**A Simulation Model for Intermodal Freight Transportation in Louisiana**

**Abstract**

With increased emphasis on intermodal freight transportation, the issues of how to evaluate an existing intermodal transportation system and how to evaluate the changes in the system have been receiving intensive attention. Because of the high complexity and high variability involved in intermodal transportation, simulation tools need to be applied. The authors built a system-level intermodal simulation model for Louisiana that includes highways, railways, and waterways and also incorporates the connections between the different modes. The research: (1) summarized the existing intermodal freight transportation simulation results; (2) developed a simulation framework based on the ARENA simulation software; (3) developed the simulation model and calculated the mobility, reliability, safety, and environmental performance measures for the existing intermodal freight system of Louisiana; (4) validated the simulation model based on traffic counters at certain locations from DOTD, energy data, safety dataset, etc; and (5) analyzed three different scenarios. In Scenario 1 the potential effects of the Panama Canal expansion have been calculated, in Scenario 2, the effects of traffic disruptions while in Scenario 3, the effects of a potential improvement in highway safety have been calculated.
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LTRC Project Number: 14-2SS
State Project Number: 30001395

conducted for
Louisiana Department of Transportation and Development
Louisiana Transportation Research Center
National Center for Intermodal Transportation for Economic Competitiveness (NCITEC)

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March 2016
ABSTRACT

With increased emphasis on intermodal transportation development, the issue of how to evaluate an intermodal freight transportation system and provide intermodal solutions has been receiving intensive attention. In order to improve freight flow efficiency and therefore support economic development in the State, it is necessary to have a systematic tool to study the freight flow over all three major surface modes and their connections and, in turn, to help DOTD identify the best way to increase freight transportation capacity and improve flow efficiency.

Because of the high complexity and high variability involved in transportation flows, it is technically difficult to use analytical models to evaluate and study freight networks. Therefore, simulation has been widely used to address transportation issues, especially for single modes and at the micro-level. However, there are very few simulation models that focus on the connections on multiple transportation modes and emphasize on the system-wide performance evaluation. One aggregate model for the network in the State of Mississippi was developed in 2004 without considering the dynamics at any nodes and the model has a very low resolution.

This system-level intermodal simulation model includes highways, railways, and waterways because all three modes, working together, play significant roles in Louisiana freight flows. The simulation model not only includes the links and nodes of all three modes but also incorporate the connections between different modes. In all existing traffic simulation models, the capacity and volume/speed relationships are only well defined for some infrastructure in a single mode, such as highway links, dams and ports, or rail links. There are no simulation models that incorporate the capacity at intermodal connections and the dwelling time vs. volume relationships at connections though most freight flow time is spent at the connection nodes between modes or within modes (e.g., classification yards or ports). The intermodal connection points are often bottlenecks for the capacity of the overall freight network. The freight transportation network is an integrated system with various impacts on the society. In addition to mobility, the intermodal simulation model also incorporates other transportation performance measures such as reliability, safety and security, environmental impact, and economic development. The research team finished a project of “Development of Performance Measurement for Freight Transportation” that identifies performance metrics for intermodal freight transportation network. Those metrics have been included in the simulation model to evaluate any intermodal network or assess the benefits of a network improvement initiative in a comprehensive way. For some metrics, such as reliability, simulation may be the only effective way to do evaluation because of the difficulty of data collection and direct calculation.
The objectives of this project were to

1. Develop a comprehensive simulation model for an intermodal freight network that considers the dynamics at the connections between transportation modes, and
2. Conduct what-if analysis of the performance of the Louisiana freight network under different scenarios and evaluate the benefits of selected network improvement initiatives.

We built a system-level intermodal simulation model for Louisiana that includes highways, railways, and waterways and also incorporates the connections between the different modes. The research has finished all tasks of the project:

- Summarized the existing intermodal freight transportation simulation results.
- Developed a simulation framework based on the ARENA simulation software.
- Developed the simulation model and calculated the mobility, reliability, safety, and environmental performance measures for the existing intermodal freight system of Louisiana.
- Validated the simulation model based on traffic counters at certain locations from DOTD, energy data, safety dataset, etc.
- Analyzed three different scenarios. In Scenario 1, the potential effects of the Panama Canal expansion have been calculated, in Scenario 2, the effects of traffic disruptions, while in Scenario 3, the effects of a potential improvement in highway safety have been calculated.
# TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................... V

TABLE OF CONTENTS ....................................................................................................................... VIII

LIST OF TABLES ................................................................................................................................ IX

LIST OF FIGURES ............................................................................................................................... X

INTRODUCTION ................................................................................................................................. 1

OBJECTIVE ........................................................................................................................................... 3

METHODOLOGY ................................................................................................................................. 4

  Summarization of Existing Intermodal Freight Transportation Simulation ........ 4

  Development of the Simulation Framework and Selection of the Simulation Platform .................................................................................. 4

  Development of the Simulation Model .......................................................................................... 4

  Validation of the Simulation Model ............................................................................................... 4

  Analysis of Various Scenarios on the Simulation Model ............................................................. 5

DISCUSSION OF RESULTS ............................................................................................................ 6

  Summarization of Existing Intermodal Freight Transportation Simulations ........... 6

    General Introduction to Simulation ......................................................................................... 6

    Introduction to Transportation Simulation ............................................................................. 7

    Simulation for Intermodal Freight Transportation ............................................................... 11

Simulation Framework and Simulation Platform ................................................................. 11

  Overall Framework ...................................................................................................................... 11

  Highway Framework .................................................................................................................... 13

  Railway Framework ..................................................................................................................... 17
Waterway Framework........................................................................................................... 18
Intermodal Connection........................................................................................................ 19
Simulation Outputs ................................................................................................................ 19
Simulation Platform Selection .............................................................................................. 22
Highway Network Simulation .............................................................................................. 26
Railway Network Simulation ................................................................................................. 31
Waterway Network Simulation .............................................................................................. 36
Output .................................................................................................................................. 37
Simulation Validation ........................................................................................................... 39
Scenario Analysis .................................................................................................................. 45
Scenario 1: Increased Demand ............................................................................................. 46
Scenario 2: Disruptions .......................................................................................................... 50
Scenario 3: Improved Highway Safety .................................................................................. 54
CONCLUSIONS ..................................................................................................................... 58
REFERENCES ........................................................................................................................ 59
LIST OF TABLES

Table 1 Volume-capacity ratio and congested speed ................................................................. 17
Table 2 Research articles/websites with key word search .......................................................... 23
Table 3 Weekday and weekend rush hour volume percentages at a location on Interstate 10 (I-10) ........................................................................................................................................ 29
Table 4 List of animations for all conditions of highway segments ............................................. 40
Table 5 Average statewide vehicle percentages by functional classification for 2015 .............. 42
Table 6 Comparison between real traffic counts and simulation results. ................................. 45
Table 7 Data requirements and sources ...................................................................................... 46
Table 8 Ton-miles (in millions) of truck shipments by state: 2002 (U.S. Department of Transportation Federal Highway Administration 2002 [40]) .................................................................................................................. 47
Table 9 Reliability before and after demand increase. ................................................................. 50
Table 10 Population, vehicle miles traveled, fatal motor vehicle crashes, motor vehicle crash deaths and motor vehicle crash death rates in Louisiana, 2013 ........................................................................ 51
Table 11 Crash rates by VMT, licensed drivers and population.................................................. 51
Table 12 Traffic deaths, by vehicle type ..................................................................................... 52
Table 13 Average of I-10 near New Orleans before and after demand increased .................... 53
Table 14 Comparison of volume to capacity ratio at different accident rates and transportation demands ............................................................................................................................... 55
LIST OF FIGURES

Figure 1 Graphic presentation of simulation results in late 60's (Sagen [3]) ............................... 8
Figure 2 17 Highway outlets and 13 railroad outlets for Louisiana ........................................... 12
Figure 3 Truck enclosed van semi-trailer (Kay, [22]) ................................................................. 13
Figure 4 Updated BPR curve ........................................................................................................ 16
Figure 5 Layout of a typical classification yard .......................................................................... 18
Figure 6 Part of ARENA model for highway network ................................................................. 26
Figure 7 Sub-model “Rapides Parish to Alexandria LA or to Natchitoches LA or to the end” ................................................................................................................................. 27
Figure 8 Part of ARENA model for railroad network ................................................................. 32
Figure 9 Details of a classification rail yard sub-model ............................................................... 33
Figure 10 Details of sub-model “Baton RougeR LA to New OrleansR LA” ............................... 34
Figure 11 Part of the ARENA model for waterway network ...................................................... 36
Figure 12 Details of sub-model “CracraftP AR to VicksburgP LA or to the end” .................. 37
Figure 13 Simulation screen shot .................................................................................................. 39
Figure 14 Demonstration of animation effect ............................................................................. 40
Figure 15 Illustration of vehicle classification ............................................................................. 43
Figure 16 Illustration and comparison between real data and simulation results ..................... 44
Figure 17 Ton-hours and ton-miles before and after the demand increase ............................. 48
Figure 18 Ton-miles before (Tonmiles_base) and after (Tonmiles_id) demand increase ......... 48
Figure 19 Ton-hours before (Tonhours_base) and after (Tonhours_id) demand increase .... 49
Figure 20 Energy consumption (BTU) before (Energy_consumption_base) and after
(Energy_consumption_id) demand increase ................................................................................. 49
Figure 21 Traffic deaths, by person type and vehicle type .......................................................... 52
Figure 22 Volume-to-capacity ratio on segments from New Orleans to Slidell (red), from
Jefferson to New Orleans (green), and from New Orleans to Jefferson (blue) over time. .... 53
Figure 23 Comparison of average speed on highway segments ................................................. 56
INTRODUCTION

With increased emphasis on intermodal transportation development, the issue of how to evaluate an intermodal transportation system and provide intermodal solutions has been receiving intensive attention since the enactments of the Intermodal Transportation Efficiency Act (ISTEA) and the Transportation Equity Act for the 21st Century (TEA-21). The new Moving Ahead for Progress in the 21st Century Act (MAP-21) asks all state DOTs to evaluate and improve the operation and maintenance of their freight networks. Louisiana plays an important role in U.S. freight transportation with a strong intermodal transportation network because of the Mississippi River and the Port of New Orleans. The freight traffic in the state is expected to significantly increase, especially after the Panama Canal expansion and with the increased trade with Latin America. In order to improve freight flow efficiency and therefore support economic development in the state, it is necessary to have a systematic tool to study the freight flow over all three major surface modes and their connections and, in turn, to help DOTD identify the best way to increase freight transportation capacity and improve flow efficiency.

