which have great influence on trucks, regardless of traffic condition.

Table 21 Rerouting Delay of Bay St. Louis Bridge

	Original travel time (min)	Rerouting travel time (min)	Delay per vehicle (min)	15 hours' volume		Total delay (min)	
				"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"
From west to east	11.6	27.3	15.7	1,622	1,813	25,465.4	28,464.1
From east to west	11.6	27.8	16.2	1,892	1,857	30,650.4	30,083.4

6.2.2.2 Analysis of Biloxi Bay Bridge

Basic Segment of I-10

The affected area of Biloxi Bay Bridge is shown in Figure 11, which was also obtained from Google maps. After damage of the Biloxi Bay Bridge, a part of I-10 basic segments between I-110 and Washington Ave was influenced. Only one section (one link per direction) of the basic segment of I-10 in the DynusT network was affected by the Biloxi Bay Bridge, which is less than the Bay St. Louis Bridge (three links per direction).

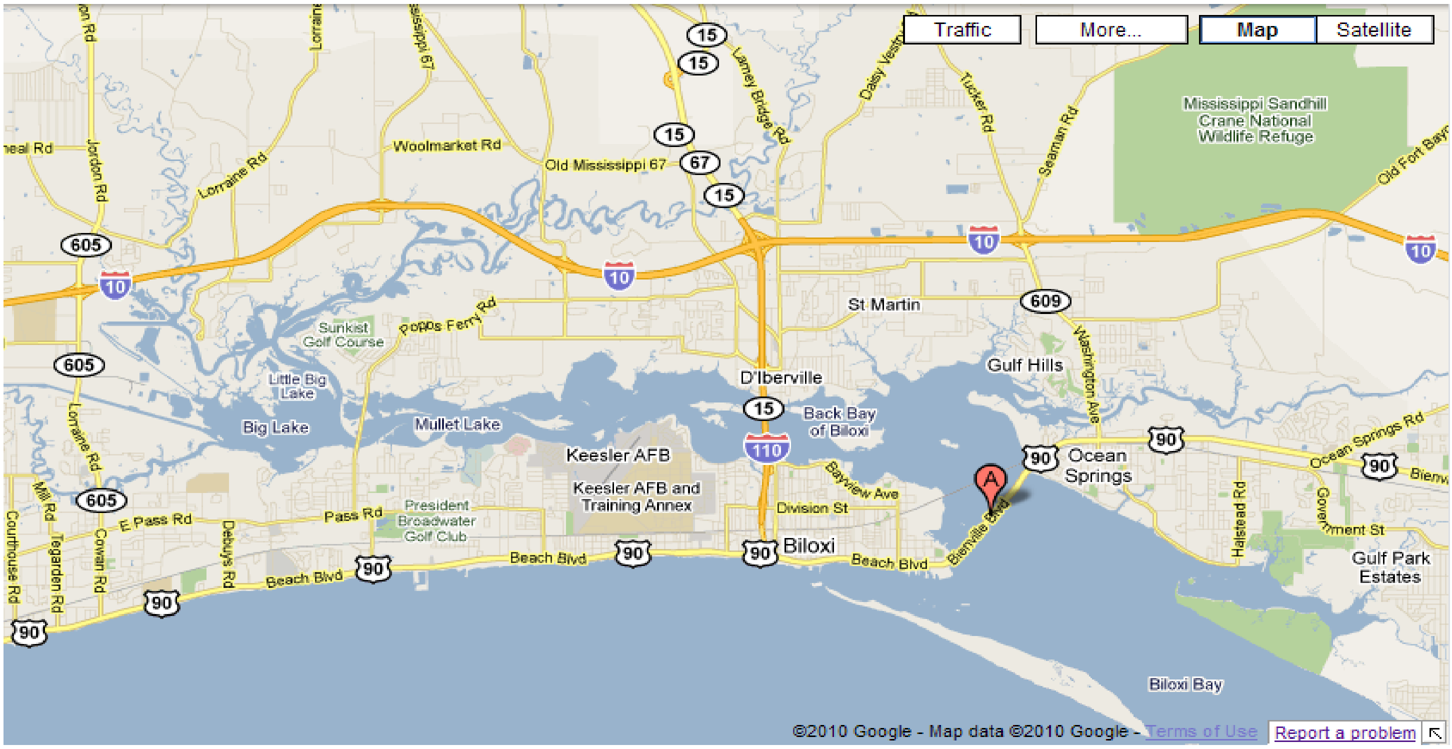

Figure 11 Map of Biloxi Bay Bridge (http://maps.google.com/)

