National Center for Intermodal Transportation for Economic Competitiveness

NCITEC

Project 2012 — 27

Integrated Intermodal Transportation Corridors for Economically Viable and Safe Global Supply Chain

Final Report: NCITEC Project 2012 - 27

The University of Mississippi

UM Principal Investigator: **Dr. Waheed Uddin,** Director CAIT
DU Principal Investigator: **Dr. Patrick Sherry,** Director NCIT
CU Principal Investigator: **Dr. Burak Eksioglu,** UG Advisor

REPORT: UM-CAIT/2015-02

July 2015, Revised August 2016

Center for Advanced Infrastructure Technology
The University of Mississippi
University, MS 38677-1848, USA
Voice: 662-915-5363 Fax: 662-915-5523
http://www.olemiss.edu/projects/cait/
cait@olemiss.edu cvuddin@gmail.com

U.S. Department of Transportation
Research and Innovative Technology Administration
Federal Grant or Other Identifying Number Assigned by Agency: DTRT12-G-UTC14

INTEGRATED INTERMODAL TRANSPORTATION CORRIDORS FOR ECONOMICALLY VIABLE AND SAFE GLOBAL SUPPLY CHAIN

Final Report: NCITEC Project 2012 - 27

ABSTRACT

Transportation infrastructure networks are essential to sustain our economy, society and quality of life. Freight transportation of consumer goods and commercial/industrial products is critical for sustainable and efficient supply chain. The primary objectives of this project are to identify major transportation corridors involving inland river ports, highway network and rail infrastructure; and to evaluate the revenue/funding aspects, economic viability, safety, and disaster resiliency of integrating selected segments of the candidate corridors. The scope of this project is limited to NAFTA trading partner countries of the United States, Canada, and Mexico.

The project investigated the aspects of multimodal freight related to congestion, intermodal integration, and impacts of fuel savings and carbon dioxide emissions. Key results of the study include:

- This project developed geospatial maps, optimization models, benefit/cost results of proposed modal integration simulation studies, life cycle economic model results of economic and environmental impacts, and intermodal infrastructure bank proposal.
- Theoretical consideration and associated field studies improved understanding of transportation professionals for tire/pavement interaction during braking and crash incidents. Guidelines are recommended for implementation to improve road safety.
- Computer simulations of commodity flow through selected port(s) and freight corridor(s) with economic and sustainability analysis are used to show the importance of the intermodal integration approach for enhancing the economic competitiveness, safety, security and disaster resilience of freight transport.
- The intermodal freight corridor case studies are used to develop a “best practice guide” for consideration by government transportation agencies, private transport operators, and other global supply chain stakeholders.
- The developed approach of freight corridor integration studies demonstrate the assessment of economic and other societal benefits, which include reduction of wastage of hours of travel time and traffic congestion, cost avoidance of fuel wastage on highway corridors, and decrease in transportation related emissions of carbon dioxide and other harmful pollutants.

It is recommended that the developed approach of multimodal freight corridor studies be applied by transportation agencies to assess economic and other societal benefits, which include reduction in highway congestion and decrease in transportation related harmful emissions.

ACKNOWLEDGEMENTS

This research project was funded by U.S. Department of Transportation / Research and Innovative Technology Administration through the National Center for Intermodal Transportation for Economic Competitiveness (NCITEC) at Mississippi State University. The research for NCITEC Project 2012-27 was conducted at the University of Mississippi Center for Advanced Infrastructure Technology (CAIT) under the overall direction and supervision of Dr. Waheed Uddin, the Principal Investigator (PI) of. Thanks are due to the project collaborators, Dr. Jody Holland of the University of Mississippi Department of Public Policy Leadership, Dr. Victor Torres-Verdin (Transportation Consultant in Mexico City), and Dr. Robert Smith (Road Pavement/Tire Friction Technology Consultant in Washington State). The advice on barge traffic flow and data for Mississippi River freight provided by Dr. Ned Mitchell of ERDC Hydraulics Laboratory is greatly appreciated.

Close interaction was maintained with the Mississippi Department of Transportation (MDOT) who provided geospatial databases of transportation network, highway bridges and rivers for the State of Mississippi. Thanks are due to the MDOT engineers who lectured on traffic engineering, planning and highway design topics to undergraduate and graduate students at the University of Mississippi.

This report is authored by Dr. Waheed Uddin with support from project partners Dr. Patrick Sherry at University of Denver and Dr. Burak Eksioglu of Clemson University. Thanks are also due to the M.S. students Seth Cobb and Muhammad Ahlan, doctoral students Quang Nguyen and Zul Fahmi Mohamed Jaafar, as well as Madeline Costelli, David May, Gergo Arany, Haley Sims, Tucker Stafford, Elizabeth Holt and other CAIT research assistants at the University of Mississippi for their contributions to the project.

DISCLAIMER

The University of Mississippi, Mississippi State University and the U.S. Department of Transportation do not endorse service providers, products, or manufacturers. Trade names or software or manufacturer’s names appear herein solely because they are considered essential to the purpose of this report.

TABLE OF CONTENTS

1. BACKGROUND

1.1 Introduction

Supply Chain Infrastructure Research Needs

This project addresses the NCITEC theme of efficient, safe, secure, and sustainable national intermodal transportation network that can be made resilient to disasters. In today's "global economy" the global supply chain interconnects each country's transportation hubs through import/export demand of agriculture commodities, manufacturing goods, and fossil fuels. Ships, air cargo, and land transport are used as freight carriers for most import and export goods. Bulk ships and supertankers are used to transport most of the agriculture products, raw industrial materials, and fossil fuel supplies, which include coal, crude oil, and liquefied gas. The global supply chain can be seriously disrupted by natural disasters. For example the earthquake and tsunami disaster that stuck Japan in March 2011 even had an effect on car manufacturing facilities in the U.S. that lasted for several months. Similarly, the 2011 mega flood of central Thailand (Infra 2011) interrupted many industrial estates around Bangkok resulting in supply shortages of clothes, electronics, and several other manufactured items to Europe and North America. This problem of disruption in the supply chain can seriously hurt local economies which depend on distribution through surface transportation modes; even if the goods are brought in from abroad as with the Federal Express aviation cargo hub at Memphis International Airport. Similarly, other global supply chain and inventory management system stakeholders depend on a smooth seamless flow of freight through interconnecting shipping ports, airports, rails, and roads.

As reported at National Press club on July 17, 2009 and discussed in a report of the National Academies that U.S. companies collectively spend a trillion dollars a year on freight logistics (NCFRP 2012a). This is nearly 10% of the nation's gross domestic product (GDP). The NCFRP report states that considering that about 80% of the population works and lives in cities and urban areas, 65% of goods originate or terminate in cities as per US DOT's statistics based on a recent Commodity Flow Survey (CFS). About 4.5 million people or 3% of total employed work force in 2008 worked in transportation and warehouse industries. The CFS survey indicates that, on average, 42 tons of freight worth $39,000 was delivered per person in the U.S. in 2007 (NCFRP 2012b). These statistics are indicative of the importance of the lifeline supply chain to support our society and everyday life. Traffic congestion on highways significantly impacts air quality degradation, greenhouse gas emissions, and global warming. Transportation contributed 31% of energy related greenhouse gas emissions in 2013 in the U.S. (EPA 2013).

The four transportation modes (shipping port, aviation, rail, and highway) are owned and operated by different entities in the U.S. For example, shipping channels are mostly maintained by the US Army Corps of Engineers/ERDC. Inland waterways like Mississippi River need annual funding for dredging operations and maintaining locks and dams for bulk barge traffic. However, ports are owned by local government bodies. Ports are generally revenue producing operations unlike highway networks. Despite being publicly owned ports are largely operated by private companies who lease space from municipalities and port authorities. In addition, the on doc labor is provided most frequently by longshoremen of the ILWU. Ports needs funding to upgrade for intermodal infrastructure and modern container ships designed for 8,000 or more Twenty Foot Equivalent Unit (TEU) containers.

Highway infrastructure assets (pavement, bridge, right of way) are owned by states/federal government with the bulk of funding support from Highway Trust Fund's federal appropriations through US DOT. The truck freight operation is wholly owned and operated by private sector companies. Trucks pay only the nominal annual registration license fee to the US DOT. On the other hand, rail infrastructure and rail vehicle stock as well as rail freight operation have historically been wholly owned and operated by private sector companies in the U.S. unlike most other countries where these are owned by the government.

According to the Association of American Railroads (AAR 2011): "America's freight railroads move 43 percent of intercity freight traffic -- more than any other mode of freight transportation -- delivering for every sector of the U.S. economy. Freight rail, which moves 1/3 of U.S. exports to ports, will be even more important to our future as the nation strives to double exports by 2015." All these modal networks operate within their own policy frameworks and profit motivations with little or no real operational integration. In some cases some modes on long haul routes like highway freight trucks compete with freight rail service.

Financing for preserving and upgrading intermodal infrastructure for both freight and rail is being handled very differently. Unlike freight trucks, whose infrastructure is supported by state and federal tax dollars, the freight rail industry has to manage their aging infrastructure by investing capital from their own profits without public involvement. This funding shortfall is a big hurdle in modernizing rail infrastructure, such as hardening of rail bridges for enhancing flood disaster resilience and rail electrification with almost zero emissions. Transport infrastructure funding crisis is evident on all levels and for all transportation modes.

Goals

Major goals of this project include development of geospatial visualization maps of freight corridors and commodity flow, improvement of supply chain delivery efficiency and cost-effectiveness by integrating four transportation modes (shipping port, aviation, rail, and highway) being operated by different entities in the U.S., exploration of innovative financing mechanisms for preserving and upgrading intermodal infrastructure, and safer operations and disaster resiliency of the global supply chain infrastructure.

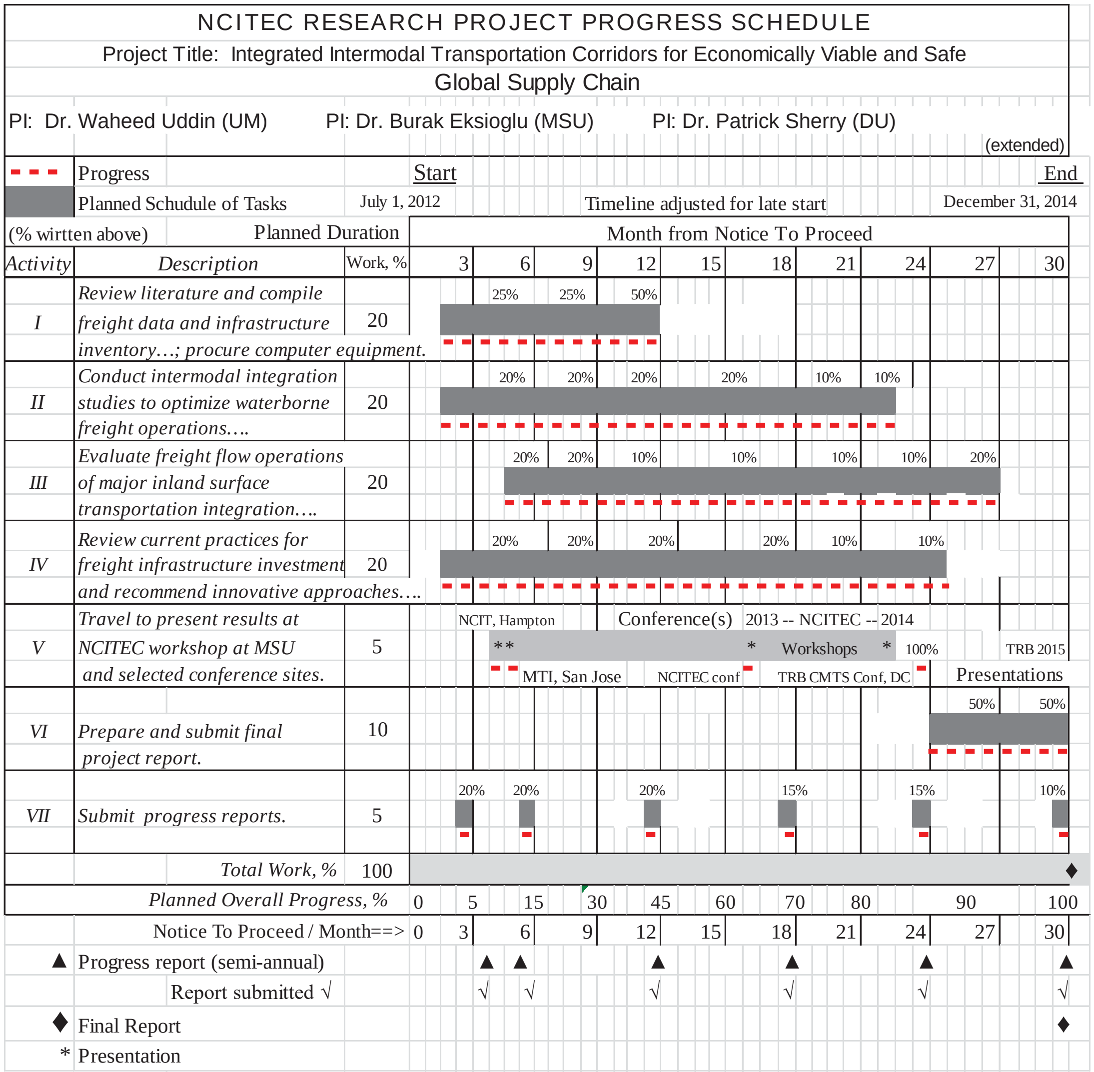
The economic competitiveness, safety, security and disaster resilience of freight transport and supply chain can be significantly enhanced if owners, operators, and users of all transportation modes understand the importance of operational integration of these modes.

Objectives

The overall objective of this applied research project is to identify major transportation corridors involving shipping ports (marine and inland river system) highway network and rail infrastructure and to evaluate the economic viability, safety, disaster resiliency, and revenue and funding aspects of integrating selected segments of the candidate corridors.

Project Timeline

The final project period was from July 1, 2012 to December 31, 2014. Figure 1 shows the updated planned activities and time line, as well as actual completion dates. The timeline and project activity schedule were updated from the original termination date of December 31, 2013 in view of one year extension to December 31, 2014. There were no significant changes in the research approach described in the approved plan.



NCITEC RESEARCH PROJECT PROGRESS SCHEDULE

Project Title: Integrated Intermodal Transportation Corridors for Economically Viable and Safe Global Supply Chain

PI: Dr. Waheed Uddin (UM) PI: Dr. Burak Eksioglu (MSU) PI: Dr. Patrick Sherry (DU)

Activity	Description	Work, %
I	Review literature and compile freight data and infrastructure inventory…; procure computer equipment.	20
II	Conduct intermodal integration studies to optimize waterborne freight operations….	20
III	Evaluate freight flow operations of major inland surface transportation integration….	20
IV	Review current practices for freight infrastructure investment and recommend innovative approaches….	20
V	Travel to present results at NCITEC workshop at MSU and selected conference sites.	5
VI	Prepare and submit final project report.	10
VII	Submit progress reports.	5
	Total Work, %	100

Figure 1. Research project tasks and timeline

Research Team and Collaborators

Key Investigators and Roles:

Dr. Waheed Uddin (PI), University of Mississippi (UM) cvuddin@olemiss.edu Professor of Civil Engineering and Director, Center for Advanced Infrastructure Technology (CAIT)

Dr. Patrick Sherry (PI), University of Denver psherry@du.edu
Executive Director of National Center for Intermodal Transportation (NCIT)
Program Director, Department of Counseling Psychology,

Dr. Burak Eksioglu (PI), Associate Professor, Department of Industrial Engineering, Clemson University, South Carolina (Formerly, Associate Professor, Department of Industrial & Systems Engineering and NCITEC Director, Mississippi State University) burak@clemson.edu

Collaborator: Dr. Kenneth Ned Mitchell, ERDC Hydraulics lab, Vicksburg, Mississippi
Collaborator: Mr. Karl Y Petrow, Maritime Information Systems, Inc., Warren, Rhode Island. This company operates a large scale Automatic Information System (AIS) network to track vessel movements in all Navigable North American Waterways.

Other UM Researchers

Other researchers of UM CAIT team include:
Dr. Jody Holland (UM Public Policy Department)
Dr. Robert Smith (consultant for roadway friction/pavement interaction), 2013 (completed)
Dr. Víctor Torres Verdín, a transportation planning expert from Mexico City, for traffic flow data related to The North American Free Trade Agreement (NAFTA) & connected corridors in Mexico, 2013
Support from the following CAIT/Civil Engineering students, 2012-2014: Five PhD students, three M.S. students, 11 UG students

Other collaborators or contacts been involved

- John Robert Smith: Current president and CEO of *Reconnecting America*, Former mayor of Meridian, MS. www.reconnectingamerica.org
- As Intergraph Registered Research Lab, CAIT Remote Sensing and Transportation Modeling Laboratories received geospatial industry support for education and training of students in geographical information system (GIS) applications for the project research. This Intergraph software grant is a testimony of industry support to the UM researchers and a cooperative feature of this project. Since January 2014 the statewide license has been provided by MARIS through Mississippi Institution of Higher Learning (IHL).
- Dr. Burak Eksioglu, PI, Clemson (formerly with MSU) collaborated with other stakeholders.
- Dr. Patrick Sherry, DU PI, works/collaborates with freight rail and truck fleet operators. He contacted selected logistics organizations for getting rail corridor infrastructure data and stakeholder survey feedback.

- Dr. Sherry and Dr. Uddin interacted with the following organizations during the NCIT & MTI workshop. The NCIT & MTI workshop was co-organized by Dr. Patrick Sherry on Oct 25, 2012 at San Jose University campus.
    - Mineta Transportation Institute (MTI), San Jose State University, NCIT & MTI workshop
    - BNSF Railways, California (Mr. Juan Acosta, BNSF Government Affairs), NCIT & MTI workshop
    - Port of Oakland, California (Mr. Richard Sinkoff, Director, Env. Planning), NCIT & MTI workshop
    - San Mateo County Transit District, California (Mr. Keith Ratner), NCIT & MTI workshop
    - Reconnecting America, California (Mr. Jeff Wood, Chief Cartographer), NCIT & MTI workshop
    - Association of American Railroads

- Dr. Uddin networked with marine transportation stakeholders at June 2014 TRB-CMTS conference (USACE, U.S. Coast guard, port authorities, container port and logistics service providers, intermodal operators, consultants).

- International Cybernetics Corporation, Tampa, Florida
  (UM-CAIT Consultant Dr. Robert Smith facilitated this collaboration for field testing to evaluate pavement/tire interaction.)

- Dr. Uddin is an appointed member of Board of Directors of the Mississippi Transportation Institute (MTI) since March 2014 and the Gulf Region Intelligent Transportation Society from 2009 to 2013. These are important state transportation organizations to benefit from the key results of the NCITEC projects.

Research Methodology

The CAIT project research team (CAIT 2014) implemented the following key steps of the research methodology:

1. Create geospatial databases and spatial maps of transportation infrastructure networks for U.S. and other NAFTA partners, Mexico and Canada. Select study sites in Mississippi.
2. Conduct vehicle tire-pavement friction tests to evaluate variable loading-based approach of a friction index that is more rational to assess road safety than the traditional coefficient of friction and skid number method.
3. Review current practices for freight infrastructure investment and recommend innovative approaches of revenue generation for creating intermodal infrastructure investment bank proposal for funding agencies and transport infrastructure stakeholders.
4. Identify major transportation corridors involving shipping ports (marine and inland river system) highway network and rail infrastructure.

5. Analyze commodity flow data analysis for interstate commerce and NAFTA trade corridors and to evaluate the economic viability aspects of integrating selected segments of the candidate corridors.
6. Establish intermodal freight corridor case studies and use the results of reductions in shipping costs and Carbon Dioxide (CO_2) emissions to develop "best practice guide" examples for consideration by government transportation agencies, private transport operators, and all other stakeholders

The economic competitiveness, safety, security and disaster resilience of freight transport can be significantly enhanced if owners, operators, and users of all transportation modes understand the importance of operational integration of these modes. Similarly, integration of passenger services can reduce wastage of millions of hours of travel time of single occupancy vehicle commuters that will result in cost avoidance of billions of gallons of fuel wastage on congested highway corridors and reduce transportation related emissions of and other harmful pollutants.

1.2 Project Accomplishments

Summary of Research Accomplished

Key outcomes and other achievements are summarized, as follow

1. This project developed spatial maps using GIS software and imagery analysis software, optimization models, benefit/cost results of proposed modal integration simulation studies, life cycle economic model results of economic and environmental impacts, and intermodal infrastructure bank proposal.
2. Theoretical consideration and associated field studies improved understanding of transportation professionals for tire/pavement interaction during braking and crash incidents. Guidelines are recommended for implementation to improve road safety.
3. Computer simulations of selected port(s) and freight corridor(s) with economic and sustainability analysis are used to show the importance of the intermodal integration approach for enhancing the economic competitiveness, safety, security and disaster resilience of freight transport.
4. The intermodal freight corridor case studies are analyzed for highway-rail corridors from Colorado to California and a selected NAFTA corridor. A case study for intermodal integration of highway and Mississippi River waterway is also conducted. These studies are used to develop "best practice guide" examples for consideration by government transportation agencies, private transport operators, and other global supply chain stakeholders.
5. The developed approach of freight corridor studies demonstrate the assessment of other societal benefits, which include reduction of wastage of hours of travel time by reducing traffic congestion, cost avoidance of fuel wastage on congested highway corridors, and a

decrease in transportation related emissions of carbon dioxide and other harmful pollutants.

6. Training of undergraduate (UG) and graduate students in transportation network analysis and development of geospatial workforce are additional benefits.

The project results have been presented at regional and national meetings and published, as summarized in the following section, and disseminated through social media.

Education and Training of Workforce Development

All graduate students and several UG students took Dr. Uddin's "Geospatial Course" in Spring and Fall 2013, May Intersemester 2014 and 2015, and Spring 2015. Three PhD students, two MS graduate students, and several UG students working on the NCITEC projects took a "highway pavements" course taught by Dr. Uddin during Fall 2014. They were taught about transportation infrastructure and life cycle analysis for asset management. One UG senior student worker pursued his M.S. degree under Dr. Uddin's supervision at the University of Mississippi. Project staff is using the computer stations and backup equipment installed in the CAIT Transportation Modeling and Visualization Lab.

Dr. Uddin directed the assigned graduate MS students for data collection and geospatial mapping of freight corridors (highways, Mississippi River, and freight rail). New MS student (previously senior UG research assistant) continued working on this project creating geospatial maps and geospatial analysis of intermodal integration benefits value engineering tools. Two more PhD students, supported by their government scholarship, also worked partially on the project for the Mexico side of NAFTA and the Canada side of NAFTA. Total 5 PhD students, 3 M.S. students, and 14 UG students were supported and trained on the project.

1.3 Results Dissemination and Outreach

Presentations to External Organizations

The PI and co-PI presented the project highlights and key results at professional meetings and other on-site presentations:

January 29-31, 2015, Denver, Colorado: Dr. Sherry interacted with the rail stakeholders who are involved in his center's advisory panel. He will be soliciting stakeholder survey feedback at the OPERATION STIMULUS 2015 conference on January 29-31, 2015, organized by Denver Transportation Club, Colorado.

January 13, 2015, Washington DC: Dr. Sherry invited rail industry executives at the 2015 TRB annual meeting exhibit hall on January 13, 2015 to share the project results of rail-highway integration. Dr. Uddin presented the background on exhaustive commodity flow data analysis and key findings of the Colorado-California corridors, and benefits of just diverting 30% of freight annually by intermodal rail line. The results showed huge savings by freight rail shipping by reduction in overall travel time, freight shipping cost, and significantly lower CO_2 emissions. Positive feedback was provided by the stakeholders and an implementation plan will be pursued by Dr. Sherry for Denver region.

January 10-14, 2015, TRB 94th Annual Meeting: Dr. Uddin presented research results of NCITEC 2012-25 project on numerical modeling and simulation of extreme flood inundation to assess vulnerability of transportation infrastructure assets (Durmus et al. 2015, Uddin and Altinakar 2015).

October 29-30, 2014: Acey Roberts, Mississippi DOT ITS Engineer and GRITS President, lectured both days about the video panel wall installed in CAIT Laboratory in collaboration with the MDOT. Visiting attendees of the winter workshop of the Gulf Region Intelligent Transportation Society toured the CAIT Transportation Lab on October 30. The workshop was held at the University of Mississippi Campus in Oxford, Oct 29-30, 2014. Dr. Uddin provided a brief overview of the Lab facilities, the NCITEC projects, and history of the Lab's evolution in cooperation with the Mississippi DOT Traffic Engineering Division as a part of the establishment of a model ITS Lab.

October 24-25, 2014: Dr. Uddin's teaching and research profile was compiled and presented at the annual banquet on October 24th in Austin, Texas to honor 2014 inductees of the University of Texas CAEE Academy of Distinguished Alumni where he received the award. On October 25th at the Academy's annual meeting on the Austin campus Dr. Uddin briefed the CAEE faculty, fellow attendees, and former professors about his journey of education, teaching, research, service, and current research projects.

October 21, 2014: Dr. Uddin attended the annual board meeting as a 2014 appointed member and the conference of the Mississippi Transportation Institute (MTI), in Convention Center, Jackson, Mississippi. Dr. Uddin briefly met with State Senator and Representative who were the workshop speakers, the Mississippi DOT Executive Director, as well as, Chief Engineer, Bridge Engineer, Aviation Engineer, and Research Division engineers.

October 3, 2014: Dr. Lucy P. Priddy visited the Lab. She is Research Civil Engineer with the ERDC Airfields and Pavements Branch in Vicksburg, Mississippi. After welcome remarks by Dr. Uddin, Dr. Priddy reflected on her experience during her University of Mississippi years as one of the first UG RAs who worked on CAIT research projects during 1999-2002.

September 14-17, 2014: Dr. Uddin attended the ITS3C regional conference and presented an overview of NCITEC projects and Gulf Coast rail study results. The conference was organized by the Gulf Region Intelligent Transportation Society (GRITS), the Intelligent Transportation Society of Florida (ITSFL) and the Intelligent Transportation Society of Georgia (ITSGA). The joint conference was held September 14-17, 2014 at the Arthur R. Outlaw Convention Center in Mobile, Alabama.

December 12, 2013: After an international conference in São Paulo, Dr. Uddin visited Brazil's Dutra Concession Highway from Rio de Janeiro to São Paulo, Project Office. (This highway passes through a major river floodplain and a portion of the highway was washed away during the flood and landslide recently. Dr. Uddin made a presentation in collaboration with Dr. Rita Fortes to the highway concession operator staff on the approach of geospatial analysis and flood simulations being pursued in this NCITEC project to protect transport infrastructure from flood disasters.)

October 28, 2013: Visiting EITs from the Mississippi DOT, Ms. Jessica Headrick (Planning Division) and Ms. Catherine Colby Willis (Roadway Design Division) were presented project overview and on-going planimetrics examples of Sardis site. The visit was held at CAIT Transportation Modeling & Visualization Lab in UM Jackson Center. Both EITs worked with CAIT on geospatial and airport laser survey projects before graduating from the University of Mississippi.

Dr. Uddin presented a project overview and examples of on-going work to the following international visiting university delegations during their scheduled visits to the CAIT Transportation Modeling & Visualization Lab in UM Jackson Ave Center (JAC):

February 28, 2013: Project presentation to visiting Fulbright Fellow Dr. Raza Bhatti from St. Louis, Missouri. Dr. Bhatti was interested in UM floodplain modeling capability and project scope because he was involved in biodiversity conservation program and voluntary aid effort in Sukkur-Khairpur area. This area near Sukkur Barrage over Indus River (the main flood breach site) was devastated during the 2010 superflood of Pakistan.

November 16, 2012: Visiting faculty of Mackenzie University (São Paulo, Brazil), Transportation Engineering Professors João Merighi and Rita Fortes, at CAIT Transportation Modeling Lab, Oxford, Mississippi. (Both visiting professors were Dr. Uddin's guests from Mackenzie University, São Paulo, Brazil, and our universities have a long standing cooperative agreement.)

Collaboration

The PI collaborated with the following organizations, who provided support to the project team:

- Intergraph for continuing academic license of GeoMedia Pro at no cost to the University of Mississippi for use on CAIT projects (worth $118,000 per year).
- As Intergraph Registered Research Lab, CAIT Remote Sensing and Geospatial Analysis Laboratory and CAIT Transportation Modeling and Visualization Laboratory is receiving geospatial industry support for education and training of students in GIS applications through the project research tasks.

  This Intergraph software grant is a cooperative feature of this project. Since January 2014 the statewide license has been provided by MARIS. This software and ArcGIS software, provided by Mississippi Mineral Resource Institute, were used to create planimetrics of roads, bridges, and buildings from high resolution aerial imagery.

Dr. Uddin interacted with Dr. Kristen Swain of the UM's Journalism Department. Her Students in the Journalism department at the University of Mississippi often contact Dr. Uddin for their video projects on sustainability related topics for the George Washington University's Planet Forward web site every year. Dr. Uddin discussed with potential Journalism students the findings and significance of their project so that sustainable intermodal transportation integration topics can become one of their projects. The following example of Planet Forward video on the use of waste glass for sustainable road applications was produced by a UM journalism student in May 2013. http://infrastructureglobal.com/sustainable-infrastructure-by-recycling-waste-glass-to-enhance-road-safety-and-reduce-emissions-guest-post-22/
Earlier another student's YouTube video on life cycle analysis for sustainability projects was posted on the *Planet Forward* web site. http://planetforward.org/idea/life-cycle-analysis-of-sustainable-technologies/
A YouTube video by Mason Herman (Public Policy/Journalism UG student), "Dr. Uddin Interview on Transportation and Air Quality Mitigation," April 30, 2014. https://youtu.be/wCJQiXaV3gc

The following organizations were cooperative features for this project:

1) Mississippi Department of Transportation (MDOT): MDOT Roadway Design Division has been contacted for access to aerial imagery.
2) MDOT Planning Division through contact with Dr. Uddin's former student and EIT for accessing overlapping aerial imagery scenes of the study sites.
3) MDOT Transportation Information Director (Mike Cresap) and MDOT Director of Structures -State Bridge Engineer (Justin Walker) have been especially helpful to provide drawings and photos for the I-55/US-51 highway bridges in northern Mississippi and updated geospatial database of all state maintained highways and bridges of Mississippi. These were very important and useful contributions to this project.
5) US Army ERDC Hydraulics Lab, Vicksburg, Mississippi (Dr. Kenneth Ned Mitchell)

Workshop and Symposium

December 5, 2014 Workshop: "Extreme Flood Inundation Mapping and Risk Modeling of Transportation Infrastructure Assets"

The workshop was opened to all by email invitations and CAIT web page posting. It was held in NCCHE Conference Room, Brevard 3rd Floor, University of Mississippi Oxford campus. Presentations were made by Dr. Uddin, Dr. Altinakar (jointly with NCCHE researchers Marcus McGrath and Vijay Ramalingam), Alper Durmus, Quang Nguyen, with closing remarks by Dr. Altinakar.

February 7, 2013 Symposium: "NCITEC-Symposium at the University of Mississippi (UM)" This UM symposium featured welcome by UM administrators, NCITEC project overview by the NCITEC Director, announcement of new NCITEC/DOT grant opportunity to all UM faculty/researchers, and presentations by all current NCITEC project investigators about their research project accomplishments.

1.4 Impacts on The Principal Discipline(s), Research Infrastructure, and Workforce

The project improved computing facilities, geospatial laboratory, geospatial software, and transportation corridor/traffic flow simulation capabilities.

- Enhancement of CAIT Transportation Modeling and Visualization Lab, shown in Figure 2(a), at off-campus location of Ole Miss Jackson Center was a major impact of the project. (An additional eight computer workstations and visualization equipment were procured using project funds and installed in CAIT Transportation Modeling & Visualization Laboratory in UM Jackson Center after approval by the DOT RITA sponsors.) These new computers and 6 old computers from CE Graphics Lab have been functioning fully since Fall 2013 after installation of geospatial software and other programs.
- The Lab is being used mostly to conduct research, offer geospatial UG and graduate courses, and train students in geospatial visualization and mapping technologies. New 2014 versions of GeoMediaPro geospatial software packs were installed on all CAIT Lab computers after creating full backup up of all project files and folders by project staff. The Lab is being used mostly to conduct research, offer geospatial UG/graduate courses, and train students in geospatial visualization and mapping technologies. The CAIT lab expanded recently with new high performance computer equipment, new computer furniture, large video monitor for presentations, and seminar/meeting tables, chairs, and accessories. The geospatial course has been taught in this facility since 2013 and most of the NCITEC project research work is conducted in this lab.
- The UM's CAIT Transportation Modeling & Visualization Lab also houses a model ITS Laboratory, as seen in Figure 2(b). The Mississippi DOT's Intelligent Transportation System (ITS) section has been collaborating for many years with the University of Mississippi to provide traffic video display wall and extend the fiberoptic backbone to the JAC building and the CAIT Transportation Modeling & Visualization Laboratory facility in order to establish a model ITS lab. In October 2014 the CAIT Transportation laboratory was provided a video panel wall by the Mississippi DOT ITS section as a part of a model ITS lab to monitor real-time traffic flow on roads and barge under bridges over the Mississippi River. Since Fall 2015 the lab has been used for real-time traffic data collection and teaching UG for research use to monitor flow attributes by UG and graduate students.

Figure 2(a). UM’s CAIT Transportation Modeling & Visualization Lab, JAC 102, Oxford, MS

Figure 2(b). Model ITS Laboratory (video wall for accessing statewide traffic video network)

- Dr. Uddin’s NCITEC projects at CAIT supported 5 PhD students, 3 M.S. students, 11 UG Civil Engineering students, and 3 UG non-engineering students.
- New graduate and undergraduate CAIT student workers were trained for geospatial analysis and transportation demand modeling research. The contents of the Transportation and Geospatial course are enhanced using the NCITEC project products.
- It is expected that the research accomplishments will lead to a specialized transportation course and disaster mitigation and safeguard courses, as well as a trained geospatial workforce.

  The contents of geospatial courses CE495 and ENGR597 Section 25, taught by Dr. Uddin, were updated using the NCITEC project work. CE495 was offered in the 2014 May intersemester. These courses were offered again in Spring 2015 and 2015 May intersemester. Beginning Spring 2017 a new section of CE495 will be offered by Dr. Uddin as regular UG technical course every year.
- Research results have been incorporated in the existing CE 495 – Geospatial Visualization course (3 credit hours), CE 481 – Transportation Engineering I course (3 credit hours), CE 570 – Infrastructure Management course (3 credit hours), CE 590 – Airport Planning and Design, and a new course ENGR 692 Section 2 – Numerical Methods and Optimization and Nonlinear Time Series Modeling in the Department of

Civil Engineering. These were taught by Dr. Uddin. CE 570 course was offered by Dr. Uddin in Fall 2013 and CE 585 – Highway pavement in Fall 2014 to UG seniors and graduate students. The new textbook for CE570 course was 2013 McGraw-Hill book *Public Infrastructure Asset Management* (Uddin, Hudson, Haas). Dr. Uddin offered ENGR 692 Section 2 in Spring 2015 and CE 590 in Fall 2015.