Because of the high complexity and high variability involved in transportation flows, it is technically difficult to use analytical models to evaluate and study freight networks. Therefore, simulation has been widely used to address transportation issues, especially for single modes and at the micro-level. For example, the microscopic simulation software CORSIM is often used by state DOTs to study a small area of highways and arterial streets, typically for planning purposes. Major railroads have developed their own simulation models to study the operations in their classification yards. Most major ports have used simulation models to improve their operations and security. However, there are very few simulation models that focus on the connections on multiple transportation modes and emphasize on the system-wide performance evaluation. One aggregate model for the network in the state of Mississippi was developed in 2004 without considering the dynamics at any nodes and the model has a very low resolution.
A system-level intermodal simulation model should include highways, railways, and waterways because all three modes, working together, play significant roles in Louisiana freight flows. The simulation model not only includes the links and nodes of all three modes but also incorporates the connections between different modes. The intermodal connection points are often bottlenecks for the capacity of the overall freight network. The freight transportation network is an integrated system with various impacts on the society. In addition to mobility, the intermodal simulation model should also incorporate other transportation performance measures such as reliability, safety and security, environmental impact, economic development, etc. The research team finished a project of “Development of Performance Measurement for Freight Transportation” to identify the performance metrics for intermodal freight transportation network. Those metrics have been included in the proposed simulation model to evaluate any intermodal network or assess the benefits of a network improvement initiative in a comprehensive way. For some metrics, such as reliability, simulation may be the only effective way to do evaluation because of the difficulty of data collection and direct calculation.
OBJECTIVE

The objectives of this project were:

1. Develop a comprehensive simulation model for an intermodal freight network that considers the dynamics at the connections between transportation modes.
2. Conduct what-if analysis of the performance of the Louisiana freight network under different scenarios and evaluate the benefits of selected network improvement initiatives.
METHODOLOGY

Five tasks were proposed with detailed methodology descriptions to achieve the project objectives.

**Summarization of Existing Intermodal Freight Transportation Simulation**

A literature review was conducted to summarize the existing freight transportation simulation models for a single transportation infrastructure, a single-mode network, or an intermodal network. The review specifically focused on data availability, models representing each major intermodal freight infrastructure, and simulation platforms.

**Development of the Simulation Framework and Selection of the Simulation Platform**

A framework for an intermodal freight network simulation was developed including all major network components, the connections of the components, the embedded relationships in each component, the variability that would be included in the model, input data, output data (including performance metrics), etc. The simulation model incorporates the freight demand data from *Freight Analysis Framework Version 3* and the *Intermodal Surface Network* data that the research team has collected from ORNL through collaboration in previous projects. Other data sources were identified in this task, especially state-level data from DOTD. A simulation package, ARENA, was selected by considering its modeling capability, speed, and animation quality.

**Development of the Simulation Model**

Following the framework defined in Task 2, this task programed a simulation model for the intermodal freight network in the State of Louisiana. The simulation model incorporates the ways to calculate system-level performance metrics for intermodal freight networks.

**Validation of the Simulation Model**

The simulation model was validated based on historical traffic data in the State of Louisiana.
Analysis of Various Scenarios on the Simulation Model

A selected number of scenarios were run on the simulation model. The developed simulation model and findings of what-if analysis will be widely disseminated in the academic community and to practitioners.
DISCUSSION OF RESULTS

Summarization of Existing Intermodal Freight Transportation Simulations

General Introduction to Simulation

Simulation is the imitation of a dynamic system using a computer program and can be used to demonstrate, evaluate, and improve system performance [1]. Simulation started its commercial applications in the 1960s and is currently a popular decision-making tool for various purposes, especially for complex systems that cannot be represented by analytical models. In addition to providing decision support, simulation provides visual animation that stimulates interest among audience and improves communication for complex system dynamics [2].

A computer simulation is an attempt to model a real-life or hypothetical situation on a computer to study how the system works [2]. Computer simulation is often used as a substitute for a system for which simple closed form analytic solutions are not possible. Although there are many types of simulation, they all generate samples of representative scenarios for a model in which a complete enumeration of all possible states would be prohibitive or impossible. Computer simulation has become a useful part of modeling many natural and human systems to obtain insights in the evolvement and operations of those systems and further to provide managerial insights for decision making. The data input plays an essential role in initial setting for a model and external data requirements vary widely across applications. Simulation is an important tool in design and optimization of engineering systems that involve many processes and entities that are highly interrelated.

Computer simulation models can be classified following various ways, including:

1) Stochastic or deterministic,
2) Continuous or discrete, and
3) Local or distributed.

Stochastic simulation models create random numbers with computer algorithms and convert them to random variables following pre-assumed distributions to represent the stochastic features of real-world systems. A discrete event simulation manages events at discrete time moments. Most computer, logic-test, and fault-tree simulations are of this type. In this type of simulation, the simulator maintains a queue of events sorted by the simulated time they should occur. The simulator reads the queue and triggers new events as each event is processed. All states of the system keep the same time interval between two consecutive events. In other words, state changes and decision makings only happen at those discrete moments. Rather than executing
simulation in real time, it is often more important to be able to access the data produced by a simulation model and to discover defects in the sequence of events. A special type of discrete simulation that does not rely on a model with any underlying equations, but can nonetheless be represented formally, is agent-based simulation. In agent-based simulation, individual entities (such as molecules, cells, consumers, pedestrians, and drivers) are represented directly (rather than by their density or concentration) and possess an internal state and set of behaviors or rules that determine how the agent's state is updated from one time-stamp to the next. A continuous dynamic simulation performs a numerical solution of differential-algebraic equations or differential equations (either partial or ordinary). Periodically, the simulation program solves all the equations and uses the numbers to change the state and output of the simulation.

Distributed models run on a network of interconnected computers, possibly through the Internet, with information exchanged among those computers with a simulation run. Simulations dispersed across multiple host computers and are often referred to as “distributed simulations”. There are several standards for distributed simulation, including Aggregate Level Simulation Protocol (ALSP), Distributed Interactive Simulation (DIS), the High Level Architecture (HLA) simulation, and the Test and Training Enabling Architecture (TENA).

Introduction to Transportation Simulation

Simulation has been widely used to evaluate and analyze transportation systems because they are often complicated and involve high variability. A transportation system may involve thousands or millions of interacted entities so that analytical models become impossible. Furthermore, traffic behaviors are difficult to be modeled by simple analytic models. The simulation of transportation systems is the mathematical modeling of transportation systems (e.g., freeway junctions, arterial routes, roundabouts, downtown grid systems, etc.) through the application of computer software to help plan, design and operate transportation systems. Simulation of transportation systems started over 40 years ago and is an important area of discipline in Traffic Engineering and Transportation Planning today. Various transportation agencies, academic institutions, and consulting firms use simulation to aid in their management of transportation networks.
Transportation researchers have developed numerous models and simulators for use in the planning, design, and operations of such systems. The use of computer simulation started when Gerlough [4] published his dissertation: “Simulation of freeway traffic on a general-purpose discrete variable computer” at the University of California, Los Angeles. From then, computer simulation has become a widely used tool in transportation engineering with a variety of applications from scientific research to planning, training, and demonstration. The five driving forces behind this development are the advances in traffic theory, computer hardware technology and programming tools, the development of the general information infrastructure, and the society's demand for more detailed analysis of the consequences of traffic measures and plans [5]. An example demonstrating the great advances in hardware and software technology. See Figure 1..

Figure 1.

Graphic presentation of simulation results in late 60s [3]
The applications of traffic simulation programs can be classified in several ways. Based on the scope and resolution, traffic simulation could be classified into microscopic, mesoscopic and macroscopic. Based on the time steps, traffic simulation can be grouped into continuous and discrete time approaches. Regarding the problem areas, researchers can categorize traffic simulation for intersection, road section, terminal, and network simulations. Other special application areas are traffic safety and the effects of advanced traffic information and control systems. Microscopic simulation is based on the description of the movement of each individual vehicle in the traffic flow by considering its relevant aspect and behaviors such as acceleration, deceleration, turning, and switching lane [6]. Microscopic simulation could also be used to estimate traffic demand [5]. Macroscopic simulation is based on the flow theory of continuous flow, whose goal is describing the evolution in space and time of variables that are characteristic of macroscopic features of traffic flows, such as volume, speed, and density [5]. In other words, the microscopic simulation uses individual vehicles as its entity, whereas, macroscopic simulation considers the mass of vehicles as an entity. Other than the previous two methodologies, mesoscopic simulation is the simplification that intends to capture the essential points of the dynamic, while requiring less data and hence is more computationally efficient than microscopic models [6]. Mesoscopic simulation models try to have some aspects of microscopic simulation with others from macroscopic models in order to represent the dynamic behaviors for a larger network. In this research, the studied network is at the state level so that modeling each vehicle is not computationally possible. The research team developed a macroscopic simulation to capture overall traffic dynamics in the state of Louisiana.

Simulation can be applied both to transportation planning and to transportation design and operations. In transportation planning, the simulation models may be used to evaluate the impacts of regional urban development patterns on the performance of the transportation system. Regional planning organizations may use these models to evaluate what-if scenarios in order to select transportation projects. On the other hand, modeling of transportation system operations and design focus on a smaller scale, such as a highway corridor. Lane types, signal timing, and other traffic related questions are investigated to improve local system effectiveness and efficiency. While certain simulation models are specialized to model either operations or system
planning, a few models have the capability to model both to some degree, which will be introduced later. Whether it is for planning or for systems operations, simulation has been used for all kinds of transportation modes.

Roadway transportation for both passenger and goods movements is perhaps the area where simulation is most used. Simulation can be carried out at a corridor level or at a more complex roadway grid network level to analyze traffic planning, design and operations such as delay, pollution, and congestion. Roadway transportation models can include all traveling entities on roadways, including passenger vehicles, trucks, buses, bicycles and pedestrians. In traditional roadway macroscopic traffic models, aggregate representation of traffic is typically used where all vehicles of a particular group obey the same rules of behavior. In micro-simulation, driver behavior and network performance are included so that detailed traffic problems can be examined [7]. However, microscopic simulation cannot be used to investigate a larger area, such as a state, because of its computational burden.

Railroad is an important mode of travel for both freight and passengers because of its large carrying capacity and good fuel efficiency. Simulation has been used to evaluate railroad performance and facilitate decision making at various levels, such as a network for one specific Class-I railroad (e.g., [8]; [9]), classification yards (e.g., [10]), or tracks (e.g., [11]). Goodman et al. provided a review of simulation models for railway systems in early days [12].