An analysis is performed for both directions using the same method previously introduced for the Bay St. Louis Bridge and results are summarized in Table 22. Except for link 3711 in the case of Class 5, the LOS of I-10's links decreased after diversion. With respect to maximum flow rate and maximum v/c ratio, all links show an increase, especially link 3711 in the case of class 3 which produced a rise in maximum flow rate of 28.5% and a maximum v/c ratio increase of 0.2 after diversion. Traffic conditions from east to west appear to be mildly better than from west to east, which is most clearly shown in the class 3 case. The range of LOS of all links is from B to D. Thus, after diversion, LOS of the I-10 basic segments is still acceptable and the traffic impact of the Biloxi Bay Bridge closure on I-10 basic segments is not serious.

Table 22 Results of Biloxi Bay Bridge Breakdown for I-10 Basic Segments

Direction		From west to east		From east to west	
Class Type		"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"
I-10 links	Link ID	3711		3708	
	Number of lanes	3		3	
	Capacity (veh/hr)	6000		6000	
	Before diversion				
	Maximum flow rate (veh/hr)	3336	4296	3172	3156
	Maximum v/c ratio	0.56	0.72	0.53	0.53
	LOS	C	C	B	B
	After diversion				
	Maximum flow rate (veh/hr)	3992	5520	4084	3952
	Maximum v/c ratio	0.67	0.92	0.68	0.66
	LOS	C	D	C	C
Biloxi Bay Bridge	Before diversion				
	Link ID	2505		5524	
	Maximum flow rate (veh/hr)	784	1300	928	916

Ramps of I-10

Similar to the Bay St. Louis Bridge, four major ramps connected with I-10 are affected by the interruption of the Biloxi Bay Bridge. As described earlier, ramps affected by the Biloxi Bay Bridge are also analyzed by direction. First, the direction from west to east was studied. Two ramps are influenced: one on ramp and one off ramp.

Table 23 displays the results of this analysis. In class 5 case, LOS for on ramp of after diversion (normal condition) is the same with before diversion, but LOS of worst condition in after diversion dropped to C. LOS for off ramp decrease from A to B after diversion (normal and worst condition) in class 5 case The density of two ramps notably increased after diversion in both normal and worst conditions. The space mean speed decreased slightly. In class 3 case, traffic impact for congestion is notable, because both on and off ramp's LOS after diversion (worst condition) is F. On ramp is influenced more serious than off ramp. LOS of on ramp is F after diversion both in normal or worst condition. And according to HCS 2000 software, the reason for this situation is on ramp failed the capacity check since the V_{R12} actual volume exceeded maximum threshold 55 and 571 veh/h after diversion in normal and worst condition, respectively. The decrease of average speed of on ramp before diversion to after diversion (worst condition) is the highest value in Table 23. For the off ramp, LOS dropped to B in normal condition of after diversion. But LOS in worst condition of after diversion is also F. Based on HCS 2000 software, it also did not pass capacity check, because V_R's actual volume over maximum limit 424 veh/h. The increase of density in worst condition is the maximum number in the table. Therefore, serious congestion would appear.