Students Supported and Degrees Completed

The project supported the following graduate and undergraduate students: 5 PhD, 3 M.S., 14 UG. Graduate students who received project funding and completed degrees: 1 PhD, 2 M.S. Ahlan, M., (M.S. 2014); Cobb, Seth (M.S. August 2015); Durmus, Alper (PhD August 2016)

Impact on Transportation Workforce

The project has a significant impact on transportation workforce development. For example, the project:

- Provided opportunities to UG students, Master's and Doctoral graduate students, other participating specialists for research in transportation management of commodities, supply chain logistics, intermodal network optimization, geospatial visualization, and related disciplines.
- Enhanced intermodal transportation education by supporting graduate and UG students. Led four PhD graduate students, two M.S. students, and five UG students to work on project related assignments at UM. Some of them completed their course projects on project related topics.
- One M.S. student completed his graduating research report by using his geospatial and CO_2 prediction results accomplished in passenger train and freight mobility projects. He implemented the research framework to his own country, Indonesia, by analyzing traffic related emissions and impacts of the loss of tropical forest cover on CO_2 production.
- Improved the performance and modern computer modeling and visualization skills of main stream professionals and members of underrepresented groups (minority students) that will improve their access to or retention in transportation research, teaching, supply chain management, or other related professions.
- Developed and disseminated new educational/training materials and provide exposure to transportation, science and technology for practitioners, public works professionals, teachers, young people, media, supply chain stakeholders, and general public. This has been accomplished through geospatial workforce training in the teaching lab, classroom, tweets, YouTube videos, and SlideShare presentations.
- Involved the Student Chapter of the Institute of Transportation Engineers (ITE) and both graduate and undergraduate transportation students in project activities. A major goal to support undergraduate students is to motivate them to pursue graduate studies in transportation systems and professional careers in transportation engineering discipline.

- Enhanced information resources and electronic means through CAIT web pages, news interviews by journalism students, YouTube video and SlideShare production, blog posts, tweets, and scientific papers. (Over 3,600 SlideShare views of 8 presentations on transportation and infrastructure and over 1,680 views of project related YouTube videos.)

1.5 Website(s) or other Internet site(s)

Web Site, Social Media and Online Postings

UM CAIT web page: http://www.olemiss.edu/projects/cait/ncitec/

The NCITEC project tab on the University of Mississippi CAIT web site, linked to Mississippi State web site, provides useful background of NCITEC goals, university partners, and UM project summaries.

Twitter: https://twitter.com/drwaheeduddin

Blog: http://infrastructureglobal.com/ Dr. Uddin's blog about infrastructure and natural disasters around the globe.

SlideShare: Over 3,600 SlideShare views of 9 presentations. A recent SlideShare presentation, based on 2014 workshop presentations and 2015 TRB paper, was posted. http://slidesha.re/1CiiDnAnother slide presentation was posted on "NCITEC Intermodal Transportation and Disaster Safeguard Research Projects at CAIT." https://www.slideshare.net/waheeduddin/uddin-caitncitecprojects11-oct2013slsh

Twitter: https://twitter.com/drwaheeduddin Started in January 2012; several lists and "Global Infrastructure" timeline created; over 22,500 tweets to date.

Twitter: https://twitter.com/disasterglobal Started in 2012 on topics of protection from natural disasters and managing infrastructure assets; over 3,300 tweets to date.

Twitter: https://twitter.com/InfrastructureG Started in January 2014 to focus on built infrastructure and transportation assets; several lists on specific categories such as sustainable transportation; over 930 tweets to date.

YouTube Videos: Over 1,680 views of project related seven YouTube videos were reported. http://youtu.be/8JjM2QEexFE https://youtu.be/8JjM2QEexFE

Planet Forward video on the use of waste glass for sustainable road applications was produced by a UM journalism student in May 2013. http://infrastructureglobal.com/sustainable-infrastructure-by-recycling-waste-glass-to-enhance-road-safety-and-reduce-emissions-guest-post-22/
Mason Herman (Public Policy/Journalism UG student), "Dr. Uddin Interview on Transportation and Air Quality Mitigation," April 30, 2014. https://youtu.be/wCJQiXaV3gc

2. TRANSPORTATION FUNDING AND PAVEMENT SAFETY RESEARCH

2.1 Stakeholder Survey for Supply Chain Infrastructure and Freight Transportation

The research team used questions related to multimodal operations, funding opportunities, and public policy perspectives to design a questionnaire. This was used to conduct a survey of a sample of global supply chain players and freight operators, infrastructure asset owners, and other stakeholders to assess supply chain challenges and opportunities.

Survey Questionnaire

This study was reviewed by The University of Mississippi's Institutional Review Board (IRB) and survey questionnaire approved. The survey form is attached in Appendix.

The anonymous opinion survey of supply chain stakeholders was conducted to learn their dependence on multimodal transportation needs and assess their willingness to consider the intermodal integration and innovative funding strategies in order to improve the intermodal infrastructure and economic competitiveness. Questions 1 through 5 relate to the supply chain markets and shipping modes. Questions 6 and 7 are about the intermodal integration operations and their impacts on efficiency and economic competitiveness. Questions 8 and 9 ask willingness to partner in public-private partnership and the support for "dedicated truck lanes" around urban areas to ease congestion. Question 10 invites feedback on user fee charges and infrastructure bank loan.

The IRRB approved supply chain survey questionnaire was transmitted to several manufacturer, logistics, port and transport stakeholders for obtaining feedback on their general freight data, intermodal operations, and funding questions. The survey respondents were a few.

Summary of Responses

The responses to Questions 8 through 10 from a transportation agency and a port on the West coast and port agency on the Gulf Coast showed support for:

a. Intermodal integration of freight corridors,
b. Dedicated truck lane
c. Additional user fee
d. More federal grants and competitive credit/loan financing program.

A freight rail operator recommended a waiver of a part of the federal business income tax instead of getting a government grant or loan to support rail infrastructure improvements.

Use of Survey Results

The results of the supply chain survey of stakeholders and the intermodal freight corridor case studies are used to develop “best practice guide” examples and intermodal infrastructure bank proposal for consideration by government transportation agencies, private transport operators, and other stakeholders.

2.2 Infrastructure Funding Needs, Revenue Mechanisms and Policy Issues

Funding Needs

Traditionally the federal government and state governments financed the highway transportation infrastructure in the United States, from the early roads built to distribute mail to the high capacity Interstate Highway System, which was funded by a Federal Aid Highway Act of U.S. Congress in 1956 by creating the Highway Trust (US Trust 2016). The expanded national highway system (NHS) served the mobility of people and goods across the United States with 90% of the highway cost provided by the federal grants to the states and the balance made available by state funding. Due to significant deficit between the funding levels and the cost of repair and maintenance needs, the overall condition of the nation’s roads and bridge network has been deteriorating since the last several decades. There is backlog of infrastructure rehabilitation and improvement for inland waterways and ports and harbors.

The American Society of Civil Engineers' 2013 Report Card for America's Infrastructure (ASCE 2013) indicates the overall infrastructure grade D+ and the deteriorating condition of transportation infrastructure and funding shortfalls, as follows:

- *Roads D grade*: Forty-two percent of America’s major urban highways remain congested.
- *Bridges D+ grade*: One in nine of the nation's 607,000 bridges is structurally deficient.
- Inland Waterways D+ grade: There is an average of 52 service interruptions a day throughout the system. “Marine highways” of inland waterways and rivers are the hidden backbone of our nation’s freight network – they carry the equivalent of about 51 million truck trips each year.
- *Ports C grade*: Our nation’s ports need to be maintained, modernized, and expanded in order to sustain and serve a growing economy and compete internationally. According to the U.S. Army Corps of Engineers, ports were the vital links for more than 95% (by volume) of foreign trade produced or consumed by the United States.
- *Rail C+ grade*: Both freight and passenger rail have been investing heavily in their tracks, bridges, and tunnels as well as adding new capacity for freight and passengers.
- *Aviation D grade*: The Federal Aviation Administration (FAA) estimates that the national cost of airport congestion and delays was almost $22 billion in 2012. If current federal funding levels are maintained, the FAA anticipates that the cost of congestion and delays to the economy will rise from $34 billion in 2020 to $63 billion by 2040.
- *Investment needs and deficit*: The total transportation investment needs are $1.864 trillion and the current funding deficit is $901 billion by 2020. About 94% deficit is in surface

transportation funding. The investment need for all infrastructure assets is $3.6 trillion by 2020.

Current Revenue Mechanisms

Federal and State Fuel Taxes

The milestones of government fuel tax in the U.S. are summarized (FHWA 2015, Sweet 1993), as follows:

- 1932: The Revenue Act of 1932 included 1-cent per gallon excise tax on gasoline sales. Other sales tax items included consumer goods, manufactured items, and communication media.
- 1933: The National Industrial Recovery Act of 1933 extended the gasoline tax and increased it to 1.5 cents per gallon. Revenue Act of 1934 rescinded the half-cent increase.
- 1941: The Revenue Act of 1941 made the gas tax permanent and increased it to 1.5 cents per gallon to help pay for the country's defense buildup.
- 1951: The Revenue Act of 1951 increased the gas tax to 2 cents per gallon as a revenue source during the Korean War that began in June 1951.
- 194-1956: President Eisenhower supported the Excise Tax Reduction Act of 1954, which extended the tax to April 1, 1955, and the Tax Rate Extension Act of 1955, which extended it to April 1, 1956.
- 1956: The Federal-Aid Highway Act of 1956, signed by President Eisenhower, increased he gas tax to 3 cents. The highway user tax revenue from excise taxes on gasoline, tire rubber, tube rubber, and the sales tax on new trucks, buses, and trailers would be credited to a new Highway Trust Fund and reserved for use on the Interstate System and other highway projects. (The Highway Trust Fund is modeled after the Social Security Trust Fund-that is, the revenue goes into the general treasury, but is credited to the Fund.)
- 1959: The Federal-Aid Highway Act of 1959 increased the gas tax to 4 cents.
- 1961-1972: The Federal-Aid Highway Act of 1961, approved by President John F. Kennedy on June 29, retained the 4-cent tax and extended it through September 30, 1972.
- 1982: The Surface Transportation Assistance Act of 1982, which President Ronald Reagan approved on January 6, increased the gas tax to 9 cents, but the legislation created two separate accounts in the Highway Trust Fund. The Highway Account would receive 8 cents of the revenue while the new Mass Transit Account would receive 1 cent of the gas tax.
- 1986: The Superfund Amendments and Reauthorization Act of 1986 added 0.1 cent tax on gasoline for the Leaking Underground Storage Tank Trust Fund.
- 1990: The Omnibus Budget Reconciliation Act of 1990 was approved by President George H. W. Bush on November 5, 1990. The Act increased the Federal gas tax by 5 cents, with half the increase going to the Highway Trust Fund, the other half to deficit reduction. The federal gas tax was 14.1 cents per gallon.

- 1993: The Omnibus Budget Reconciliation Act of 1993 was signed by President Bill Clinton on August 10, 1993, which increased the federal fuel tax by 4.3 cents to 18.4 cents per gallon on gasoline. Revenues from 18.4 cents gas tax and 24.4 cents per gallon of diesel fuel and related excise taxes went to the federal Highway Trust Fund.
- 2015: The fuel taxes for gas and diesel remain the same as established in 1993.

Other revenue sources for The Highway Trust Fund include the following Federal Highway-User Tax Rates (FHWA 2015):

- Other fuel taxes per gallon: Liquefied Petroleum Gas (18.3 cents), Liquefied Natural Gas (24.3 cents), M85-85 percent methanol (9.25 cents), Compressed Natural Gas (48.54 cents per thousand cubic feet)
- Non-fuel federal taxes:
    - Tires: 9.45 cents per each 10 pounds in excess of 3,500 lbs
    - Truck and Trailer Sales: 12 percent of retailer's sales price for tractors and trucks over 33,000 pounds gross vehicle weight (GVW) and trailers over 26,000 GVW
    - Heavy Vehicle Use: Annual tax
      Trucks 55,000-75,000 pounds GVW, $100 pus $22 for each 1,000 pounds (or fraction thereof) in excess of 55,000 pounds
      Trucks over 75,000 pounds GVW, $550

The Highway Trust Fund, which funded highway and bridge construction and maintenance, as well as mass transit, has been on the brink of depletion for the last two decades and the inaction of the Congress to increase the tax base could lead to additional shortfalls down the road. States, realizing the backlogs of roads and bridges in need to maintenance and rehabilitation or replacement, established additional state fuel taxes. These vary widely, as discussed by Tax Foundation (Tax 2016).

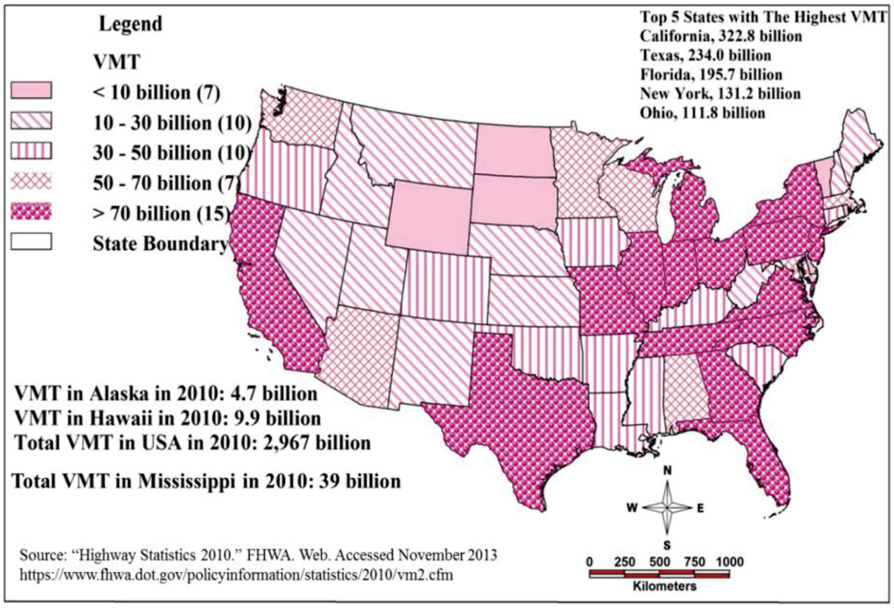
- The highest state gas tax is assessed in Pennsylvania, at 50.4 cents per gallon (cpg).
- Washington State (44.5 cpg) and New York (42.64 cpg) following closely behind.
- Alaska drivers pay the lowest rate in the country at 12.25 cents per gallon.

The Inland Waterways Fuel Tax was established by Congress in 1978 to support the development and rehabilitation of inland waterway infrastructure, which includes 257 locks at 212 sites on more than 12,000 miles (19,200 km) of inland waterways. Revenues from the tax fund 50 percent of the cost of inland navigation projects each year as authorized. The amount of tax paid by commercial users is $0.20 per gallon of fuel, generating approximately $85 million in contributions annually to the Inland Waterways Trust Fund (IWTF). In December 2014, tax extension legislation included a 9 cent per gallon increase to IWTF collections. As of April 1, 2015, tow boaters transiting the inland waters of the U.S. now contribute 29 cents per gallon to the fund (PNWA 2015).

The Harbor Maintenance Trust Fund (HMTF) was established by Congress in 1986 to fund operation and maintenance work on coastal navigation channels, including dredging. The HMTF brought in about $1.8 billion in 2014 in taxes on cargo from importers and domestic shippers using coastal and Great Lakes ports (Roll Call 2015).

Summary of Revenue Sources at all Government Levels

The traditional revenue generation models for investing in transport infrastructure network are the federal “Highway Trust Fund” and The “Inland Waterways Fuel Tax,” which primarily depend on federal fuel tax. Some states also impose state fuel tax but the revenue may not be allocated to transport infrastructure assets. In a recent TRB study (NCFRP 2012c) the following revenue mechanisms were evaluated for freight transport investment: fuel surcharge, vehicle miles travel (VMT) based fee, and federal vehicle sales and annual use taxes. Figure 3 shows spatial distribution of VMT by state in 2010 and total 2,967 billion VMT in the United States.



Source: “Highway Statistics 2010.” FHWA. Web. Accessed November 2013 https://www.fhwa.dot.gov/policyinformation/statistics/2010/vm2.cfm

Figure 3. Spatial Map of Vehicle Miles Traveled by States in the United States, 2010

NCHRP Synthesis 487 (NCHRP 2016) reviews the background and piolet studies by states to implement user fees based on miles driven to generate revenue. Examples are: mileage-based user fee (MBUF), road usage charge (RUC), VMT fee, or per-mile tax. As of 2015, the synthesis reports that 26 states have begun considering these revenue mechanisms, such as a small-scale pilot study (Oregon) and developing a prototype program (California). Concerns regarding the application of user fees and on impacts on drivers include:

- Technology and administrative problems related to possibility of improper charges.
- Fraud practices by some drivers to avoid payment.
- Cost of more expensive revenue collection system.
- Driver to pay for miles driven during out-of-state travel.

- Charging out-of-state vehicles or out-of-state drivers escaping fee payment.
- Perception of being tracked and invasion of privacy.
- Electric and fuel efficient vehicles and traditional auto paying unequal share of road costs.
- Concerns about the new user charge system versus the familiar and simple gas tax system.

In summary, the following revenue sources for infrastructure funding have been practiced or being assessed to expand the revenue and funding resources:

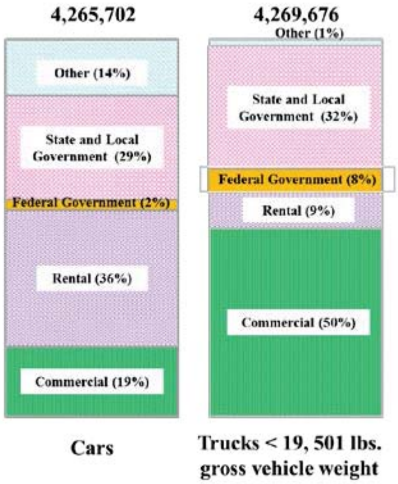
1) Federal fuel tax, collected at gas stations (revenue collection mechanism already in place)
2) State fuel tax, collected by dozens of states in addition to federal tax (revenue collection mechanism already in place)
3) Federal non-fuel taxes on tire, sales taxes on truck tag and trailer, annual taxes on heavy truck use (revenue collection mechanism already in place)
4) Other auto tag registration and license plate tax by state and counties (revenue collection mechanism already in place)
5) Tolls by states and cities on designated roads and bridges, tag registration and license plate tax (revenue collection mechanism already in place)
6) Property taxes collected by cities and counties and in some cases used on local roads and streets (revenue collection mechanism already in place)
7) State and municipal bonds in practice for public schools and other infrastructures (revenue collection mechanism already in place)
8) Fees based on road and highway travel miles as pilots studies by some states (revenue collection not in place and may be costly as discussed later)
9) Traffic congestion based road user fee.
10) Fuel tax for inland waterways, which is currently at 29 cents per gallon and already higher than the truck diesel fuel tax of 24.4 cents per gallon. Additional excise or service tax for the use of waterway infrastructure can bring more revenue for maintenance.
11) The harbor and port excise and service tax on ships in addition to the diesel fuel tax can generate more revenue for maintenance and operation of infrastructure.

The above revenue collection and funding mechanisms have been based on traditional auto/truck traffic and waterborne transport operated on gasoline and diesel. The revenue will vary based on the vehicle fuel efficiency and range of miles driven depending upon the fuel cost. There is a growing demand of electric vehicles (EV), pedal-cycles, and pedestrian traffic sharing highways and roads. These new travel modes do not consume gasoline or diesel. Moreover, these revenue generation practices are primarily limited to highway mode only and do not present a comprehensive approach for integrated multimodal transport network. These issues should be considered while formulating user fee and tax alternatives.

The guiding principles must consider:

- Equity based on both fossil fuel types and EVs
- Space shared on highways and roads
- Additional user fee on auto-share customers and non-car owners
- Commercial use versus work and other travel purposes
- Damage potential to pavements (freight trucks not paying enough and cause more damage)
- User fee on barges and ships traveling on waterways and marine highways
- Excise taxes for ports/harbors serving barges, ships, rail, trucks
- Waiver of a part of the federal business income tax for privately owned transportation infrastructure instead of paying "user fee" charge
- Investment opportunities for infrastructure banks to attract pension and retirement funds
- Reasonable cost of user fee collection, preferably through the existing mechanisms
- Interoperability to other jurisdictions and states

The cost of user fee collection can be reduced if a sliding scale of annual miles driven is formulated based on the ownership, different ranges of miles driven annually, and a separate fee for taxi/vehicle sharing model. Inventory of vehicle fleets in the U.S. (Figure 4) shows that 36% cars are in rental business and 19% cars are for commercial use. On the other hand, 50% of large trucks are for commercial use and only 9% are in rental business. It is rational to charge a higher user fee or fuel tax in proportion to the commercial and rental use of vehicles. A life cycle assessment approach for costs and benefits can help to analyze the long term impacts of a road user fee and or/infrastructure tax structure for any of the current travel models and the future of autonomous vehicle (AV) technologies that may lead to less auto ownership and more car ridership sharing.



(Source: Stacy C. Davis, Susan W. Diegel , and Robert G. Boundy. Transportation Energy Data Book: Edition 31 - 2012." Oak Ridge National Laboratory, Oak Ridge, Ten., July 2012.)

Figure 4. U.S. Fleet Vehicles in Service as of January 1, 2011

Innovative Investment Approaches and Infrastructure Bank

An innovative approach is a possible federal regulation of a carbon tax on vehicle-miles traveled by trucks, cars, and rail. A similar carbon tax can be formulated for barges and ships on inland and coastal waterways, as well as ports and harbors. This approach presents a shift of responsibility to freight transporters and other general transport users for damaging impacts of fossil fuel based economy. Assuming both rail and truck freight operated on diesel fuel, trucks produce six times more nitrogen oxides than rail per ton-km (Uddin 2012). Rail infrastructure modernization and electrification can reduce fossil fuel consumption and rail emissions too.

The carbon tax must be equitable and fair. California has already experimented raising significant revenue from carbon tax. These and other innovative approaches for generating revenue and funding mechanism can be realized through the creation of “Bank of Infrastructure Investment for Intermodal Transportation” at federal and/or state levels. Moreover, public-private partnership investments for the bank can attract municipal type “infrastructure” bonds, pension and retirement funds, and foreign investments.

A detailed policy paper on infrastructure bank is included in Appendix. The technical memorandum paper, prepared by UM team’s Dr. Holland, addresses innovative infrastructure funding mechanisms to support intermodal transportation asset management for a secured, safe, sustainable and efficient global supply chain and America's economic growth. The document includes the literature review of existing funding policies, Public-Private-Partnerships (PPPs), and policy and legal issues related to the creation of infrastructure banks.

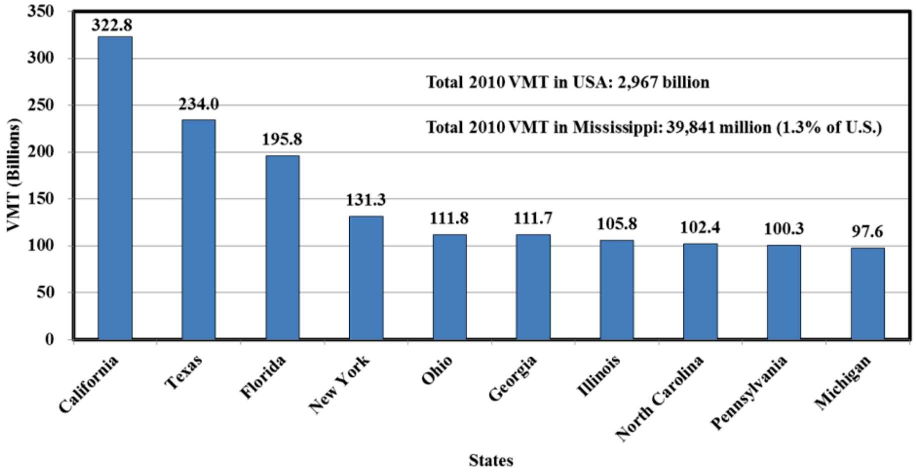
By creating a new revenue/funding model and taking advantage of new taxes on transportation modes (carbon tax) will help to pay for essential maintenance and modernization (without borrowing from other countries and not increasing federal budget deficits). An innovative approach is that road infrastructure (dedicated truck lane/freight road corridor) owned by government, rail infrastructure be owned by rail and new corridors by private rail (with payable loan from the new intermodal infrastructure bank concept. Most transit agencies in the U.S. are publicly owned with aging bus fleet with large replacement backlogs, low passenger ridership in many cities, lack of funds, and increasingly high fare. It is recommended that all operations must be managed by private enterprises (freight truck, rail, and transit) under an oversight board (appointed by the United States President and USDOT).

2.3 Evaluation of Pavement-Tire Friction Properties for Improving Safety

Highway and Road Safety Overview

Out of 4,866 billion mile passenger travel, 86.9% of this travel in 2011was on highways and roads. An American traveled on average 36 miles per day (BTS 2014). Figure 5 shows VMT for the top 10 states and Table 1 lists the VMT distribution by road functional classification (Ahlan 2014).

The Interstate and national highway system comprises of only four percent of the total paved roads in the U.S.; however, approximately 43% of all VMT and 70% of all truck freights travel occur on this network annually. The total number of fatalities on the nation's roads and highways has been falling from 43,510 in 2005 to 32,999 in 2010 and 32,675 in 2014 (BTS 2016). However, "2015 likely was the deadliest driving year since 2008" (NPR 2016). This was the largest percentage rise in motor vehicle deaths in the past 50 years as 38,300 people died on U.S. roads and 4.4 million were seriously injured.



Source: "Statistics." FHWA. Web. Accessed on November , 20, 2013. http://www.fhwa.dot.gov/policyinformation/statistics/2010/.

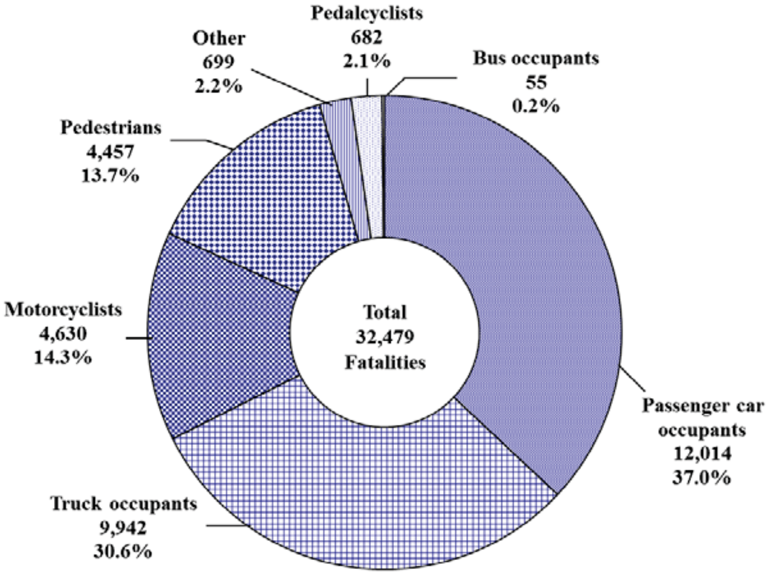
Figure 5. Top Ten VMT States in the U.S.A., 2010

Table 1. VMT Comparison of Country-Wide and Rural Travel Demand

VMT by Functional Class	The U.S.A.	Mississippi
2010 VMT	2,967 billion	39.8 billion (1.3% of U.S.)
VMT in rural areas	33.2% of total VMT	59% of total VMT
VMT in arterials	72.5%	60.8%
VMT in collectors	13.8%	16.0%
VMT in locals	13.7%	23.2%

The annual fatality involving light and large trucks was 30-32% of total annual highway fatalities (BTS 2016). Large truck fatality rates with respect to truck-mile traveled is higher than the non-truck fatality rate for total vehicle miles traveled. In 2011 highway fatalities were 94.26% of all 34,456 transportation fatalities in the U.S. (Ahlan 2014) and motorized vehicles comprised of about 82% of all highway fatalities (Figure 6).

About 70 % road fatalities in the U.S. are attributed to drunk driving and speeding (Uddin 2007). Other contributing factors are inadequate friction on tire-pavement contact area, adverse wet weather, geometry and line of sight, and slush and standing water (Uddin 2015). Pavement-tire friction and skid resistance are two important pavement surface properties that are measured by ASTM Skid Trailer at 40 miles per hour (mph). Average Skid Number is used to identify pavement sections with poor skid resistance for highway safety management systems and pavement asset management. A range of minimum Skid Number from 28 to 41 is used for maintenance intervention to improve road safety (Murad 2006).



Highway Fatalities in Mississippi in 2011: 630 (1.9 % of U.S. Highway Fatalities)

Source:
[1] "National Transportation Statistics." DOT. Web. Accessed August, 14, 2014.
http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/index.html
[2] "State of Mississippi FY – 2014 Highway Safety Plan." State of Mississippi. 2011.

Figure 6. Highway Fatalities by Highway Travel Mode in the U.S.A., 2011

Traditional Pavement-Tire Friction Measurement

Traditionally, pavement-tire friction measurement is expressed as Coefficient of Friction or multiplied by 100 to calculate Skid Number. In the standard skid test using ASTM E274 Locked Wheel Skid Tester (ASTM 2011) at 40 mph, Skid Number is calculated for a wet pavement surface based on the horizontal force developed when brakes lock, as follows:

Coefficient of Friction (CoF) = (Horizontal Force, F_T) / Vertical Load (F_N) .... Eq. 1

Skid Number (SN) = (CoF) x 100 .... Eq. 2

This approach applies metallic friction theory that was originally developed in the 1940s and 1950s for metallic surfaces. As discussed in Smith's book *Analyzing Friction in the Design of*

Rubber Products and Their Paired Surfaces, use of the CoF-approach arose during the important studies of metallic machinery industry (Smith 2008). This CoF and SN approach for metallic or hard surfaces does not rationally apply to rubber as it is not a material property of elastomers. Tire-pavement skid test generates the rubber microhysteretic friction force, which is ignored in the traditional CoF and SN analysis. It is shown that increases in F_N can increase the effective area of tire/pavement contact. Such contact growth can produce greater adhesion, a principal tire/pavement friction force. Greater adhesion can also increase tire contact area with pavement macroroughness, adding to microhysteretic (F_H) friction force development through greater bulk deformation of the tire tread (Smith 2008).

Note the traditional CoF and SN parameters are used to identify pavement section with low skid resistance for highway asset management programs, as well as used by traffic police in crash investigations and experts involved in crash reconstruction studies. Road safety management systems, based on traditional friction and skid parameters, do not analyze the adhesion effect of tire tread with the macrotexture of pavement surface treatment.

Macrotexture surfaces that provide larger contact area due to tire rubber adhesion and microhysteretic friction force may indicate improved skid resistance and safer pavements. This has been validated using the 2013 field tests in Florida, which is described in the following section.

Variable Loading-based Pavement-Tire Friction Measurement

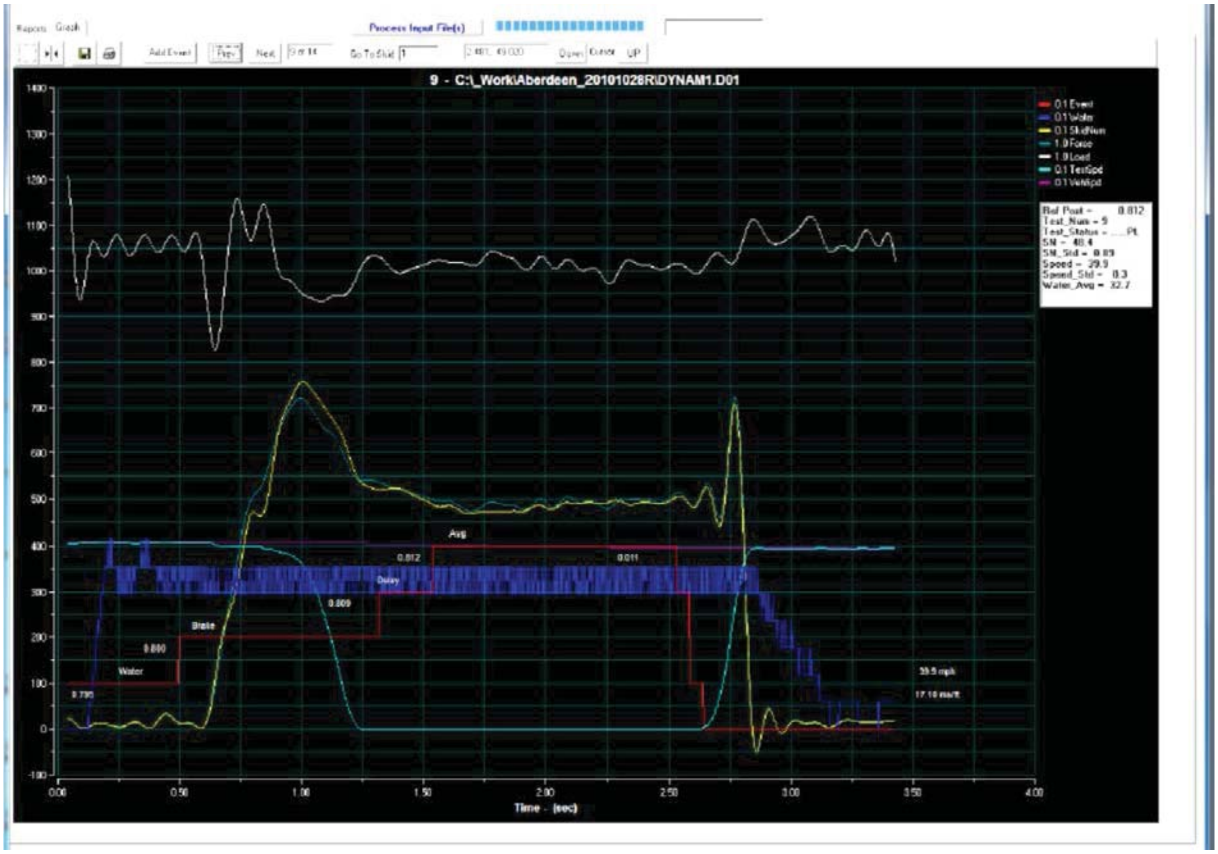
Considering this road safety aspect it is proposed to evaluate a variable loading-based approach for measuring the coefficient of roadway friction by focusing on the individual traction forces generated at the tread/pavement interface (Smith 2008, Smith and Neubert 2011). This allows the friction forces to be calculated to within engineering accuracy under the environmental conditions of interest. The goal is to help enhance the basic understanding of skid/crash incidents on roads and recommend guidelines to improve road safety. This research activity was conducted by UM project consultant Dr. Robert Smith in collaboration with International Cybernetics Corporation (ICC) of Largo, Florida. Full report is contained in a technical memorandum in Appendix which includes a detailed review of relevant literature and a proposed friction parameter.

The tests in this research study generated the rubber microhysteretic friction force by use of a standard, full-scale ASTM ribbed tire in locked-wheel testing (ASTM 2011) and so indicates its existence to within engineering accuracy. In the current study, the following tasks were carried out to:

- Develop a field testing plan involving both asphalt and concrete road pavements.
- Identify and recruit a competent and well-equipped pavement-testing organization.
- Conduct traction measurements on dry and wet concrete and asphalt pavements.