Waterway and airway transportation presents two areas that are important for certain types of freight. Waterway plays a key role in global freight flow and is the major mode for transporting goods across continents. Inland waterway transportation, which is the most cost-effective and fuel-efficient transportation mode, is appropriate for commodity with low value and low lead time requirement. However, the access to inland waterway is often geographically restricted. Waterway simulation primarily includes container terminal modeling that deals with the logistics of container handling to improve system efficiency [13] and may help to manage barge management in an inland waterway network [14]. Airway transportation is mainly for special goods with small volume but high value and very high requirement of short transportation lead time. This project will not include airways because of its small volume for freight movement from the viewpoint of a state DOT.
Simulation for Intermodal Freight Transportation

In addition to simulating a single mode, it is often more important to simulate an intermodal network, since modern supply chains often transport goods through multiple transportation modes from their origins to their destinations. In a freight network, various modes are closely integrated and represent high complexity that studying modes individually can overlook. Intermodal network simulation can help a better understanding on the impact of a certain network from a comprehensive perspective to more accurately represent its impact in order to realize important policy implications. In the literature, several simulation models have been developed for overall intermodal transportation in one region (e.g., a state) or nation from the planning viewpoint. For example, Tan et al. [15] developed a simulation, called virtual network, for the intermodal network for the state of Mississippi; and Wittmann et al. [16] developed a similar simulation model for the metropolitan area of Hamburg, Germany. Certain simulation models are at the micro-level for intermodal terminals (e.g., [17]; [18]; [19]) There are also a few advanced simulation models (e.g., [20]) addressing design and operational problems involving intermodal transportation from the viewpoint of carriers and/or shippers rather than from the viewpoint of intermodal network planning and operations. In many papers for intermodal transportation simulation, the biggest concern is the lack of available data on the analyzed situations, what decreases the accuracy of the simulation and proposed models validation. Authors often mention as next steps the gathering of empirical data in order to perform a more extensive validation of their models. This research is similar to the one done by Tan et al. [15] but will take advantage of the newly available traffic demand data and traffic network data along with a different choice of simulation package.

Simulation Framework and Simulation Platform

Overall Framework

Transportation simulation models are based on two types of data: traffic demand data and network data. Freight Analysis Framework Version 3 (FAF³) combines data from a variety of sources to create a comprehensive picture of freight movement by all modes of transportation and provides estimates for tonnage and value, by commodity type, mode, origin, and destination for 2007, 2009, and forecasts through 2040 (FHWA, 2012 [21]). The traffic demand data in this project is obtained from FAF³ 2007 tonnage data by three modes (truck, rail, and water), origin,
or destination Louisiana. The network data is available from the ORNL Intermodal Surface Network.

The basic nodes for the Louisiana transportation network consists of 64 parishes of Louisiana (LA), 17 highway outlets (major Louisiana State border crossing points for highway) and 13 railroad outlets (major Louisiana State border crossing points for railroad), etc. In Figure 2, red circles and numbers denote highway outlets, and green squares and letters denote railroad outlets.

![Map of Louisiana showing 17 Highway Outlets and 13 Railroad Outlets](image)

Figure 2.

17 Highway Outlets and 13 Railroad Outlets for Louisiana State

Take two highway shipments for example to illustrate the nodes and links in this model. Figure 2 presents the two paths in blue. The first shipment origins from Calcasieu Parish and its destination is No.1 Highway Outlet. Sulphur, LA is a must-through node for both shipments originated from (or ended in) Calcasieu Parish and along the Interstate 10 highway. Therefore there are 3 nodes and 2 links in this Origination-Destination (OD) pair:
OD1: Calcasieu Parish → Sulphur, LA → No.1 Highway Outlet.

The second shipment originates from Rapides Parish and ends in No.1 Highway Outlet. For the same reason with first path, Alexandria, LA, Iowa, LA, and Oakdale, LA are also basic and indispensable node. There are 6 nodes and 5 links needed in OD2:

OD2: Rapides Parish → Alexandria, LA → Oakdale, LA → Iowa, LA → Sulphur, LA → No.1 Highway Outlet.

It shares the same link with a piece of segment from the first path: Sulphur, LA → No.1 Highway Outlet. These two paths make a significant part of highway network in southwest Louisiana.

The two examples will also appear again in next section to explain the calculation of truckloads in a shipment and how to turn the raw data from previous project, “Development of Performance Measurement for Freight Transportation” into data used here in this simulation model.

**Highway Framework**

![Figure 3. Truck enclosed van semi-trailer (22)](image)

On highways, trucking is the only mode to deliver shipment via private carriers or for-hire carriers. In for-hire sector, full truckload (TL) is 80% of all trucking, including less-than-truckload (LTL) and package express (PX) [23]. Commercial trucks include 5-axle tractor semi-trailers and other double trailer combination and triple trailer combination with different weights and combinations [24]. As the most common truck trailer, the dimension, and cube and weight capacity of the 5-axle semi-trailer is shown in Figure 3. The max truckload of a 53-foot semi-trailer truck is 25 tons.
In this simulation model, five 53-foot semi-trailers are pressed into a batch or a fleet, and each animated truck stands for a 70-ton shipment or a 5-truckload shipments with the assumption that each truck holds 14 tons.

The previous project provides the traffic demand data between 64 parishes in Louisiana and 17 highway outlets. Continued from last section’s example, the first path, each year 949.37 kiloton (KT) cargos need to be transported from Calcasieu Parish to No.1 Hwy Outlet. On average, 104 truckloads are estimated as average daily volume. The simulation model also captures variability of traffic demand over time.

\[
\frac{\text{traffic demand data} \times \text{KT to Ton}}{\text{max truckloads for semitrailer} \times \text{days in a year}} = \frac{949.37 \times 1000}{25 \times 365} = 104
\]

Because as five truckloads are assumed for a batch, 21 animated highway entities, on average, travel daily from Calcasieu Parish to No.1 Highway Outlet in the simulation model.

Similarly, for the second path, 269.89 KT cargos need to be shipped annually from Rapides Parish to No.1 Hwy Outlet. There are 30 truckloads required to be transported daily on average:

\[
\frac{\text{traffic demand data} \times \text{KT to Ton}}{\text{max truckloads for semitrailer} \times \text{days in a year}} = \frac{269.89 \times 1000}{25 \times 365} = 30
\]

Considering 5 truckloads for a batch, there are 6 animated highway entities traveling daily from Rapides Parish to No.1 Highway Outlet in the simulation model. On average every 4 hours, an animated truck (a batch of 5 semi-trailer trucks) drives from Rapides Parish to No.1 Highway Outlet. The Exponential Distribution is assumed to generate random arrival process of the animated highway entities here: EXPO(4), 4 hours is the mean. This is a necessary parameter in the “Create” block in the simulation model with software Arena and it will be covered in detail later.

Many parishes, such as Iberville Parish and Livingston Parish, need respectively 1 and 0 animated highway entities to transport their daily cargos to No.1 Highway Outlet. In the simulation model, travel time for trucks is based on the max limited free-flow on the given roads.
or highways. To simulate the road congestion more accurately, the speed-flow relationship is required to be involved in the model. Numerous scholars in the transportation research field have presented various speed-flow functions to predict the congested speed as function of traffic flow in last several decades. The 1965 and 1985 highway Capacity Manual (HCM) provides speed-flow functions with parabolic-shape curves derived from empirical study. The negatives of these functions are the over estimation on speeds for the volume-capacity ratio greater than 1 and under estimation on speeds for volume-capacity ratio less than 1 [25]. The speed-flow function from 1994 HCM, also parabolic in shape, fails to predict speeds for the volume-capacity ratio larger than 1 [26]. The most commonly used Bureau of Public Roads (BPR) function based on 1965 HCM is as follows:

\[
V = \frac{V_0}{1 + a \left(\frac{v}{c}\right)^b}
\]

Here:

- \(V\) = Congested speed,
- \(V_0\) = Free – flow speed,
- \(\frac{v}{c}\) = volume – capacity ratio, and
- \(a = 0.15\) and \(b = 4\) are two coefficients for model calibration.

Skabardonis and Dowling [27] recommended an updated BPR function with better validation result for the coefficients of \(a = 0.05\) and \(b = 10\). In this simulation project, the updated BPR function is used in the simulation. Assumed trucks on an interstate highway in Louisiana travel at the max limited speed 75 mph. As volume-capacity ratio goes from 0 to 2 in the updated BPR function, the congested speed is illustrated in Figure 4. Please note that the volume includes both truck volume and background passenger vehicle volume. Although the focus of this project is to study freight flows, the passenger vehicle flows must be included in the model. Furthermore, the passenger vehicle volume varies a lot over a day. The developed simulation incorporates the rush hours (the hourly passenger vehicle volume) in the model to represent the reality better in order to obtain more accurate performance metrics.
The following Table 1 also describes the relationship between the volume-capacity ratios and the corresponding congested speeds in Louisiana highways. The congested speed will keep the max limited free-flow speed as the volume-capacity ratio smaller than 0.7 and will go down gradually from 71 to 20 mph as the ratio down from 1.0 to 1.5. The speed will decrease dramatically as the ratio in excess of 1.5.
Table 1

Volume-capacity ratio and congested speed

<table>
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<th>Volume-Capacity Ratio</th>
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Railway Framework

In railway transportation, cargos could be transported by carload (CL) and less-than-carload (LCL). In most situations, a railcar will be cubed out before it reaches its upper limit for weight. The max railcar loads here in this model will take 50 tons for easy calculation. In this project, we assume a train consists of max 100 railcars so each animated train entity stands for a max 5000-tons shipment.
A typical classification rail yard incorporates three areas: receiving area, classification area and departure area. Railcars arrive in the receiving area and get rearranged in the classification area. In the classification area, they are sorted into different groups with different directions. Then the sorted railcars move to the departure area waiting for their corresponding train to depart. As a result, railcars in one train don’t always have the same destination. Figure 5 shows the layout of an example classification rail yard. R1-R4, C1-C6 and D1-D4 represent 4 tracks in the receiving area, 6 tracks in the classification area, and 4 tracks in the departure area. Each track in the departure area connects the distinct railroad from this rail yard to the next one.

**Figure 5**

*Layout of a typical classification yard*

For example on the D1 track, a departing train contains three blocks of railcars going to three destinations (a block of 40 railcars has one direction to d1, another 33 railcars’ destination is d2, and the last block of 24 railcars will ends in d3). All of these 97 railcars share the same route from this rail yard to d1 and they form a Train1 on the track of D1. The block of 40 railcars gets unloaded in d1. If d1 is another classification yard, the remaining 57 railcars will wait for the departure train together with another same direction no-more-than-43 railcars block. If not classified, the Train1 will continue its driving through next rail yard. Only the network and traffic of Class-I railroads are considered in this simulation, The delay at rail yards in the United States has an average of 24 hours and the dwell time at each yard is reported by six Class-I railroads weekly at [http://www.railroadpm.org/](http://www.railroadpm.org/). On links, train speed takes 20 miles per hour on average after considering siding for single line links.

**Waterway Framework**

Waterway transportation is a low-carbon transportation mode compared to highway and railroad methods, especially in certain commodity transport, such as chemical and agriculture products. The Mississippi River system has been a vital part of the U.S. inland waterway network. On the east state border of Louisiana, the Lower Mississippi River (LMR) provides a crucial and low-cost way to carry large amount of bulk commodities.
There are no locks between St Louis and New Orleans [28]. The LMR river condition allows for large tows with up to 40 barges [29]. In this simulation model, an animated boat stands for a large tow with 30 barges (6 barges long and 5 barges wide), with each barge capacity of 1,000 tons. It is assumed the barge speed takes an average of 10 mph after considering the rest time of tugboats based on a former waterway project [30].