Table 23 LOS of Ramps Affected by Biloxi Bay Bridge from West to East

Class Type	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"
Link ID	3371		3790	
Ramp type	On ramp		Off ramp	
Length of acceleration or deceleration lane (ft)	900		2000	
Before diversion				
V_R (pcph)	815	1075	840	1159
V_{12} (pcph)	552	2395	2168	2187
V_{R12} (pcph)	1367	3470	---	---
D_R (pc/mi/ln)	10.1	26.4	4.9	5.1
S_R (mph)	63	60	60	59
LOS	B	C	A	A
After diversion				
V_R (pcph)	1571	2260	1613	2045
V_{12} (pcph)	645	2395	3068	2945
V_{R12} (pcph)	2216	4655	---	---
D_R (pc/mi/ln)	16.4	35.1	12.6	11.6
S_R (mph)	63	52	58	57
LOS	B	F	B	B
Worst case condition				
V_R (pcph)	1638	2440	1663	2524
V_{12} (pcph)	1711	2731	3195	4190
V_{R12} (pcph)	3349	5171	---	---
D_R (pc/mi/ln)	25.2	39.0	13.7	22.3
S_R (mph)	61	45	57	55
LOS	C	F	B	F

From Figure 11, it can be seen that there are several roads surrounding the affected I-10 segment which can be selected for rerouting traffic due to a Biloxi Bay Bridge closure. The rerouting would redistribute ramp traffic and alleviate congestion on the ramps. Thus, rerouting locally would be an effective method to alleviate congestion and improve MOR. In addition, adding an additional lane to the on and off ramp to improve merging/diverging performance is another option to enhance the resilience and improve LOS. For the on ramp, adding the second acceleration lane with the same length as the existing one (900ft) is proposed. For the off ramp, adding a 1,000 ft deceleration lane is proposed. Table 24 shows that after the addition of one lane, the LOS of the on ramp in normal conditions after a diversion and off ramp in worst conditions after a diversion are increased from Fs to C and B, respectively. Although LOS of the on ramp in worst condition after diversion is still F, its V_{12}, V_{R12} and D_R notably decreased and S_R is improved. Combined with the effect of rerouting, the traffic condition of the on ramp in worst conditions after diversion would be acceptable. For example, the research team manually decreases the volume of the on ramp in after diversion worst condition to simulate the effect of rerouting. If 274 vehicles could be diverted to other ramp from eastbound I-110/I-10 ramp, the LOS of the ramp is C. In that case, traffic to I-10 east from I-110 is reduced to 1980vph. It is noticed however, when the ramp volume is increased from 1,986 vph to 1,987 vph, LOS of the on ramp changes from C to F. It seems that the calculation method of Highway Capacity Manual [26] led to this jump and warrants further investigation by HCM committee in the future.

Table 24 After Add Lanes LOS of Ramps Affected by Biloxi Bay Bridge from West to East

Class Type	"Class 3 User Equilibrium"		"Class 3 User Equilibrium"	
Situation	Current situation	Add one lane	Current situation	Add one lane
Link ID	3371		3790	
Ramp type	On ramp		Off ramp	
Length of first acceleration or deceleration lane (ft)	900	900	2000	1000
Length of second acceleration or deceleration lane (ft)	----	900	----	1000
After diversion				
V_R (pcph)	2260	2260	2045	2045
V_{12} (pcph)	2395	2205	2945	2748
V_{R12} (pcph)	4655	4465	---	---
D_R (pc/mi/ln)	35.1	22.3	11.6	0.9
S_R (mph)	52	60	57	57
LOS	F	C	B	A
Worst case condition				
V_R (pcph)	2440	2440	2524	2524
V_{12} (pcph)	2731	2515	4190	4032
V_{R12} (pcph)	5171	4955	---	---
D_R (pc/mi/ln)	39.0	26.1	22.3	11.9
S_R (mph)	45	54	55	55
LOS	F	F	F	B

Next, the ramps are analyzed from east to west. The two influenced ramps are also one on ramp and one off ramp. An analysis was performed and a summary of results are listed in Table 25. For this direction, on ramp and off ramp's LOS are B before diversion and C after diversion (normal and worst conditions) according to both Class 3 and Class 5 cases. After diversion (normal or worst conditions), density increased and difference between normal and worst condition after diversion is minor. With respect to average speed, it slightly decreased. Therefore, impacts as a result of damage to the Biloxi Bay Bridge are minor from the east to west direction. Based upon a two direction analysis, closure of the Biloxi Bay Bridge has notable influence on ramps, especially in the west to east direction of the Class 3 case which shows that traffic would congest around the on and off ramp area. According to the structure of this road network, rerouting and redistributing ramp traffic would be a useful strategy for improvement of MOR. Besides, adding additional lane to the on and off ramp is also a valid solution for enhance MOR.