- Interpret the results as traditionally reported CoF and SN values.
- Evaluate the field test results using the variable loading-based data analysis and compare them with the results of traditional pavement-tire friction parameters.
- Propose the use of a sliding friction index as a replacement for the use of the traditional coefficient of friction and skid number.

In the current study controlled sliding-tire friction testing of asphalt and concrete pavement was accomplished by using a locked-wheel skid trailer device fitted with a standard, full-scale tire. Instead of the conventional single-load, locked-wheel testing, however, eight different loads were applied to the tire sliding on both asphalt and concrete pavements in wet and dry conditions. Locked-wheel skid testing was used in the field tests to validate the variable loading-based theory and illustrate the use of the associated data analysis approach, as well as traditional CoF and SN parameters at the conventional single-load.

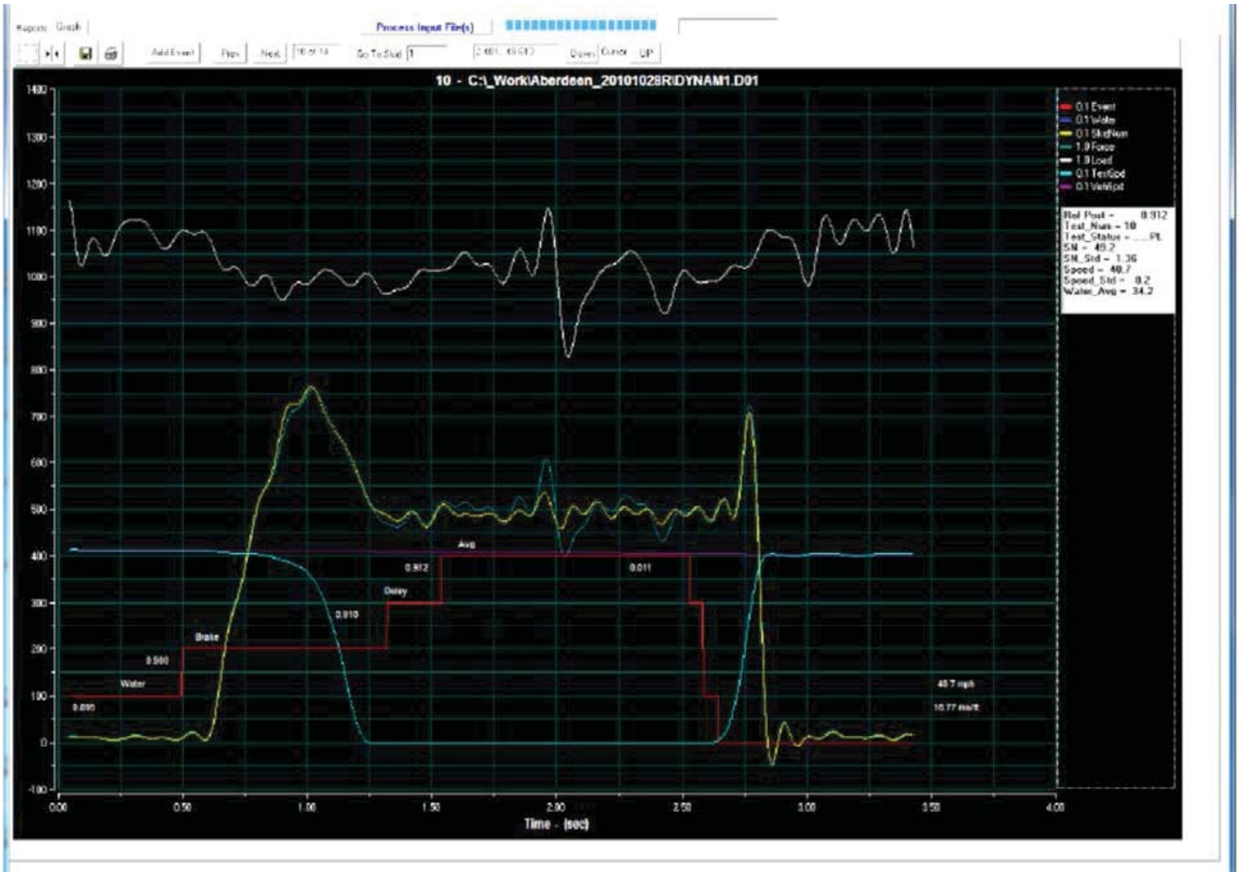


Ref Post = 0.812
Test_Num = 9
Test_Status = ...PL
SN = 48.4
SN_Std = 0.89
Speed = 39.9
Speed_Std = 0.3
Water_Avg = 32.7

Figure 7(a). Graph of Typical Filtered Skid Test Data

Figure 7(a) shows a plot of the data collected from the standard skid test after the required filtering. The following description is copied from the ICC manual (ICC 2013). “There is a key to the colors on the graph, in the upper right hand graph corner. The white line near the top of the graph is the Vertical Load in pounds as shown by the scale marks on the left. The light greenish blue line is the Horizontal Force also in pounds. The yellow line is the calculated Skid (Friction)

Number which consists of the Horizontal Force divided by the Vertical Load multiplied by 100. The scale on the left must be divided by ten to get the value. For example, 700 represents 70. The terms on the graph are Load and Force as above. The yellow vertical lines indicate a range of data selected to show the average Skid/Friction number calculated between the lines by a manual selection while viewing the graph. For all the following lines, the scale on the left is ten times the value, so one set of values represents all. The light blue line represents the speed of the locked wheel in mph. The magenta line represents the speed of the vehicle in mph. The darker blue line represents the water flow to the wheel in Gallons Per Minute (GPM). The Red line represents an output referred to as the Skid Cycle Event State. The steps in the red line represent the different test states the skid test measurement cycle is in. The scale along the bottom is the time in seconds."



```
Ref Post -      0.912
Test_Num - 10
Test_Status - ___PL
SN - 49.2
SN_Std - 1.36
Speed - 40.7
Speed_Std - 0.2
Water_Avg - 34.2
```

Figure 7(b). Graph with Horizontal and Vertical Changes During Averaging Showing SN Line

Figure 7(b) show the traditional interpretation of the test results conducted in this study, as follows (ICC 2013). "The Skid Tests were run at 40 mph which is approximately 60 feet per second. Thus, the 1 second average data represents a 60 foot section of pavement. For these graphs run at 40 mph, the following is true. After the test start, the vehicle moved 30 feet with the water on before the brake was applied. The vehicle moved another 30 feet with the brake applied before the peak force was observed. At 1.3 seconds, 75 feet, the brake was locked. At 1.55 seconds, 93 feet from the start, the averaging was started. The averaging ended at 2.55 seconds, 150 feet. The test ended at 3 seconds or 180 feet from the start and the system was ready to start another test cycle at 4 seconds, about 240 feet. ICC uses a target sensor on the front of the vehicle to trigger tests sensing reflective tape on the pavement to make good repeatable tests at the same section of pavement. The distance from the target sensor to the location of the center of the trailer test wheel is stored in the system to allow the system to calculate the exact position of the wheel relative to the distances on the pavement surface referenced by the target sensor. The distance from the sensor to the wheel is very close to 30 feet. For 40 mph, this means the trailer wheel is about at the test start point when the brake is applied after 0.5 seconds. The averaging point for the trailer wheel data is then about 63 more feet from the start. The distances can be measured out to set targets to measure exact locations when desired. This will be slightly shorter for lower horizontal forces and slightly longer for higher forces. The example graph shown is for Skid Number averaging at 49.”

Variable Loading-based Friction Test Results

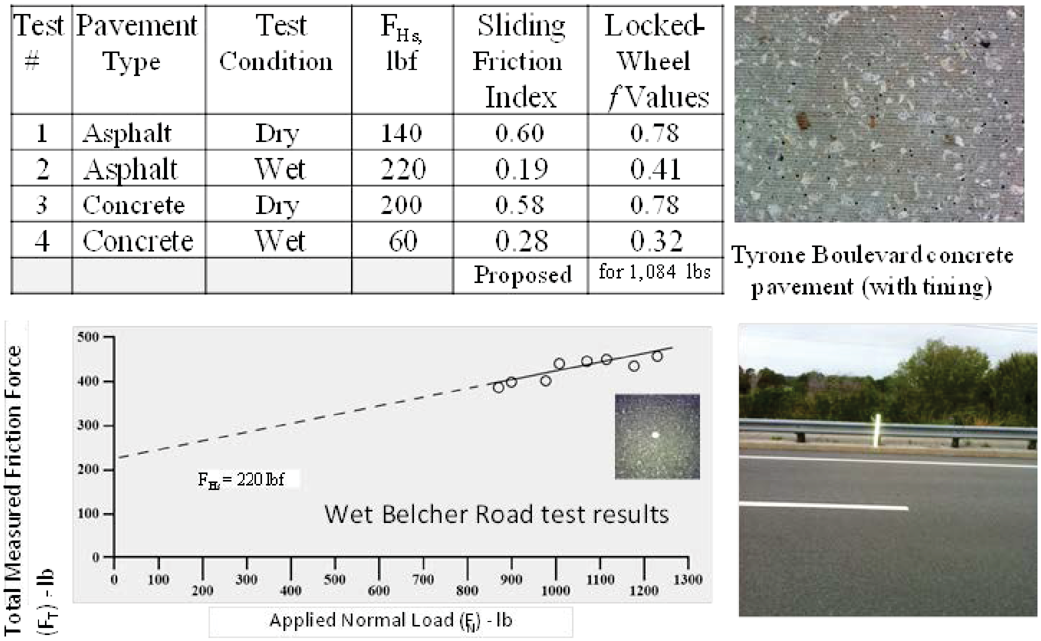
The following two factors were considered for conducting field tests: (1) pavement type at two levels (asphalt surfaced and concrete surfaced pavements) and (2) pavement surface condition (dry and wet). Figure 8 shows the test vehicle and skid trailer during the field tests.

Figure 8. Skid Resistance Test Vehicle on Pavement Sections

For the variable loading-based theory application, instead of the conventional single-load, locked-wheel testing, however, eight different loads were applied to the tire sliding on both asphalt and concrete pavements in wet and dry conditions. Each test was conducted at standard speed using eight F_N loads (883, 930, 984, 1034, 1084, 1132, 1188, and 1242 lb). Temperatures of the tested pavements were recorded. Five lockups were carried out for each load in the dry condition. Five sets of three lockups were carried out for each different tire load in the wet condition. This sampling resulted in four sets of test data collected at each of the eight normal test loads. The two road test sections included: (1) Belcher Road asphalt pavement in Largo, Florida and (2) concrete pavement on Tyrone Boulevard in St. Petersburg, Florida.

Tests started on March 18, 2013 and completed on March 22, 2013. The ICC test vehicle was always operated by the same experienced engineer. In accordance with ASTM E274/E274M – 1113 , the locked-wheel tester slid the test tire at a constant 40±1 mph velocity. The eight different vertical loads ranging from 883 to 1,242 lb were applied to the tire's centerline under the different test conditions. In accordance with Section 4.7 of this standard concerning pavement wetting, the quantity of water applied in the simulated wet tests at 40±1 mph was 4.0 gal ± 10 %/min·inch of wetted width, amounting to 28 gal/minute.

Using the loading-based approach, a "Sliding Friction Index" (SFI) is proposed as an improved metric for sliding-tire friction calculations. Higher values of the microhysteretic force for the unpolished asphalt indicates superior macrotexture characteristics at the time of testing compared to the polished concrete pavement. Figure 9 shows the pavement surface and key results.



Test #	Pavement Type	Test Condition	$F_{Hs,}$ lbf	Sliding Friction Index	Locked-Wheel *f* Values
1	Asphalt	Dry	140	0.60	0.78
2	Asphalt	Wet	220	0.19	0.41
3	Concrete	Dry	200	0.58	0.78
4	Concrete	Wet	60	0.28	0.32
				Proposed	for 1,084 lbs

Tyrone Boulevard concrete pavement (with tining)

Figure 9. Full-scale Locked Wheel ASTM Skid Resistance Tests on Asphalt and Concrete Roads, Florida

Details of the SFI calculations, field test data, and results are provided in Smith's technical memorandum in Appendix and in a published paper (Smith and Uddin 2016). Figure 10 shows key results and compares the proposed Sliding Friction Index with the traditional Locked-Wheel friction *f* values. The proposed SFI values are generally lower than the traditional CoF values. Example for the wet asphalt pavement section is the SFI value 0.19 (or SN 19 obtained by multiplying SFI with 100), which is less than the traditional CoF value 0.41 (or SN value of 41). This result has major implication because based on traditional skid resistance of SN value 41 this section's skid resistance is rated higher than the SFI based SN value 19. In reality, there will be higher probability of skidding and losing driving control during wet weather, which presents unsafe condition and even crash or fatality consequence.

2.4 Summary and Recommendations

Road safety management systems, based on traditional friction and skid parameters, do not analyze the adhesion effect of tire tread with the microtexture of pavement surface treatment. Field testing has been conducted to validate the variable loading based approach for characterizing tire-pavement friction and skid resistance. This research study shows that macrotexture surfaces that provide larger contact area due to tire rubber adhesion and microhysteretic friction force may indicate improved skid resistance and safer pavements. The results and recommendations considering the contribution of surface microtexture will help improve the safety aspects of pavement and tire interaction.

Current highway infrastructure funding practices are reviewed and innovative approaches are identified to generate more revenues in view of the serious funding deficits. The integrated intermodal infrastructure network will be essentially a public-private enterprise so that each team player works in a complementary spirit and not competing as rail and freight trucks do now for serving national and global supply chain. However, depending on the independence from government oversight, the policy outcomes can produce unintended consequences. These issues should be explored from a public policy perspective. Thus, the proposed infrastructure bank can be a linking mechanism among policy making and bureaucrats as well as a linking mechanism between public and private infrastructure development. As a linking mechanism, decision makers will have more control over planning and coordination of future multimodal transportation policy. Finally, this type of banking structure can promote significant shifts in economic and tax policy.

3. STUDIES FOR INTEGRATING MULTIMODAL FREIGHT CORRIDORS

Several studies conducted for optimization of economically viable integration of multimodal freight transport are described in this chapter based on the following approach:

(1) Review global and cross border commerce data.
(2) Identify major freight transportation corridors involving shipping ports (marine and inland waterways), highway and rail infrastructure;.
(3) Analyze alternative corridors for intermodal integration to increase the share of rail, waterway, and short-haul trucks.
(4) Estimate modal transport demand, visualize routing scenarios, and optimize locations of intermodal terminals.
(5) Evaluate the economic competitiveness considering travel time efficiency, safety, emissions, and economic development opportunities over 10-20 years

3.1 Supply Chain, Freight Corridors, and Commodity Flow Analysis

Supply Chain Logistics Management for Economic Competitiveness and Sustainability

Import and export rely heavily on weight of freight moved by ships through ports and by trucks and rail across land border posts. The following statistics from the Bureau of Transportation Statistics (BTS) highlight the crucial role of multimodal transportation systems on efficient import and export, as well as within-state and interstate commodity flows (BTS 2015a, 2015b):

- The U.S. freight-transportation system moves 48.3 million tons of goods worth $46 billion each day.
- In 2012, the U.S. freight-transportation system moved 17.6 billion tons of freight, a 16% increase from the recession low. This shows that freight shipments are returning to their pre-recession levels, meaning an increase of truck freight traffic on the NHS.
- Trucks ship 67% of the freight in 2012, followed by rail 10%, and waterborne transport 5%.
- International trade is affecting the national transportation system. The largest increase in freight shipment to states is by truck, which will be more than double in 2040 (2,365 million tons valued 7,852 billion dollars) compared to 2007.

Figure 10 shows the weight of freight shipments in the U.S. by transportation mode for 2012. The total freight shipment is projected to increase 45.1% from 2012 to 2040 (FHWA 2015, Cobb 2015). All these fright transportation data is leading to the argument that freight truck traffic is growing at a rate that cannot be matched by the construction of new highways. Proper use of alternative surface modes for long haul freight routes could help alleviate this congestion. Much of the rail infrastructure is unutilized, and more freight could also be moved by the nation’s inland waterway system.

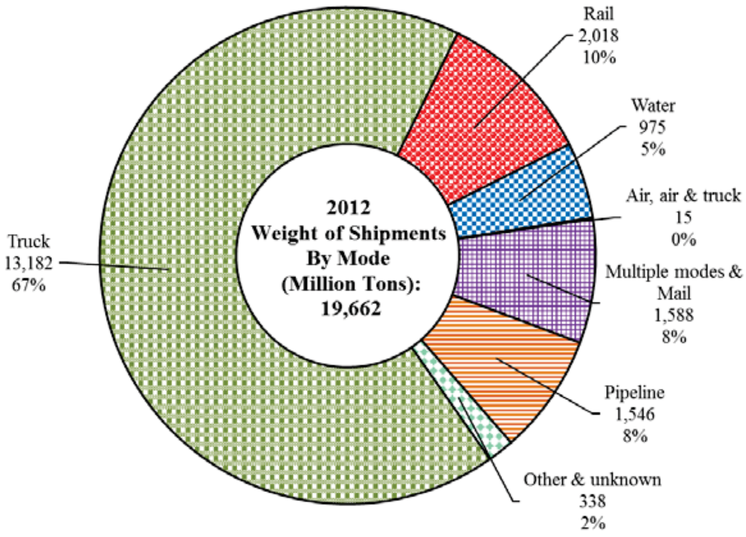


Figure 10. Weight of Freight Shipments by Mode in Million Tons, 2012

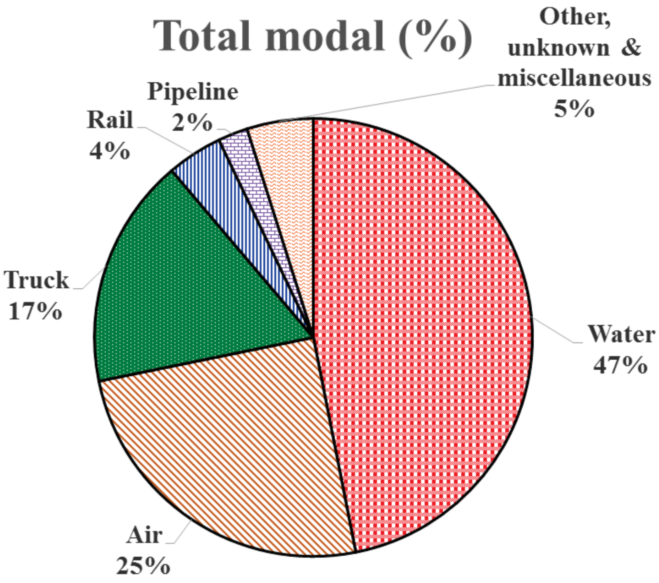


Figure 11. Distribution of International Trade Shipments by Mode in Million Dollars, 2011

Figure 11 shows the dollar values of U.S. international trade for 2011. Total value of U.S international merchandise trade in 2011 was 3,687,622 million dollars (current). By mode of transportation the dollar value distribution was 47% Waterborne, 25% air, 17% Trucks, 4% Rail, 2% pipelines, and 5% other. Table 1 lists the imports, exports and total foreign shipment in short tons by transportation mode for 2011 (USDOT 2013). Total export and import was 1,974 million short tons. Waterborne transport tops the list at 75% of all foreign trade shipments, followed by 10.5% by trucks, 7.2% by rail, 6.2% by pipeline, and 0.4% by air. Truck shipments are from NAFTA countries bordering the U.S.

Table 1.Distribution by Mode of International Imports and Exports and Tonnage, 2011

Mode	Short Tons x 1000			Mode
	Import	Export	Total	Percent
Water	631,217	848,733	1,479,950	75.0%
Truck	118,949	88,933	207,882	10.5%
Rail	61,945	80,109	142,054	7.2%
Pipeline	15,840	107,139	122,979	6.2%
Air	4,005	4,221	8,226	0.4%
Other, Unknown, & Misc.	5,465	7,751	13,216	0.7%
Total	837,421	1,136,886	1,974,307	100%

As the population grows, the demand of freight shipments (both international and domestic) will grow. Based on the trends and projections of domestic commodity flows and international import and export freights, there is and will continue to be a huge need for efficient and economically competitive freight infrastructure. The demand for goods and services continues to increase, in turn increasing the freight truck volumes on the current National Highway System (NHS), which is increasing congestion, growing bottlenecks, and decreasing efficiency of the traffic flow and supply chain service. This congestion is most notable at urban areas with higher population having a higher demand for goods. The cost of this congestion to the economy is becoming too high with respect to more travel time, wastage of fuel, and increased CO_2 emissions and other pollutants. Intermodal integration of highways with rail and waterways offers a long term sustainable solution to this problem in the U.S., which will also reduce congestion and emissions.

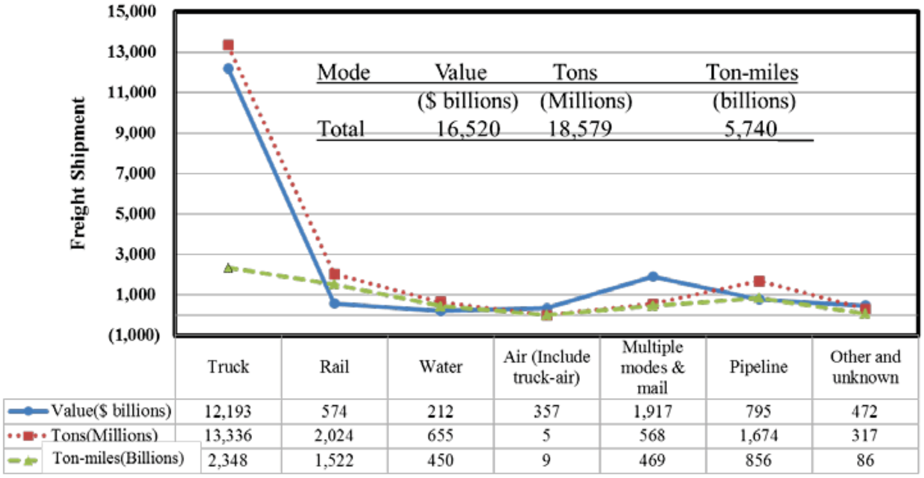
Geospatial mapping of Surface and Waterborne Freight Corridors and Commodity Flow

The research team conducted literature review and collected supply chain and freight/commodity flow statistics for all modes (both current and historical data), infrastructure asset inventory, NAFTA and statewide freight volume demand data, and available spatial maps related to the identified major transportation corridors. UM Project staff used the computer stations and backup equipment installed in the CAIT Transportation Modeling and Visualization Lab located off-campus at the Ole Miss Jackson Avenue Center. Major findings from geospatial and freight traffic studies are shown in the following sections and illustrated by sample figures and tables. Table 2 shows a breakdown of the miles of infrastructure by transportation mode in the U.S. in 2011 (FHWA 2015, Cobb 2015). There are approximately 4 million miles of road in the U.S., only 138,518 of rail infrastructure, and just over 13,000 miles of inland waterways. As the population continues to increase and economic base expands, congestion on the nation’s NHS will continue to outgrow the current highway infrastructure leading to even worse traffic flow conditions on roadways. Alternative thinking to integrate different transportation modes is the most effective solution instead of adding more lanes and building more highways. Both Atlanta and Houston added more traffic and congestion by building more highways in the past and received less federal transportation funding due to degraded air quality and non-attainment status (USDOT 2002, Uddin and Boriboonsomsin 2005).

Table 2. Miles of Infrastructure by Transportation Mode

Transportation Mode	2011
Public roads, route miles	**3,929,425**
National Highway System (NHS)	163,741
Interstates	46,960
Other NHS	116,781
Other	3,765,684
Strategic Highway Corridor Network (STRAHNET)	**63,887**
Interstate	46,960
Non-Interstate	16,927
Railroad	**138,518**
Class I	95,387
Regional	10,355
Local	32,776
Inland waterways	
Navigable channels	11,000
Great Lakes-St. Lawrence Seaway	2,342
Pipelines	
Oil	178,809
Gas	1,563,527

Figure 12 shows freight shipments within the U.S. by mode for dollar value, tons, and ton-miles. Truck shipment shares in some Gulf States are: 48% Louisiana, 66% Texas, and 85% Mississippi. Mississippi presents a challenge to reduce truck share and opportunity to reduce long-haul truck trips by having more intermodal terminals. Trucks carry 15 times more freight by dollar values compared to rail and waterborne transport combined and almost same truck ton-mile. This implies that a greater freight share of rail and waterway will reduce congestion on highways due to long-haul trucks, operating long-haul costs, and emissions.



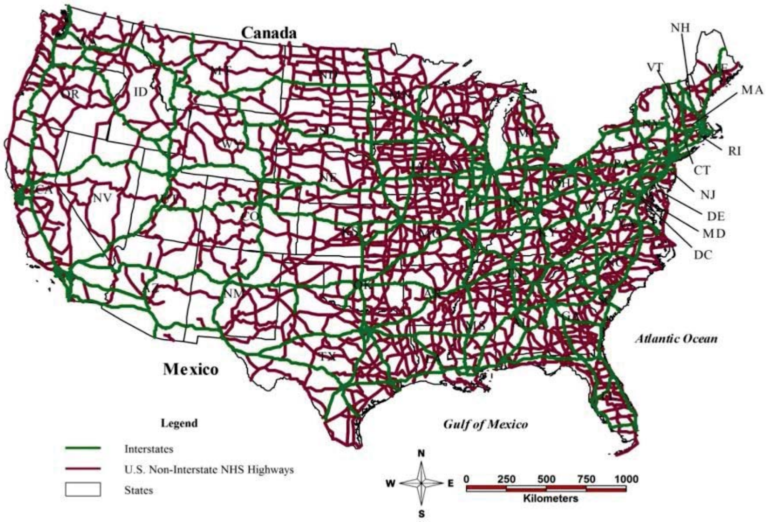
Mode	Value ($ billions)	Tons (Millions)	Ton-miles (billions)
Total	16,520	18,579	5,740

	Truck	Rail	Water	Air (Include truck-air)	Multiple modes & mail	Pipeline	Other and unknown
Value($ billions)	12,193	574	212	357	1,917	795	472
Tons(Millions)	13,336	2,024	655	5	568	1,674	317
Ton-miles(Billions)	2,348	1,522	450	9	469	856	86

Figure 12. Freight Shipments within the U.S. by Mode for 2007

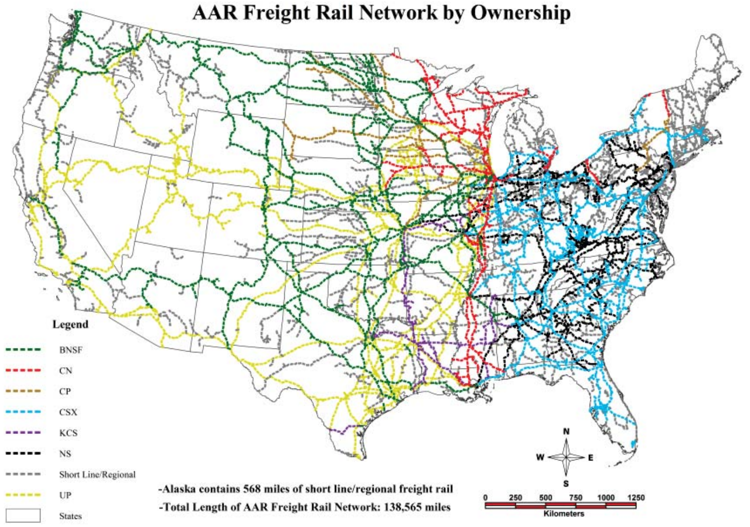
NAFTA Transportation Infrastructure – Geospatial Database and Spatial Maps

Initial efforts were devoted to collect freight and commodity data from U.S. DOT web resources, Canada Transport Ministry web links, and feedback from the transportation consultant in the team. A full report of the consultant on Mexico’s transportation infrastructure networks and freight data is attached in Appendix. Examples of the geospatial maps created for intermodal integration research are provided in Figures 13 through 17. More maps are included after Chapter 4.



Source of data: U.S. DOT, Federal Highway Administration
http://www.fhwa.dot.gov/planning/national_highway_system/nhs_maps/

Figure 13. Spatial Map of Interstate and U.S. Highway Network in the U.S.



Source of data: American Association of Railroads (AAR) https://www.aar.org/

Figure 14. Freight Rail Networks in the U.S. by Ownership

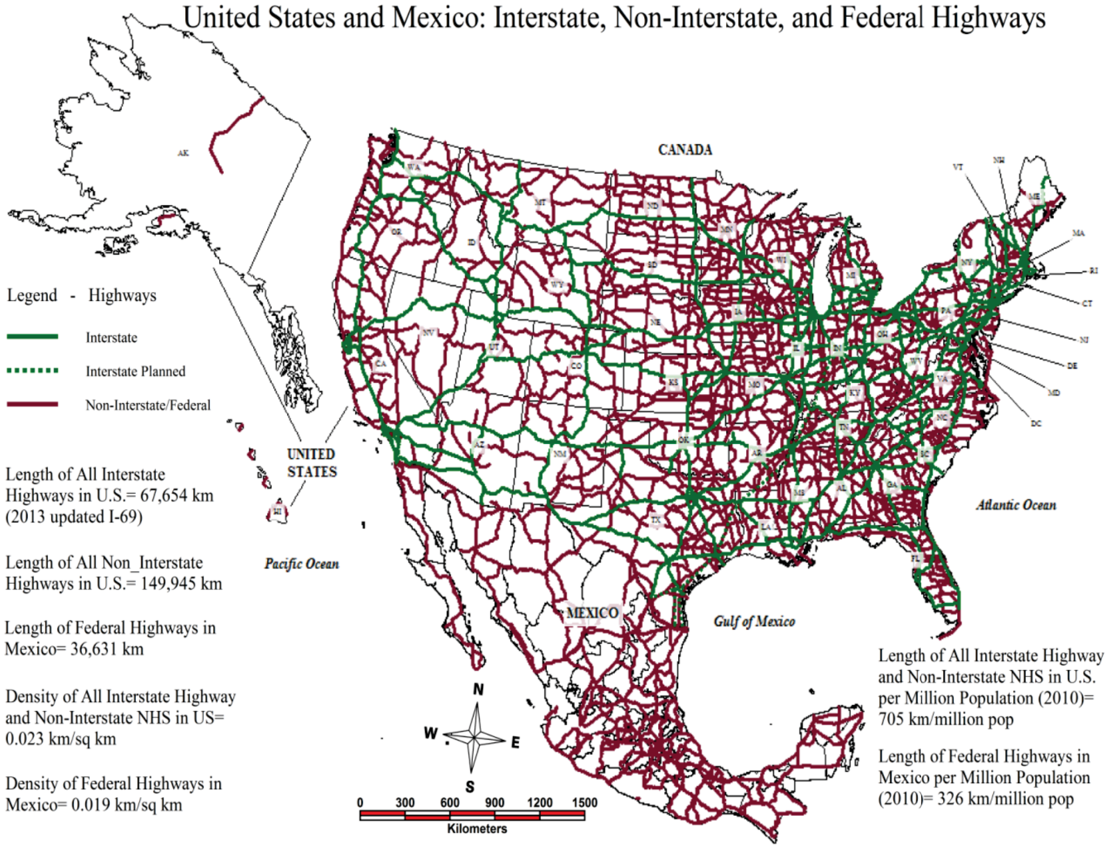


Figure 15. Highway Networks in The U.S. and Mexico

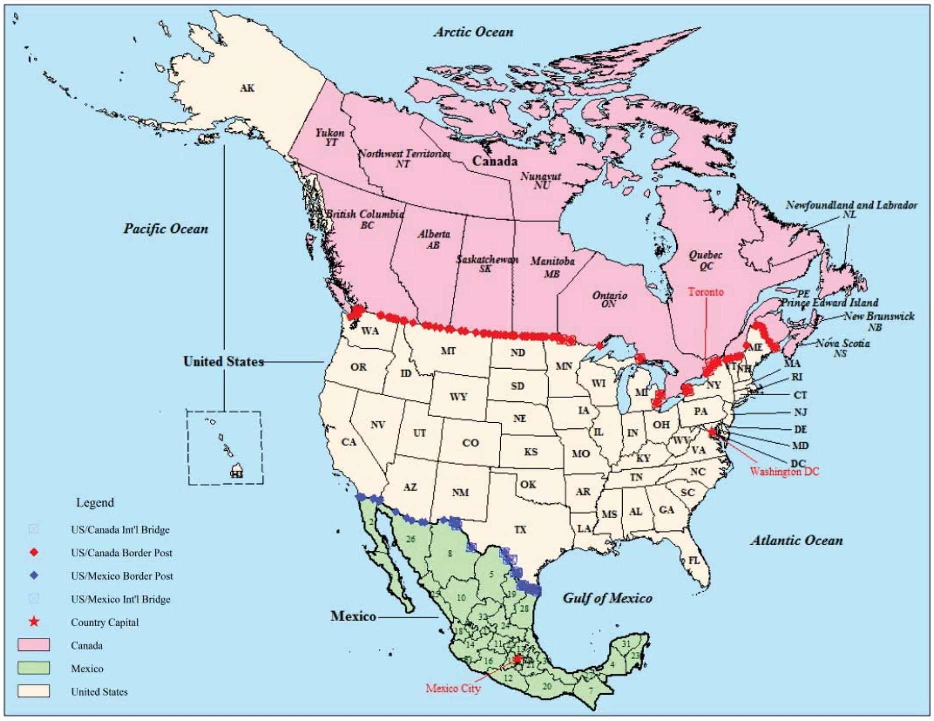
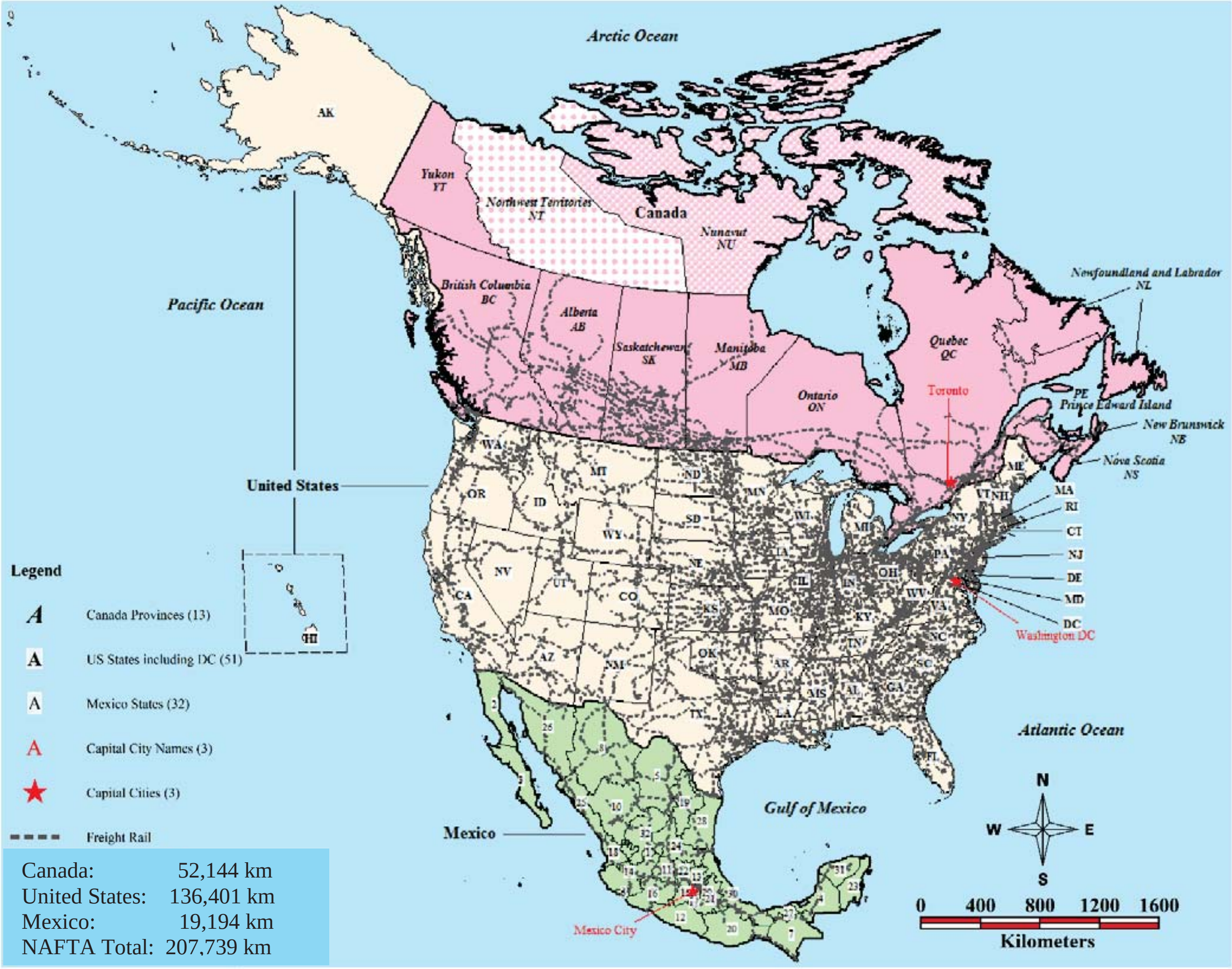


Figure 16. Spatial Map of NAFTA Border Posts



State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name
1	Aguascalientes	5	Coahuila de Zaragoza	9	Distrito Federal	13	Hidalgo	17	Morelos	21	Puebla	25	Sinaloa	29	Tlaxcala
2	Baja California	6	Colima	10	Durango	14	Jalisco	18	Nayarit	22	Querétaro	26	Sonora	30	Veracruz de Ignacio de la Llave
3	Baja California Sur	7	Chiapas	11	Guanajuato	15	México	19	Nuevo León	23	Quintana Roo	27	Tabasco	31	Yucatán

Sources: Transport Canada, http://www.tc.gc.ca/eng/policy/acg-acgd-menu-highways-map-2151.htm Accessed on September 22, 2014
Statistics Canada, http://www12.statcan.gc.ca/census-recensement/2011/ref/dict/table-tableau/table-tableau-8-eng.cfm Accessed on September 22, 2014
Research and Innovative Technology Administration (RITA) Bureau of Transportation Statistics (BTS) http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/north_american_transportation_atlas_data/index.html Accessed on September 22, 2014

Figure 17. Spatial Map of Freight Rail Network in NAFTA Countries

Commodity Flow and Freight Integration of Major Inland Surface Transportation Modes
The UM PI and CAIT graduate and UG student staff members worked intensively on geospatial mapping of collected freight data from literature review in 2014. They created geospatial maps of the commodity flow among states in the Continental U.S., NAFTA corridors, Mississippi River, and the Ohio River, as well as 26 adjoining Middle American states. Examples of the project outputs for top commodity shipping within and between states are shown in Figures 18 through 22 and further described in the following sections. Data sources include USDOT and Oak Ridge National Laboratory (ORNL 2014). Several maps for spatial analysis of shipping distances from an origin state to destination states were prepared to use for optimization problems. Figure 23 shows a spatial map of linear distances from Louisiana to other 25 states.