**Intermodal Connection**

Intermodal connections have been included in the simulation model at this stage. To simulate the transportation condition of a whole state vividly, the macro-simulation is a must-have perspective. We also incorporate intermodal possibility at several important transshipment centers such as New Orleans and Baton Rouge. The freight transportation on railway to New Orleans could be transshipped to highway system by disaggregating the freight into multiple truckloads. In the same manner, the waterway transportation to the port of New Orleans and Baton Rouge will be transferred to highway system as well. For the intermodal connection, delay between transportation, including storage, unloading, classification, and transloading, are random and assumed to be exponentially distributed with an average of 28 hours per vessel/train. This number can be further adjusted if any real data is revealed. Note that, the purpose of this performed simulation is only an illustration of possibility to investigate the intermodal freight movement. This example shows a possibility to examine the performance of intermodal system.

**Simulation Outputs**

The simulation model to develop is used to evaluate the freight network in Louisiana and identify the measures to improve the overall performance following certain metrics. The performance metrics included in the simulation model includes mobility, reliability, safety, and environmental stewardship. These metrics are the outputs of the simulation.

**Mobility**

Mobility is a measure of transportation system effectiveness and is defined as the average travel time (ton-hour) per ton mile required (TMR). TMR is obtained from geographic distance. The computation model for Mobility ($M$) is the rate of total ton-hour divided by the total ton-mile required:

$$M = \frac{\sum_{(i,j,n) \in R} p_{i,j,n} T_{i,j,n}}{\sum_{(i,j,n) \in R} p_{i,j,n} l_{i,j}}$$
$R$ is a set of all trips in the network. An origin-destination pair (O-D pair) is described by $(i,j)$, where $i$ is the index for origin, $j$ for destination. The triplet $(i,j,n)$ stands for one trip and $n$ is the index of trips with same O-D pair $(i,j)$. $p_{i,j,n}$, the freight tonnage carried on the trip $(i,j,n)$. The travel time for whole trip $(i,j,n)$ is denoted by $T_{i,j,n}$ and $l_{i,j}$ is the geographic distance from origin $i$ to destination $j$.

Freight tonnage on $(i,j,n)$ is available from traffic demand data and the geographic distance between O-D pair $(i,j)$ also accessible from network data. Hence, $p_{i,j,n}$ and $l_{i,j}$ is known before simulation. The entire travel time, $T_{i,j,n}$, from origin $i$ to destination $j$, is the single parameter needed to collect from simulation model. Time for each vehicle arriving system and leaving system is recorded and the difference is $T_{i,j,n}$. After calculation, the mobility for highway network, railroad network, waterway network, and overall network is available.

Reliability

Reliability is a measure of transportation system variability and is defined as the coefficient of overall variation of travel time per travel mile required. The statistical model for reliability ($R$) is:

$$R = \sqrt{\frac{\sum_{(i,j,n) \in R} p_{i,j,n} l_{i,j} \left( \frac{T_{i,j,n}}{l_{i,j}} - M \right)^2}{\sum_{(i,j,n) \in R} p_{i,j,n} l_{i,j}}}$$

$M$ is for mobility. Smaller $R$ is desirable to reduce variability in travel time, decrease recurrent congestion, and get a better estimate of travel time. Two types of delays are frequently addressed in a transportation engineering study, recurrent delays and nonrecurring delays. Recurrent delay is regularly and predictable, while nonrecurring delay is unpredictable. The above expression of $R$ accounts for the recurrent delays. The nonrecurring delay is the other measure of reliability, denoted by $R_u$ and is expressed by:

$$R_u = \sqrt{\frac{\sum_{(i,j,n) \in R} p_{i,j,n} l_{i,j} \left( \frac{T_{i,j,n}}{l_{i,j}} - f_{i,j,n} \right)^2}{\sum_{(i,j,n) \in R} p_{i,j,n} l_{i,j}}}$$

$M$
where \( f_{i,j,n} \) is the expected travel time for trip \((i,j,n)\), obtainable after calculation with all known information.

Safety

Safety is assessed by two measures, the Fatality Rate \( S_F \) and Injury Rate \( S_I \).

Fatality Rate \( S_F \) is the number of fatalities per TMR, defined by:

\[
S_F = \frac{\sum_{(i,j,n) \in R} F_{i,j,n}}{\sum_{(i,j,n) \in R} p_{i,j,n} l_{i,j}}
\]

where \( F_{i,j,n} \) is the fatality numbers for trip \((i,j,n)\) and \( \sum_{(i,j,n) \in R} p_{i,j,n} l_{i,j} \) is the summation of TMR for each trip \((i,j,n)\).

Injury Rate \( S_I \) is the injury numbers per TMR, expressed by:

\[
S_I = \frac{\sum_{(i,j,n) \in R} I_{i,j,n}}{\sum_{(i,j,n) \in R} p_{i,j,n} l_{i,j}}
\]

where \( I_{i,j,n} \) is the injury numbers for the trip \((i,j,n)\).

Environment Stewardship

Environment stewardship is measured by Energy Consumption Rate \( EC \) and Pollutant Released Rate \( P \). Energy Consumption Rate \( EC \) is the average unsustainable energy consumption (BTU) per TMR, defined by:

\[
EC = \frac{\sum_{(i,j,n) \in R} E_{i,j,n}}{\sum_{(i,j,n) \in R} p_{i,j,n} l_{i,j}}
\]
where $E_{i,j,n}$ is the unsustainable energy consumption for trip $(i,j,n)$. Pollutant Released Rate ($P$) is the tons of emissions from transportation systems per TMR and is defined by:

$$
P = \frac{\sum_{(i,j,n) \in R} PO_{i,j,n}}{\sum_{(i,j,n) \in R} p_{i,j,n} l_{i,j}}
$$

Where $PO_{i,j,n}$ is the tons of mobile pollutants emissions caused by trip $(i,j,n)$.

**Simulation Platform Selection**

Simulation software is getting better in a variety of different ways. With new advancements in mathematics, engineering, and computing, simulation software programs are increasingly becoming faster, more powerful, more detail-oriented and more realistic. It is more common to experiment with traffic networks in a computer simulated environment because experimenting with traffic in the real environment is not practical [15].

Transportation models generally can be classified into microscopic, mesoscopic, macroscopic, and macroscopic models. Microscopic models study individual elements of transportation systems, such as individual vehicle dynamics and individual traveler behavior. Mesoscopic models analyze transportation elements in small groups, within which elements are considered homogeneous. A typical example is vehicle platoon dynamics and household-level travel behavior. Macroscopic models deal with aggregated characteristics of transportation elements, such as aggregated traffic flow dynamics and zonal-level travel demand analysis. Among all of microscopic software packages in transportation models, CORSIM is outstanding. It has been widely used in countless transportation projects, including many critical emergency evacuation studies. As well, it is the most trusted traffic simulation software among research communities in the U.S. It combines NETSIM (the surface street traffic simulation software) and FRESIM (the freeway simulation software), both of which had been developed since the 1970s with the support from FHWA.

The National Transportation Library (NTL) database and Google searches (Google.gov) on March 2008 and December 2014 related to the traffic simulation tool key words are summarized in Table 2. The research articles with CORSIM keywords are about two and half times as many as articles with the second most used traffic simulation software, according to NTL. The .gov Google searches confirm that CORSIM are most likely to be used in research and U.S. government-sponsored projects as well.
The records above demonstrate the pivotal roles that CORSIM has played in the nation’s transportation research for microscopic traffic simulation. The number of papers shows the strong demand from the research community. However, although CORSIM plays pivotal roles in the nation’s transportation research, it has a limitation that it is a microscopic simulation software package. But the statewide intermodal transportation network portion forms the macroscopic portion, while terminals and ports form the microscopic portion. Entity speed on the transportation network, for example, is calculated based on the macroscopic parameters of flow rate and capacity [15]. Therefore, we need to find other software package that is better for macroscopic intermodal simulation model.

Below is a list of some well-known simulation packages for macroscopic transportation models:

(1) Emme/2 is an urban transportation planning system, offering planners a comprehensive set of tools for traffic and transportation modeling. It provides decision-support capabilities, allowing the simultaneous description, analysis, and comparison of several proposed scenarios and provides methods for evaluating various transportation and land use development alternatives [31].

(2) Aimsun is traffic modelling software that allows users to model anything from a single bus lane to an entire region. With thousands of licensed users in government agencies,

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1 By CORSIM or NETSIM or FRESIM keywords
2 By CORSIM only
consultancies, and universities all over the world, Aimsun stands out for the exceptionally high speed of its simulations and for fusing travel demand modelling, static and dynamic traffic assignment with mesoscopic, microscopic and hybrid simulation, all within a single software application [32].

(3) TransModeler is a powerful and versatile traffic simulation package applicable to a wide array of traffic planning and modeling tasks. TransModeler can simulate all kinds of road networks, from freeways to downtown areas, and can analyze wide area multimodal networks in great detail and with high fidelity. Users can model and visualize the behavior of complex traffic systems in a 2-dimensional or 3-dimensional GIS environment to illustrate and evaluate traffic flow dynamics, traffic signal, and ITS operations, and overall network performance [33].

(4) ProModel is a flexible, general-purpose discrete-event simulation language and simulator that can be coded by users to develop specific functions and capabilities required in statewide freight transportation simulation models. It is capable of handling both macroscopic and microscopic elements that are required for the simulation [15].

(5) ProcessModel has four building blocks: activities, entities, resources, and stores. Within each block and for each routing option (connecting line), there is the capability of adding complex logic. Global variables and entity attributes can be easily defined within ProcessModel. ProcessModel also has a Label Block that can be used to display the current content of selected global variables during the simulation. ProcessModel provides the capability in a Label Block to display data from the global variables during the simulation [34].

(6) AnyLogic helps users to deal with various transportation issues, including the most challenging task, transportation management. Simulation modeling will allow you to maximize the transportation load, minimize your costs, and also calculate the probability of traffic costs overrun. You will be able to “play” various schemes of transportation and fleet management, which will allow you to reveal and prevent potential problems. In addition, anylogic java class can be integrated into a java program. The native Java environment provides multi-platform support. Both the AnyLogic IDE and models work on Windows, Mac, and Linux. On the other hand, external routines can be integrated either by including external classes or using the JNT interface to non-java libraries [35].

(7) ARENA is a generic discrete-event simulation and automation software developed by Systems Modeling. It uses the SIMAN processor and simulation language. Also ARENA can be integrated with Microsoft technologies. It includes Visual Basic for Applications so models can be further automated if specific algorithms are needed. It also supports importing Microsoft Visio flowcharts, as well as reading from or outputting to Excel spreadsheets and Access databases. Hosting ActiveX controls is also supported. In ARENA, users build an experiment model by placing modules (boxes of different shapes) that represent processes or logic. Connector lines are used to join these modules together and specify the flow of entities. While modules have specific actions relative to entities,
flow, and timing, the precise representation of each module and entity relative to real-life objects is subject to the modeler. Statistical data, such as cycle time and WIP (work in process) levels, can be recorded and outputted as reports [36].