Table 25 LOS of Ramps Affected by Biloxi Bay Bridge from East to West

Class Type	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"
Link ID	1012		3706	
Ramp type	On ramp		Off ramp	
Length of acceleration or deceleration lane (ft)	2000		800	
Before diversion				
V_R (pcph)	760	836	953	983
V_{12} (pcph)	2570	2415	2317	2430
V_{R12} (pcph)	3330	3251	---	---
D_R (pc/mi/ln)	18.6	17.9	17.4	18.0
S_R (mph)	63	63	59	59
LOS	B	B	B	B
After diversion				
V_R (pcph)	1697	1676	1844	1806
V_{12} (pcph)	2591	2415	3013	3147
V_{R12} (pcph)	4288	4091	---	---
D_R (pc/mi/ln)	25.6	24.1	23.0	24.1
S_R (mph)	58	60	57	57
LOS	C	C	C	C
Worst case condition				
V_R (pcph)	1735	1798	1928	1945
V_{12} (pcph)	2591	2608	3268	3259
V_{R12} (pcph)	4326	4406	---	---
D_R (pc/mi/ln)	25.9	26.5	25.2	25.1
S_R (mph)	58	57	57	57
LOS	C	C	C	C

Diversion Delay

As shown in Table 26, for the Biloxi Bay Bridge, delays associated with rerouting each vehicle are 5.0 and 6.1 min. in the west to east direction and revised orientation. The minimum and maximum total delay is 33,730 vehicle min. (562.2 vehicle hours) in the west to east direction of the Class 5 case and 46,366.1 vehicle min. (772.8 vehicle hours) in the east to west direction of the Class 3 case, respectively.

Table 26 Rerouting Delay of Biloxi Bay Bridge

	Original travel time (min)	Rerouting travel time (min)	Delay per vehicle (min)	15 hours' volume		Total delay (min)	
				"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"	"Class 5 Pre-trip Information"	"Class 3 User Equilibrium"
From west to east	6.9	11.9	5.0	6,746	7,527	33,730	37,635
From east to west	6.9	13.0	6.1	7,589	7601	46,292.9	46,366.1

6.2.2.3 Conclusion

Based on an analysis of two bridges in this section, damage to the bridges would affect traffic condition of I-10 basic segments to limited extent. Biloxi Bay Bridge has a greater influence on I-10 basic segments than Bay St. Louis Bridge. Interruption of the Biloxi Bay Bridge resulted in a notable increase in maximum flow rate and v/c ratio of 656 veh/hr and 0.11, respectively. However, disrupting these bridges did not significantly influence LOS on basic segments of I-10. All links of basic segments' LOS range from B to D after diversion in both Class 3 and 5 cases.

For ramps, all LOS were remained for the Bay St. Louis Bridge closure, especially in the east to west direction, which the LOS ranged from C to A. For the Biloxi Bay Bridge, diverting vehicles would also accommodate acceptable operational conditions in terms of LOS in both directions of Class 5 case and direction from east to west in class 3 case. But congestion would occur in the west to east direction in the Class 3 case. On ramp's LOS is F in after diversion normal condition. And both on and off ramp's LOS is F in worst condition of after diversion. Based on a study composition of the highway network around Biloxi Bay Bridge, there are several roads can choose for diversion and distribute the ramp traffic which are shown in Figure 11. Thus, rerouting would be a valid measure for modifying traffic condition and improving MOR. Besides, adding one lane to the on and off ramp is also another applicable method. The two approaches used altogether would highly enhance traffic condition and improve MOR.

Total delay due to Biloxi Bay Bridge closure is more serious than that due to Bay St. Louis Bridge closure, although delay per vehicle in each direction of Bay St. Louis Bridge is at least 10 min. longer than the Biloxi Bay Bridge. This indicates that more vehicles passed Biloxi Bay Bridge before diversion and thus, closure of the Biloxi Bay Bridge has a greater influence than the closure of Bay St. Louis Bridge.