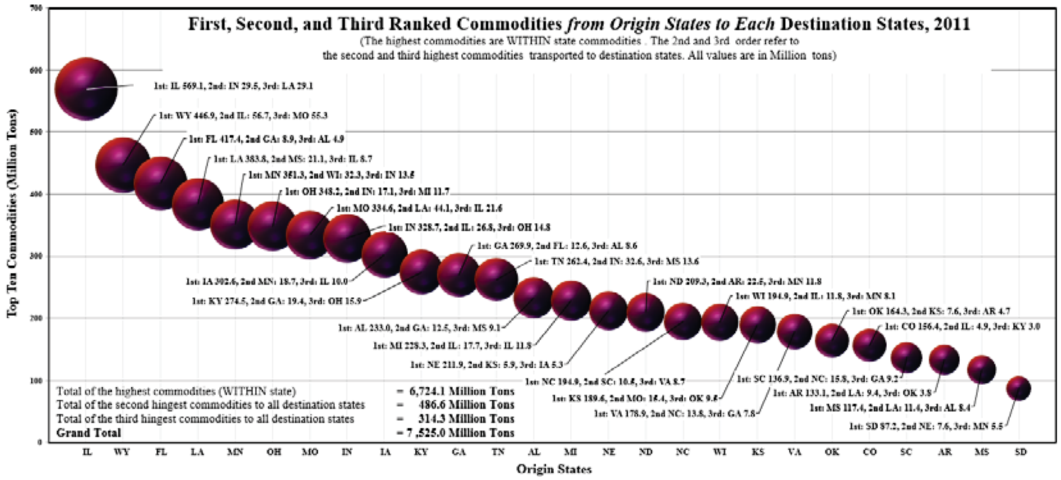


Figure 18. Top Three Coomodities from Origina States to Destinations States

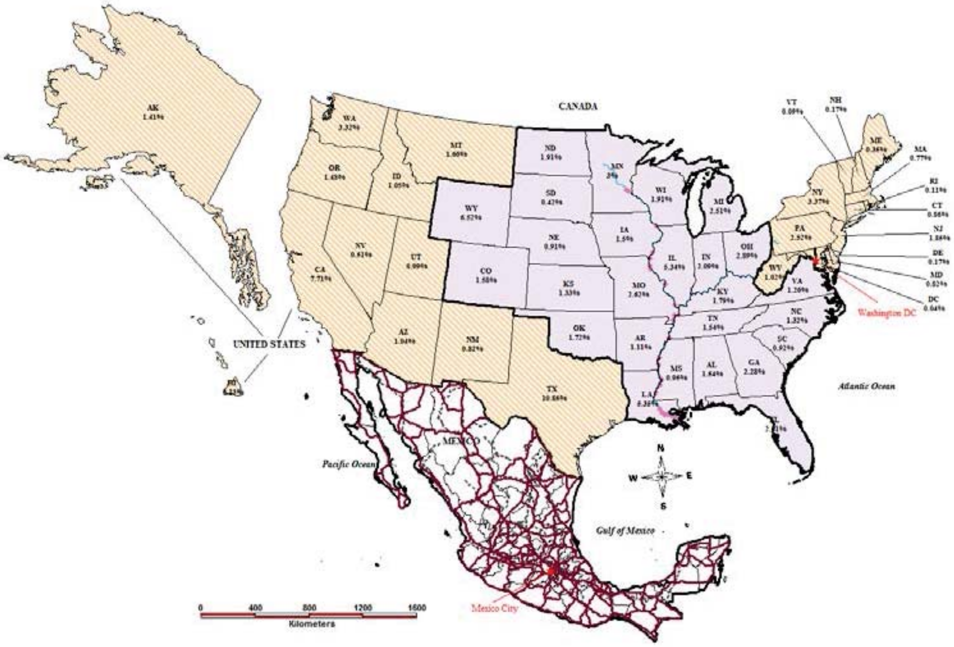


Figure 19. Spatial Map of Total Inbound and Outbound Freight for all 51 States

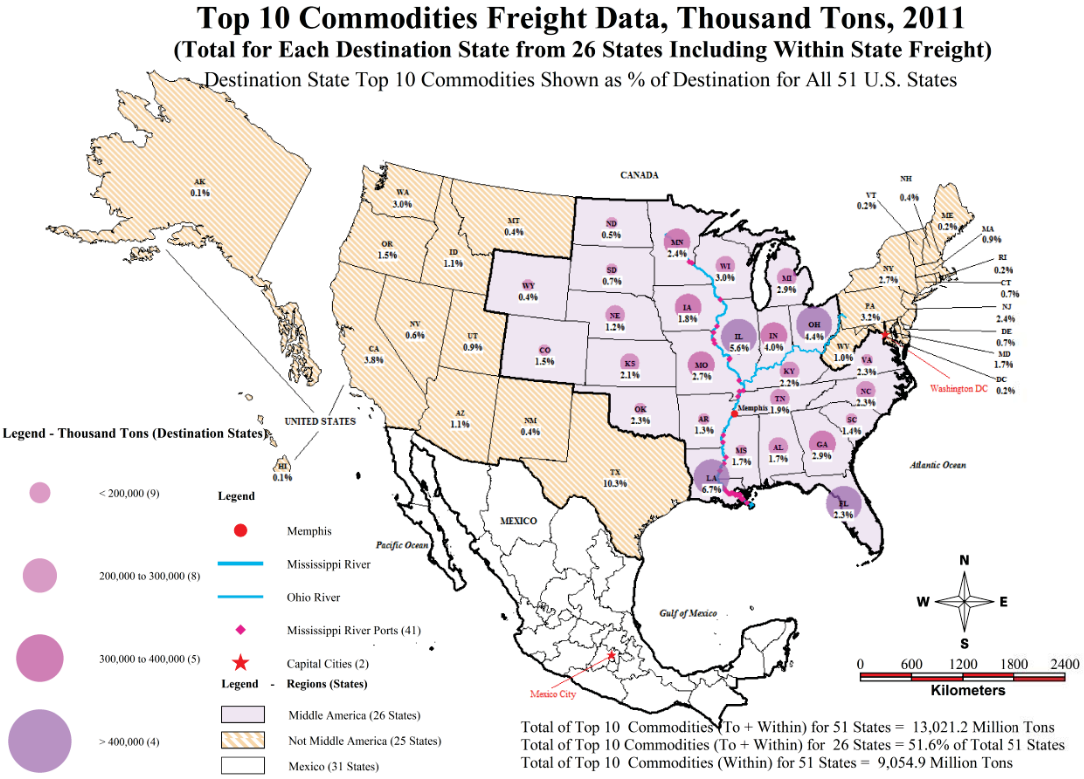


Figure 20. Spatial Map of Top 10 Commodities Flow From The Middle America States

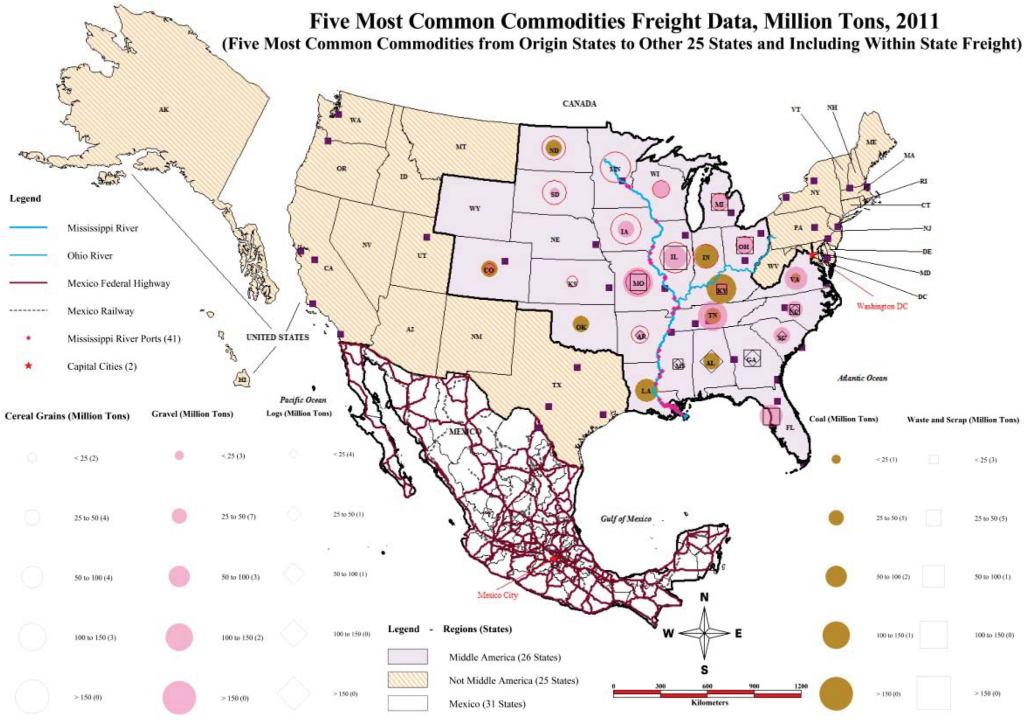


Figure 21. Spatial Map of Top 5 Commodities Flow From The Middle America States

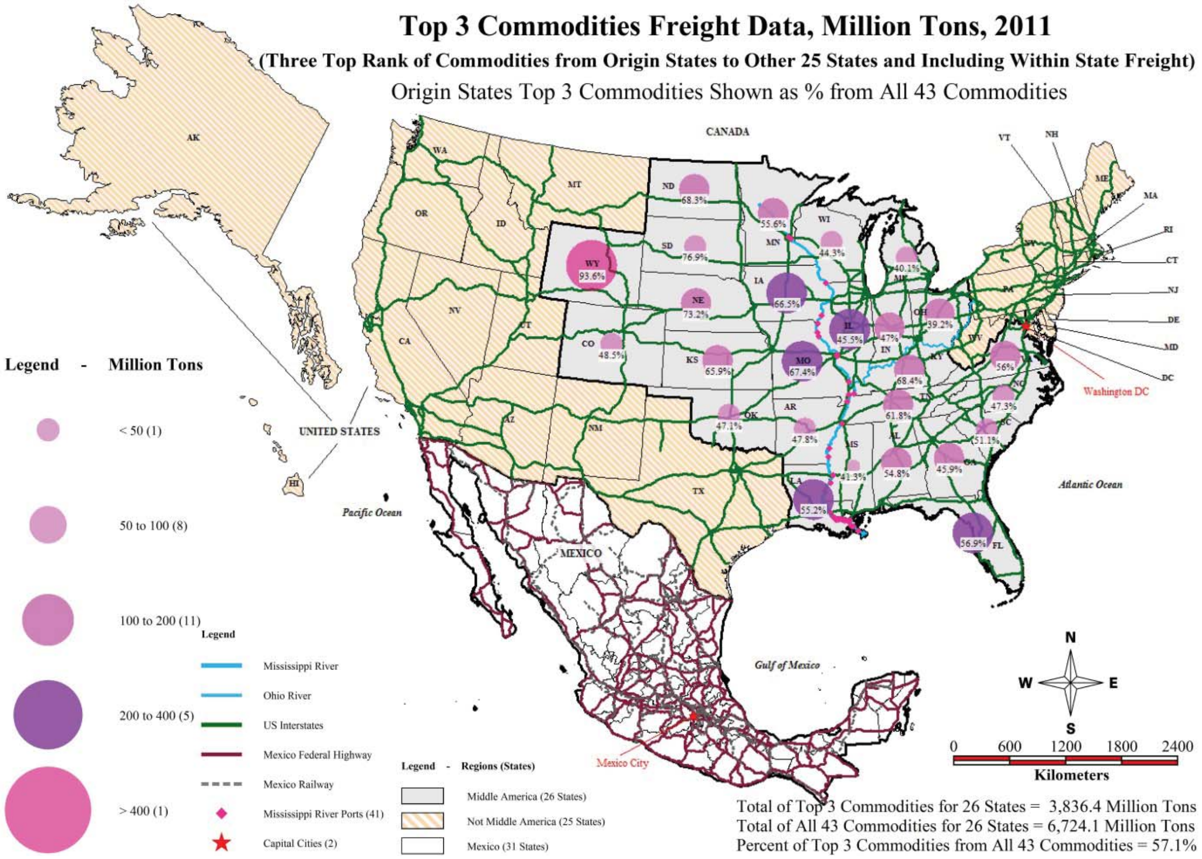


Figure 22. Spatial Map of Top 3 Commodities Flow From The Middle America States

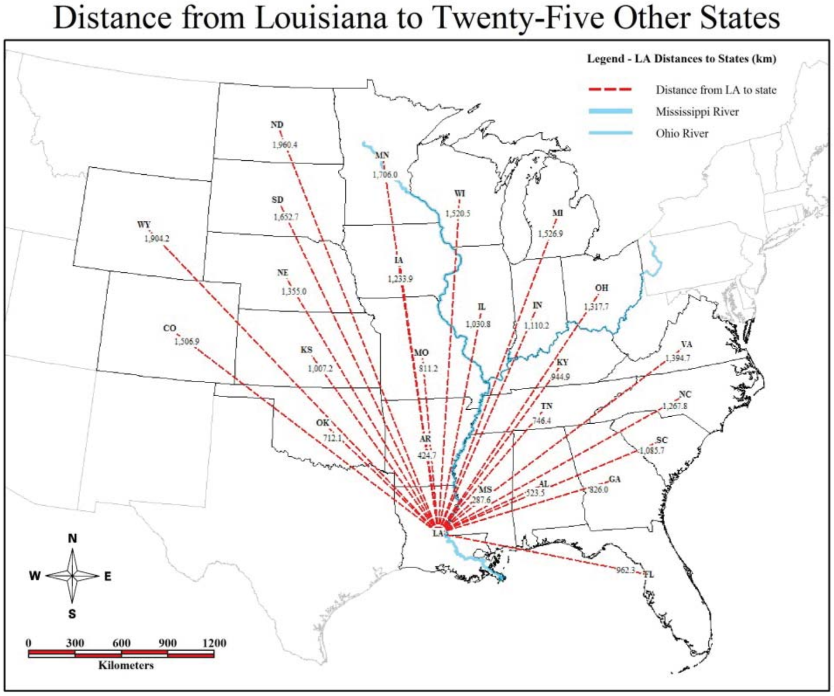


Figure 23. Spatial Map of Linear Distances from Lousiana to other 25 states

3.2 Study of Highway and Rail Corridor Integration for Colorado

Freight flow integration of major inland surface transportation modes

The commodity data maps were used for spatial analysis to identify candidate rail and highway corridors with minimum shipping distance form an origin to destination state(s). Figure 23 illustrates an example. The intermodal integration of selected freight network of highway and rail was evaluated for the least distance to optimize the least cost shipping corridors within the continental United States.

Dr. Sherry and Dr. Uddin discussed the possibility of finding out a new rail-highway intermodal corridor from Colorado intermodal terminal. Dr. Uddin directed this research through an extensive commodity flow data analysis by a PhD student. One M.S. student completed his M.S. thesis (Cobb 2015) that included mapping freight-rail intermodal and highway networks, conducting commodity analysis for opportunity to use freight rail, and analyzing two highway corridors and a freight rail line corridor for shipping electronic goods from Colorado to California. The following summary of the spatial analysis methodology is described in detail by Cobb (2015).

Commodity Flow for Colorado Freight Highway-Rail Integration Study

Colorado is located right at the center of the Midwest portion of the U.S. This allows Colorado to act somewhat as a freight hub connecting the eastern and middle U.S. to the western portion. For this reason, Colorado was chosen as a site of focus for freight traffic for this case study. Colorado could be used as a major freight hub in the freight transportation network due to its centralized location in the U.S. Commodity flow analysis with focus on non-perishable, bulk freight coming to and from Colorado.

For this purpose the FHWA Freight Analysis Framework (FAF) version 3 was extensively used. It uses classification systems to divide transported goods into commodity categories (FHWA 2016, ORNL 2015a). The ORNL web site describes FAF as follows: “The Freight Analysis Framework (FAF), produced through a partnership between BTS and FHWA, integrates data from a variety of sources to create a comprehensive picture of freight movement among states and major metropolitan areas by all modes of transportation. Starting with data from the 2012 Commodity Flow Survey (CFS) and international trade data from the Census Bureau, FAF incorporates data from agriculture, extraction, utility, construction, service, and other sectors. FAF version 4 (FAF4) provides estimates for tonnage (in thousand tons) and value (in million dollars) by regions of origin and destination, commodity type, and mode. Data are available for the base year of 2012, the recent years of 2013 - 2015, and forecasts from 2020 through 2045 in 5-year intervals” (ORNL 2016).

The FAF database uses different coding levels ranging from 2-digit codes to 5-digit codes, with 2-digit being the most general with 42 categories and 5-digit being the most detailed with 504 categories. For this analysis, the 2-digit coding system was used (Table 3), which provides an analytical overview of the freight (Census 2007). This system provides enough information to determine non-perishable, bulk materials from time-sensitive materials

Table 3. 2-Digit Standard Classification of Transported Goods (SCTG) Commodity Codes

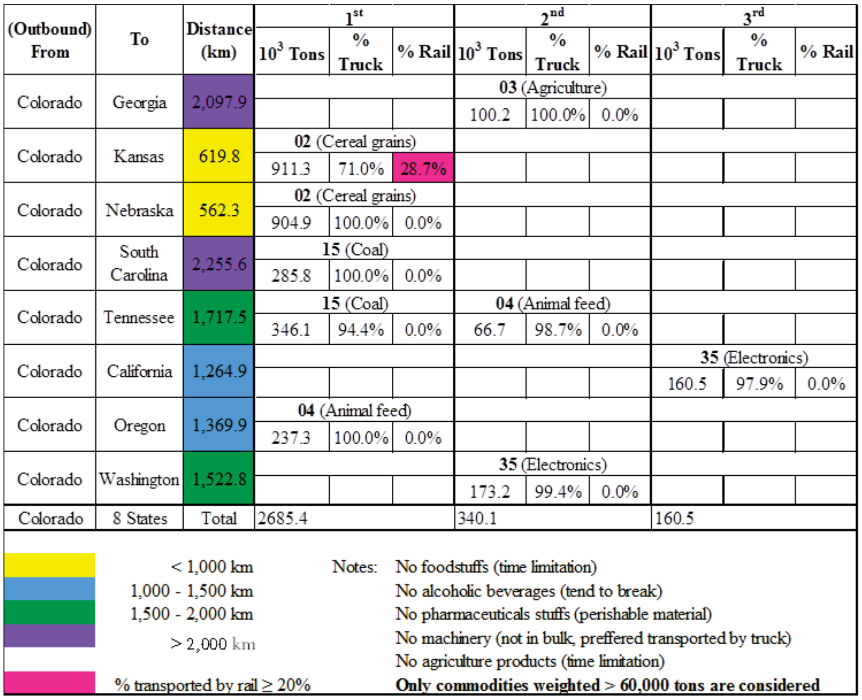
SCTG Code	Commodity	SCTG Code	Commodity
01	Live Animal, Fish	22	Fertilizers
02	Cereal Grains	23	Chemical Products and Preparations
03	Other Agricultural Products	24	Plastics and Rubber
04	Animal Feed	25	Logs and Other Wood in the Rough
05	Meat/Seafood	26	Wood Products
06	Milled Grain Products	27	Pulp, Newsprint, Paper, and Paperboard
07	Other Foodstuffs	28	Paper or Paperboard Articles
08	Alcoholic Beverages	29	Printed Products
09	Tobacco Products	30	Textiles, Leather, and Articles of Each
10	Monumental or Building Stone	31	Non-Metallic Mineral Products
11	Natural Sands	32	Base Metal in Primary or Semi-Finished Forms
12	Gravel and Crushed Stone	33	Articles of Base Metal
13	Non-Metallic Minerals	34	Machinery
14	Metallic Ores and Concentrates	35	Electronic and Other Electrical Equipment
15	Coal	36	Motorized and Other Vehicles
16	Crude Petroleum Oil	37	Transportation Equipment
17	Gasoline and Aviation Turbine Fuel	38	Precision Instruments and Apparatus
18	Fuel Oils	39	Furniture, Mattresses, Lamps, Illuminated Signs
19	Coals and Petroleum Products	40	Miscellaneous Manufactured Products
20	Basic Chemicals	41	Waste and Scrap
21	Pharmaceutical Products	43	Mixed Freight
99	Commodity Unknown		

The FAF database provides very detailed data on freight going to and from each state, separated by mode and by commodity type. Using the data, analysis was performed to determine what type of freight was leaving Colorado, by what mode it was going, and the state the freight was going to. The analysis began with the outbound freight leaving Colorado. The top three commodities going to each state from Colorado were analyzed (Figure 22) and commodities that were bulk, non-perishable items that had less than 20% going by rail were separated from the rest. Those that were greater than 20% were highlighted in magenta. The following steps were followed to identify the best state that can provide an opportunity for highway-rail integration:

- The distance from the center point of Colorado to the center point of each state was calculated and then categorized into the following categories using different highlight colors: less than 1,000 km (yellow), 1,000 km to 1,500 km (blue), 1,500 km to 2,000 km (green), and more than 2,000 km (purple).
- These distances were categorized because those goods that travel further provide greater opportunity to be moved to rail, and the color code provides an easy visual to determine further distances.
- Non-perishable bulk commodities that shipped over 60,000 tons of freight were than selected and placed into a table.

Table 4 shows the states that provide the greatest opportunity for integration between highway and rail based on the distances, the amount of freight being shipped, and which mode the freight is currently being shipped by (ORNL 2015b).

Table 4. Outbound Freight from Colorado to Surrounding States, 2011



(Outbound) From	To	Distance (km)	1st			2nd			3rd		
			10^3 Tons	% Truck	% Rail	10^3 Tons	% Truck	% Rail	10^3 Tons	% Truck	% Rail
Colorado	Georgia	2,097.9				**03** (Agriculture)					
						100.2	100.0%	0.0%			
Colorado	Kansas	619.8	**02** (Cereal grains)								
			911.3	71.0%	28.7%						
Colorado	Nebraska	562.3	**02** (Cereal grains)								
			904.9	100.0%	0.0%						
Colorado	South Carolina	2,255.6	**15** (Coal)								
			285.8	100.0%	0.0%						
Colorado	Tennessee	1,717.5	**15** (Coal)			**04** (Animal feed)					
			346.1	94.4%	0.0%	66.7	98.7%	0.0%			
Colorado	California	1,264.9							**35** (Electronics)		
									160.5	97.9%	0.0%
Colorado	Oregon	1,369.9	**04** (Animal feed)								
			237.3	100.0%	0.0%						
Colorado	Washington	1,522.8				**35** (Electronics)					
						173.2	99.4%	0.0%			
Colorado	8 States	Total	2685.4			340.1			160.5		

🟨 < 1,000 km
🟦 1,000 - 1,500 km
🟩 1,500 - 2,000 km
🟪 > 2,000 km
🟥 % transported by rail ≥ 20%

Notes: No foodstuffs (time limitation)
No alcoholic beverages (tend to break)
No pharmaceuticals stuffs (perishable material)
No machinery (not in bulk, preffered transported by truck)
No agriculture products (time limitation)
Only commodities weighted > 60,000 tons are considered

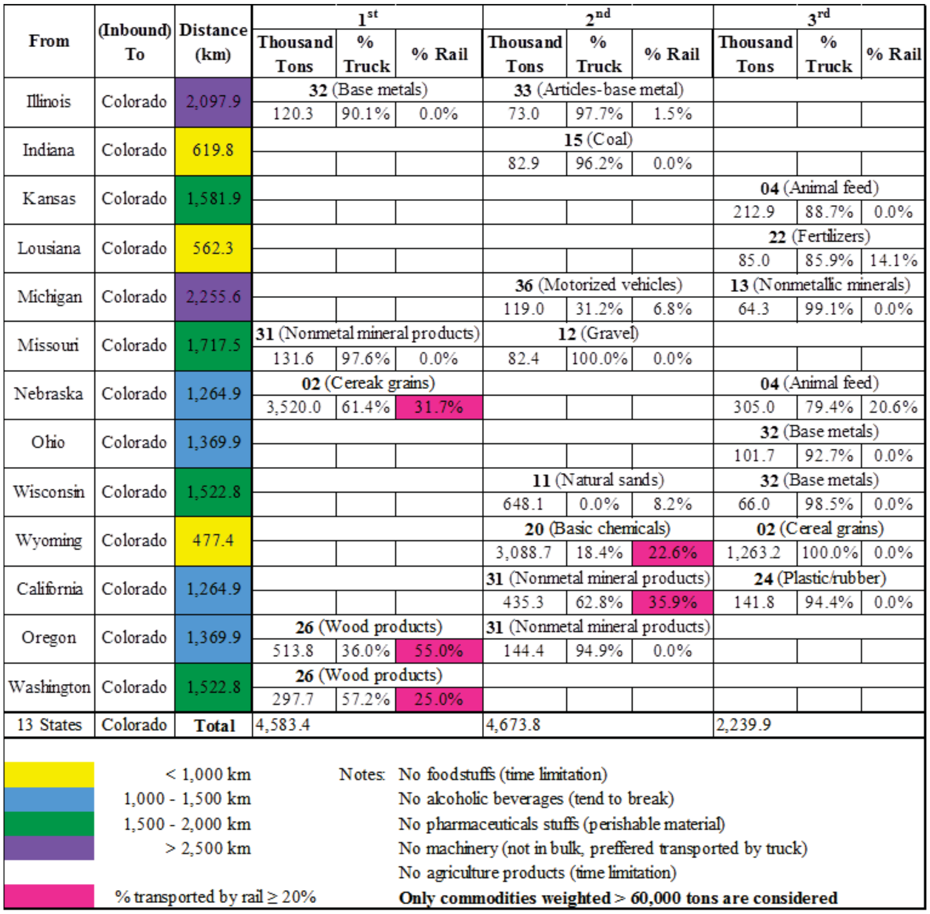
The following limitations were also placed on the types of commodity chosen:

- No foodstuffs due to time limitations.
- No agriculture products due to time limitations.
- No alcoholic beverages due to possible breaking.
- No machinery due to not being a bulk item.
- No pharmaceuticals due to being a perishable material.

There were eight states that met the criteria established for the commodity flow analysis, and those states were Georgia, Kansas, Nebraska, South Carolina, Tennessee, California, Oregon, and Washington. The commodities that provided opportunity for integration include cereal grains, coal, animal feed, electronics, and agriculture.

The same process was completed for the inbound freight coming to Colorado from surrounding states. The same criteria were used in selecting which commodities would provide the best opportunity for intermodal integration. The results of the commodity analysis can be seen in Table 5.

Table 5. Inbound Freight to Colorado from Surrounding States, 2011



From	(Inbound) To	Distance (km)	1st			2nd			3rd		
			Thousand Tons	% Truck	% Rail	Thousand Tons	% Truck	% Rail	Thousand Tons	% Truck	% Rail
Illinois	Colorado	2,097.9	**32** (Base metals)			**33** (Articles-base metal)					
			120.3	90.1%	0.0%	73.0	97.7%	1.5%			
Indiana	Colorado	619.8				**15** (Coal)					
						82.9	96.2%	0.0%			
Kansas	Colorado	1,581.9							**04** (Animal feed)		
									212.9	88.7%	0.0%
Lousiana	Colorado	562.3							**22** (Fertilizers)		
									85.0	85.9%	14.1%
Michigan	Colorado	2,255.6				**36** (Motorized vehicles)			**13** (Nonmetallic minerals)		
						119.0	31.2%	6.8%	64.3	99.1%	0.0%
Missouri	Colorado	1,717.5	**31** (Nonmetal mineral products)			**12** (Gravel)					
			131.6	97.6%	0.0%	82.4	100.0%	0.0%			
Nebraska	Colorado	1,264.9	**02** (Cereak grains)						**04** (Animal feed)		
			3,520.0	61.4%	31.7%				305.0	79.4%	20.6%
Ohio	Colorado	1,369.9							**32** (Base metals)		
									101.7	92.7%	0.0%
Wisconsin	Colorado	1,522.8				**11** (Natural sands)			**32** (Base metals)		
						648.1	0.0%	8.2%	66.0	98.5%	0.0%
Wyoming	Colorado	477.4				**20** (Basic chemicals)			**02** (Cereal grains)		
						3,088.7	18.4%	22.6%	1,263.2	100.0%	0.0%
California	Colorado	1,264.9				**31** (Nonmetal mineral products)			**24** (Plastic/rubber)		
						435.3	62.8%	35.9%	141.8	94.4%	0.0%
Oregon	Colorado	1,369.9	**26** (Wood products)			**31** (Nonmetal mineral products)					
			513.8	36.0%	55.0%	144.4	94.9%	0.0%			
Washington	Colorado	1,522.8	**26** (Wood products)								
			297.7	57.2%	25.0%						
13 States	Colorado	**Total**	4,583.4			4,673.8			2,239.9		

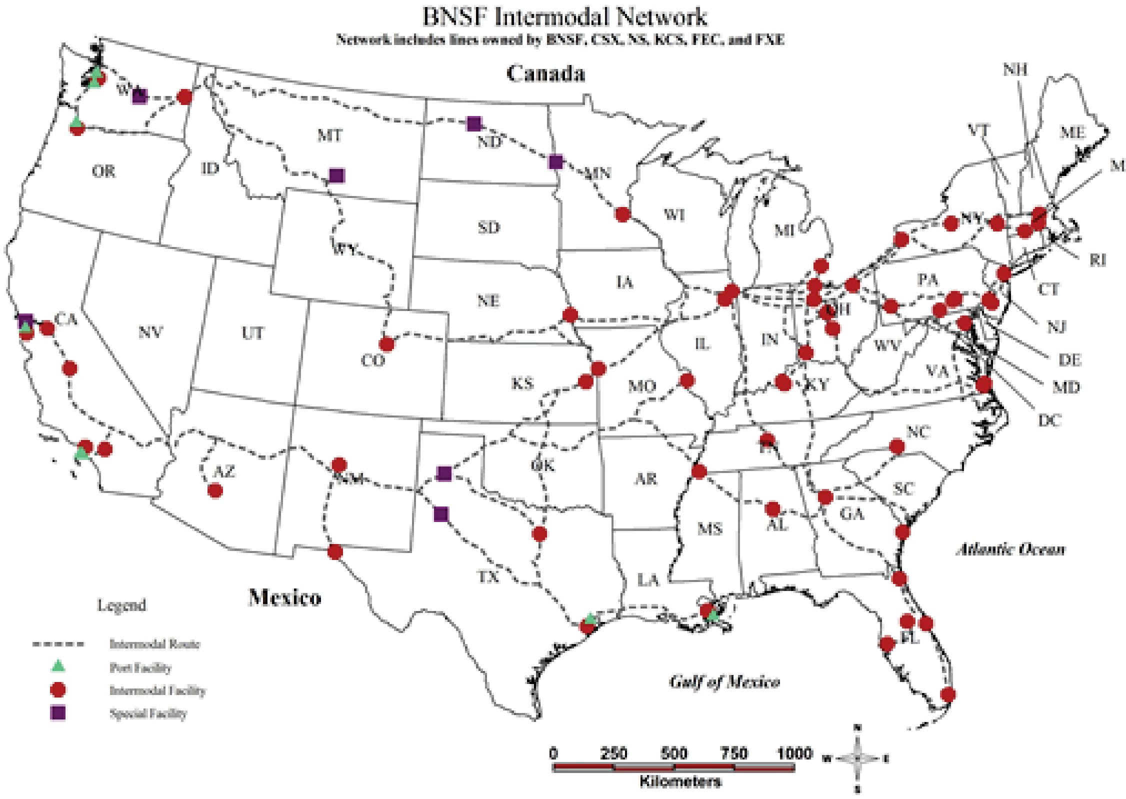
🟨 < 1,000 km
🟦 1,000 - 1,500 km
🟩 1,500 - 2,000 km
🟪 > 2,500 km
🟥 % transported by rail ≥ 20%

Notes: No foodstuffs (time limitation)
No alcoholic beverages (tend to break)
No pharmaceuticals stuffs (perishable material)
No machinery (not in bulk, preffered transported by truck)
No agriculture products (time limitation)
Only commodities weighted > 60,000 tons are considered

There were 13 states that met the criteria provided in the commodity flow analysis, and those were Illinois, Indiana, Kansas, Louisiana, Michigan, Missouri, Nebraska, Ohio, Wisconsin, California, Oregon, and Washington. The commodities shipped among these states were found to be base metals, coal, cereal grains, nonmetal mineral products, wood products, vehicles, natural sands, chemicals, gravel, animal feed, fertilizers, nonmetallic minerals, base metals, and plastic/rubber.