Transportation planners often need to justify transportation related investments to public officials. Although the preceding software packages have enough functions on transportation simulation, their operational cost is very large and it is relatively complicated to use. In contrast, ARENA has powerful visualization capabilities that complement data generated by analysis of freight transportation scenarios and a relatively lower simulation cost. ARENA’s drag and drop elements and structures allow you build simulations and visualize results with engaging 2D and 3D animation capabilities that do not require programming assistance. Furthermore, ARENA has a proven track record of enabling companies to model and evaluate virtually every aspect of their transportation network. ARENA’s flowchart modeling methodology makes it easy to define and communicate the intricacies of complex transportation. Its built-in dynamic dashboards provide the model analysis you need to facilitate logistics optimization. Within ARENA users can build customized displays of the model information to enable users to better understand what is happening in a transportation network. ARENA is a commercial simulation software system with a wide variety of application in business, transportation, logistics, manufacturing, and healthcare system, etc. [37]. As the most widely used discrete event simulation software, ARENA is designed to address the needs for both end users in enterprises and researchers in educational system. It’s suitable for macro-simulation especially in constructing complicated network. ARENA is powerful in complex system modeling and has built-in integration with other applications, Visual Basic, Microsoft Excel or Access, and AutoCAD, etc. [38].

Freight Analysis Framework (FAF) is a comprehensive database initiated by the Federal Highway Administration Office of Freight Management and Operations in 1999 [39]. It attempts to develop a complete database of transportation flows in the US traffic network. Major freight measures, including values, tons, and ton-miles, are easy to access through FAF by years, modes of transportation, types of commodity and zones. As the newest version of FAF, FAF3 is based on the data from 2007 Economic Census [21]. FAF3 incorporates FAF3 Origin-Destination Data, FAF3 Summary Statistics and FAF3 Network Data. In this simulation, FAF3 Origin-Destination Data is used for research, available at http://www.ops.fhwa.dot.gov/freight/freight_analysis/af/faf3/netwkdbflow/. FAF3 has 131 FAF traffic analysis zones including 123 domestic regions and 8 foreign regions, only 4 regions for Louisiana. To extract detailed traffic flow information from these 4-regions data, a disaggregation process is conducted in previous project. The traffic demand data for this simulation model benefits from the working result of that project. Very soon, FAF4 will be released with more FAF zones and based on more recent Commodity Flow Survey conducted in 2012. The research team is able to incorporate new FAF3 data into the simulation model to be developed with relatively little additional effort.
Simulation Development

Highway Network Simulation

ARENA converts highway nodes, links and highway freight transportation system into logic models illustrated in Figure 6.

Highway Network

The “Create” block in Pentagon shape “Origin from Rapides Parish to No.1 Hwy Outlet” generates arriving entities to the system. The amount or the frequency of the arriving entities is based on the exponential mean EXPO (4), thus the Exponential Distribution is assumed to generate random arrival process of the animated arriving entities here: EXPO(4), 4 hours is the mean.

The “Assign” block after each “Create” block specifies the attributes of the arriving entity when an entity comes to the system, i.e., cargos from the same origination could be transported to various destinations with different destination index. The “Assign” block (e.g., “Assign 12”) sets up destination index equals to 1 (destination index = 1 means destination is No.1 Highway Outlet) and origin index equals to 2 (origin index = 2 means origin is Rapides Parish).
The rectangular shape sub-model (with a turn-down arrow at front) “Rapides Parish to Alexandria, LA or to Natchitoches or to the end” here tells ARENA which path the cargos will be transported through. For example, “Rapides Parish to Alexandria LA or to Natchitoches, LA” means that cargo originated from Rapides Parish could drive south to Alexandria, LA, or it also could drive north to Natchitoches, LA. It all depends on the destination of the cargo. The Sub-model will direct various cargos by Decide block (“Decide 4”) to their destinations based on the attributes set up in Assign block. Figure 7 gives an inside look to sub-model “Rapides Parish to Alexandria LA or to Natchitoches or to the end”.

Figure 7

Sub-model "Rapides Parish to Alexandria LA or to Natchitoches LA or to the end"

The “Decide” block makes decisions according to different conditions. For example, “Decide 4” in Figure 7 sends the cargos to Alexandria LA if destination index = 1, and to Natchitoches LA if destination index = 0 (destination is No.5 Highway Outlet), and so on. “Decide 4” also carries cargo to Rapides Parish to dispose (transport out of Rapides Parish Highway Station) if di=27 (destination is Rapides Parish). “Decide 183” directs cargos from various origin to its corresponding Assign block. The cargos originate from Lafayette Parish (origin index = 3) to “Assign 453”, from Ouachita Parish (Origin Index =4) to “Assign 486” from East Baton Rouge Parish (Origin Index = 6) to “Assign 472.” The three assign blocks are involved in the calculation of some parameters (such as arriving time at finish line, etc.) of each entity required in highway mobility design.
The variables and entities in highway network are the following:

- \( o_i \): origin index, variable, established in the “Assign” block;
- \( d_i \): destination index, variable, established in the “Assign” block; and
- Batches of Truckloads: 1 batch of truckloads = 1 animated truck = a 70-ton shipment by truck. Entity, established in the “Create” block.

Instead of simply estimating the traffic volume and traveling speed based on an average traffic count that is the same over time, our model considered the variation of traffic volume during rush hours and non-rush hours. The total traffic volume in each segment was computed as a summation of truck volumes and background traffic volumes. The truck volumes were derived from O-D matrixes that are generated from FAF3 data set. The background traffic volumes were computed based on the traffic counts and highway condition of each segment, including number of lanes in each direction, length, and free flow speed on each segment.

Researchers also incorporated rush hour factor for passenger vehicles that indicate a varying coefficient that is unique during each hour. In doing so, the peak hour factors formed a set of 24 coefficients and these coefficients were assigned to the computational formula at the beginning of each hour depending on what time it is in the simulation. Furthermore, also considered the different patterns of traffic volume in rush hour on weekdays and weekends. The rush hour may come at a different time and with a different volume on weekends than weekdays. Therefore, the model assigned rush hour factors for weekday and weekends separately. In doing so, the traffic volumes were counted each hour and the numbers of traffics are compared to the overall average traffic volume, which indicates the proportions of average traffic volume observed in the corresponding time period. The observation results are illustrated in Table 3. This set of data provides evidence for modeling background vehicle numbers and freight transportation volume in each specific time period.

In order to incorporate the above rush hour designing idea into the model, the authors built up a DATE/TIMER BLOCK that generated a timer entity that comes at the beginning of each hour. This entity enters the assign block and reads the current time in the simulation system so that it could identify whether currently it is in the rush hours or non-rush hours and it is on weekdays or weekends. In doing so, the entity will then read a peak hour factor from the data set according to the current time and this factor will be brought into a formula to compute the rush hour traffic volume. The computed background and total traffic volume should reflect the real world traffic counts that vary over time with peaks and off-peaks. This traffic volume will finally contribute to the computation of the volume to capacity ratio and the traveling speed.
The percentage of traffic volumes in this table were separately listed by weekday and weekend. It enables us to compute weekday and weekend rush hour traffic volume separately. With the hourly traffic volume in Table 3, the authors are able to simulate the hourly total volume for pair \((i, j)\) on day \(k\) by

\[
TT(i,j,k) = t\text{rk}_{ij} + p_{k/hr} \cdot AADT_{ij} \cdot (1 - \alpha_{ij}) \cdot l_{ij} / (\beta_{ij} \cdot FFS_{ij} \cdot 24)
\]

where

\( t\text{rk}_{ij} \) = number of trucks on pair \((i, j)\);

\( p_{k/hr} \) = peak hour factor that varies over time and indicates the percentage of average traffic volume in each hour. Here, \( k = 0 \), indicate it is weekday and the data will be pulled from the WD\% row in Table 3 while \( k = 1 \), indicate it is a weekend and the data will be pulled from the WE\% row in Table 3;

\( \alpha_{ij} \) = percentage of truck over total traffic volume; and

\( l_{ij} \) = the length of lane segment lanes on pair \((i, j)\).
Based on the computed total traffic volume, the volume to capacity for pair \((i,j)\) on day \(k\) can be written as

\[
\frac{v}{c}(i,j,k) = \frac{trk_{ij} + pk_{hrk} \cdot AADT_{ij} \cdot (1 - \alpha_{ij}) \cdot l_{ij} / (\beta_{ij} \cdot FFS_{ij} \cdot 24)}{ln_{ij} \cdot l_{ij} \cdot fcp}
\]

where

\(trk_{ij}\) = number of trucks on pair \((i,j)\);

\(pk_{hrk}\) = peak hour factor that varies over time and indicates the percentage of average traffic volume in each hour. Here, \(k = 0\), indicate it is weekday and the data will be pulled from the WD\% row in Table 3 while \(k = 1\), indicate it is a weekend and the data will be pulled from the WE\% row in Table 3;

\(\alpha_{ij}\) = percentage of truck over total traffic volume;

\(l_{ij}\) = the length of lane segment lanes on pair \((i,j)\);

\(ln_{ij}\) = the number of lanes per direction on pair \((i,j)\);

\(\beta_{ij}\) = constant number indicates the estimated average percentage of free flow speed vehicles could travel on pair \((i,j)\). Here we assume \(\beta_{ij} = 80\%\);

\(FFS_{ij}\) = free-flow speed on pair \((i,j)\); and

\(fcp\) = factor of capacity, number of vehicles on lane when it reaches the capacity, constant, here \(fcp = 45\) vehicle/mile/lane.

With this volume to capacity ratio in mind, the traveling speed is computed based on Bureau of Public Roads (BPR) formula [27] as

\[
f(i,j,k) = \frac{FFS_{ij}}{1 + 0.05 \left[ \frac{v}{c}(i,j,k) \right]^{10.}}
\]

A set of ACCIDENT GENERATOR blocks was designed to generate signals of accident. For example, every 6 hours, there will be a truck accident in somewhere in LA, then every 6 hours, ACCIDENT GENERATOR will send a signal (the signal is a special number that belongs to one running truck on the map) of accident to a random point in the LA highway network. This rate
can be changed and calculated based on the actual performance per ton-mile of each vgmode in Louisiana.

Each LA highway route was plugged in a SIGNAL RECEIVER (located in the sub-model to adjust speed according to capacity or density on that route) that will compare the signal and the special numbers (we choose the Entity Number as the identifier) of the running trucks on their route. If the two numbers match, then the highway will be set as ACCIDENT AREA. The velocity of running trucks on the highway, on the accident direction and not passing the accident spot yet, will be set to 10 mph. The trucks on the other direction of accident highway and trucks passed the accident spot will be driving on their normal speed. Depending on the severity of the accident, the trucks on opposite direction and trucks passed the accident spot, within the ACCIDENT AREA, will also travel slower than usual.

Specified hours after the accident, the velocity of trucks in ACCIDENT AREA will be set to normal speed. The cycle of truck accident on highway comes to the end in our simulation.