Thus, closure to these two bridges had slight effects on basic segments of I-10 and significantly influenced some ramps. Congestion appeared around an on ramp (link 3371) and off ramp (link 3790) in the west to east direction affected by Biloxi Bay Bridge in the Class 3 case. However, based on the topology of the highway network near the Biloxi Bay Bridge area, rerouting and redistributing ramp traffic would be an effective method to improve traffic condition and enhance the resilience. And adding an additional lane to the on and off ramp is also a valid method. Furthermore, total delay of vehicles due to rerouting was significant which indicates that damage to the two bridges would have a serious impact on economic conditions in the Golf Coast area. According to the analysis of the basic segment of I-10, ramps and delay, interruption of the Biloxi Bay Bridge had a greater influence than that of Bay St. Louis Bridge.

6.3 Simulation Experience in DynusT

As discussed before, “Class 3 User Equilibrium (UE)” and “Class 5 Pre-trip Information” were used for this project. “Class 5 Pre-trip Information” is a “one shot” approach in DynusT software which means it only iterates once during simulation [33]. “Class 3 User Equilibrium (UE)” is an “iterative” method which iterates several times before reaching user equilibrium and the maximum number of iterations can be controlled by the user [33]. One iteration typically takes 2 to 3 hours for a 15 hour simulation period based on the research team’s experience (Operation system: Microsoft Windows Server 2003 R2 Standard x64 Edition; 2XCPU: dual core 3.40GHz; RAM: 8G). For “Class 3 User Equilibrium (UE)”, the number of iterations was set between 10 and 15 as suggested by DynusT technical support team according to the size of the Gulf Coast network (Dr. Chiu, Yi-Chang, unpublished data). Thus, one simulation of “Class 5 Pre-trip Information” of the Gulf Coast network required 2 to 3 hours for completion, but the time needed to simulate “Class 3 User Equilibrium (UE)” of the Gulf Coast network varied based on how many iterations were needed to reach user equilibrium [33]. The research team determined that the minimum and maximum number of iterations for one “Class 3 User Equilibrium (UE)” simulation of the Gulf Coast network was between 2 and 15, respectively. As a result, time cost for one simulation of “Class 3 User Equilibrium (UE)” of the Gulf Coast network ranges from 4 to 45 hours. A combination of this characteristic with the experiences described earlier involving the loss of trucks during simulation caused the research team to switch from DynusT to the HCM method for measuring the effectiveness of rerouting. Results of the “Class 3 User Equilibrium (UE)” and “Class 5 Pre-trip Information” cases, obtained by using the HCM method, support the conclusion that rerouting has some effects on improving traffic conditions and MOR in the Gulf Coast network.

7 CONCLUSIONS AND RECOMMENDATIONS

A framework of MOR assessment for intermodal network was presented and strategies for improving MOR are proposed and evaluated with respect to effectiveness. To create intermodal transportation system snapshots, TransCAD software was employed to model the intermodal network before and after Hurricane Katrina and to generate traffic data for the MOR calculation. A disaggregation procedure was developed to estimate the population and employment at the 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 with some resilience indicators was designed to evaluate the system's mobility. Based on the resilience indicators, 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. Then, result analysis of a case study on the Mississippi Gulf Coast showed that truck speed was the most vulnerable performance due to the loss of capacity in major roads.