Geospatial Analysis to Optimize Candidate Corridors for Highway-Rail Integration

For Colorado case study, focus was on freight flow to and from Colorado and opportunities for a new intermodal line were explored. The first step for this case study was to develop a spatial map which shows an existing intermodal network that is in place. BNSF has one of the largest intermodal networks in the country, so their network was used to develop the spatial map (Figure 24). The BNSF intermodal network is made up of different rail lines throughout the U.S., including BNSF, CSX, NS, KCS, FEC, and FXE, which allows it to reach all regions of the U.S. Using the image registration and planimetrics geospatial analysis tools, the map in Figure 28 was developed. In Figure 24, the intermodal routes can be seen as grey dashed lines. Intermodal facilities are shown throughout the U.S. as red squares, and BNSF “Special-Use” facilities are shows as purple squares. All major coastal ports in the intermodal network are also shown as magenta diamonds.



Source of data: BNSF Intermodal Map.
http://www.bnsf.com/customers/pdf/maps/small-intermodal-map.pdf Accessed July 27, 2014

Figure 24. BNSF Freight Intermodal Rail Networks in the U.S.

The results from the commodity flow analysis were also used to develop additional spatial maps. for commodities 1, 2, and 3. These maps in Figures 25, 26, and 27 provide a visual representation of how freight was moving to and from Colorado. These maps show the overlay of the existing BNSF intermodal network overlaid on the map.

Figures 25, 26 and 27 show the freight distribution of top three commodities shipped to and from Colorado. The maps show beige triangles for freight shipped from Colorado to other states and purple diamonds for freight being shipped to Colorado from other states. These triangles and diamonds increase in size based on the amount of freight being shipped. These categories can be seen in the legend of the figures. The specifications for the intermodal facilities and routes remained the same as that shown in Figure 24. A green star was placed on the state of Colorado, implying that Colorado is the state of focus for this study.

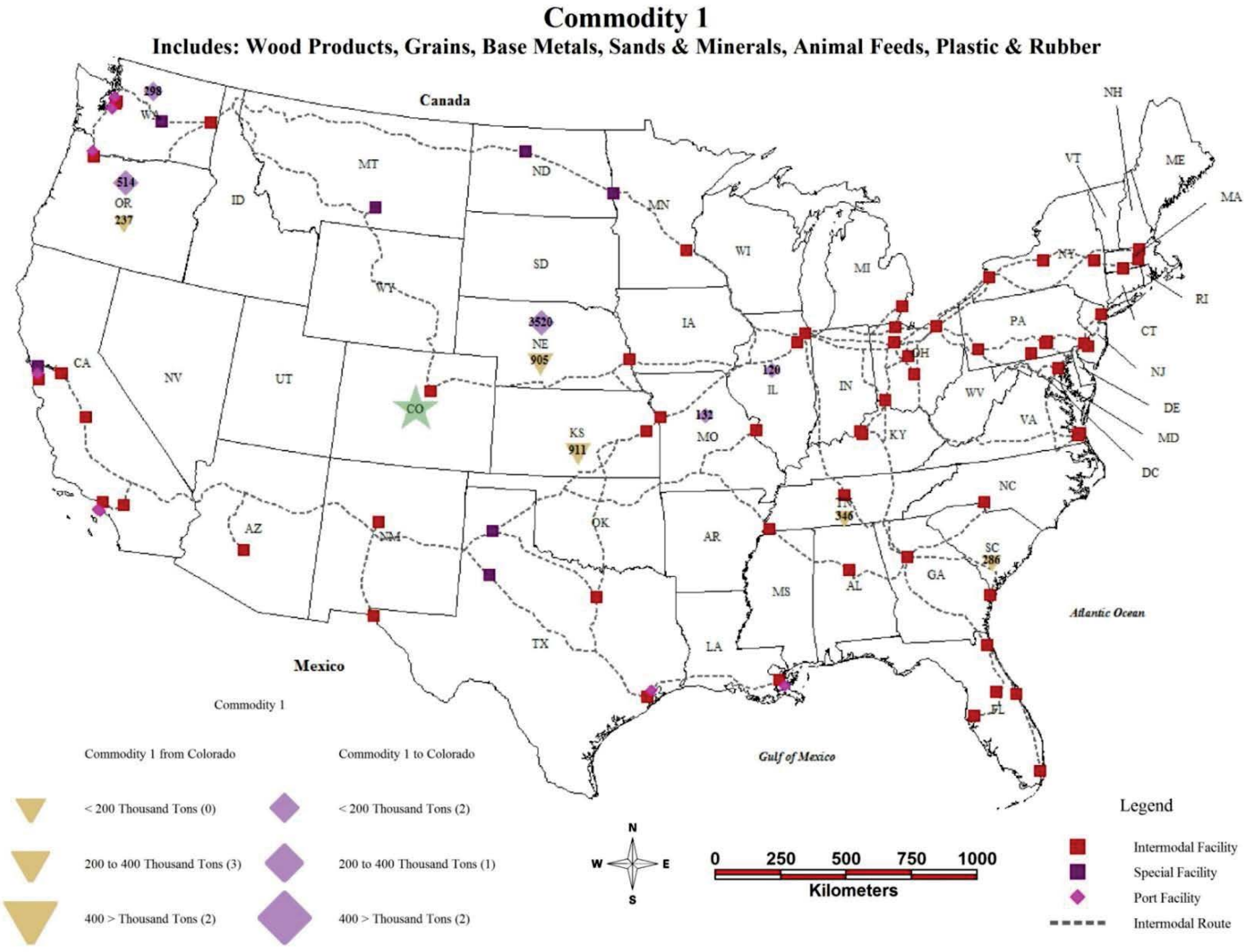


Figure 25. Freight Distribution of Commodity 1 To and From Colorado

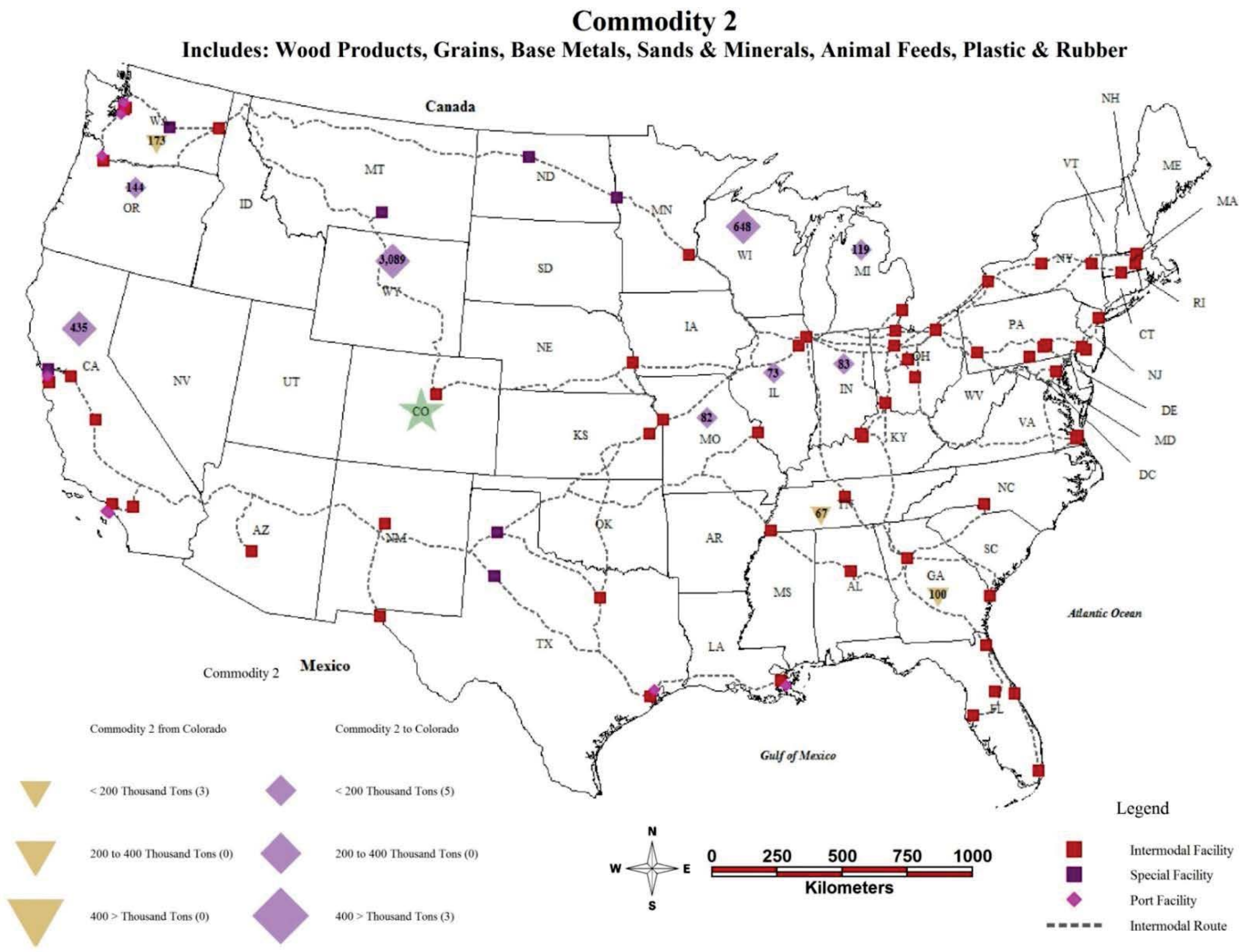


Figure 26. Freight Distribution of Commodity 2 To and From Colorado

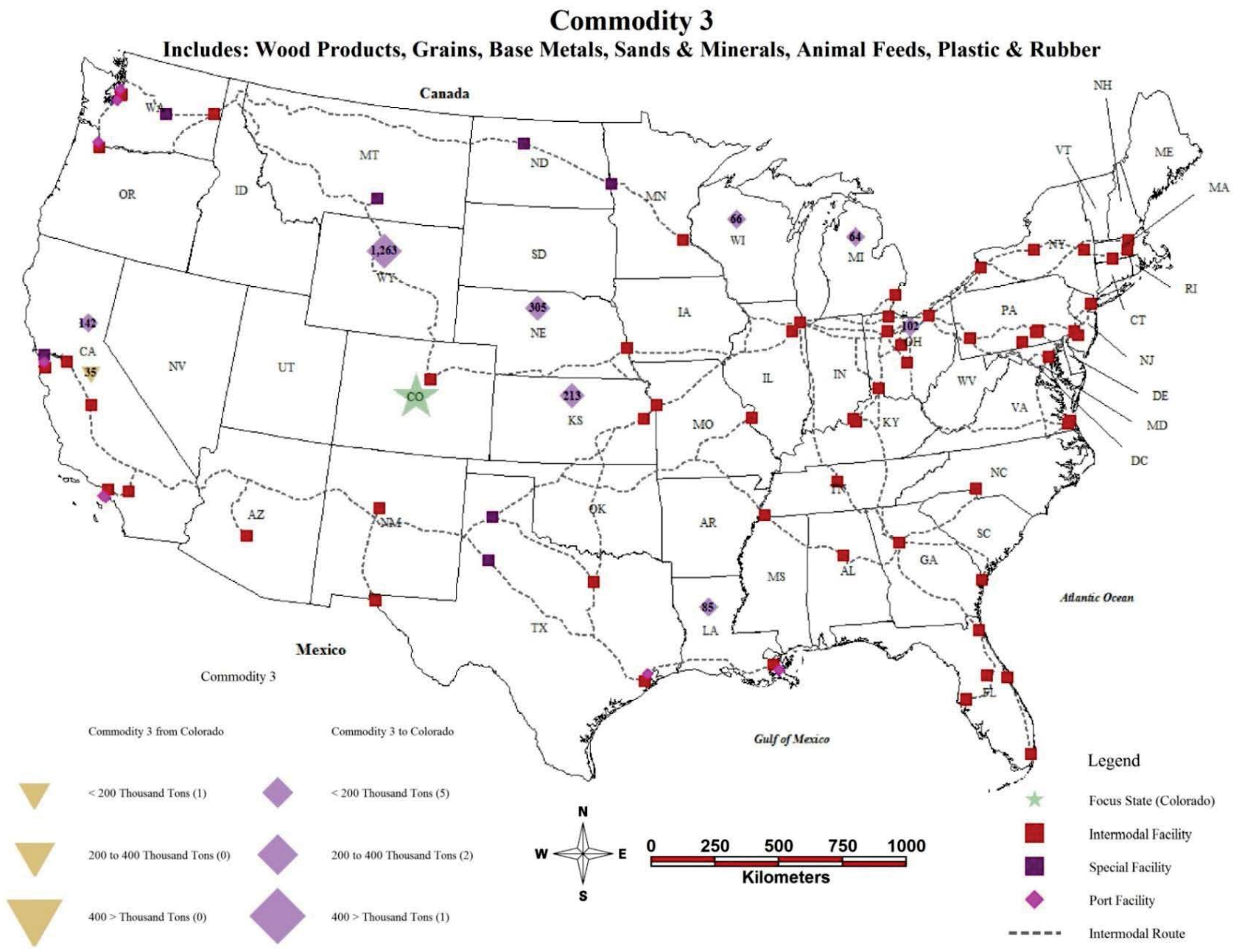


Figure 27. Freight Distribution of Commodity 3 To and From Colorado

By showing the commodity data to and from Colorado on the map with the intermodal network, the opportunities for new intermodal lines can easily be seen based on where high amounts of freight are going. The freight distributions in Figures 25, 26, and 27 show a lot of the freight going to surrounding states such as Wyoming, Nebraska, and Kansas, but due to their close proximity to Colorado, these are easy short truck hauls and are not far enough to justify moving the freight to rail. The decision criteria for route selection included shipping non-perishable commodities and the route must be minimum 500 miles in length. Some opportunity was also shown for intermodal integration to Washington and Oregon, but the infrastructure is in place and already ships much of the freight to this location by rail. There remain two opportunities for intermodal integration and the opening of a new intermodal line which are to Wisconsin and to California. Due to the time constraints, only one corridor analysis was performed, and that was for California. Future work may include performing the benefit analysis of opening an intermodal line directly to Wisconsin if not planned already by the rail industry.

Once the opportunity for integration was found, possible highway and rail routes were determined. This was done by using spatial analysis with the NHS and AAR Freight Rail maps. Using these maps, two highway routes and one rail route were found using infrastructure already in place that would run directly to a major freight hub in California. The routes selected run directly from Denver, CO, to Oakland, CA. Oakland, CA, is home to two intermodal facilities, a major port facility, and also a special-use facility. Economic analysis was performed for each highway route and for the rail route to determine the benefits of diverting a portion of freight from highway trucks to rail freight cars.

Figure 28 shows the spatial maps of the proposed corridor routes for economic analysis. The intermodal network to which the proposed rail line would be added is shown along with the entire Eisenhower Interstate System. This is done to show how the routes were selected and fit into the current transportation systems. The two proposed highway routes for study are shown in the pink diagonal buffer zone. The routes are labelled “North Route” and “South Route” based on where they are located with respect to the rail line. The proposed line selected from the AAR freight rail network to be added to the BNSF intermodal network is highlighted in a light green dashed line.

Figure 29 provides a visually simple spatial map of just the proposed corridor routes without other existing highway and rail infrastructure features. These proposed corridors in Figures 28 and 29 provide direct shortest routes from Colorado to California which are lacking in the existing intermodal network. Other possible routes will be not viable because of longer route length. The proposed northern highway corridor consists of portions of I-25 and I-80, and stretches 1,231 miles. The southern highway corridor includes parts of I-70, I-15, I-80, US-50, US-6, and US-50. The southern corridor is slightly shorter than the northern route at 1,201 miles.

The proposed rail corridor is owned by Union Pacific railroad and is 1,353 miles in length, making it the longest of the three routes (Table 6).

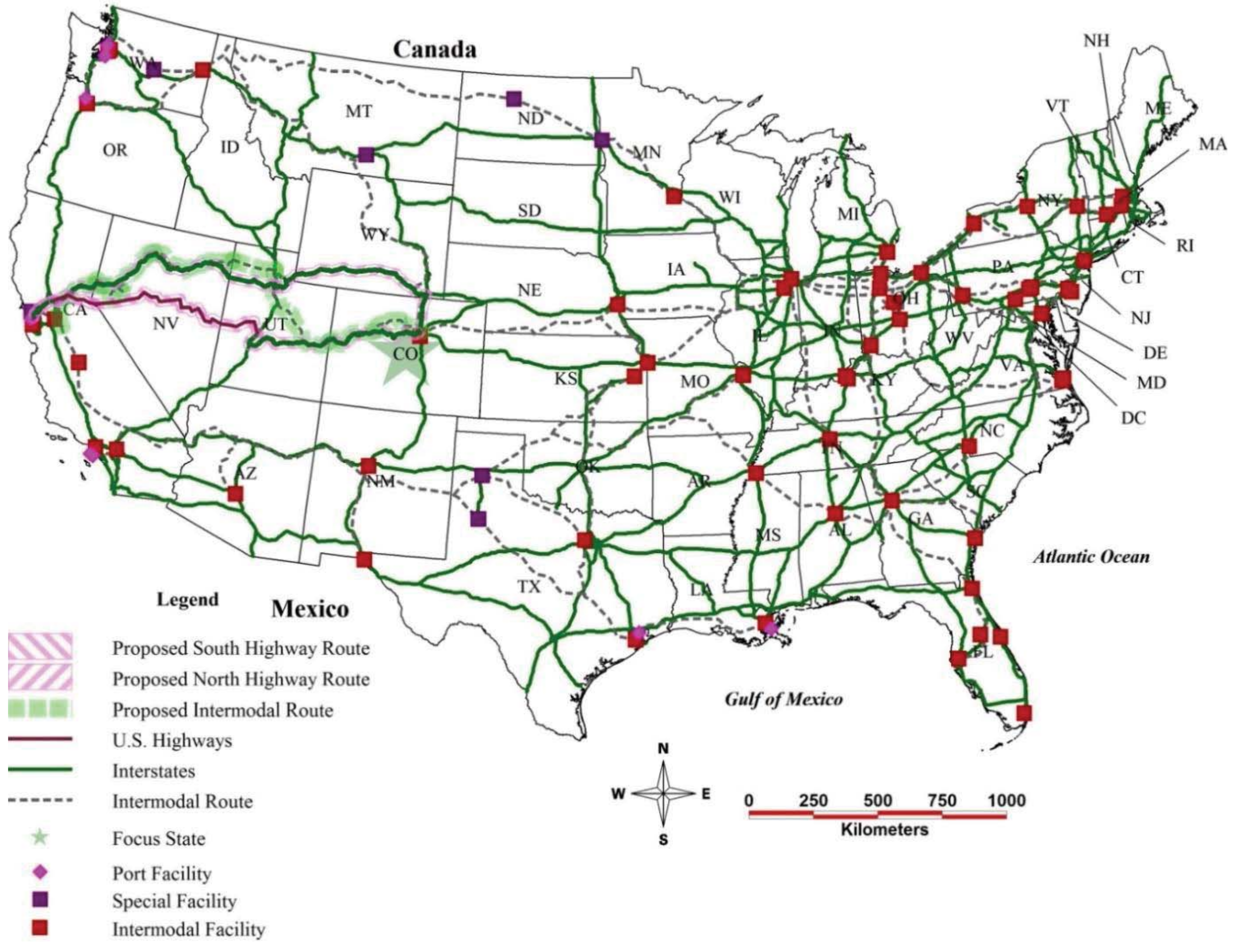


Figure 28. Spatial Map of Proposed Highway and Rail Routes from Colorado to California

Table 6. Proposed Route Lengths from Colorado to California

Route	Length (miles)
Highway Freight Route – North	1,231
Highway Freight Route – South	1,201
Proposed Intermodal Rail Route	1,353

From the freight distribution maps, it was determined that 612,000 tons of bulk, non-perishable electronic equipment freight was traded between Colorado and California in 2013. Benefits were calculated for moving different percentages of this freight from highway to rail. The following costs and benefits were calculated for this case study.

- Travel Time Savings
- Ton-Mile Costs and Savings
- CO_2 Emission Reduction
- Fuel Savings

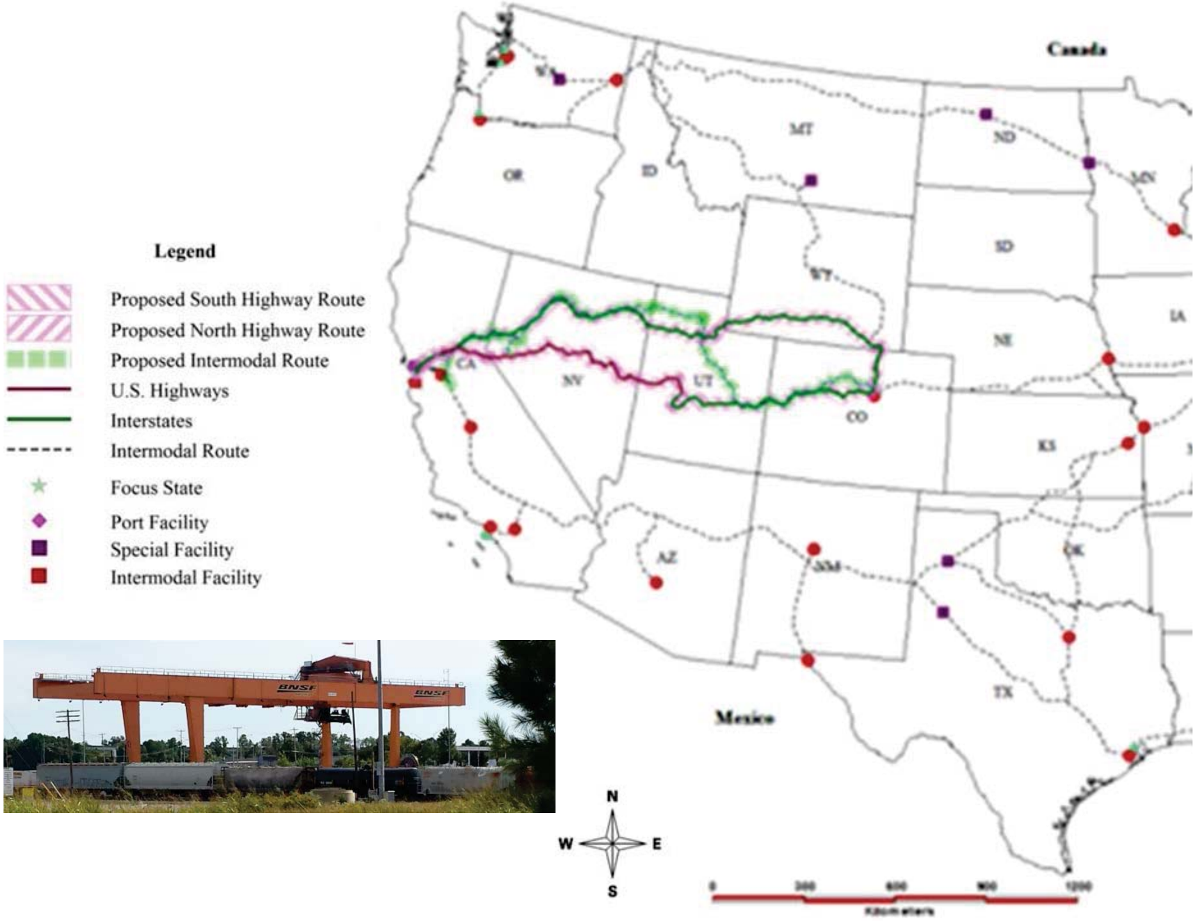


Figure 29. Spatial Map of Proposed Routes without Other Existing Infrastructure

Fuel Consumption Rates and Unit Costs Used for Economic Analysis of Truck and Rail
In the calculation of these benefits and savings, some average unit cost values were used, as listed in Tables 7 and 8. Table 7 shows the average net freight ton-miles per gallon of diesel fuel for truck, rail, and barge. These values are used in the calculation of CO_2 emissions. Table 8 shows the average ton-mile cost in cents for truck, rail, and barge. Both tables show truck to have the highest ton-mile cost with the lowest net freight ton-miles per gallon of diesel. They also show the barge to have the lowest ton-mile cost with the highest net freight ton-mile per gallon. These values are used in the total ton-mile cost savings calculations.

Table 7. Net Freight Ton-Mile per Gallon of Diesel by Mode (MODOT 2012)

Mode	Net Freight (Ton-Mile)per Gallon of Diesel
Truck	155
Rail	413
Barge	576

Table 8. Average Ton-Mile Cost (Cents) by Mode (BTS 2012, MODOT 2012)

Mode	Average Ton-Mile Cost (Cents)
Truck	34.39
Rail	3.95
Barge	2.17

(a) Travel Time Savings

Trips were calculated using Equation 3, and travel time per trip was calculated using Equation 4. These calculations are made to compare the travel time savings from moving 30% of the total bulk, non-perishable freight shipped between Colorado and California along the three routes.

$$\text{Number of Trips} = \frac{\text{Total Freight (Tons)}}{\text{Capacity (Tons per Vehicle)}} \qquad \text{Eq. 3}$$

$$\text{Travel Time per Trip (hrs)} = \frac{\text{Length (miles)}}{\text{Speed (mph)}} + \text{Time for Stops (hrs)} \qquad \text{Eq. 4}$$

The following freight data and several assumptions were used in calculating the travel time for the two highway routes and one rail corridor selected between Colorado and California.

- Total Freight Amount: 612,000 Tons
- 30% of Freight Moved to Rail: 183,600 Tons
- Assumptions for Base Scenario Trucks:
  - 25-Ton Truck Capacity
  - 55 mph Average Speed
  - 8 hours of stops for rest, fuel, and food per trip.
- Assumptions for Rail Scenario:
  - 100-Ton Rail Car Capacity
  - 25 mph Average Speed
  - 4 hours of stops for rest, fuel, and food per trip.
  - 10 cars per train trip dedicated to freight moved to rail from highway.
  - Train car carries 4.4 truckloads, 44 cars per train trip.

Using the data above, the following calculations were made for each of the proposed corridors:

- North Highway Freight Route: Travel Time Calculations
    - Total Number of Truck Trips 30% of Total Freight between CA and CO (Eq. 3):
      183,600 Tons/25 Tons per Truck = **7,344 Trips**
    - Total Time taken per Truck to Travel from CA to CO (Eq. 4):
      (1,231 Miles/55 mph) + 8 hours (stops, fuel, food) = **30.4 hours per Truck Trip**
    - Total Travel Time for 7,344 Truck Trips (30% of Freight):
      (30.4 hours x 7,344 Trips) (Travel) + (8 hours x 7,344 Trips) (Stops) = **223,111 Hours**

- South Highway Freight Route: Travel Time Calculations
    - Total Number of Truck Trips 30% of Total Freight between CA and CO (Eq. 3):
      183,600 Tons/25 Tons per Truck = **7,344 Trips**
    - Total Time taken per Truck to Travel from CA to CO (Eq. 4):
      (1,201 Miles/55 mph) + 8 hours (stops, fuel, food) = **29.8 hours per Truck Trip**
    - Total Travel Time for 7,344 Truck Trips (30% of Freight):
      (29.8 hours x 7,344 Trips) (Travel) + (8 hours x 7,344 Trips) (Stops) = **219,118 Hours**

- Proposed Rail Intermodal Route: Travel Time Calculations
    - Total Number of Rail Trips for 30% of Total Freight from CA to CO (Eq. 3):
      (183,600 Tons/110 Tons per rail car)/44 Cars per Train Trip= **42 Trips**
    - Total Time taken per Truck to Travel from CA to CO (Eq. 4):
      (1,353 Miles/25 mph) + 4 hours (stops, fuel, food) = **58.1 hours per Truck Trip**
    - Total Travel Time for 7,344 Truck Trips (30% of Freight):
      (58.1 hours x 42 Trips)(Travel) + (4 hours x 42 Trips)(Stops) = **2,436 Hours**

Total travel time saving by using rail for sipping 30% freight is 216,682 Hours or 98.9% compared to shorter truck trips on South Highway route.

(b) Ton-Mile Costs and Savings

Total ton-mile cost was calculated using Equation 5. Average ton-mile costs for each surface mode shown in Table 8 were also used in the following ton-mile cost calculations.

$$\text{Ton} - \text{Mile Cost per Year (\$)} = (\text{Tonnage x Length})\text{x}\left(\frac{\text{Average Ton}-\text{Mile Cost (Cents)}}{100}\right) \qquad \text{Eq. 5}$$

- North Highway Freight Route: Ton-Mile Cost Calculations
    - Total Ton-Mile Cost for Trucks Carrying 30% of Total Freight (Eq. 5):
      (183,600 Tons x 1,231 Miles) x (34.39 cents/100) = **$259 Million**
- South Highway Freight Route: Ton-Mile Cost Calculations
    - Total Ton-Mile Cost for Trucks Carrying 30% of Total Freight (Eq. 5):
      (183,600 Tons x 1,201 Miles) x (34.39 cents/100) = **$253 Million**
- Proposed Rail Intermodal Route: Ton-Mile Cost Calculations

- Total Ton-Mile Cost for Rail Carrying 30% of Total Freight (Eq. 5):

(183,600 Tons x 1,353 Miles) x (3.95 cents/100) = **$33 Million**

Savings in freight cost by using rail for sipping 30% freight is $220 Million or 87% compared to shorter truck trips on South Highway route.

(c) CO_2 Emission Reduction

CO_2 emissions were calculated using Equation 6 (Uddin 2012). Also, the net freight ton-miles per gallon values from Table 7 were used in these calculations. According to the U.S. Environmental Protection Agency (EPA), the average CO_2 emissions per gallon of diesel fuel are 22.2 lbs/gal (EPA 2005, Uddin 2012).

$$\mathrm{CO_2\ Emissions\ (Tons)} = \left(\frac{\mathrm{Tonnage\ x\ Length\ (Miles)\ x\ Emissions\ per\ Gal\ of\ Diesel}\left(\frac{\mathrm{lb}}{\mathrm{gal}}\right)}{\mathrm{Net\ Freight\ Ton{-}Miles\ per\ Gallon}\ \left(\frac{\mathrm{Ton{-}Mile}}{\mathrm{Gal}}\right)}\right)/2000\ \mathrm{lb} \qquad \text{Eq. 6}$$

- <u>North Highway Freight Route:</u> CO_2 Emission Calculations
  - CO_2 Emission for Trucks Carrying 30% of Total Freight (Eq. 6):
    (183,600 Tons x 1,231 Miles x 22.2 lbs/gal / 155 Ton-Miles/gal)/2000 lbs = **53,947 Tons**
- <u>South Highway Freight Route:</u> CO_2 Emission Calculations
  - CO_2 Emission for Trucks Carrying 30% of Total Freight (Eq. 6):
    (183,600 Tons x 1,201 Miles x 22.2 lbs/gal / 155 Ton-Miles/gal)/2000 lbs = **52,636 Tons**
- <u>Proposed Rail Intermodal Route:</u> CO_2 Emission Calculations
  - CO_2 Emission for Rail Carrying 30% of Total Freight (Eq. 6):
    (183,600 Tons x 1,353 Miles x 22.2 lbs/gal / 413 Ton-Miles/gal)/2000 lbs = **22,250 Tons**

Reduction in CO_2 emissions by using truck-barge intermodal for shipping 30% freight is 30,386 Tons or 57.7% compared to shorter truck trips on South Highway route.

(d) Fuel Cost Savings for Colorado/California Corridor

Another indirect benefit of intermodal integration is fuel cost savings from diverting trucks from highways to other fuel efficient modes. This savings was calculated for each case study using Equation 7, as follows:

$$\mathrm{Fuel\ Cost\ Savings\ per\ Truck} = \left(\frac{\mathrm{Route\ Length}}{\mathrm{Fuel\ Efficiency}}\right)\mathrm{x\ Fuel\ Cost} \qquad \text{Eq. 7}$$

According to Uddin (2012), the average fuel efficiency for a diesel engine heavy duty truck is 5.9 miles per gallon. The fuel cost for these calculations used $2.50 per gallon at the general market price in 2015. Although diesel prices may be slightly higher, the larger the increase in price, the more the amount of savings will increase.

Using Equation 7, by diverting 30% of the non-perishable, bulk freight between Colorado and California from highway to rail, there will be a significant savings in fuel cost. By diverting 30% of truck freight from the North highway route, \$522 per truck can be saved; and by diverting 30% of freight form the South highway route, \$509 per truck can be saved. The total savings for integration each highway route with rail is shown in Table 9.

Table 9. Fuel Cost Savings from Diverting 30% of Freight from Highway Corridors

Route	Total Fuel Cost Savings for Intermodal integration
Highway Freight Route – North	\$3,830,394
Highway Freight Route – South	\$3,737,349

Key Results of Colorado Freight Study

Based on the results from the calculations, significant savings can be observed by moving just 30% of the total non-perishable, bulk freight from highway to rail between Colorado and California. Table 10 shows the two probable highway routes that would be taken between the two states and one proposed rail route for freight to be moved to. This table includes the lengths of each route in miles, the total freight shipped between Colorado and California, and the ton-miles for each of the routes.

Table 10. Proposed Corridor Data

Route	Length (miles)	Freight between CA and CO (Tons)	Ton-Miles
Highway Freight Route – North	1,231	183,600	225,993,240
Highway Freight Route – South	1,201		220,503,600
Proposed Intermodal Route	1,353		248,355,720

Based on the results summarized in Table 11, the rail intermodal route showed a significant reduction in travel time per year at just over 2,400 hours, where the highway routes were each well over 219,000 hours. This is due to such a small capacity of the trucks causing the need to make many more truck trips, whereas the rail cars have a much larger capacity. Therefore there is no need to make near as many trips as the trucks. Ton-mile costs to move 30% of the proposed freight amount were also significantly lower for the rail route at just \$33 million, whereas both highway routes were over \$252 million. The CO_2 emissions for the rail route were 22,250 tons of CO_2 at 42% of that of the highway route. The highway routes both emitted just over 52,600 tons of CO_2 each.