**Railway Network Simulation**

The railroad network consists of 13 railroad outlets (the major Louisiana State border crossing points for railroads) and five major railroad yards at Shreveport, Alexandria, Baton Rouge, Lake Charles and New Orleans. The five rail yards are all classification rail yards. The basic blocks, “Create” and “Assign” for railroads are similar to those for highways. Although the ARENA model for the Railroad network in Figure 8 has a similar look with the highway one in previous section, their sub-models have differing logic and internal structure.
The highway sub-model directs cargos to their desired destinations immediately, while a classification rail yard sub-model collects railcars from its originations or from an existing train in receiving area. All railcars are released from the existing train and go to classification area for sorting. In the departure area, railcars are put up together again to form a train with the same direction. The simulation model limits train capacity up to 100 railcars. A block of railcars stay together from their origin to destination and are not separated at any time on their trip. Figure 9 shows the details of a classification rail yard “Baton RougeR LA to New OrleansR LA or to OpelousasR LA or to AlexandriaR LA or to the end”. The letter R after each location name represents that it is a railroad station.
The other four sub-models were nested in the sub-model “Baton Rouge LA to New Orleans LA or to Opelousas LA or to Alexandria LA or to the end.” They are “Baton Rouge LA to New Orleans LA,” “Baton Rouge LA to Opelousas LA,” “Baton Rouge LA to Alexandria LA,” and “Baton Rouge LA to Hammond LA.” The details of the first sub-model are shown in Figure 10.
Figure 10
Details of sub-model ”Baton Rouge R LA to New Orleans R LA”

This sub-model describes a typical classification and departure process in the classification and departure area. Followed is the logic for the sub-model ”Baton Rouge R LA to New Orleans R LA.”

\[
\text{Blk}18 = \text{TL}18 = \text{TM}18 \equiv 0; \quad /* \text{initial value of three parameters are 0}*/
\]

18 is the index of route from Baton Rouge Rail Station to New Orleans Rail Station/

\[
\text{Blk}18 = \text{Blk}18 + 1; \quad /* \text{count the number of blocks}*/
\]

\[
\text{TL}18 = \text{TL}18 + \text{RCsize}; \quad /* \text{record the existing length of the train}*/
\]

\[
\text{TM}18 = \text{TL}18 / \text{maxsize}; \quad /* \text{calculate a measure factor}*/
\]

IF

\[
\text{TM}18 \leq 1; \quad /* \text{train is not full}*/
\]

THEN

HOLD for signal 6551; /* railcars stay at the track to wait for another blocks of railcars*/

/* waiting for full train signal 6551 to proceed*/

ELSE

Send SIGNAL 6551 /* indicate the train is full, the existing railcars could form a train*/

HOLD for signal 6550 /* wait for the completion of train formation process*/

Batch size = AINT(Blk18 - LN(TM18)) /* Batch size = Truncate (Blk18 - Natural logarithm (TM18))*/

/* batch the railcars to a new train*/

\[
\text{Blk}18 = \text{TL}18 \equiv 0 \quad /* \text{go back to 0}*/
\]

Send SIGNAL 6550 /* Finished to form a train. The last block of railcars could go back to track to wait for next train*/

PROCESS /* loaded train wait for inspection, the time follows TRIA (1.5, 2, 2.5)*/

HOLD for signal 655 /* wait for the train to departure on schedule*/

/* “Signal 94” in Figure 7 send the signal 655, a coming train signal*/
ROUTE from Baton Rouge Rail Station to New Orleans Rail Station

The variables, entity, resource, expression, and schedule in railroad network list as following:

- **rv**: train speed, constant. Equals to 20 mph.
- **RR**: railroad destination index, variable, established in Assign block.
- **Maxsize**: max number of railcars a train can contain. Constant. Equals to 100.
- **RCsize**: the number of railcars in a block, variable, established in Assign block. Cargos with the same origin-destination pair share the same RCsize.
- **Blk\_m**: the \( n \)th block in a train.
- **TL\_m**: the number of railcars in a train. \( m \) represents origin-destination pair index. Initial value is 0.
- **TM\_m**: measure factor in forming a train. \( TM\_m = \frac{TL\_m}{maxsize} \). If \( TM\_m > 1 \), the train is full.

The last block of railcars will remain on departure tracks waiting for next train. The existing railcars just wait for uploading to the coming train and depart. If \( TM\_m \leq 1 \), another block of railcars could be added to the train. Initial value is 0.

- **Batches of Railcars**: 1 batch of railcars = 1 block of railcars. Entity, established in Create block.
- **Inspection time**: inspection time for train. Established in Expression. Follows triangular distribution TRIA (1.5, 2, 2.5) the min inspection time is 1.5 hours, max inspection time 2.5 hours, and the most likely (the mode) inspection time 2 hours.
- **Inspection person \( p \)**: the index for inspection person. Established in Resource.
- **Schedule \( q \)**: the index for different train schedules. Established in Schedule.

At the station of New Orleans and East Baton Rouge, the freight transportation on railway to New Orleans could be transferred to the highway system by disaggregating the freight into 8 highway entities which is equivalent to 40 truckloads. For the intermodal connection, delay between transportation, including storage, unloading, classification, and transloading, are assumed to be exponentially distributed with an average of 28 hours per vessel/train. This number can be further adjusted if any real data is revealed. Note that the purpose of this performed simulation is only an illustration of possibility to investigate the intermodal freight movement. This example shows a possibility to examine the performance of an intermodal system.
Waterway Network Simulation

The waterway network consists of six ports on lower Mississippi river along the east state border of Louisiana. From north to south, the ports are Cracraft, Vicksburg, Natchez, Above Old River, Baton Rouge, and New Orleans.

Figure 11 shows part of the ARENA model for the waterway network. The “Create” and “Assign” blocks and sub-models for waterway are similar to those for both highway and railroad models. Figure 12 shows the details of one sub-model “CracraftP AR to VicksburgP LA or to the end.” The letter P following each location name indicates it’s a port. The logic of this sub-model is much the same as the logic of the highway sub-model.

The variables and entity in waterway network are the following:

- WW: waterway destination index, variable, established in Assign block
- wv: speed, constant. Equals to 10 mph.
- \( d_i \): destination index, variable, established in Assign block
- Tows with 30 barges: 1 Tows with 30 barges = 1 animated boat = a 30000-ton shipment by water. Entity, established in Create block.

**Figure 11**
Part of the ARENA Model for Waterway Network
The freight transportation to the port of New Orleans and Baton Rouge are also transferred to the highway system. The freight on each vessel will be disaggregated to 48 highway entity, which is equivalent to 240 trucks. For the intermodal connection, delay between transportation, including storage, unloading, classification, and transloading, are assumed to be exponentially distributed with an average of 28 hours per vessel/train. This number can be further adjusted if any real data is revealed.

Output

The simulation model generates the flow of freight transportation on the roads, on the Class-I railroads and on the Mississippi river in Louisiana. The traffic flow on other rivers of Louisiana (like Red River) is so small relative to the Mississippi river traffic that it would not show on the simulation run, so we disregarded it.

As described earlier, no individual vehicles (trucks, rail cars, or barges) are generated because it would be possible only for a small part of the Louisiana freight network, for the whole of Louisiana it would result in too much complexity and computer running time. In this research, the studied network is at the state level so that modeling each vehicle is computationally not possible. On the other hand, if just a total aggregate of the daily traffic flow is generated, it does not capture the daily changes in the transportation network, missing the dynamics and uncertainty effects. So we had to find an appropriate compromise.
Microscopic simulation uses individual vehicles as its entity whereas macroscopic simulation considers the mass of vehicles as an entity. Other than the previous two methodologies, mesoscopic simulation is the simplification that intends to capture the essential points of the dynamic, while requiring less data and hence is more computationally efficient than microscopic models.

The authors developed a simulation model that combines some aspects of microscopic simulation with others from macroscopic models in order to represent the dynamic behavior of a larger, complex network. Forming batches of trucks, railcars, and barges, we are able to capture the overall traffic dynamics and illustrate it by animation in the complex multimodal transportation network of the State of Louisiana. Further, it provides the tool to estimate the performance measures more accurately.

As described earlier, the highway framework considers five 53-ft. semi-trailers as a batch, each animated truck entity stands for a 70-ton shipment or a 5-truckload shipment. In the railway framework, a train consists of maximum 100 railcars, so each animated train entity stands for a maximum of 5,000-ton shipment. The dwell time at each yard is based on the weekly report provided by the six Class-I railroads weekly at http://www.railroadpm.org/. In the waterway simulation model, an animated boat stands for a large tow with 30 barges (6 barges long and 5 barges wide), with each barge capacity of 1,000 tons.

The simulation model considers replications, where the replication length is 30 days, 720 hours, and takes for more than 3 hours computer running time. Figure 13 shows the print screen for animation. Animated batches of trucks are in grey; animated trains are longer with blue and red color; and animated tows are in gray and black on the Mississippi River. The simulation model at the current stage calculates the mobility, reliability, safety, and environmental stewardship measures.
In order to better animate the volume to capacity ratio on the highway system, all highway segments will be classified into four conditions. If a segment is less than half used, the segment will be colored in green; while if the traffic volume in this segment is near its capacity, the representing block will be filled with red color showing a possible overflow or accident congestion. In between these two regions, the highway segment is mildly used and this segment will be shown in orange and yellow color. The overall animation effect is listed in Table 4 and demonstrated in Figure 14.
Table 4
List of animations for all conditions of highway segments

<table>
<thead>
<tr>
<th>Volume to Capacity Ratio</th>
<th>Animation Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.5</td>
<td>Green</td>
</tr>
<tr>
<td>[0.5, 0.8)</td>
<td>Yellow</td>
</tr>
<tr>
<td>[0.8, 0.9)</td>
<td>Orange</td>
</tr>
<tr>
<td>&gt; 0.9</td>
<td>Red</td>
</tr>
</tbody>
</table>

Figure 14
Demonstration of animation effect
Simulation Validation

In the simulation model, the demand data is based on the *Freight Analysis Framework Version 3* (FAF3) and the *Intermodal Surface Network* data. The traffic on each link in the network was obtained through traffic assignment based on the shortest time rule by using (FAF³) Origin-Destination Data at [http://www.ops.fhwa.dot.gov/freight/freight_analysis/faf/faf3/netwkdbflow/](http://www.ops.fhwa.dot.gov/freight/freight_analysis/faf/faf3/netwkdbflow/).

According to the derived dataset, we assigned the traffic to the major connections in the transportation system. The simulation model was validated based on historical traffic data in the state of Louisiana. The simulation result was compared to the traffic counts at certain locations provided by DOTD. We took the annual average daily traffic (AADT) counts (Louisiana Department of Transportation and Development 2013) and used it to estimate the number of trucks on the highway on a daily basis.

The simulation model calculates system-level performance metrics for the intermodal freight network of Louisiana. The model has the capability of allowing users to change parameter settings, input data, and define different scenarios.

The segments used for illustration were chosen from the most congested area on I-10 that connects New Orleans to other cities. I-10 was heavily used due to import and export freight transportations. The port of New Orleans is connected with west states with I-10 through Jefferson and it is linked with east states through Slidell. A large portion of the increased demand was allocated to import to southeast states and export from west states. The volume of truck movement was derived from the LaDOTD information of the percentage of the different vehicles types as it is summarized in Table 5 and illustrated in Figure 15.