An HCM analysis was performed when the traffic of U.S. 90 was diverted to I-10. The consequences of the HCM method showed that traffic conditions of basic segments and most influenced ramps of freeway were acceptable. According to the analysis, the ramps from west to east in the Biloxi Bay Bridge affected area would develop congestion. However, according to the topology of the road network between I-110 and Washington Ave, rerouting and redistributing traffic to nearby local roads would be an effective way for improving traffic condition and therefore enhancing MOR in response to the disruption. And adding one more lane to the on and off ramp is another applicable solution to enhance the resilience and improve LOS. It was also found that delay due to diversion was significant and would have a great economic consequence. Furthermore, based on analysis of the basic segment, ramp and delay of two bridges, the Biloxi Bay Bridge closure had a greater impact on the research area than the Bay St. Louis Bridge closure. In addition, the results of the traffic assignment experience section showed that rerouting could slightly mitigate the effects of Katrina for daily traffic and then improve MOR, but not notably, due to the traffic characteristics in the affected regions. The reason is that I-10 has sufficient capacity to handle diverting vehicles from the two US 90 bridges. Thus, combining the results of all applied methods, rerouting would be a valid strategy and adding an additional lane to the on and off ramp would also be a useful method for increasing MOR. Moreover, simulation experience in DynusT was also discussed.

This report focuses on evaluating intermodal transportation resilience in response to disasters and assessing the usefulness of rerouting for increasing MOR of intermodal transportation system. The results of the calculation facilitate the transportation agency to make decisions on the location of the most vulnerable part of the intermodal transportation system, such as which facility has the most significant impact on intermodal system performance if broken down or which transportation mode plays the most important role in the intermodal network or what strategies should be applied to mitigate the system congestion and therefore enhance the system's MOR. 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 methods were proved to be intuitive and effective for quantifying system resilience. Although the MOR calculation method was developed for system-level evaluation, it could be applied to specific facilities. Two methods were experimented for measuring effectiveness of rerouting, including the HCM method which was shown to be a reasonable approach.

In summary, this MOR study have discovered generally the Intermodal Transportation Resilience in Gulf coast of the Mississippi state with respect to the Hurricane Katrina are relatively weak within one week after the disaster occurred when the US 90 was completely inaccessible (Scenario 2 in this report). After that period of time, the resilience was increasing. Especially in Scenario 4, the US 90 was restored except the

Bay St. Louis Bridge and the Biloxi Bay Bridge, the traffic had been closed to the pre-Katrina level while the vehicles on US 90 had to divert to I-10 due to the two bridges closure. However, some local congestion appeared around the Biloxi Bay Bridge influenced area. The on ramp and off ramp from west to east between I-110 and Washington Ave shows LOS F after diversion in class 3 case. Solution to improve the MORs includes the diverting and redistributing the traffic to nearby local roads and/or adding one more lane to the ramps.

In this report, the calculated system-wide resilience corresponds to a specified disaster. With a lack of information concerning other disasters, 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. Rerouting was proved as an effective method for improving MOR in this report. Delay due to rerouting has a considerable impact for transportation systems, even if the traffic congestion condition is acceptable after diversion. This situation can be detrimental for economic development in the disaster area. The essential purpose behind the study of methods for improving MOR of transportation systems is to reduce the economic impact of various levels of transportation system interruption by modifying traffic conditions. Thus, economic cost is a vital factor which needs to be considered in evaluating the degree of effectiveness of rerouting. The research team will further examine this subject in subsequent research.

8 ACKNOWLEDGEMENTS

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Project Investigator:
Dr. Li Zhang
Co-Project Investigator:
Dr. Minzhou Jin

Major contributors include:
Dr. Li Zhang: principle investigator of this project
Yi Wen: author of first four sections of this report
Zhitong Huang: author of literature review and improvement of MOR section
Joshua A. Walden: revised this report

Participators:
Jizhan Gou: gave many useful suggestions
Inga B. Lehman: female/provided support
Whitney S. Niven: female/provided support
Christopher D. Wilbanks: provided support
Matthew F. McKenzie: data collection
Jennifer L. Sloan: female/data collection

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APPENDIX A: LIST OF INTERMODAL TERMINALS DATA COLLECTION

Biloxi International Airport:

Contact: Jim Pitts

- No significant cargo flights
- Cargo flights currently consist of small supplies mostly in the medical field and are inbound
- Outbound cargo flights are domestic and typically go to Houston, Chicago or Atlanta
- Planning for a new cargo facility on site by the end of the year with projections of beginning 1 flight per week that will carry 100,000 lb to 120,000 lb and slowly progressing to 2-3 flights per week.