Table11. Summary of Colorado Corridor Results for 30% Annual Freight

Route	Total Ton-Mile Cost, Million $	Total Travel Time per Year (hours)	Total CO_2 Emissions per Year (Tons)
Highway Freight Route – North	$259	223,111	53,947
Highway Freight Route – South	$253	219,118	52,636
Proposed Rail Intermodal Route	$33	2,436	22,250

A plot of the travel time and CO_2 emissions for each route can be seen in Figure 30.

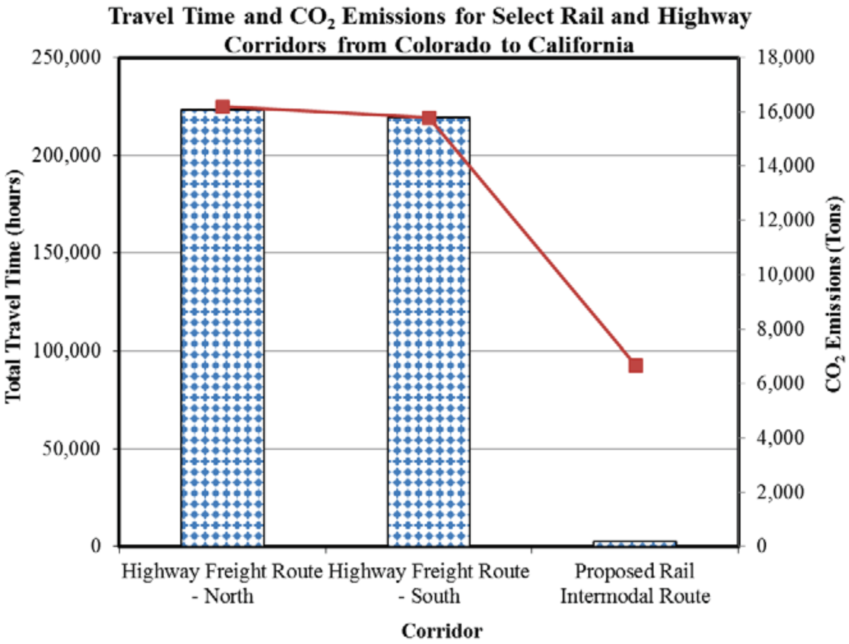


Figure 30. Highway Corridors vs. Rail Intermodal Route from Colorado to California

Discussion

Cost reductions and benefits for 30% trucks diverted to rail from the shorter highway route (South) are:

Travel Time Reduction	Ton-Mile Cost Savings	CO_2 Reduction	Fuel Savings
98.9%	87%	57.7%	$3,737,349

The same results are valid for diverting 10, 20, or 100% of freight to rail shipping. These cost-benefit calculations determined that the proposed intermodal rail route provides a good opportunity for utilizing the existing rail line for diverting a portion or all of selected freight between Colorado and California. Future research work may include performing the cost-benefit analysis of opening an intermodal line directly to Wisconsin if not planned already by the rail industry.

Based on the study results, the commodity flow analysis shows opportunity to divert some freight to rail between Colorado and California. By utilizing existing rail infrastructure, there would be a significant reduction in total travel time, total ton-mile cost, CO_2 emissions, and fuel costs. Rail is a slower alternative, so by shipping non-perishable, bulk freight, time would be not an issue.

3.3 Study of Highway and Rail Corridor Integration for NAFTA Freight

NAFTA Freight Flow and Surface Transportation Infrastructure

Dr. Uddin reviewed the final report prepared by the Mexican transportation expert consultant, Dr. Víctor Torres- Verdin, who provided the freight data on Mexican border ports and transportation infrastructure databases associated with NAFTA's corridors. This data was used to generate geospatial maps of international bridges on US-Mexico border and road/rail infrastructure. Dr. Uddin and the primary MS graduate student with assistance from one PhD student and two UG students conducted further spatial analysis to evaluate benefits of highway-rail intermodal integration. Figure 31 shows the ports on both the north and south borders and the top border ports of commodity flow at the Canadian and Mexican borders.

Synthesis of NAFTA Freight Flow Data and Spatial Analysis for Candidate Corridors

Today, NAFTA is a key player to U.S. trade and economy. The North American NAFTA trilateral trade pact, established in 1994, celebrated its 20th anniversary oin 2014 and the following is a brief summary of its trade impacts (Wilson Center 2014, CEC 2011):

- The United States trade 57% with Canada and 43% with Mexico: $2.4 million every minute of every day, $3.4 billion every day of every year, total $1,251 billion annual.
- Canada trade 95% with The United States and 5% with Mexico: $1.4 million every minute of every day, $2 billion every day of every year, total $740 billion annual.
- Mexico trade with 96% with The United States and 4% with Canada: $1.1 million every minute of every day, $1.6 billion every day of every year, total $572 billion annual.
- NAFTA serves North America and Mexico: 470 million Population, $19.2 trillion U.S. dollars Gross Domestic Product, 26 percent of Global GDP, and $41,000 U.S. dollars GDP per Capita.

NAFTA's economy has a combined output of $17 trillion. In 2008, the U.S. traded $919.9 billion with NAFTA partners, and 25.1 million jobs have been created from 1993 to 2008 as a result of NAFTA (NAFTA 2012). Other freight mode data of US NAFTA related and north-south freight transportation corridors is as follows (CEC 2011):

- Regarding modal shares, in 2008
    - Trucks moved 33% of tonnage of total land trade imports
    - Rail moved 32%
    - Pipelines accounted for 35%

- Trucks transported a larger percentage of the tonnage of US land imports from Mexico (74%) than from Canada (25%)
- In 2008, rail transported 24% of the tonnage of land imports from Mexico and 33% from Canada.

The commodity flow analysis focuses on freight imported into the U.S. from Mexico and also provides commodity flow through the top ten border ports on the Mexican border by tonnage and dollar value. Figure 31 shows a tri-country spatial map created to display the locations of existing NAFTA ports along the Mexican and Canadian borders. The underlying legend displays the 2010 population in each of the states in the U.S. The blue bubbles show how many Canadian border ports are in each U.S. state along the Canadian border, and the green shows how many ports are in each state along the Mexican border.

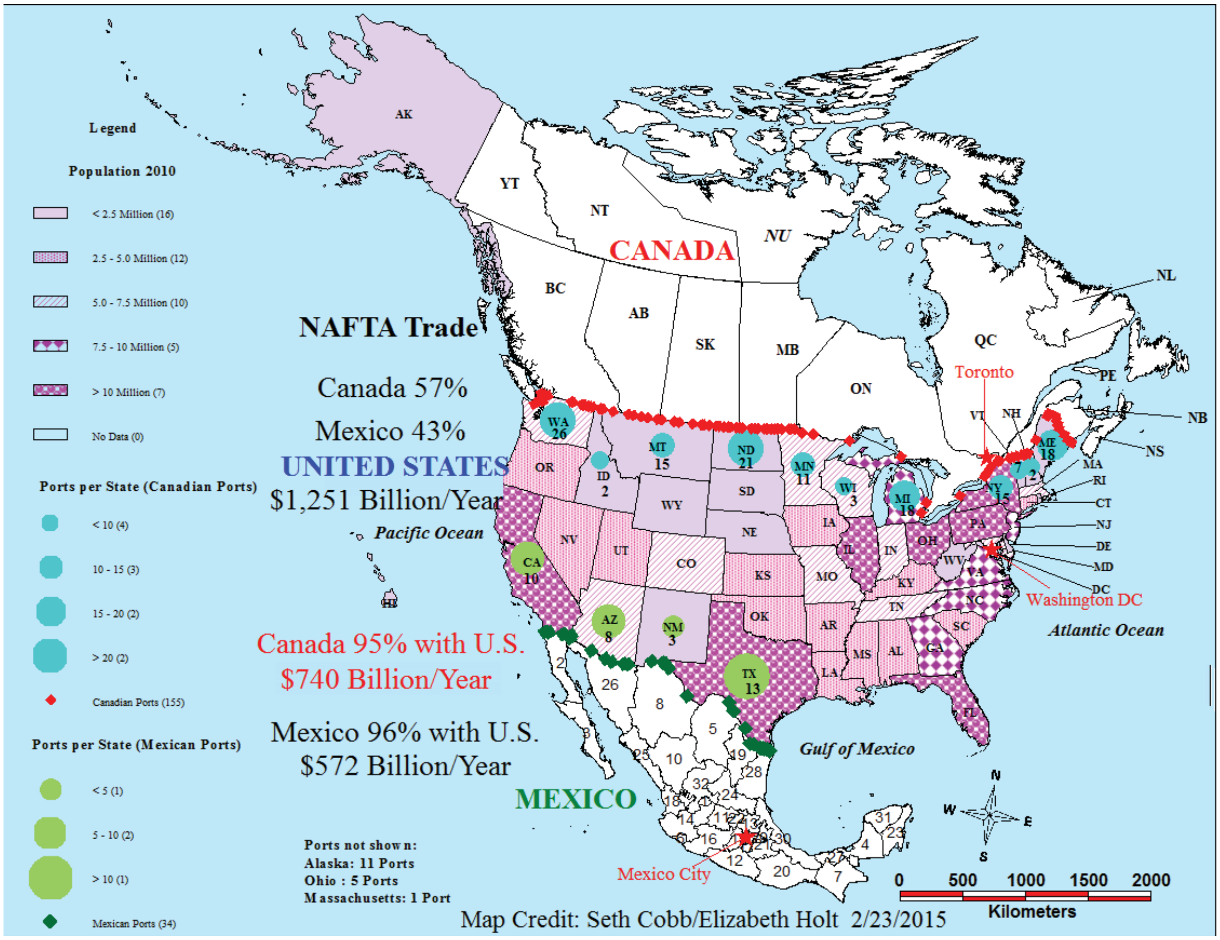


Figure 31. Spatial Map of Existing U.S./Mexico and U.S./Canada Border Ports

From Figure 31, it can be seen states that have larger populations contain more border ports. The largest on the Mexican border was Texas, containing 13 border ports followed by California with 10. Along the Canadian border, Washington contains the most border ports at 26. From this map, it can be seen where freight is coming into the U.S. and where it is coming in large volumes. The map also shows how much of each country's total trade is shared among partners. For Mexico, 96% of its' total NAFTA trade was with the U.S. and was valued at $572 billion in 2013. Canada traded 95% of its' total NAFTA trade with the U.S. and was valued at $740 billion in 2013.

Figure 32 shows the top ten ports on the Mexican border in terms of tonnage of freight passing through on truck or rail (BTS 2013). The figure also shows the percentage of total truck and rail freight that the port accounts for. From Figure 32, out of just over 50 million tons imported into the U.S. from Mexico, it can be seen that the Laredo, TX, border port accounted for a large majority of the freight imported on truck and rail at 39.2% in 2013. The Eagle Pass, TX, border port accounted for the next highest at 11.15%, followed by Nogales, AZ, at 10.83%. Figure 33 is a similar plot showing value of imported freight rather than weight (BTS 2013). In 2013, roughly $226 billion worth of goods were imported into the U.S. from Mexico via truck and rail. The Laredo, TX, border port led all 34 ports with 40.5% of this value passing through. The El Paso, TX, border port was a distant second at 15.01% and the Otay Mesa port in third at 10.13%. From Figures 32 and 33, it can be seen that Laredo, TX, is the primary hub for freight entering the U.S. from Mexico.

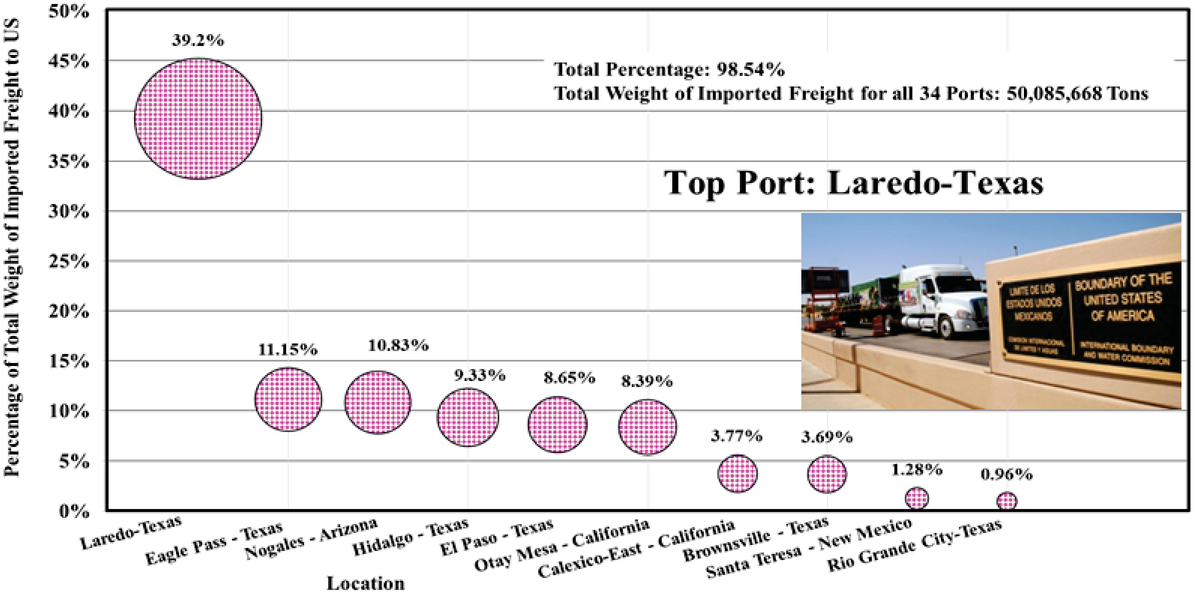


Figure 32. Top Ten Mexico/US Border Ports by Weight (US Short Tons), 2013

For corridor integration analysis, the modes by which commodities are coming into the U.S. must be known. Figure 33 shows freight entering the US through Mexican border ports by truck and rail in 2013 (BTS 2013). Just over 50 million tons of freight entered the U.S. in 2013, and of that, roughly 74% was brought into the country from Mexico by truck, 25% by rail, and only 1% by pipeline. With 74% of all freight entering by truck, there seems to be much opportunity for rail to be utilized depending on the distance that the freight will be travelling. Pipelines are limited to the type of commodity that can be transported by it, such as gas and oil.

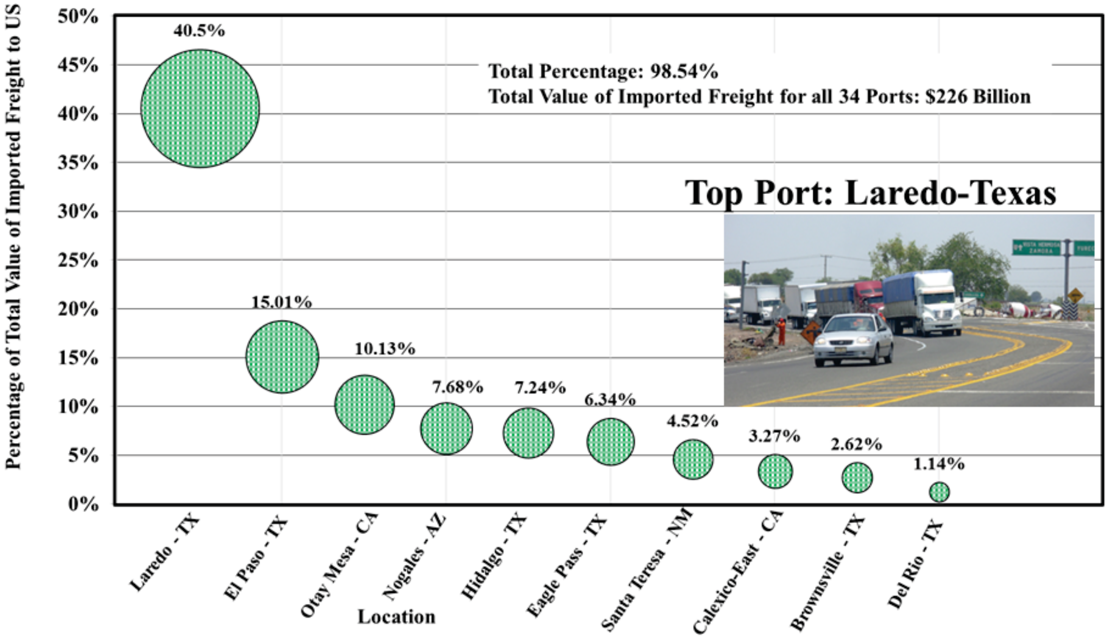


Figure 33. Top Ten Mexico/US Border Ports by Value (US Dollars), 2013

The selection of the border ports were based on some of the following factors:

- Amount of truck freight passing through the border port
- Location of the border port along the U.S./Mexico border
- Proximity to major freight corridors

Using these factors and the spatial analysis results and, the border ports at Laredo, TX and Otay Mesa, CA were selected to be the focus of the NAFTA case study. The two border ports had the largest volume of freight entering the U.S. through them and also provided routes that reach the west coast as well as the central U.S. The commodity analysis showed that the Laredo, TX, port passed 15.6 million tons of freight by truck through it in 2013 and Otay Mesa/San Ysirdo, CA, ports passed 4.2 million tons by truck.

Once the border ports of focus were determined, routes could be selected for further analysis. This was done by displaying the NHS map as shown in Figure 34 and determining routes that were fed by this border port. Only interstate routes were selected for spatial and optimization analyses. Also, the interstate infrastructure is what primarily feed large freight hubs in the U.S., so finding interstate routes from Mexico to Canada was not difficult.

Figure 34. Freight Entering U.S. from Mexican Border Ports by Surface Mode, 2013

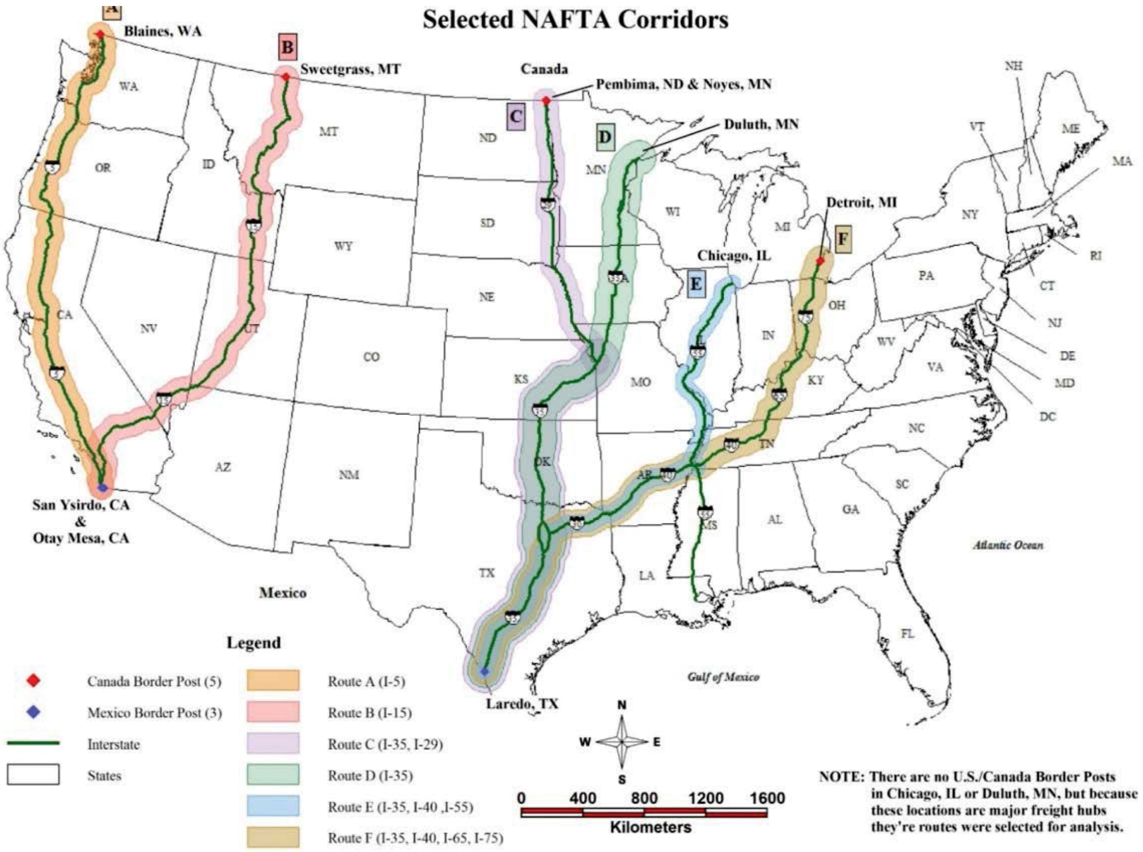
Figure 35(a) shows the highlighted highway corridors that were chosen for the analysis. Once these corridors were selected, rail corridors that run parallel to each highway corridor were selected using the AAR freight rail network map. The highways and corresponding rail lines can be seen in Figure 35(b). Although routes only connect with two Mexican border ports, they split as they make their way through the U.S. and connect with four Canadian border ports and two major freight hubs that are not technically border ports. The Canadian Border ports that are connected are Blaines, WA, Sweetgrass, MT, Pembima, ND/Noyes, MN, and Detroit, MI. The two which are not Canadian border ports are Chicago, IL, and Deluth, MN.

Each of the highway and rail corridors shown in Figures 35(a) and 35(b) were analyzed to determine the benefits of moving freight from highway to rail. Each of the NAFTA highway corridors made up of the following interstates and the lengths of each corridor can be seen in Table 12.

- Route A: only I-5 all the way to Blaines, WA
- Route B: only I-15 all the way to Sweetgrass, MT
- Route C: I-35 to I-29 into Pembina, ND/Noyes, MN
- Route D: I-35 into Deluth, MN
- Route E: I-35 to I-30 to I-40 to I-55 into Chicago, IL
- Route F: I-35 to I-30 to I-40 to I-65 to I-75 into Detroit, MI

Table 12. NAFTA Corridor Lengths

NAFTA Route	Mode	Length (miles)
A – Interstate 5	Truck	1,359
	Rail	1,732
B –Interstate 15	Truck	1,436
	Rail	1,737
C – Interstate 35 & 29	Truck	1,800
	Rail	1,833
D – Interstate 35	Truck	1,677
	Rail	1,600
F – Interstate 35, 30, 40, and 55 (Chicago)	Truck	1,424
	Rail	1,481
E – Interstate 35, 30, 40, 65, and 75 (Detroit)	Truck	1,594
	Rail	1,777



NOTE: There are no U.S./Canada Border Posts in Chicago, IL or Duluth, MN, but because these locations are major freight hubs they're routes were selected for analysis.

Figure 35(a). NAFTA Highway Corridors of Focus

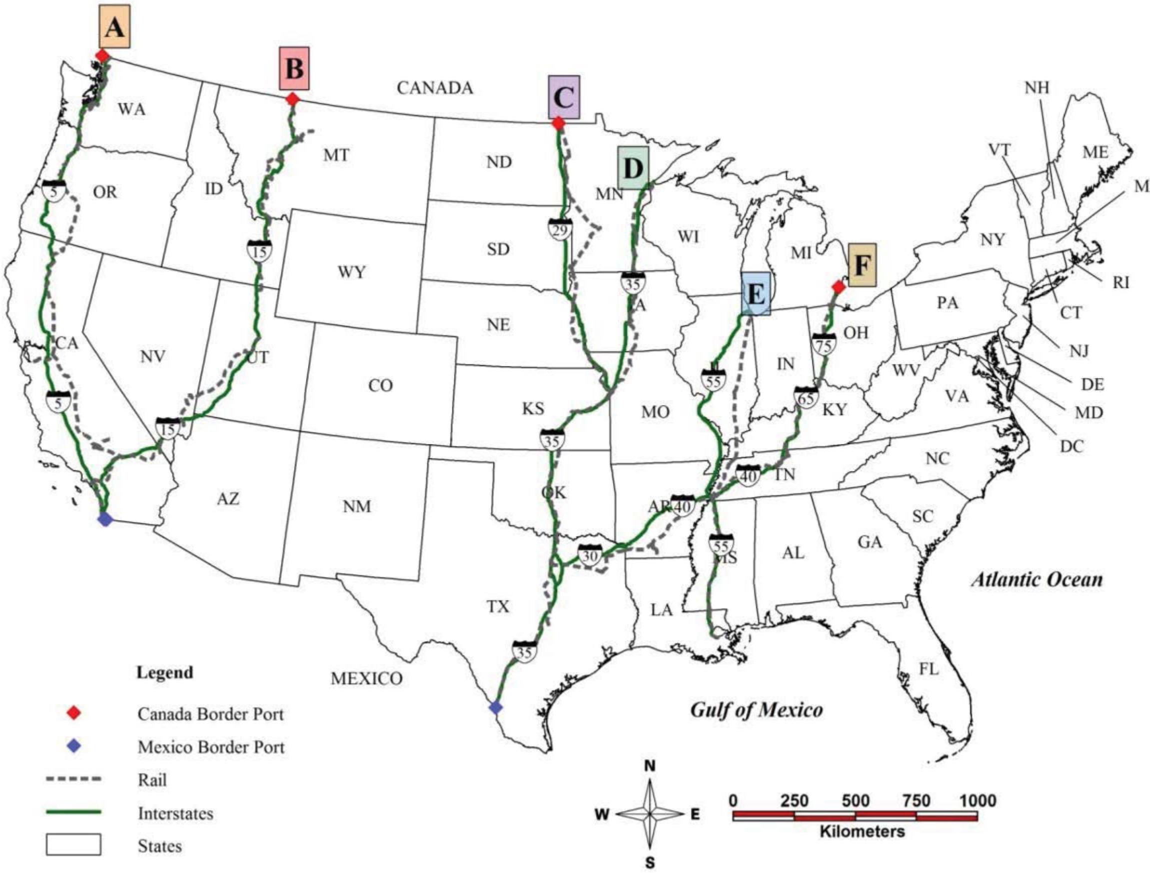


Figure 35(b). NAFTA Highway and Rail Corridors of Focus

The following benefits were calculated for this case study:

- Travel Time Savings
- Ton-Mile Costs and Savings
- CO_2 Emission Reduction
- Fuel Savings

Cost and Benefit Analysis for Intermodal integration of NAFTA Corridors

The cost and benefit calculations were completed for each route, but the example shown is only for Route A to provide how the equations were used to calculate the results. The results for the other routes are summarized in the table in the “Results and Discussion” section. The calculations below were also completed for 20%, 40%, 60%, and 100% of total freight, but because it is the most conservative of the options, 20% was chosen to be shown in the final results.

(a) Travel Time Savings

Trips were calculated using Equation 3, and travel time per trip was calculated using Equation 4, both of which were previously discussed. These sample calculations are made to compare the travel time savings of moving 20% of the total truck freight entering the U.S. from Mexico from highway to rail. The following given data and assumptions were used in calculating the travel time for each of the selected highway and rail NAFTA corridors.

- Total Freight Amount Entering U.S. on Trucks: 4,201,887 Tons for Otay Mesa, CA and 15,693,635 Tons for Laredo, TX
- 20% of Freight Moved to Rail: 840,377 Tons for Otay Mesa, CA 3,138,727 Tons for Laredo, TX
- Assumptions for Base Scenario Trucks:
  - 25-Ton Truck Capacity
  - 55 mph Average Speed
  - 8 hours of stops for rest, fuel, and food per trip.
- Assumptions for Rail Scenario:
  - 100-Ton Rail Car Capacity
  - 25 mph Average Speed
  - 4 hours of stops for rest, fuel, and food per trip
  - 10 cars per train trip dedicated to freight moved to rail from highway
  - Train car carries 4.4 truck loads, 44 cars per train trip
- Route A Highway: Travel Time Calculations
  - Total Number of Truck Trips 20% of Total Freight along Route A (Eq. 3): 840,377 Tons/25 Tons per Truck = **33,615 Trips**
  - Total Time taken per Truck to Travel on Route A (Eq. 4): (1,359 Miles/55 mph) + 8 hours (stops, fuel, food) = **32.7 hours per Truck Trip**
  - Total Travel Time for 33,615 Truck Trips (20% of Freight):

(32.7 hours x 33,615 Trips)(Travel) + (8 hours x 33,615 Trips)(Stops) = **1,099,519 Hours**

- Route A Rail: Travel Time Calculations
  - Total Number of Rail Trips 20% of Total Freight along Route A (Eq. 3): (840,377 Tons/110 Tons per rail car)/44 Cars per Train Trip= **174 Trips**
  - Total Time taken per Rail Trip to Travel on Route A (Eq. 4): (1,732 Miles/25 mph) + 6 hours (stops, fuel, food) = **75.3 hours per Truck Trip**
  - Total Travel Time for 174 Train Trips (20% of Freight): (75.3 hours x 174 Trips)(Travel) + (6 hours x 174 Trips)(Stops) = **13,071 Hours**

(b) Ton-Mile Cost Savings

Total ton-mile cost was calculated using Equation 3. Average ton-mile costs for each surface mode shown in Table 13 were also used in the following ton-mile cost calculations.

- Route A Highway: Ton-Mile Cost
  - Total Ton-Mile Cost for Trucks Carrying 20% of Total Freight (Eq. 5): (840,377 Tons x 1,359 Miles) x (34.39 cents/100) = **$393 Million**
  - Total Ton-Mile Cost per 100 miles for Trucks Carrying 20% of Total Freight: $393 Million/(1,359 Miles/100 Miles) = **$28.90/100 miles**

- Route A Rail: Ton-Mile Cost
    - Total Ton-Mile Cost for Trucks Carrying 20% of Total Freight (Eq. 5): (840,377 Tons x 1,732 Miles) x (3.95 cents/100) = **$57 Million**
    - Total Ton-Mile Cost per 100 miles for Trucks Carrying 20% of Total Freight: $393 Million/(1,359 Miles/100 Miles) = **$3.32/100 miles**

(c) CO_2 Emission Reduction

CO_2 emissions were calculated using Eq. 6 (Uddin 2012). Also, the net freight ton-miles per gallon values from Table 7 were used in these calculations. According to the EPA, the average CO_2 emissions per gallon of diesel fuel are 22.2 lbs/gal (EPA 2005). The following sample calculations are provided for Route A corridors.

- Route A Highway: CO_2 Emissions
    - CO_2 Emission for Trucks Carrying 20% of Total Freight (Eq. 6):

(840,377 Tons x 1,359 Miles x 22.2 lbs/gal / 155 Ton-Miles/gal)/2000 lbs = **81,787 Tons**

    - CO_2 Emission per 100 miles for Trucks Carrying 30% of Total Freight:

(81,787 Tons / (1,359 Miles/100 Miles) = **6,018 Tons/100 Miles**

- Route A Rail: CO_2 Emissions
    - CO_2 Emission for Trucks Carrying 20% of Total Freight (Eq. 6):

(840,377 Tons x 1,732 Miles x 22.2 lbs/gal / 413 Ton-Miles/gal)/2000 lbs = **39,120 Tons**

    - CO_2 Emission per 100 miles for Trucks Carrying 30% of Total Freight:

(81,787 Tons / (1,732 Miles/100 Miles) = **2,259 Tons/100 Miles**

Table 13. Fuel Cost Savings for Each NAFTA Corridor (20% Trucks Diverted to Rail)

NAFTA Route	Fuel Savings per Truck	Total Fuel Cost Savings
A – Interstate 5	$576	$19,357,168
B –Interstate 15	$608	$20,453,931
C – Interstate 35 & 29	$763	$95,757,773
D – Interstate 35	$711	$89,214,325
E – Interstate 35, 30, 40, and 55 (Chicago)	$603	$75,755,038
F – Interstate 35, 30, 40, 65, and 75 (Detroit)	$675	$84,798,828

(d) NAFTA Corridor Fuel Cost Savings

Due to such a large amount of freight being transported through the border ports and the long length of the routes used in the calculations, there were significant fuel cost savings (Table 13) observed for all NAFTA corridors. The methodology was the same as used for Colorado-California highway-rail integration study. Table 13 shows a complete summary of results for fuel cost savings by diverting 20% truck to rail for each NAFTA route, which includes fuel cost savings per truck and total fuel cost savings. The largest savings was Route C with $763 per truck. This is due to the large amount of freight coming through Laredo, TX, and the longer length of the route. The smallest savings was Route A, which had a lower amount of freight coming through the Otay Mesa border port and was a slightly shorter route than the others. Even though some savings were lower than others, all routes showed significant fuel cost savings from removing only 20% of trucks from the highway corridors. The lowest amount saved was still found to be just over $19 million for Route A, and the greatest savings was just over $95 million for Route C.

Results and Discussion

The calculations previously shown were made for each NAFTA route and corresponding rail line route for the amount of truck freight that enters the border port each route was connected to. For routes A and B, the Otay Mesa and San Ysirdo border ports were used, and for routes C through F, the Laredo, TX, border ports were used. A full breakdown of each corridor, their length, the Mexican border port and Canadian border port they connect to, and the freight entering the Mexican border port by truck in 2013 can all be seen in Table 14.

Table 14. Selected NAFTA Corridor Information

NAFTA Route	Mode	Length (miles)	Mexico Border Post	Canada Border Post	2013 Freight Entering U.S. by Truck (Tons)
A – Interstate 5	Truck	1,359	San Ysirdo, CA/ Otay Mesa, CA	Blaines, WA	4,201,887
	Rail	1,732			
B –Interstate 15	Truck	1,436	San Ysirdo, CA/ Otay Mesa, CA	Sweetgrass, MT	4,201,887
	Rail	1,737			
C – Interstate 35 & 29	Truck	1,800	Laredo, TX	Pembima, ND/ Noyes, MN	15,693,635
	Rail	1,833			
D – Interstate 35	Truck	1,677	Laredo, TX	Duluth, MN (no border post)	15,693,635
	Rail	1,600			
E – Interstate 35, 30, 40, and 55 (Chicago)	Truck	1,424	Laredo, TX	Chicago, IL (no border post)	15,693,635
	Rail	1,481			
F – Interstate 35, 30, 40, 65, and 75 (Detroit)	Truck	1,594	Laredo, TX	Detroit, MI	15,693,635
	Rail	1,777			

Table 15 shows a complete breakdown of the results calculated in the previous sections for each truck and rail corridor, and Table 16 shows the percent change in the highway and rail options. For all corridors, the travel time savings was the most significant, reducing approximately 98% to 99% in hours of travel on each of the NAFTA corridors by moving 20% of the freight from highway to rail. All corridors also saw a significant reduction in CO_2 emissions and in ton-mile costs for each corridor. The reduction in CO_2 for all corridors was significant with the smallest reduction being 52.2% for Route A and the largest being 64.2% for Route D. By diverting the freight, and significant savings in ton-mile cost was also observed with all corridors reducing in the 85% to 90% range.