Among all the vehicles, categories 9 to 12 are the most commonly used freight carriers and we count with them in our simulation model validation. According to the commercial freight vehicle study from Michigan Department of Transportation, 4% was adopted as the truck percentage. Among those trucks, 70% of total trucks are loaded while the other 30% are assumed to be empty. Because empty returning trucks are not simulated in our system, the total number of trucks can be derived from the simulation result by considering the percentage of loaded trucks.
Table 5

Average statewide vehicle percentages by functional classification for 2015

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Principle Arterial-Interstate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cycles</td>
</tr>
<tr>
<td>2</td>
<td>Cars</td>
</tr>
<tr>
<td>3</td>
<td>2A-4T</td>
</tr>
<tr>
<td>4</td>
<td>Buses</td>
</tr>
<tr>
<td>5</td>
<td>2A-SU</td>
</tr>
<tr>
<td>6</td>
<td>3A-SU</td>
</tr>
<tr>
<td>7</td>
<td>4A-SU</td>
</tr>
<tr>
<td>8</td>
<td>4A-ST</td>
</tr>
<tr>
<td>9</td>
<td>5A-ST</td>
</tr>
<tr>
<td>10</td>
<td>6A-ST</td>
</tr>
<tr>
<td>11</td>
<td>5A-MT</td>
</tr>
<tr>
<td>12</td>
<td>6A-MT</td>
</tr>
<tr>
<td>13</td>
<td>7A-MT</td>
</tr>
</tbody>
</table>
Figure 15
Illustration of vehicle classification [38]
The model was simulated for 2 weeks for 30 replications. The simulation model run for 1 week as a warm up session in order to get close to the practical conditions. After running the model for 30 replications, and compared the results with the real traffic counts. The comparison between the simulation data and the real traffic counts is summarized and listed in Table 6 and Figure 16. Compared with the traffic count data, the simulation average was close to the real traffic data. All real data were covered by the confidence interval of the simulation averages. It indicates that the simulation model could mimic the real traffic transportation data in an acceptable manner and so it can provide the basis of our further analysis and discussion.

**Figure 16**

Illustration and comparison between real data and simulation results
### Table 6
Comparison between real traffic counts and simulation results

<table>
<thead>
<tr>
<th>Origin</th>
<th>Destination</th>
<th>AADT</th>
<th>Daily Trucks (5% of AADT)</th>
<th>Simulation Average</th>
<th>With Unloaded Trucks (142% of Left)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Orleans</td>
<td>Slidell</td>
<td>147578</td>
<td>7379</td>
<td>4151</td>
<td>5929</td>
</tr>
<tr>
<td>Jefferson</td>
<td>New Orleans</td>
<td>150543</td>
<td>7527</td>
<td>5674</td>
<td>8107</td>
</tr>
<tr>
<td>New Orleans</td>
<td>Jefferson</td>
<td>126335</td>
<td>6317</td>
<td>5403</td>
<td>7719</td>
</tr>
</tbody>
</table>

The results are illustrated with a part of the I-10 corridor by New Orleans. I-10 is one of the busiest freight corridors connecting west states from California and east states, such as Louisiana, and Florida. In that sense, the study should be further focused on investigating how the increased transportation demand, disruptions or any improvements on this highway system performance could help with the freight transportation system. In the light of this, the I-10 segments connecting New Orleans, are also selected as the focal point of our scenario analysis in the illustration next.

### Scenario Analysis

This section illustrates the scenario analysis capabilities of our model on three specific hypothetical scenarios. The impact of several factors on the performance of the intermodal freight system in Louisiana State is simulated. The data requirements and sources are summarized in Table 7.
### Table 7
Data requirements and sources

<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>Required Data</th>
<th>Sources</th>
<th>Other Possible Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobility and Reliability</td>
<td>Mobility ((M)) (hour per mile)</td>
<td>Geographic OD data, Travel time data</td>
<td>Statewide or regional transportation planning data, GIS software</td>
</tr>
<tr>
<td>Mobility and Reliability</td>
<td>Reliability ((R, R_u)) (no unit)</td>
<td>Travel time data, Data to obtain (M)</td>
<td>Survey data collection, Data to obtain (M)</td>
</tr>
<tr>
<td>Safety</td>
<td>Fatality ((S_F)) (fatalities per (TMR))</td>
<td>Fatality occurrence data</td>
<td>GIS-based accident information system</td>
</tr>
<tr>
<td>Safety</td>
<td>Injury Rate ((S_I)) (injuries per (TMR))</td>
<td>Injury occurrence data</td>
<td>GIS-based accident information system</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TRANSEARCH data, Ground counts data, Commodity Flow Survey data, FAF3, U.S. Waterway Data, ORNL Intermodal Surface Network</td>
</tr>
</tbody>
</table>


### Scenario 1: Increased Demand

As of 2002, the total ton miles related to Louisiana was 38,791 million (shown in Table 8). In 2007, the Panama Canal began an expansion project that is expected to create additional demand for New Panamax ships. In 2016, this ongoing project is expected to double the capacity of the Panama Canal, creating a new lane of traffic and allowing a greater volume of freight transitions. As one of the most important seaports in the southeast, the freight movement
through the port of New Orleans is expected to grow remarkably. The transportation volume by truck and railroad is expected to increase by more than 50%, possibly as high as 300%, by 2040. As a consequence, higher demand of transshipment is expected in the transportation system of the whole state. There is a need to study the allocation of freight transport demand and traffic assignment in advance. In the first scenario, the travel volume related to New Orleans is increased by 50% in order to show the impact of increased transportation demand on the multimodal transportation system performance of the state.

Table 8

<table>
<thead>
<tr>
<th>State</th>
<th>Leaving</th>
<th>Entering</th>
<th>Within</th>
<th>Local</th>
<th>Through</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Louisiana</td>
<td>7,386</td>
<td>6,620</td>
<td>15,381</td>
<td>91</td>
<td>9,312</td>
<td>38,791</td>
</tr>
</tbody>
</table>

In Scenario 1, the traffic volume on I-10 from New Orleans to Slidell, from Jefferson to New Orleans, and from New Orleans to Jefferson was increased by 50%. The traffic volume in other areas of Louisiana was not changed. The runtime of the simulation model was 14 days. Figure and Figure 18 illustrate the aggregate ton-hours and ton-miles for the State resulted during the simulation. Figure 17 and Figure 18 show that, after freight volume increase, the confidence intervals of ton-miles and ton-hours were not overlapping with the base case. This indicates that both measures were significantly increased by the increased transportation demand (shown in Figure 18). The ton-miles were increased from 1,734 million per month to 1,935 million per month, which represents a 11.6% increase; while the ton-hours were raised from 197 million to 220 million per month, which indicates a 11.5% increase.
Along with the increased ton-miles, energy consumption also considerably increased (shown in Figure 20). This indicates that a higher O-D demand leads to higher energy consumption level which in turn indicates a higher degree in dependency on the petroleum products. The amount of pollutant release will finally rise as well. Overall, the increased demand induces a growing number of trucks and railcars in the system and aggravates the load of the entire system.

**Figure 17**

*Ton-hours and ton-miles before and after the demand increase (both in millions)*

**Figure 18**

*Ton-miles before (Tonmiles_base) and after (Tonmiles_id) the demand increase*
The system level mobility became worse that is represented by an increase from 0.1240 hour/required mile to 0.1306 hour/required mile. This change is mainly attributed to higher demand in freight movement for export and import affairs. The mobility only counts for the loaded trucks; however, the returning empty trucks may also contribute to a worse mobility performance in the real world situation.

The measurements for the reliabilities that describe recurring and nonrecurring delays are summarized in Table 9. Recurring delay measures the differences between the ratio of real travel time to the travel distance and the system mobility. This term describes the system level variance of the freight movement performance. The nonrecurring delay measures the deviation from ideal travel time and characterizes the accumulated deviation of freight movement from ideal transportation conditions. Both reliability measures are variances, that means higher values indicate a larger variability and uncertainty.

The measurement of recurring delays decreased by 7.83% and the nonrecurring delays were increased by 9.32% from the base. This result implies the travel time could be considerably affected by the increased traffic volume. The higher transportation volume leads to lower traveling capability and heavier congestion which results in lower recurring delay. Note that
intermodal transportation transloading time, such as transshipment at port and classification and storage at rail yard, are all counted into the travel time. In more realistic cases, lower recurring delay could happen. However, the nonrecurring delay has a different behavior. The declining nonrecurring delay reliability reflects a heavier congestion and worse transportation capability.

Table 9
Reliability before and after demand increase.

<table>
<thead>
<tr>
<th></th>
<th>Base</th>
<th>150% of the Base Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability (recurring delay)</td>
<td>1.3229</td>
<td>1.2193</td>
</tr>
<tr>
<td>Reliability (nonrecurring delay)</td>
<td>19.8342</td>
<td>21.6844</td>
</tr>
</tbody>
</table>

The results in this part indicate that an increased demand could significantly impact total throughput and energy consumption. The larger freight movement leads to a higher variance in transportation time even though the differences are not statistically significant. The results seem to be suggesting that vehicles, especially freight transportation vehicles, travel for a longer time because of congestion caused by demand increase. This implies a need for studying the origin of increased mobility and reliabilities. Considering the nonrecurring reliability is also increased from further traffic demand on the road, the amount of deviation could be even more exaggerated with higher freight movement in the future.

Scenario 2: Disruptions
In this scenario, we study the influence of disruption on the system performance. The disruption will be represented as different types of accidents. The population, vehicle miles traveled (VMT), fatal motor vehicle crashes, motor vehicle crash deaths, and motor vehicle crash death rates per state and crash rates by vehicle miles traveled are listed for 2013 (IIHS-HLDI, 2013/41) in Table 10. Crash Rates by VMT, Licensed drivers and population are listed in Table 11. For a crash to be classified as fatal, at least one person must have perished as a result of the crash.
Table 10

Population, vehicle miles traveled, fatal motor vehicle crashes, motor vehicle crash deaths and motor vehicle crash death rates in Louisiana, 2013

<table>
<thead>
<tr>
<th>Population</th>
<th>Vehicle miles traveled (millions)</th>
<th>Fatal crashes</th>
<th>Deaths</th>
<th>Deaths per 100,000 population</th>
<th>Deaths per 100 million vehicle miles traveled</th>
</tr>
</thead>
<tbody>
<tr>
<td>4,625,470</td>
<td>46,513</td>
<td>651</td>
<td>703</td>
<td>15.2</td>
<td>1.51</td>
</tr>
</tbody>
</table>