Stennis International Airport:

Contact: William Cotter

Port of Gulfport:

Contact: Enrique Hurtado

Port of Pascagoula:

Contact: Allen Moeller

Port of Bienville:

Contact: Larkin Simpson

- Referred the research team to Steve Landry see Port of Bienville Rail below.

Port of Bienville Rail:

Contact: Steve Landry

- 70% reduction in both trucking and freight because a major company changed locations after the hurricane and decided to truck in products as opposed to train.
- No statistical data recorded; above is Landry's estimation.

APPENDIX B: INTERVIEW OF THE PORT OF GULFPORT

----Interview with Mr. Enrique Hurtado on Hurricane Katrina to the Port of Gulfport

Brief introduction of Mr. Enrique Hurtado

Deputy Director of the Trade Development

Mississippi State Port Authorities at Gulfport

Email: ehurtado@shipmspa.com

Tel: 228-865-4300

Interviewed by Li Zhang, Yi Wen and Zhitong Huang.

Generally, there are four types of freight: container, breakbulk, bulk and project (special) goods in the port of Gulfport. During Hurricane Katrina, almost all facilities in the port were destroyed. On September 27, 2005, the port restored operations with reduced warehouse storages. Several piers were destroyed and 2,500 square feet of refrozen space were gone. So far, one out of 110 berths has not been restored. Two berths and 2,500 square feet restoration costs $2 million.

The effect of Katrina did not show until 2007. The details of SHIPs and TEUs (TEU: Twenty-foot Equivalent Unit) are attached at the end of this interview. One carries importing aluminum from Argentina and all chicken exporters to East Europe have moved their exports from Gulfport to other ports. The most likely locations are Lake Charles, Mobile, Pascagoula, and New Orleans. Mobile has three times the frozen space. $21 million of investment were proposed; however there was no formal commitment from chicken industries to add more frozen spaces for $21million, the plan was dropped. It is difficult to figure out ports where chicken exports. It is also difficult to determine if the ports change will cause additional transport distance since the chicken industry may have relocated their chicken farm as well (e.g., to Houston, TX and Kentucky), in order to coordinate their export ports. One thing is sure that those chickens will not come back to Gulfport.

Most (95%) of Gulfport's freight are transported to the port by highway trucks. Others are transported by Kansas City South Railroad (E/W). The port has received $50 million to expand the export capacity three times as it has now. The project is expected to be finished within 10 years. That would be about 1,200 trucks per day. There is also a plan that the port and KCS would create a ship yard in Hattiesburg, and the freight will be transported from there to the port via KCS railroad. The port will be elevated to 25ft above sea level at the time when the project is finished. The port has an evacuation plan to move all containers at least two miles north. The shippers will be required to pay for the cost.

Statistical Data

Cargo type Comparison

Cargo Type / Year	Container	Breakbulk	Bulk
2007	1,687,867	9,055	295,923
2006	1,573,858	8,419	0
2005	1,462,205	249,382	266,545
2004	1,683,325	405,972	353,866

Ship Calls

Year	Total	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2007	241	19	16	19	18	20	18	19	21	26	21	21	23
2006	234	19	18	23	22	21	20	19	20	17	18*	19	18
2005	274	32	27	34	26	28	25	26	29	1	12	17	17
2004	353	22	29	28	30	31	29	29	32	26	32	30	35

Note: * This data has different value in the statistic data which were obtained from the port of Gulfport.