Table 15. Travel Time, Ton-Mile Cost, and CO_2 Emission Results for NAFTA Corridors

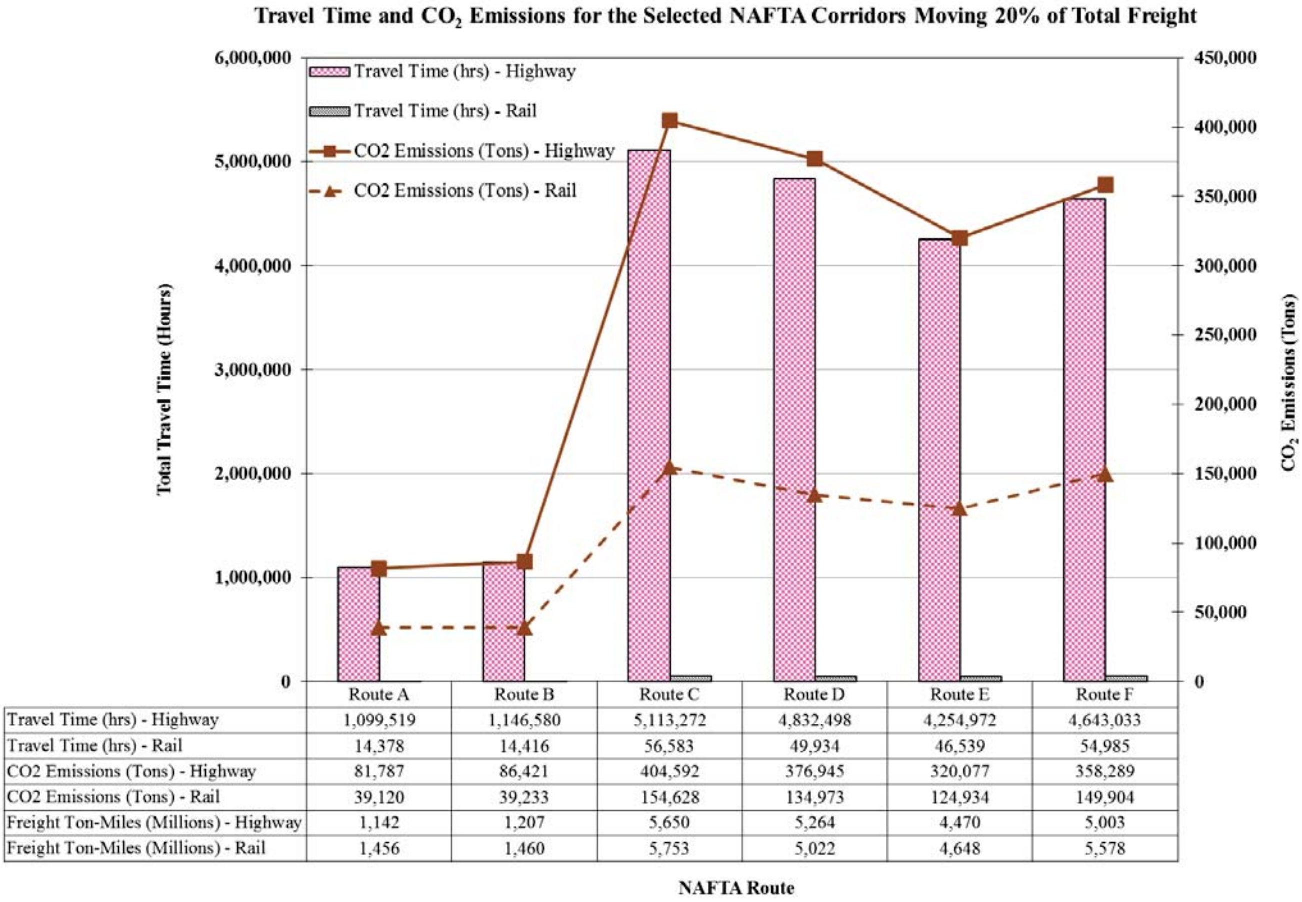
NAFTA Route	Mode	Travel Time per Year for 20% Freight (hrs)	Total Ton-Mile Cost per Year ($ Millions)	Total CO_2 Emissions (Tons per Year)
A – Interstate 5	Truck	1,099,519	$393	81,787
	Rail	14,378	$57	39,120
B –Interstate 15	Truck	1,146,580	$415	86,421
	Rail	14,416	$58	39,233
C – Interstate 35 & 29	Truck	5,113,272	$1,943	404,592
	Rail	56,583	$227	154,628
D – Interstate 35	Truck	4,832,498	$1,810	376,945
	Rail	49,934	$198	134,973
E – Interstate 35, 30, 40, and 55 (Chicago)	Truck	4,254,972	$1,537	320,077
	Rail	46,539	$184	124,934
F – Interstate 35, 30, 40, 65, and 75 (Detroit)	Truck	4,643,033	$1,720	358,289
	Rail	54,985	$220	149,904

The benefit and cost analysis was conducted to determine the impact of diverting 20%, 40%, and 60% truck freight to rail. For brevity, detailed results are shown only for 20% truck freight diverted to rail. Table 16 shows percent change in benefits for NAFTA corridors in the case of diverting 20% truck freights to rail.

Figure 36 provides a plot of the travel time savings and CO_2 emission reductions for each of the NAFTA corridors. This plot provides a visualization of the significant reductions that can be expected by just moving 20% of truck freight entering the U.S. to rail for long haul trips.

Table 16. Percent Change in Benefits for NAFTA Corridors

Benefit for Moving 20% Freight from Highway to Rail						
NAFTA Route	**Reduction in Travel Time (hrs)**	**Percent Change**	**Reduction in CO$_2$ Emissions (Tons per Year)**	**Percent Change**	**Reduction in Ton-Mile Cost ($ Millions)**	**Percent Change**
A - Interstate 5	1,085,141	98.7%	42,667	52.2%	$335	85.4%
B -Interstate 15	1,132,164	98.7%	47,189	54.6%	$357	86.1%
C - Interstate 35 & 29	5,056,689	98.9%	249,964	61.8%	$1,715	88.3%
D - Interstate 35	4,782,564	99.0%	241,972	64.2%	$1,612	89.0%
E - Interstate 35, 30, 40, and 55 (Chicago)	4,208,434	98.9%	195,143	61.0%	$1,353	88.1%
F - Interstate 35, 30, 40, 65, and 75 (Detroit)	4,588,048	98.8%	208,384	58.2%	$1,500	87.2%



Travel Time and CO$_2$ Emissions for the Selected NAFTA Corridors Moving 20% of Total Freight

	Route A	Route B	Route C	Route D	Route E	Route F
Travel Time (hrs) - Highway	1,099,519	1,146,580	5,113,272	4,832,498	4,254,972	4,643,033
Travel Time (hrs) - Rail	14,378	14,416	56,583	49,934	46,539	54,985
CO2 Emissions (Tons) - Highway	81,787	86,421	404,592	376,945	320,077	358,289
CO2 Emissions (Tons) - Rail	39,120	39,233	154,628	134,973	124,934	149,904
Freight Ton-Miles (Millions) - Highway	1,142	1,207	5,650	5,264	4,470	5,003
Freight Ton-Miles (Millions) - Rail	1,456	1,460	5,753	5,022	4,648	5,578

Figure 36. Travel Time and CO$_2$ Emissions for Selected NAFTA Corridors

Optimization Analysis of NAFTA Freight Corridor, from Laredo, TX to Detroit, MI

Out of the six corridors A through F shown in Figures 35 and 36, corridors E and F were selected for optimization to minimize shipping costs from Laredo, TX, to Michigan (Figure 37). In 2008 Laredo, Texas had the highest amount of truck traffic (1,555,000) at the US-Mexico border of NAFTA corridor in the United States and it transported 115,759 million dollars worth of the merchandise (Kong and Wroth 2015). In 2013, the total amount freight entering the U.S from Laredo, TX on truck and rail was 19,652,674 tons. The following data shows how much freight flows from Laredo, TX, to Michigan.

- Total Freight Entering U.S. through Laredo, TX: 19,652,674 Tons
- Percentage of Laredo Freight that goes to Michigan by Truck: 5.51%
- Percentage of Laredo Freight that goes to Michigan by Rail: 7.21%
- Truck (5.51%): 19,652,674 Tons x 0.0551 = 1,082,862 Tons
- Rail (7.21%): 19,652,674 Tons x 0.0721 = 1,416,957 Tons
- Total Freight to Michigan: 2,499,819 Tons

Percentage entering Michigan from Laredo on Truck = (1,082,862/2,499,819) x 100 = **43.3%**
Percentage Entering Michigan from Laredo on Rail = (1,416,957/2,499,819) x 100 = **56.7%**

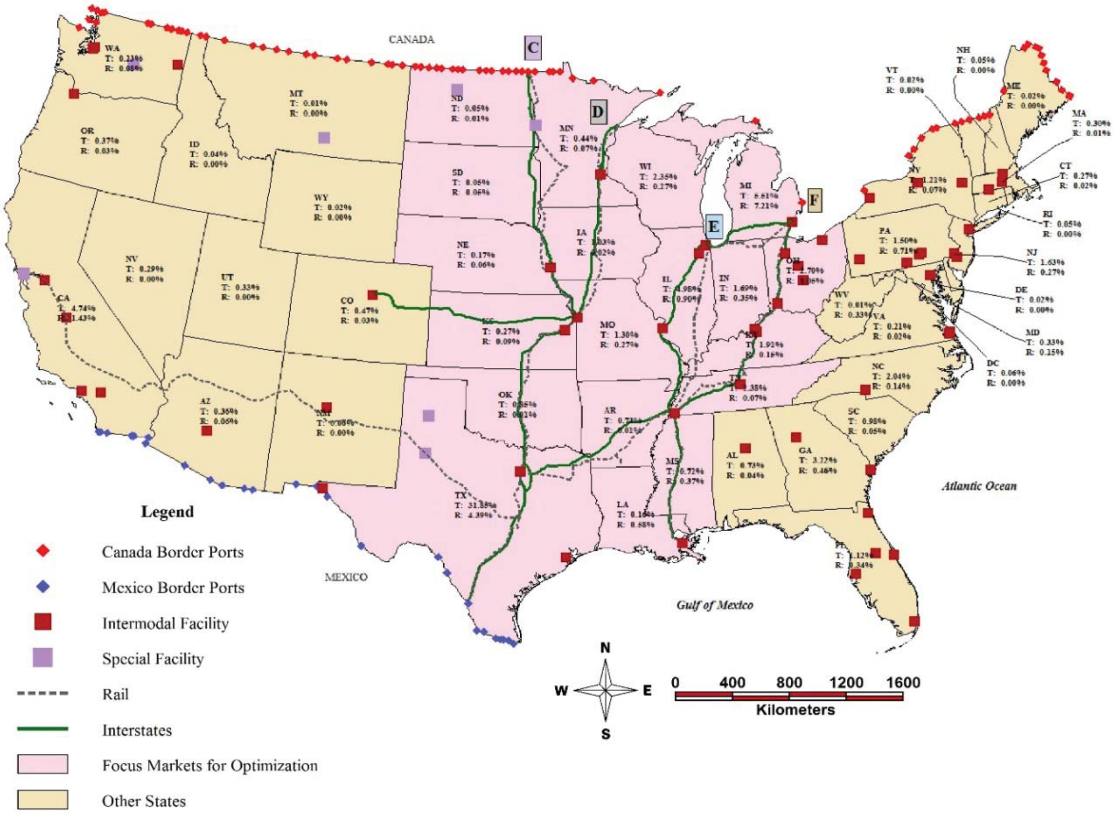


Figure 37. Spatial Map Showing Routes Chosen for Optimization

The geospatial analysis helped to identify and discard all unfeasible routes considering only interstate highway segments and major rail lines with intermodal terminals in the corridors. For example, Memphis has a large rail-truck intermodal terminal facility. The final selected highway and rail routes extend from Laredo, TX, to Dallas, TX, from Dallas, TX to Memphis, TN, and from Memphis, TN, to Detroit, MI. The spatial map of NAFTA freight routes chosen for optimization is shown in Figure 37. Route E and F on the map and the distance detail is shown in Table 17. The routes, E and F, selected to optimize the minimum shipping cost share the same corridor segment from Laredo, TX, via Dallas to Memphis, TN. The corridor then splits at Memphis into two segments (East and West), and each run separately to Michigan. The East corridor segment goes from Memphis to Detroit via Cleveland, OH, and the West corridor segment goes from Memphis to Detroit via Chicago, IL.

Table 17. Optimization Corridors and Distances (miles)

Corridor	1-East Corridor	Distance (mi)		2-West Corridor	Distance (mi)	
		Highway	Rail		Highway	Rail
Laredo, TX - Dallas, TX	☑	415.3	432.5	☑	415.3	432.5
Dallas, TX - Memphis, TN	☑	443.2	509.9	☑	443.2	509.9
Memphis, TN - Detroit, MI	via Cincinatti, OH	695.3	714.2	via Chicago, IL	810.9	732.1

Since there is only one corridor from Laredo to Memphis, this shipping cost is fixed for a given proportion of rail and highway shipments and unable to be optimized. Equation 6 was used to calculate the shipping cost for the single corridor from Laredo to Memphis for the base scenario, which is moving the freight as is and not diverting any more to rail.

$$\mathrm{CLDM} = \left((.433 - \mathrm{j}) * \mathrm{T} * \mathrm{HD}_{\mathrm{Memphis}} * \mathrm{CH}\right) + ((.567 + \mathrm{j}) * \mathrm{T} * \mathrm{RD}_{\mathrm{Memphis}} * \mathrm{CR}) \qquad \text{Eq. 8}$$

CLDM = Cost to ship freight from Laredo via Dallas to Memphis
T = Total Freight from Laredo to Memphis, Tons
j = Reduction in Proportion of Freight Shipped on Highway (0, 0.05, 0.1, 0.15, 0.2)
$\mathrm{HD}_{\mathrm{Memphis}}$ =Highway Distance from Laredo via Dallas to Memphis, miles
$\mathrm{RD}_{\mathrm{Memphis}}$ = Rail Distance from Laredo via Dallas to Memphis, miles
CH = Shipping Cost by Highway Truck, 34.39 cents per ton-mile
CR = Shipping Cost by Rail, 3.95 cents per ton-mile

The CLDM shipping costs were calculated for j equal to 0%, 5%, 10%, 15%, and 20% reduction in highway truck freight and can be seen in Table 18.

Table 18. Shipping Cost for Laredo-Dallas-Memphis Freight Corridor

Corridor	Shipping Cost ($Millions)				
	j = 0%	j = 5%	j = 10%	j = 15%	j = 20%
Laredo, TX - Dallas, TX	$372	$340	$308	$276	$243
Dallas, TX - Memphis, TN					
Memphis, TN - Detroit, MI					

Once the shipping cost for the single segment of the corridors (Laredo, TX to Memphis, TN) was calculated for the base scenario, the objective function was developed to optimize the shipping cost on the corridors where the split in corridors occurs. Equation 9 shows the objective function used for this optimization.

$$\text{Minimize TC} = \sum_{i=1}^{I}\sum_{m=1}^{2}\sum_{j=1}^{J}[\, D_{i,m} \text{x}\, C_m \text{x} \{ (T_{m=1} \text{ x} (1 - j) + (T_{m=2} \text{ x} (1 + j)\} \,] \qquad \text{Eq. 9}$$

Where,

TC = Total Cost to ship freight from Memphis to Detroit, $
m = Mode of Shipping Freight (1 = Truck, 2 = Rail)
$D_{i,m}$ = Distance from Memphis to Detroit for corridor i and mode m
C_m = Shipping Unit Cost, $ per Ton-Mile for mode m
T_m = Total Freight from Memphis to Detroit, tons for mode m,
$T_{m=1}$ for Truck, $T_{m=2}$ for Rail
i = Corridor 1, 2…..to I (For this case study: 1 = East Corridor, 2 = West Corridor)
j = 1, 2…to J; Reduction in Proportion of Freight Shipped on Highway (0, 0.05, 0.1, 0.15, 0.2) for m =1 and addition in Proportion Diverted to Rail for m =2

For the objective function, the term T is the total freight going from Memphis to Detroit and is a function of the mode it is being transported by, m. The corridor distance (D) is a function of the corridor (i) and the mode (m). The unit cost C is determined by which mode (m) is transporting the freight. The total shipping cost (TC) for each corridor is a function of the reduction (j) in freight being shipped on the highway (m=1) and corresponding increase in freight on rail (m=2).

The objective function is subject to the following constraints:

$$\sum_{m=1}^{2} T_m \leq 2{,}499{,}818 \text{ Tons} \qquad \text{Eq. 10}$$

$$j \leq 20\% \qquad \text{Eq. 11}$$

Also a non-negative constraint is applied to ensure that tonnage values shipped by each mode always stay positive for the optimization.

The linear programming optimization was then completed using Excel Solver for the base scenario (j = 0%) and for diverting 5%, 10%, 15%, and 20% freight from the highway to rail. These results can be seen in Table 19 and Figure 38.

Table 19. Shipping Costs for East and West Corridor

1 - East Corridor	Shipping Cost ($Millions)				
	0%	5%	10%	15%	20%
Laredo, TX - Dallas, TX	$372	$340	$308	$276	$243
Dallas, TX - Memphis, TN					
Memphis, TN - Detroit, MI	$299	$272	$246	$220	$193
Total	$671	$612	$554	$496	$436
2 - West Corridor	Shipping Cost ($Millions)				
	0%	5%	10%	15%	20%
Laredo, TX - Dallas, TX	$372	$340	$308	$276	$243
Dallas, TX - Memphis, TN					
Memphis, TN - Detroit, MI	$343	$312	$280	$249	$218
Total	$715	$652	$588	$525	$461

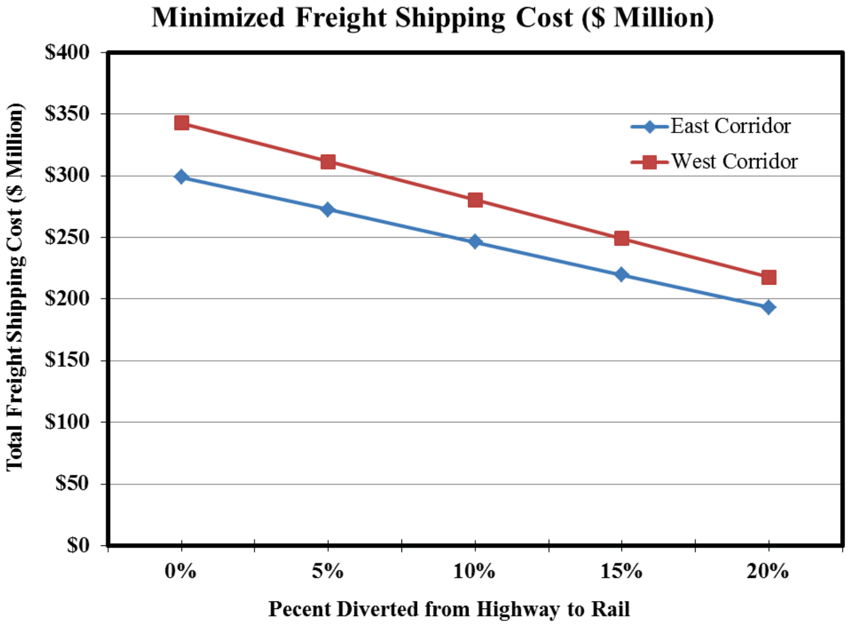


Figure 38. Minimized Freight Shipping Cost ($ Million) from Memphis to Detroit Segment

Based on the results from the optimization, the East corridor shows minimum shipping costs for all values of j. The East corridor is slightly shorter than the West which could account for the lower shipping costs. Figure 38 shows a plot of the each corridor segment of Memphis to Detroit and the freight cost reduction by different proportions of freight from highway to rail. There was an 8.7% decrease in shipping cost from the base scenario to diverting 5% to rail on the East Corridor, and an 8.8% savings for the West Corridor. The optimization analysis shows linear reduction in shipping cost as more trucks are diverted to rail.

Reduction in CO_2 emissions by using rail for shipping 20% freight is 208,384 Tons per year or 58.2% compared to 100% freight shipped by long-haul truck trips.

Key Results of NAFTA Freight Integration Study and Discussions

These NAFTA intermodal integration studies involved candidate freight highway and rail corridor segments within NAFTA corridors from Mexico City to Canada through Laredo. Laredo, TX border port and Detroit, MI border port were chosen because Laredo manages a volume large enough to justify diverting truck freight to rail. Geospatial analysis was useful tomorrow to possible corridors to just a few. The detailed optimization analysis for the route with the least shipping cost is presented after calculating costs and benefits for each of the two alternative corridors. Using the base scenario of highway (43.3%) and rail (56.7%) freight distribution, optimization analysis was performed on the two selected routes. Results are compared for savings from diverting 5%, 10%, 15%, and 20% truck loads to rail.

By diverting 20% truck freight to rail corridor connecting Laredo and Detroit, the annual benefits of the integration of highway and rail corridors include the following (from Tables 15 and 16 and Figure 36):

- Saving in travel time = 4.6 million hours = 98.8%
- Saving in ton-mile cost = $1,500 million = 87.2%
- Reduction in CO_2 produced = 208,384 tons = 58.2%
- Saving in fuel cost = $84,798,828 or 85 million dollars
- About 80% part of truck freight will still be transported by long-haul trucks

It is demonstrated that the spatial analysis reduced the number of feasible alternatives. The linear optimization analysis showed that East corridor is a better alternative with the least total shipping costs per year to transport freight from Laredo, TX to Detroit, MI and onwards to Canada.

3.4 Study of Highway and Mississippi River Corridor Integration

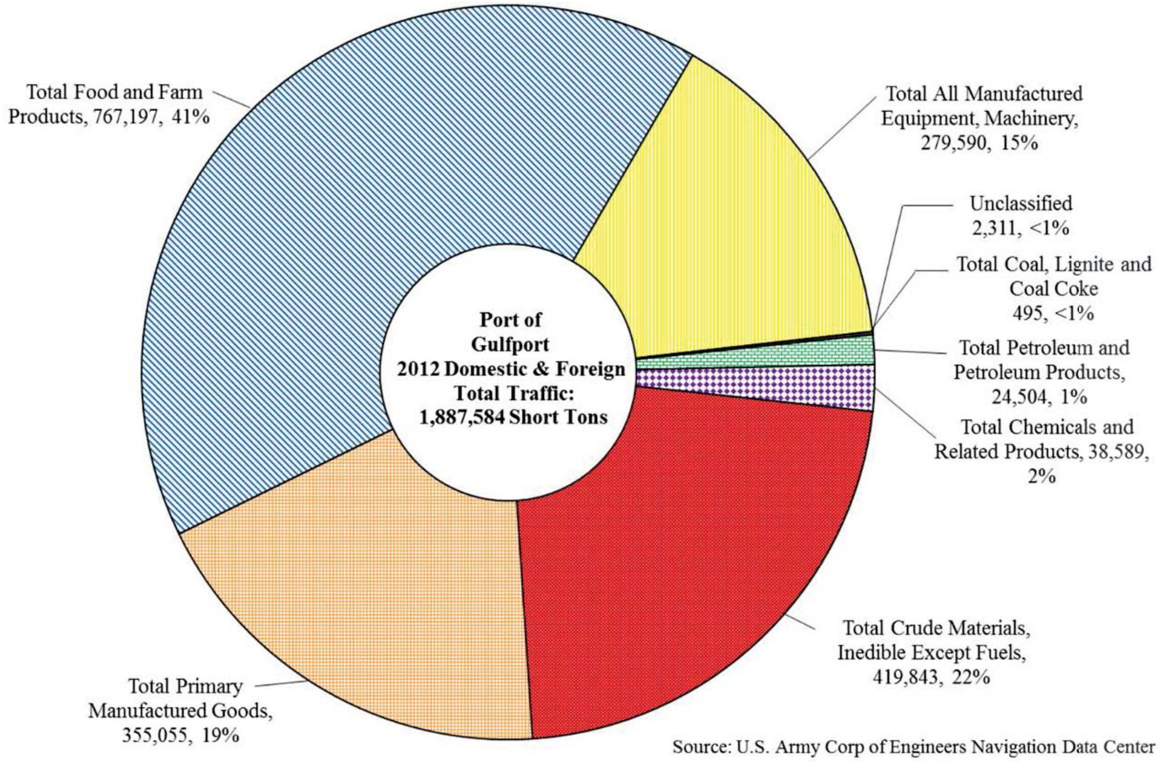
Some highway bridges on the Mississippi river carry a large proportion of commercial truck traffic, such as I-40 bridge at Memphis serves typically 55,000 vehicles daily including 10,000 trucks traveling in East-West direction across Mississippi River. Additionally, I-55 highway bridge on Mississippi River also carries traffic North to Chicago and South to Mississippi and Louisiana. It is estimated that it will cost billions of dollars to the economy if I-40 or I-55 bridge on Mississippi river is lost in a disaster. In the NCITEC project on flood risk vulnerability, a methodology has been presented for using the flood simulation results to assess the potential damage to transportation infrastructure (Durmus et al. 2015, Durmus 2016, Uddin and Altinakar 2015). Therefore, diverting truck freight from highways to barges through the Mississippi River provides a viable strategy for enhancing supply chain resilience to natural disasters.

Synthesis of Commodity Flow Data for Gulfport, Mississippi

Figure 39 shows a spatial map of the states surrounding Mississippi River, highways and major cities.

Figure 39. Spatial map of the states surrounding Mississippi River

For this part of highway-waterway freight integration, Gulfport, MS to St. Louis, MO corridor was chosen to assess the benefits of diverting a part of truck traffic from I-55 highway to barges on Mississippi River. The Port of Gulfport is the second largest importer of green fruit in the United States and the third busiest container port on the US-side of the Gulf of Mexico. Located right in the center of the Mississippi Gulf Coast, the Port of Gulfport is in close proximity to inland locations along the Mississippi River. It also facilitates easy to access for shipments from Central America and a handful from South America (Gulfport 2014). Figure 40 shows a plot representing total freight by commodity type for the Port of Gulfport in 2012 (USACE 2014).



Source: U.S. Army Corp of Engineers Navigation Data Center

Figure 40. Port of Gulfport Data for 2012 Domestic & Foreign Total Freight Traffic

According to the U.S. Army Corps of Engineers (USACE) source, Gulfport includes several navigation channels (USACE 2014), as follows. “Gulfport, MS- Section included: Mississippi Sound Channel, Ship Island Pass Channel, and Small Craft Harbor about 4,300 feet long west of the anchorage basin. Maintained Depth: Mississippi Sound, 30 feet; Ship Island Pass, 32 feet; Small Craft Harbor, 8 feet. Tidal Range to 3 feet at mean higher high water.”

From Figure 40, in 2012 the largest commodity handled by the Port of Gulfport was shown to be “Food and Farm Products,” accounting for 41% of the total freight handled by the port. Crude oil was the second largest commodity handled at 22% of the total freight, followed by Manufactured Goods at 19%. Machinery accounted for 15% of the total freight. The remaining commodities, Chemicals, Petroleum Products, Coal, and Unclassified, accounted for the remaining 3% of the total freight. The Port of Gulfport handled just under 2,000,000 short tons of total incoming and outgoing freight in 2012. Figure 41 shows a plot that represents total freight traffic in short tons moved through the Port of Gulfport in 2012. The graph shows both the total receipts to and shipments from the port for eight different commodity types, which include coal, petroleum materials, chemicals, manufactured goods, crude materials, food and farm products, machinery, and unknown. The green hatch shows incoming goods received by the Port of Gulfport, and the purple hatch displays outgoing shipments from the port. This data includes shipments to and from foreign destinations.

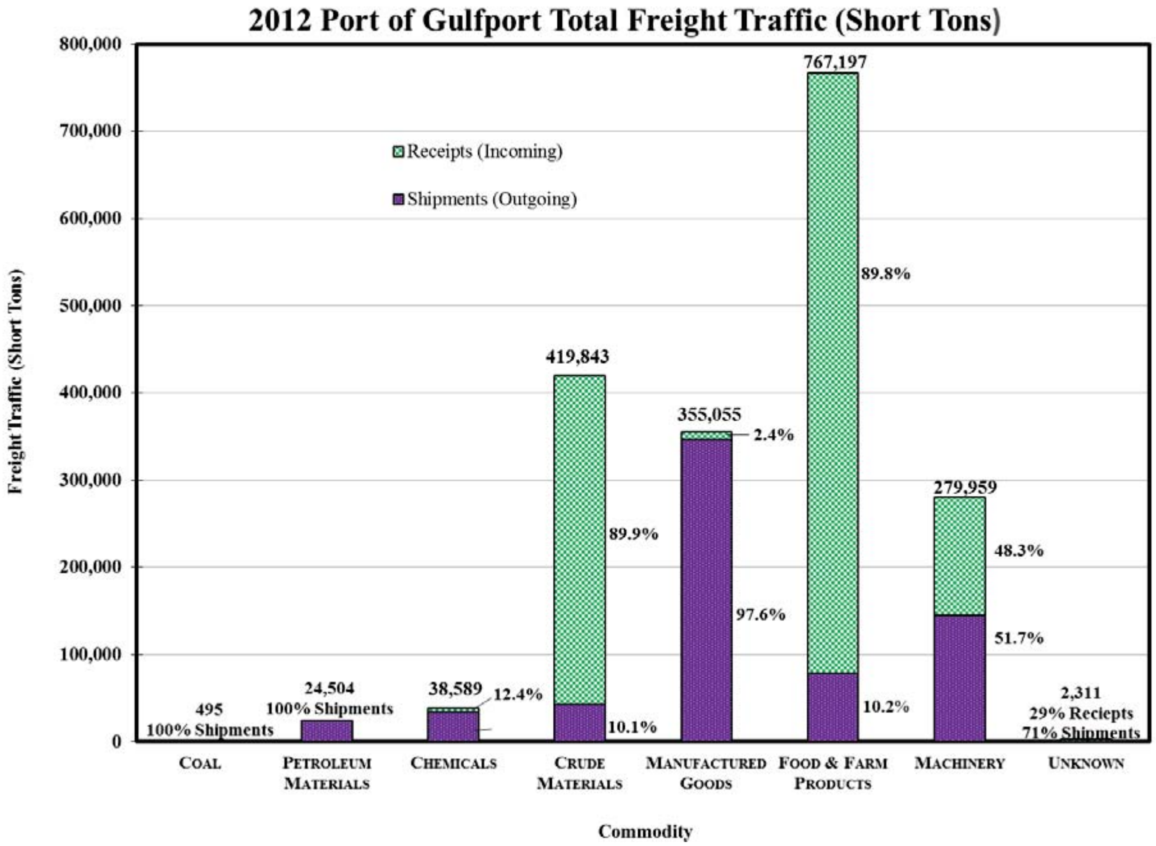


Figure 41. Port of Gulfport's Total Freight Traffic (Short Tons), 2012

Figure 41 also shows the percentages of outgoing and incoming freight for each commodity type. From the commodity flow data, the following integration opportunities for non-perishable, bulk freight were determined:

1. Food and farm products were the largest trafficked commodity at the port with 767,197 short tons being moved through the port: 89.8% were incoming and 10.2% being shipments.
2. The second largest was crude materials at 419,843 short tons. 89.9% were incoming freight and 10.1% was outgoing.
3. Manufactured goods, which accounted for 355,055 short tons, were found to be the largest shipped commodity out of the Port of Gulfport at 97.6% outgoing. This commodity was all foreign shipments or receipts.
4. Machinery was the fourth largest category at 279,959 short tons with half shipped and half received.

5. Total domestic outgoing freight for 2012 was 25,588 tons, 100% of which was Iron & Steel Scrap.

With its' centralized location along the Mississippi Gulf Coast, the Port of Gulfport is a major contributor to truck traffic along the southern portion of the state and along the major interstates passing through Mississippi. This case study explores the benefits of moving shipments from the Gulfport through the Mississippi River to its Port of St. Louis, Missouri.

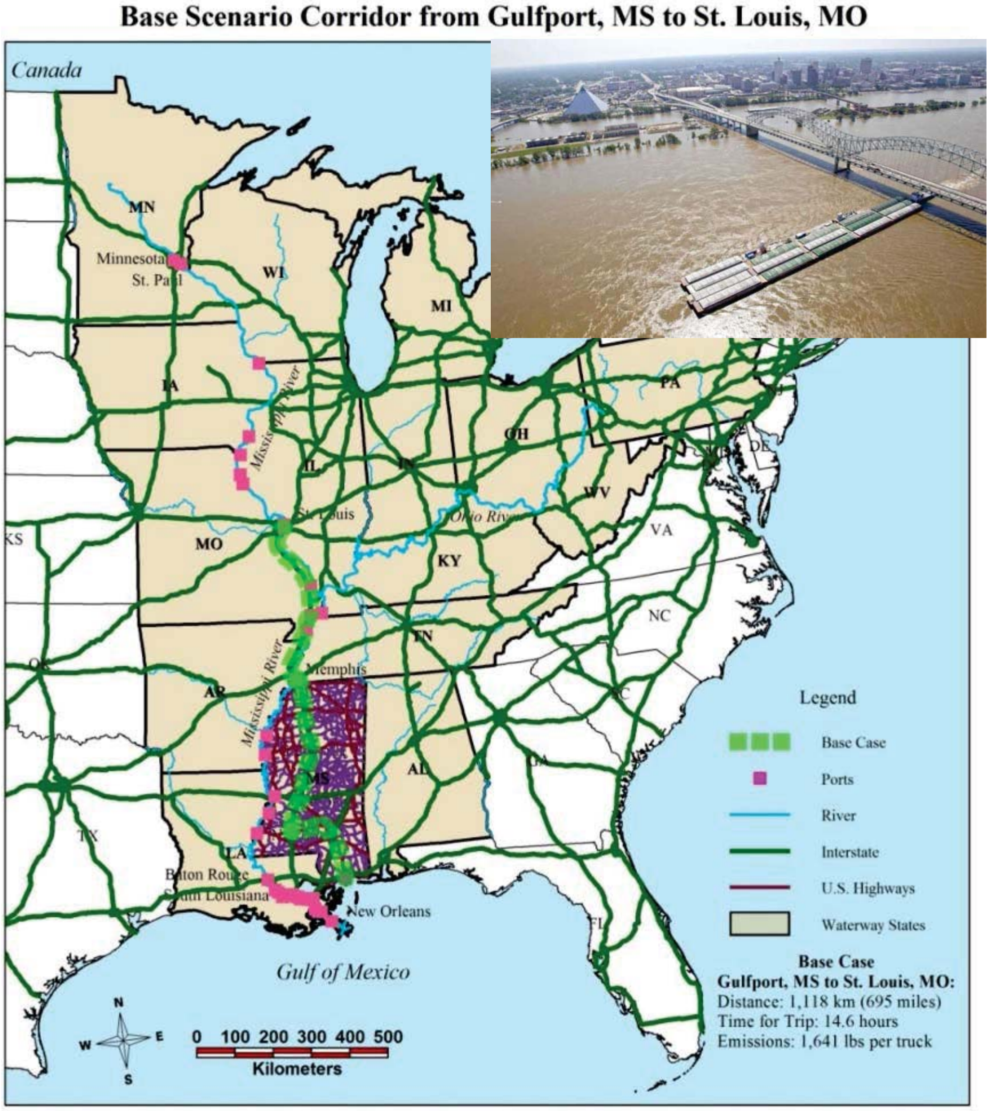


Figure 42. Base Shipping Scenario for Freight Shipped from Gulfport, MS, to St. Louis, MO

Geospatial Analysis and Mapping of Surface and Waterborne Modes of Freight

The Port of St. Louis is a major freight hub centered on the Mississippi River corridor. For this reason, a base scenario corridor was proposed for freight only being moved by truck to the Port of St. Louis. Figure 42 is a spatial map developed in GeoMedia Professional that shows the base shipping scenario of the probable route taken for commodities shipped by truck to St. Louis, MO, from Gulfport, MS. The proposed base route would be to take US-49 North 96.1 miles, then turn onto US-84 West 56.5 miles. From US-84, the driver would turn onto I-55 North and travel 542.6 miles straight into St. Louis, MO. The directions and distances for the base route are summarized and shown in Table 20. The spatial map displays all existing highway infrastructure in the state of Mississippi, including U.S. and state highways, and all interstate highways for the rest of the United States. Interstate highways are shown as the green lines were used to analyze the base scenario and to find where there would be opportunity for moving bulk, non-perishable truck freight to barge. The Mississippi River and other waterway tributaries, ports, and effected states' features are also displayed to help find opportunities. The total length of the base interstate corridor scenario is 695.2 miles.