Table 11

Crash rates by VMT, licensed drivers and population

<table>
<thead>
<tr>
<th>Year</th>
<th>100 Million Miles Traveled</th>
<th>100,000 Licensed Drivers</th>
<th>100,000 Population</th>
<th>100 Million Miles Traveled</th>
<th>100,000 Licensed Drivers</th>
<th>100,000 Population</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>INJURY CRASH RATES</td>
<td>FATAL CRASH RATES</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>93.5</td>
<td>1,481</td>
<td>938</td>
<td>1.41</td>
<td>22.4</td>
<td>14.2</td>
</tr>
<tr>
<td>2011</td>
<td>93.2</td>
<td>1,494</td>
<td>948</td>
<td>1.35</td>
<td>21.7</td>
<td>13.8</td>
</tr>
<tr>
<td>2012</td>
<td>95.3</td>
<td>1,523</td>
<td>969</td>
<td>1.4</td>
<td>22.3</td>
<td>14.2</td>
</tr>
<tr>
<td>2013</td>
<td>91.2</td>
<td>1,480</td>
<td>942</td>
<td>1.36</td>
<td>22.1</td>
<td>14.1</td>
</tr>
<tr>
<td>2014</td>
<td>92.8</td>
<td>1,522</td>
<td>963</td>
<td>1.37</td>
<td>22.5</td>
<td>14.3</td>
</tr>
<tr>
<td>2015</td>
<td>96.4</td>
<td>1,572</td>
<td>1,000</td>
<td>1.36</td>
<td>22.1</td>
<td>14.1</td>
</tr>
</tbody>
</table>

The traffic deaths has been disaggregated by person type and vehicle type (FindTheData, 2010 [42]) as listed in Table 12 and illustrated in Figure 21. The assumption is that the proportion of the involved vehicles has not been changed drastically in recent years.
Table 12

Traffic deaths, by person type

<table>
<thead>
<tr>
<th>Person Type</th>
<th>Number of Accidents</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver</td>
<td>386</td>
</tr>
<tr>
<td>Passenger</td>
<td>166</td>
</tr>
<tr>
<td>Motorcyclists</td>
<td>71</td>
</tr>
<tr>
<td>Pedestrian</td>
<td>74</td>
</tr>
<tr>
<td>Pedalcyclist</td>
<td>10</td>
</tr>
<tr>
<td>Other or Unknown</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 21

Traffic deaths, by vehicle type

Accident occurrences were simulated on the selected highway segments to study the influence of disruptions on the highway system. The accidents were set to be triggered on average every 2.6 hours based on the statistics. That means between two accidents, no matter whether fatal or
injury only, the travel speed is determined by the volume to capacity ratio. When an accident occurs, travel would be fixed at 30 mph for an injury accident or 10 mph for a fatal crash. The vehicles, including passenger cars and freight trucks, need to wait for clearance on the highway. Only after clearance, could the vehicle speed be recovered to a normal level.

Table 13

Average of I-10 near New Orleans before and after demand increased

<table>
<thead>
<tr>
<th></th>
<th>Average Speed (mph)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>New Orleans to Slidell</td>
</tr>
<tr>
<td>Base O-D</td>
<td>53.11</td>
</tr>
<tr>
<td>150% O-D</td>
<td>50.79</td>
</tr>
</tbody>
</table>

The volume to capacity ratio of the I-10 segments is plotted near New Orleans in Figure 22. Notably, this ratio was affected in all three segments by increased transportation demand. The congestion seems to be increasingly severe over time. All ratios were greater than 0.6 which indicates these segments were heavily used. With increased traveling volume in the highway system, the volume to capacity ratio raised by 4-10% on all of these segments.

Figure 22
Volume-to-capacity ratio on segments from New Orleans to Slidell (blue), from Jefferson to New Orleans (red), and from New Orleans to Jefferson (green) over time

Among all these segments, the segment from Jefferson to New Orleans was the busiest one. The volume-capacity (v/c) ratio was at over 1 even in current state. The variation in the ratio increases over time. Keep in mind that the accident rate was also increased due to increased demand because as more heavy or light duty trucks are on the highway they may cause further potential accidents and additional congestion. It contributes to the increasing congestion that was shown in v/c ratio of these segments. Given the current 2.6 hours average time between accidents with 2% of them are fatal crashes this will cause severe congestion for a certain amount of time (which is assumed to follow an exponentially distribution with an average time of 1 hour). During this period, all traffics are assumed to be travelling at most 30 miles per hour with some as low as 10 miles per hour. It can be foreseen that a decrease in accident rate could largely contribute to an increased throughput of I-10, or even to the entire Louisiana State Transportation System.

Scenario 3: Improved Highway Safety

The analysis in the previous scenario shows a large impact of the accident rate on the highway freight transportation system. Scenario 3 shows the effects of a potential highway accident rate decrease. A 50% decrease is assumed in the New Orleans area and simulate the impact on the performance of the total Louisiana transportation system.

For two different demand assumptions, with the same amount of demand as in the basis scenario (Scenario 1) and also with 150% of the demand of the basic scenario, the total fatality rate was decreased by 50%. Table 14 lists and compares the volume to capacity ratio for segments from New Orleans to Slidell, from Jefferson to New Orleans, and from New Orleans to Jefferson correspondingly. From the table, we found that from basic scenario (Scenario 1), the accident rate reduction contributes to a lower level of congestion on segments from New Orleans to Slidell and from Jefferson to New Orleans. This phenomenon is consistent with what we found from increased O-D (as compared between Scenario 1 and Scenario 3). A greater number of freight carriers could get through I-10 near New Orleans to its waterway port and rail station or from the waterway port and rail station to other places. This proves the crucial role of I-10 in the freight movement within South Louisiana and adjacent areas.
Table 14

Comparison of volume to capacity ratio at different accident rates and transportation demands

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Accident Rate</th>
<th>Demand Level</th>
<th>$V/C$ from New Orleans to Slidell</th>
<th>$V/C$ from Jefferson to New Orleans</th>
<th>$V/C$ on from New Orleans to Jefferson</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>100% of Base</td>
<td>100% of Base</td>
<td>0.82</td>
<td>1.03</td>
<td>0.68</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>50% of Base</td>
<td>100% of Base</td>
<td>0.75</td>
<td>0.95</td>
<td>0.64</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>100% of Base</td>
<td>150% of Base</td>
<td>0.88</td>
<td>1.14</td>
<td>0.71</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>50% of Base</td>
<td>150% of Base</td>
<td>0.77</td>
<td>0.99</td>
<td>0.67</td>
</tr>
</tbody>
</table>

A higher traffic demand certainly leads to heavier usage of the highway system. However, the volume to capacity ratios were unchanged on the highway from New Orleans to both Slidell and Jefferson with reduced accident rate, whereas it is slightly smaller on the highway from Jefferson to New Orleans with a reduced accident rate. Note that this segment is used heavily to undertake export freight movements. Different usage of the highway on various directions leads to differences in the impact of reduced accidents. The highway from Jefferson to New Orleans was heavily used for export freight movements and the congestion level is the highest among all these three segments (See Table 14). In this perspective, the reduced accident rate affects the most on this segment than the other two.

The travelling speed on these segments is compared in Figure 23. Note that the Interstate 10 is not symmetrically built. The movement from east to west is faster than that from west to east because there are 4 lanes to west but 3 lanes to east. Furthermore, the free flow speed is 70 mph to west but 60 to east. That leads to lower speed and heavier congestion on one direction but less delay on the other.

With reduced accident rate the freight in these regions moved faster and smoother. Compared to Scenario 3, the freight movement is 7 miles faster per hour in scenario 4 which could facilitate the increased export freight transportation. The decreased accident rates contributed to lower congestions. Even with increased transportation demand, average traveling speed was still increased from 32.73 mph to 39.22 mph from Jefferson to New Orleans. That indicates that a
safer driving environment could enhance the traveling speed which in turn will contribute to overall system performance improvement. Moreover, the increased freight movement demand near the New Orleans port could be compensated for by a reduced accident rate in the future.

![Figure 23](image)

Comparison of average speed on highway segments
CONCLUSIONS

With increased emphasis on intermodal freight transportation, the issues of how to evaluate an existing intermodal transportation system and how to evaluate the changes in the system have been receiving intensive attention. Because of the high complexity and high variability involved in intermodal transportation, simulation tools need to be applied. We built a system-level intermodal simulation model for Louisiana that includes highways, railways, and waterways and also incorporates the connections between the different modes.

The research has finished all tasks of the project:

Summarized the existing intermodal freight transportation simulation results.

1. Developed a simulation framework based on the ARENA simulation software.
2. Developed the simulation model and calculated the mobility, reliability, safety, and environmental performance measures for the existing intermodal freight system of Louisiana.
3. Validated the simulation model based on traffic counters at certain locations from DOTD, energy data, safety dataset.
4. Analyzed three different scenarios. In Scenario 1 the potential effects of the Panama Canal expansion have been calculated, in Scenario 2, the effects of traffic disruptions while in Scenario 3, the effects of a potential improvement in highway safety have been calculated.

In summary, this project first developed a framework for an intermodal freight network simulation to evaluate the overall performance of the multimodal freight transportation in Louisiana. A simulation model was built following the framework, including all major network components, the connections of the components. The model considers the embedded relationships in each component, the variability in the model, and the performance metrics. The simulation model incorporated the demand data from Freight Analysis Framework Version 3 and the Intermodal Surface Network data and according to the derived dataset, capability speed was assigned to the major connections in the transportation system. The simulation model was validated based on traffic counters at certain locations from DOTD, energy data, and safety dataset. The simulation model incorporated the calculation of the system-level performance metrics for intermodal freight networks. The model has the capability of allowing users to change settings, input data, and define scenarios.

Based on the simulation model, a system performance and scenario analysis was conducted in order to provide further insights and suggestion for future states. In 2016, an ongoing project will
double the capacity of the Panama Canal by creating a new lane of traffic and allowing more and larger ships to transit. At that time, there will be increasing volume of freight movements. The traffic volume in the New Orleans area was increased by 50% and the impact of increased demand on the Louisiana transportation system was studied. It was found that a growing degree of highway congestion occurred due to higher transportation demand. Three segments on I-10 were chosen to illustrate the differences. According to the simulation result, nonrecurring delay was increased due to higher transportation volume, and the raised volume to capacity implied a heavier use on the I-10. With the goal of generating managerial insights, the impact of disruptions was studied based on that result. The accident rate was incorporated in line with the increased transportation volume. The usage in the segment from New Orleans to Slidell and the segment from Jefferson to New Orleans showed notable increase. Both of these two segments connect New Orleans port with other cities. I-10 was heavily used due to import and export affairs. I-10 connects the New Orleans port to other southeast states such as Mississippi and Alabama State through Slidell. A larger portion of the increased demand was allocated to import to southeast states rather than other freight movements. Equally importantly, export from Texas, Arkansas, and Mississippi also caused a growing magnitude of congestion on I-10 near the New Orleans port area.

An additional what-if analysis was built based on the concluding remarks from earlier sections. With the knowledge that segments from Jefferson to New Orleans and from New Orleans to Slidell primarily contributed to the import and export freight movements. The simulation results show that reducing the accident rate could notably improve the system performance. The volume to capacity ratio reduced by 6-13% in all these segments with an increased demand. The freight traveled smoother in these regions and the decreased accident rate should be attributable to the relieved congestions. The freight movement consumes 1 million fewer hours. With increased transportation demand, average traveling speed increased from 32.73 mph to 39.22 mph. That indicates a safer driving environment could enhance the traveling speed, which in turn will contribute to overall system performance improvement. Moreover, the increased freight movement demand near the New Orleans port could be met by a reduced accident rate in the future.
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