FEU'S INBOUND/OUTBOUND

CY: Calendar year	CY 2005 (Jan 05-Dec 05)	CY 2006(Jan06-Dec 06)	CY 2007(Jan07-Dec 07)
Total Containers	96,782	98,714	103,311
Total in	50,000	48,751	50,952
Total out	46,782	49,963	52,359
Jan Import	3,359	3,769	4,215
Jan Export	4,353	3,820	4,590
Feb Import	4,347	4,155	3,443
Feb Export	4,406	3,439	3,733
Mar Import	5,831	4,073	4,441
Mar Export	5,056	4,440	4,606
Apr Import	7,459	3,724	4,288
Apr Export	4,509	4,114	4,532
May Import	5,560	4,470	4,761
May Export	5,370	4,578	4,611
Jun Import	5,360	4,387	4,356
Jun Export	5,511	4,607	4,486
Jul Import	4,383	4,059	4,273
Jul Export	4,549	3,941	4,413
Aug Import	4,200	4,175	4,520
Aug Export	4,501	4,456	4,548
Sep Import	378	3,899	4,203
Sep Export	258	4,128	4,339
Oct Import	2,143	4,281	4,726
Oct Export	1,897	4,486	4,756
Nov Import	3,508	3,756	3,805
Nov Export	3,131	4,042	4,025
Dec Import	3,472	4,003	3,921
Dec Export	3,241	3,912	3,720

FY: Fiscal year	Total in	Total out	Total Containers
FY 2008 (July 07-June 08)	25,448	25,801	51,249
FY 2007(July 06-June 07)	24,173	24,965	49,138
FY 2006(July 05-June 06)	18, 084	17,577	35,661

APPENDIX C: INTERVIEW OF THE PORT OF PASCAGOULA

----Interview with Director of Operations and facilities, Capt. Allen Moeller, Port of Pascagoula

During the Hurricane Katrina, the water surged about 16 ft and the elevation of the port docks is about 10-12 ft. So the water is about is 4 ft high and the port was flooded. There is no major structural damage except the freezer facilities was damaged and the concrete surface was damaged. Goods, such as lumbers and rubbers on the warehouse and docks were no longer useful. First shipment of lumbers was disposed in Domino Republic and scattered robbers were cleared out at the port and disposed. After the Hurricane Katrina, the port almost lost its capability of handling goods. It took 7-10 days to clean the debris and damaged goods during which the port could not handle anything.

Two to three days after that, a contractor was asked to start planning on clean up and repairs, such as temporarily patching the roof. About 10 days after the hurricane Katina, the first shipment was lumber and followed by the second shipment of poultry for disposal. After one month the freight shipment started to mover and about 4-5 month the ship traffic restored to normal level. Around 9 month the freezer was repaired. After Katrina there are no major freight tonnage changes in the port. The rubber shipper was lost and one poultry shipper was attracted from Gulfport at the half tonnage level of the robber shipment. During the port restoration, highway traffic remains about the same and the congestion level does not change. The major factor for the port delay was caused by the lack of labor, especially for the shipment of labor intensive freight such as lumber and poultry. It is estimated that the lumber shipment was delay to 8-10 hours and there are some delays on poultry shipment, although it would take a week or so to load the product.

The average daily shipment is 2-3 ship per day while in the peak day there are 4-5 shipments. About 60-70% freight is from highway and the rest of the freight is from rail. There are about 200 trucks for the 2-3 shipment and about 50 trucks if there is no shipment on that day. There was emergence plan for the port during hurricane Katrina in which the equipment was moved to a warehouse, which was flooded. Now the new evacuation plan allows shippers take care of their goods and equipment while the equipment of port will be moved outside area. Mr. Moeller would send us month or year freight chart/table and he would also finish our survey. So far we have not received those information back.

APPENDIX D: CSX REPORT

From the available resources, it was found that:

- CSX has only 94 miles of railroad in the state of Mississippi, all of which are on the Gulf Coast.
- Majority of products shipped to Mississippi are coal related products, lumber/paper products, grain/crops and chemicals.
- Majority of products shipped from Mississippi are chemicals, pulp/paper, auto/parts and lumber.

The table below is part of data shows the re-routed traffic during Katrina by origin and destination state. And it is the 2005 annualized originations and terminations on the line from Pascagoula to New Orleans. (This data was obtained from Robert C. Martin, Community Affairs and Safety, CSX Transportation.)

Sum of Carloads	
Business Unit	Total
Agriculture	1,870
Automobiles	2
Chemicals	10,402
Coal	66
Emerging Markets	6,736
Food & Consumer	6,424
Metals	1,010
Paper	5,330
Fertilizers	2,857
Grand Total	34,697