Table 20. Directions and Distances for Base Corridor

Base Scenario Corridor to St. Louis, MO		
Route	Length	
U.S. 49 North from Gulfport, MS	96.1	miles
Exit onto U.S. 84 West	56.5	miles
I-55 North into St. Louis, MO	542.6	miles
Total Distance	695.2	miles

A scenario was also developed for moving the same freight from Gulfport, MS, to St. Louis, MO, but utilizing the Mississippi River to develop a "multimodal corridor" to move the freight. Figure 43 shows the proposed integrated highway/waterway corridor from the Port of Gulfport in Gulfport, MS, to St. Louis, MO. This proposed route is displayed with an orange dashed line overlay. The proposed freight integration corridor includes a short haul truck trip to the Port of Natchez in Natchez, MS, where truck freight will be loaded onto a barge. This will include travelling North on US-49 for 91.5 miles from the Port of Gulfport and then heading West on US-82 for 118.9 miles, which will run into Natchez, MS. From there, freight will be transferred from truck to barge and shipped upstream on the Mississippi River 769.8 miles, which will run directly into St. Louis, MO. The directions and distances for the base route are summarized and shown in Table 21. From St. Louis, freight can be shipped by truck on a short haul route to surrounding cities. This map shows the same highway infrastructure features as the base scenario map in Figure 43, which includes interstates for the U.S., U.S. and state highways in the state of Mississippi, and also inland waterways within the focus area of the case study. The focus states are shown in the beige color on the map. St. Louis' centralized location allows for easy short truck hauls to major freight hubs in the northern U.S. such as Detroit, MI, Chicago, IL, and Minneapolis, MN. The total distance for the integrated corridor is 980.2 miles from Gulfport to St. Louis. Due to the curvy nature of the Mississippi river, there is a significant difference in length between the two corridor scenarios.

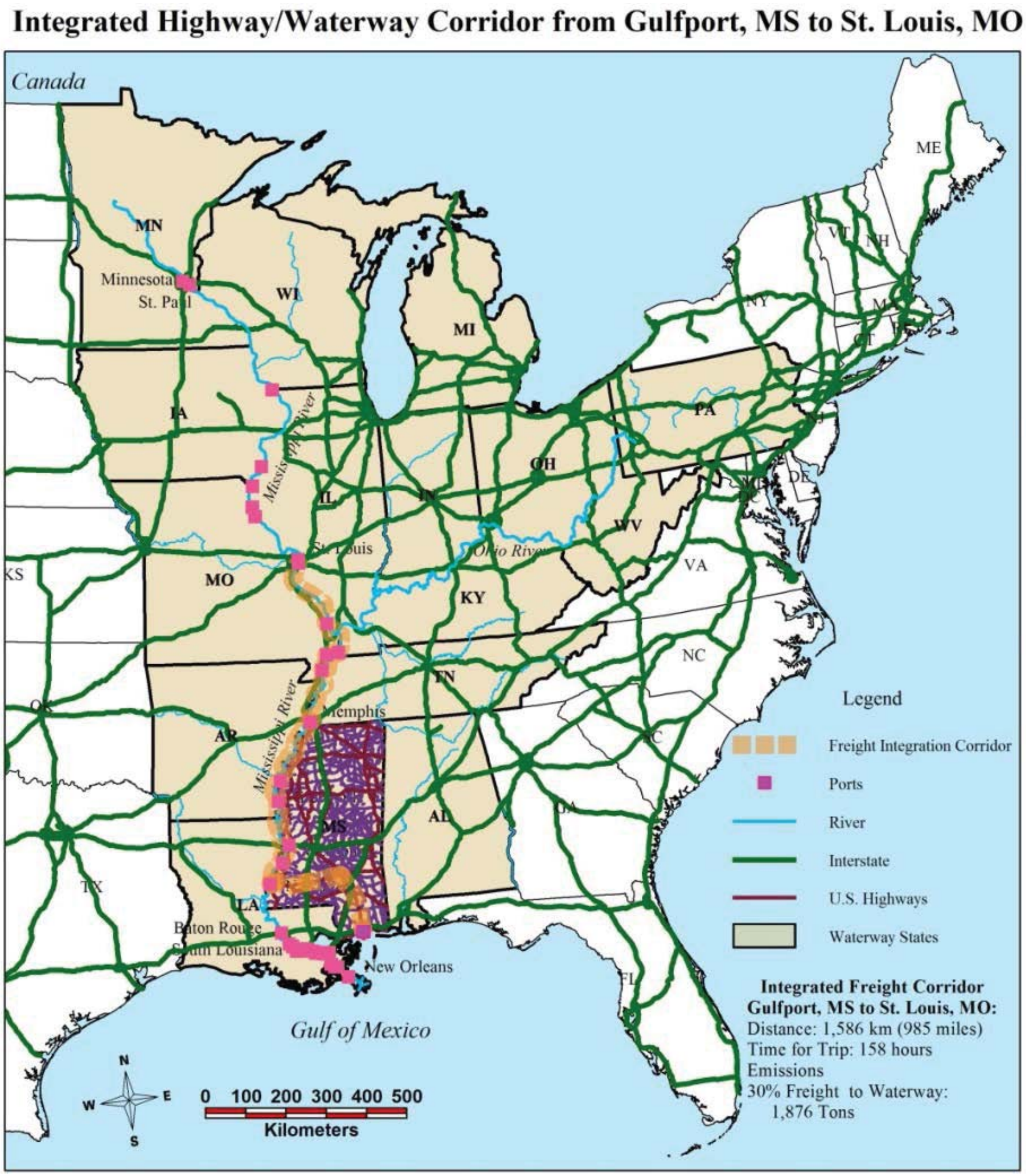


Figure 43. Integrated Highway/Waterway Corridor from Gulfport, MS, to St. Louis, MO

Table 21. Directions and Distances for Integrated Corridor

Integrated Highway/Waterway Corridor to St. Louis, MO		
Route	Length	
U.S. 49 North from Gulfport, MS	91.5	miles
U.S. 82 West	118.9	miles
North on Mississippi River into St. Louis, MO	769.8	miles
Total Distance	980.2	miles

Based on the commodity flow analysis, there were 25,588 tons of domestic outgoing freight leaving from the Port of Gulfport, all of which were iron and scrap metal. For this case study, the benefits were calculated for moving 30% of this freight from highway to the Mississippi River. The following benefits were calculated for this case study, as presented discussed in the following section:

- Travel Time Savings
- Ton-Mile Costs and Savings
- CO_2 Emission Reduction
- Fuel Cost Saving

Economic Analysis of Highway Truck and Waterborne Barge Intermodal integration

Mississippi River barge transport integration with freight truck was evaluated for diverting partial shipment from Gulfport short-haul trucks to the Vicksburg River Port in Mississippi and using barges from there to St. Louis, Missouri. In 2012, Gulfport Port handled a total of 1.9 million short tons of freight, which included 22% crude material (except fuels) and 19% manufactured goods.

It is important to consider only nonperishable and non-breakable commodity for barge traffic because barge flows at about one-tenth of the average speed of a freight truck on highways. However, a barge typically can take about 75 truck-loads of 20-ton trucks. Dr. Ned Mitchell of ERDC advised the project team about barge flow speed for the Mississippi River based on standardized Automatic Identification System (AIS) data and freight shipment monitoring practices by ERDC and Coast Guard (Mitchell 2013).

There are areas where there could be significant benefits in considering alternative modes to move freight rather than highway corridors. For each of the case studies discussed, the travel time savings, ton-mile cost savings, and CO_2 emission reductions were calculated. In the calculation of these benefits and savings, there were some average values that were used. These can be seen in Tables 7 and 8. Table 7 shows the average net freight ton-miles per gallon for truck, rail, and barge. These values are used in the calculation of CO_2 emissions. Table 8 shows the average ton-mile cost in cents for truck, rail, and barge. Both tables show truck to have the highest ton-mile cost with the lowest net freight ton-miles per gallon. They also show the barge to have the lowest ton-mile cost with the highest net freight ton-mile per gallon. These values are used in the total ton-mile cost savings calculations.

Mississippi River Corridor Integration with Highway Truck Freight

(a) Travel Time Savings

Below are some of the known data and assumptions used for calculating total travel time for the Base Truck Scenario which is hauling all freight from Gulfport, MS, by truck to St. Louis, MO on the route shown in Figure 43. All calculations are made to determine the savings and benefits, assuming 30% of the total domestic freight (for illustration) is being diverted from highway and onto barge to travel on the Mississippi River.

- Total Domestic Freight Amount for Port of Gulfport: 25,588 Tons
- 30% of Domestic Freight for Highway/Waterway Integration: 7,676 Tons
- Assumptions for Base Scenario Trucks (MODOT 2012):
    - 20-Ton Truck Capacity
    - 55 mph Average Speed
    - 4 hours of stops for rest, fuel, and food per trip
- Truck trips were calculated using Equation 12, and travel time per trip was calculated using Equation 13.

$$\text{Number of Trips} = \frac{\text{Total Freight (Tons)}}{\text{Capacity (Tons per Vehicle)}} \qquad \text{Eq. 12}$$

$$\text{Travel Time per Trip (hrs)} = \frac{\text{Length (miles)}}{\text{Speed (mph)}} + \text{Time for Stops (hrs)} \qquad \text{Eq. 13}$$

- <u>Base Scenario Trucks:</u> Travel Time Calculations
    - Total Number of Truck Trips for All Outbound Freight (Eq. 12): 25,588 Tons/20 Tons per Truck = **1,280 Trips**
    - Total Time taken per Truck from Gulfport, MS, through US-49, US-82, and I-55 to St. Louis, MO, (Eq. 13): (695 Miles/55 mph) + 4 hours (stops, fuel, food) = **16.6 hours per Truck Trip**
    - Total Travel Time for Truck Trips: 16.6 hours per trip x 1,280 trips = **21,248 hours**

The calculations below are for the short haul truck portions of the Integrated Highway/Waterway Scenario. The truck portion of the integrated scenario uses the same assumptions as that in the Base Truck Scenario for the trucks hauls. The only change is the length of the route being driven, which is now from Gulfport, MS, to Natchez, MS, and there are no stops for rest due to a significantly shorter trip.

- <u>Integrated Highway/Waterway Corridor</u> Travel Time Calculations for Truck Portion (using same truck assumptions as for base scenario):
    - Number of Short Haul Truck Trips to Move 30% of Outbound Freight (Eq. 12): 7,676 Tons/20 Tons per Truck = **384 Truck Trips**
    - Total Time taken per Truck from Gulfport, MS up US-49 North, US-82 West into Natchez, MS (Eq. 13): 216 Miles/55 mph = **4 hours per Truck Trip**
    - Total Travel Time for 384 Truck Trips to Natchez, MS: 4 hours x 384 Short Haul Trips = **1,536 hours**

Barge trips were calculated using Equation 12, and travel time per trip was calculated using Equation 13. The following are some assumptions used for the calculations of travel time and barge trips for the Mississippi River Corridor from Natchez, MS, to St. Louis, MO.

- Assumptions for Barge Freight on the Mississippi River from Port of Natchez to St. Louis, MO
    - 1500 Tons per Barge (75 20-Ton Truck Loads)
    - 4 knots (5 mph) upstream
    - Non-stop travel using multiple operators (no stoppage for fuel, food, rest, etc.)

The following calculations were made using the assumptions previously listed for barge:

- Integrated Highway/Waterway Corridor: Travel Time Calculations for Barge
    - Total Number of Barge Trips (Assuming slight overload) (Eq. 12):
      7,676 Tons/ 1500 Tons per Barge = **5 Barge Trips**
    - Hours per Trip from Gulfport, MS, to Natchez, MS, by Truck and from Natchez, MS, to St. Louis, MO, by Barge (Eq. 13):
      (216 Miles/55 mph) (Truck) + (768 Miles/5 mph) (Barge)
      = 4 Hours (Trucks) + 154 Hours (Barge) = **158 Hours per Trip**
    - Total Travel Time:
      (4 Hours x 384 Trips) (Truck) + (158 Hours x 5 Barge Trips)
      = 1,536 Hours (Truck) + 770 Hours (Barge) = **2,306 Hours**
    - Travel Time for Remaining 70% of Freight by Highway:
      (1280 Trips – 384 Short Haul Trips) x 16.6 hours per trip = **14,874 Hours**
    - Total Time to Move 100% of Freight Using Multimodal Integration:
      14,874 Hours + 2,306 Hours = **17,180 Hours**

The following should be noted about the calculations made:

- Tug boat operators can move more than one barge of commodities and shipments, but assuming different trips to move total outgoing amount since freight will not ship at one time.
- The above analysis does not consider interruptions in freight truck travel due to highway incidents or barge travel interruptions due to draught and incidents.

(b) Ton-Mile Cost Savings

Total ton-mile cost was calculated using Equation 14. Also, the average ton-mile cost values from Table 8 were also used in these calculations.

$$\text{Ton} - \text{Mile Cost per Year (\$)} = (\text{Tonnage x Length})\text{x}\left(\frac{\text{Average Ton}-\text{Mile Cost (Cents)}}{100}\right) \qquad \text{Eq.14}$$

- Base Scenario Corridor Long Haul Trucks Cost
    - Total Ton-Mile Cost for Trucks Carrying 30% of Total Freight (Eq. 14):
      (25,588 Tons x 695 Miles) x (34.39 cents/100) = **$6.1 Million**

- Integrated Highway/Waterway Corridor Cost
  - Total Ton-Mile Cost for 30% of Freight to Be Moved to New Integrated Highway/Waterway Corridor (Eq. 14): (7,676 Tons x 216 Miles) x (34.39 cents/100) + (7,676 Tons x 768 Miles) x (2.17 cents/100) = **$0.7 Million**
  - Total Ton-Mile Cost to Ship Remaining 70% by Highway Corridor: (17,912 Tons x 695 Miles) x (34.39 cents/100) = **$4.3 Million**
  - Total Ton-Mile Cost to Ship by Multimodal Corridor: $4.3 Million + $0.7 Million = **$5.0 Million**

(c) CO_2 Emission Reduction

CO_2 emissions were calculated using Equation 6 (Uddin 2012). Also, the net freight ton-miles per gallon values from Table 7 were used in these calculations. According to the EPA, the average CO_2 emissions per gallon of diesel fuel are 22.2 lbs/gal (EPA 2005, Uddin 2012).

- Integrated Highway/Waterway Corridor Barge from Natchez, MS, to St. Louis, MO:
  - CO_2 Emissions for Barge Carrying 30% of Total Freight on Mississippi River to St. Louis, MO (Eq. 6):
    (7,676 Tons x 768 Miles x 22.2 lbs/gal / 576 Ton-Miles/gal)/2000 lbs = **114 Tons**
- Integrated Highway/Waterway Corridor Remaining 70% of Freight by Tucks
  - CO_2 Emissions for Trucks Carrying 70% of Total Freight Highway (Eq. 6):
    (17,912 Tons x 695 Miles x 22.2 lbs/gal / 155 Ton-Miles/gal)/2000 lbs = **891 Tons**
- Integrated Highway/Waterway Corridor Total CO_2 Emissions
  - Total CO_2 Emissions for Integrated Multimodal Corridor
    118 Tons + 114 Tons + 891 Tons = **1,123 Tons**

(d) Fuel Cost Saving

The fuel cost saving methodology was the same as used for Colorado-California highway-rail integration study (Eq. 7). According to Uddin (2012), the average fuel efficiency for a diesel engine heavy duty truck is 5.9 miles per gallon. The fuel cost for these calculations used $2.50 per gallon at the general market price in 2015.

By choosing to ship freight that is going to St. Louis, MO, by barge rather than by the base scenario highway route, there is a savings of $294.50 per truck making the trip. Eliminating 30% of the truck freight from the highway, which is 384 truck trips, there is a fuel savings of $113,088, using the 695-mile truck route for the calculations.

Results and Discussion

Based on the calculations, much benefit can be found in moving just 30% of the total out going freight from the Port of Gulfport from the highway to barge on the Mississippi River. A summary of the results can be seen in Table 22. Although the base scenario provides a much shorter route, there is a 19% reduction in travel time dropping from 21,248 hours to move all freight by highway to 17,180 hours by integrating the Mississippi River. This is due to a significant drop in the number of trips due to barge having a much larger capacity to haul freight. Using an integrated corridor also shows a reduction in CO_2 emissions by 11.7 % from 1,274 tons of CO_2 emitted to 1,124 tons. By removing 30% of the freight to waterway there was a savings of approximately $1.1 million, which is a large amount of money for a relatively small amount of freight. There was an 18% decrease in total ton-mile cost to ship by the integrated route rather than the base scenario corridor. Figure 44 shows a visual comparison of the two corridors and the reduction in total travel time and CO_2 emissions. The integrated corridor beats the base corridor scenario in each category.

Table 22. Summary of Benefit and Savings Calculations

Route	Length (miles)		Total Travel Time (hours)	CO_2 Emission (Tons)	Total Ton-Mile Cost per Year, $Million
	Highway	Barge			
Base Interstate Corridor Scenario	695	0	21,248	1,274	$6.1
Integrated Highway/Waterway – 30% Diverted to Water	216	768	17,180	1,124	$5.0

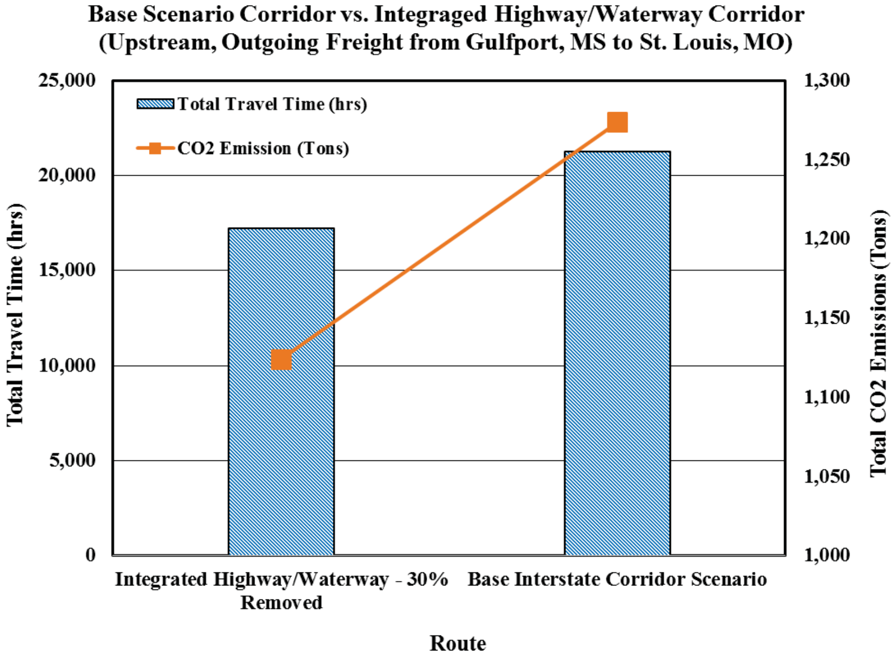


Figure 44. Base Scenario Corridor vs. Integrated Highway/Waterway Corridor Results

Figure 44 shows the results of total travel time, freight transport cost, and CO_2 emission for diverting 30% truck freight by integrated corridor were compared with the base case of all highway truck shipments from Gulfport to through I-55 to St. Louis.

- Total travel time using the integrated corridor is reduced by 19% of the I-55 highway corridor.
- Total shipping cost by the integrated corridor is reduced by 18%.
- Total CO_2 emission is reduced by 11.7%.
  Total fuel saving is $ 113,088 at $294.5 per truck for 695-mile truck route. .

The results indicate significant benefits using the barge-truck integrated corridor in terms of reduced total travel time, freight cost, less wasted fuel cost, and reduction in emissions. Long haul truck traffic is reduced and short haul truck traffic increased from sea ports to the inland waterway terminals (Uddin et al. 2014).

Final cost reductions and benefits for 30% trucks diverted to barges on Mississippi River are:

Travel Time Reduction	Ton-Mile Cost Savings	CO_2 Reduction	Fuel Savings
19%	18%	11.7%	$113,088

Additional Societal Benefits and Concerns Related to Freight Intermodal Integration

Major findings from geospatial analysis and intermodal freight traffic integration studies are discussed in the above sections and illustrated by sample figures and tables for reductions in travel, time, shipping costs, fuel consumption, and CO_2 emissions. There are many other societal benefits associated with diverting truck traffic from the nation's major freight corridors, which are discussed in the following sections.

Avoidance of Truck Driver Fatigue and Crashes: Cobb outlined and discussed the benefits of reduction in truck driver fatigue and crashes to improve safety (Cobb 2015). One of the top issues surrounding freight transportation is operator fatigue (Vector 2009). According to Advocates for Highway & Auto Safety, each year truck crashes kill over 5,000 people and injure 150,000 more, and heavy duty trucks are involved in multiple-vehicle fatal crashes at twice the rate of passenger vehicles (Advocates 2015). Truck driver fatigue contributes to as many as 30-40% of all heavy truck crashes. Even though many rules and regulations have been developed in recent years to limit truck drivers' hours behind the wheel, many drivers resist rules on sleep, despite the risks, due to strict time constraints on freight arrival (NYT 2014). By diverting freight to alternative modes, the possibility for driver fatigue related crashes is being reduced. Modes such as rail and barge do not have a constant encounter with passenger traffic like that of trucks on the highway. Fewer trucks making long haul routes on the highway reduce the chances of these crashes to occur. Moreover, driver fatigue and stress will be less for short-haul trucking jobs.

Fear of Losses of Trucking Jobs and Employment of Truck Drivers: Many see the diversion of truck freight from the highway as an issue due to the elimination of trucking jobs, but this is not necessarily the case. When diverting freight trucks to waterway and rail, there will still be a need for short haul trucking to reach intermodal terminals of rail and waterway ports. The same number of trips will be made just not the same distance drivers were originally travelling. This makes highways less congested as well as reduces driver fatigue on the highways. When utilizing rail corridors, the development of more intermodal facilities and the heavier operation and maintenance of the rail will develop many jobs. Where there is a possibility for long-haul truck driver job reduction by utilizing rail, there will be a huge increase in short haul trucks in the supply chain logistics industry. Due to these reasons, there should be no decline in jobs and business demand due to short haul trucking operations.

Energy Conservation, CO_2 Reduction, and Climate Impacts: According to the latest Energy Information Administration (EIA) report, the CO_2 emissions from energy production is decreasing as coal is being used less and natural gas more for generating electric power (EIA 2015). However, CO_2 emissions from petroleum fuel used in transportation fleets is on the rise. The impacts of U.S. and global CO_2 emissions are grave for our future generation, as follows (Durmus et al. 2015, IPCC 2014, Melillo t al. 2014, White House 2014):

- Climate is being affected and more weather related disasters are on the rise.
- Disruptions in transportation networks are happening due to extreme weather events.
- Communities are being uprooted due to extreme weather events resulting in more traffic congestion and emissions in urban areas.
- Long-term impacts on the planet are severe as polar ice masses and glaciers are melting and seal level may rise in future by the end of this century.

The fossil fuel based economy and transportation technologies have to face depletion of these natural resources in future so energy conservation is important in all economic sectors. Every economic sector has to contribute to the reduction of greenhouse gases (GHG) in which anthropogenic CO_2 is the largest contributor (Uddin 2012). So the CO_2 emissions from transportation sector must be reduced by having more fuel efficient and electric vehicle technologies.

3.5 Environmental Impacts of Multimodal Integration and CO_2 Emissions

Environmental Degradation and CO_2 Emissions

The burning of petroleum-based fuel primarily emits the following pollutants regulated by the EPA: hydrocarbons, volatile organic compounds, carbon monoxide, nitrogen oxides, and particulate matter (PM). Long-term exposure of these air pollutants contribute greatly to the contamination of ground-level air, causing smog, ozone, cancer, lung diseases, and respiratory diseases. This leads to enormous mortality and morbidity rates and related public health costs (Uddin 2006). Anthropogenic CO_2 is also emitted by petroleum and gas used to operate transport vehicles on multimodal transportation networks and the 600 coal burning power plants across the U.S.

Anthropogenic CO_2 has been shown to contribute to global warming (EPA 2014, Uddin 2012). These GHG emissions are further blamed for changes in climate and possible sea level rise of up to 2 m by year 2100 (NOAA 2012, NOAA 2015, IPCC 2015, White House 2014), which may drown many coastal cities (NOAA 2012, NOAA 2015, IPCC 2015). The U.S. Global Change Research Program reported that weather events, linked to climate changes, are occurring at an increasing frequency (Melillo et al. 2014). One of the key messages that the report points out is that disruption of transportation networks are happening nationwide due to extreme weather events; and that "such disruptions will increase." The U.S. federal government has taken it seriously and Climate Action Plan has been developed to prepare U.S. citizens and communities for climate change adaptation (White House 2014)). Disaster resilient infrastructure assets are important to prepare resilient cities, such as practicing flood protective design for the safeguard of infrastructure. The critical infrastructure assets include roads, bridges, rail lines, levees and dams (Durmus et al. 2015, Durmus 2016, Uddin 2015). These issues need serious considerations under extreme weather events and future climate change scenarios.

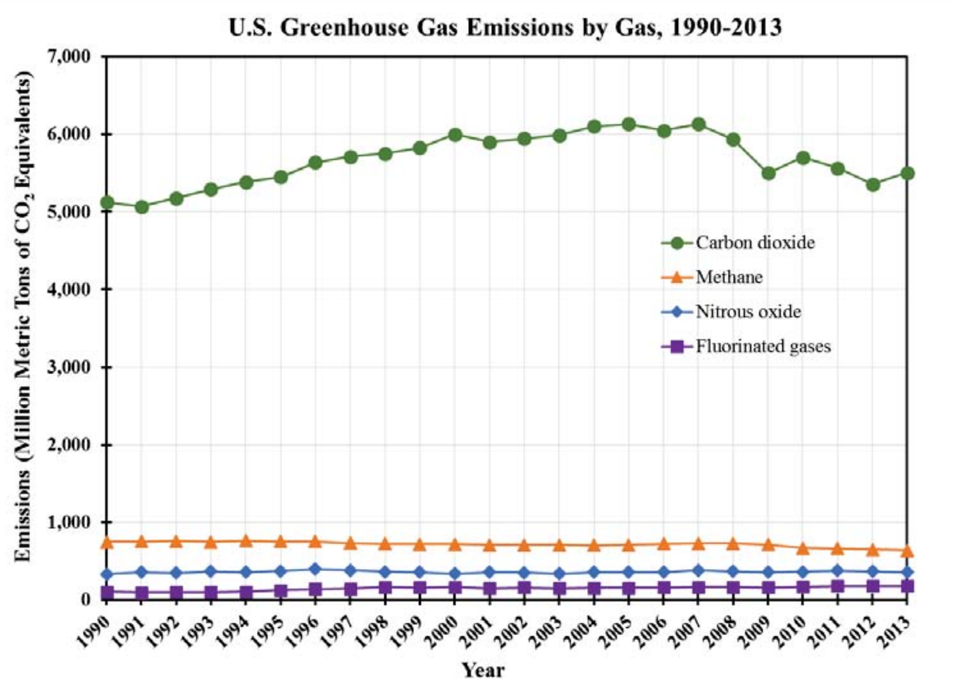


Figure 45. U.S. GHG Emissions by Gas, 1990-2013

Cobb (2015) plotted a time-series of GHG emissions in Figure 45, categorized by gas in the U.S. from 1990 to 2013 (EPA 2015). The four GHG gases shown in the figure include carbon dioxide, methane, nitrous oxide, and fluorinated gases. Of the four, CO_2 was the leader of the four GHG gases with over 5 billion tons being emitted each year from 1990 to 2013. A 7.4% increase occurred over the 13 year time span, rising from 5.12 billion metric tons in 1990 to 5.51 billion metric tons in 2013. The largest amount of CO_2 was shown to be emitted in 2007 with just over 6 billion tons being emitted right before the drop-off that occurred due the 2008 economic recession. Methane, nitrous oxide, and fluorinated gases all emitted less than 1 billion metric tons over the 13 year observation period.

Figure 46 shows the GHG emissions in the U.S. categorized by the economic sector for the period from 1990 to 2013 (EPA 2015). Electricity generation was the leader in GHG emission production from 1990 to 2013. Emissions from electricity generation are continuing to rise, showing an 11.4% increase over the 13 year observation period. Until 1993, industry was second in the production of GHG emissions but was passed by transportation due to continued population growth. Transportation has continued to separate the gap between itself and the industrial category, increasing 16.4% from 1990 to 2013, while industrial GHG emission have decreased over the time period, possibly due to stricter EPA regulations on industrial emissions. Transportation showed a decrease in emissions in 2009, probably as a result of the 2008 recession, but they are beginning to rise again as the economy is rebounding (Cobb 2015). Agriculture, commercial, and residential GHG emissions continue to be significantly lower than that of the electricity generation, transportation, and industrial sectors. Roughly 82% of all GHG emissions is CO_2 which is produced by human activities in the U.S. in 2013.

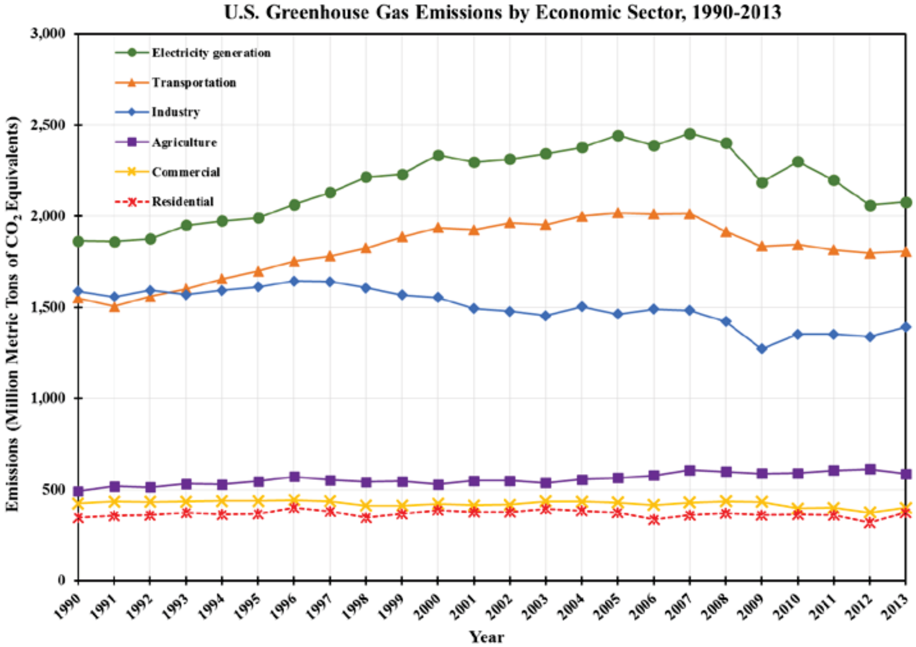


Figure 461. U.S. GHG Emissions by Economic Sector, 1990-2013

Figure 47 shows the U.S. CO_2 emissions by the economic sector in 2013. The leading source of CO_2 emissions in 2013 was electricity at 37%, followed closely by transportation at 31% (EPA 2015). Figure 48 shows 2011 GHG emissions by transportation end user (EPA 2014), where 40% emission is from trucks.

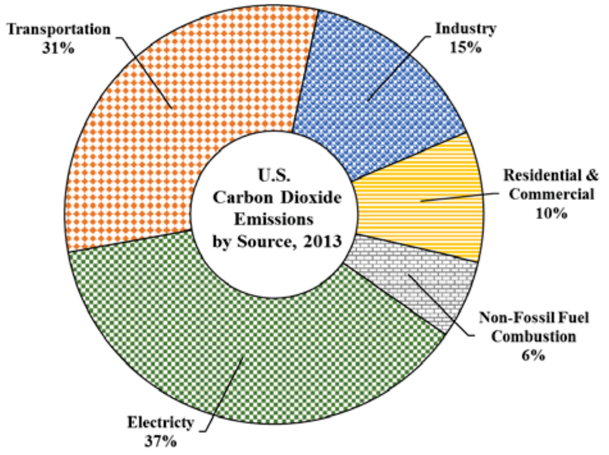


Figure 47. U.S. Carbon Dioxide Emissions by Economic Sectors, 2013

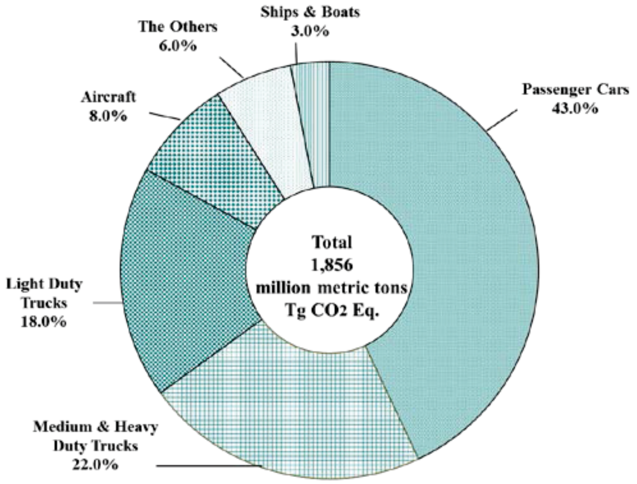


Figure 48. U.S. Transportation End-Use Sector GHG Emissions by Source, 2011

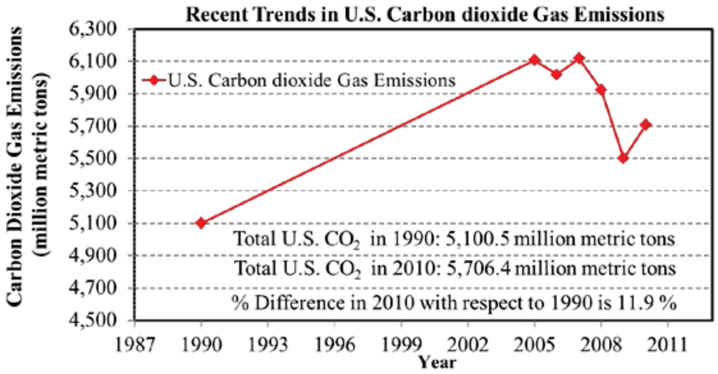


Figure 49. Total Annual Total U.S. Carbon Dioxide Gas Emissions from 1990 to 2010

Figure 49 shows recent trend of CO2 emissions in the U.S. with a reduction after 2007, probably due to economic recession. Figure 50 shows time series of fuel consumption by the transportation sector by each mode and vehicle technology. Trucks consume the bulk of petroleum fuel among surface transportation modes (ORNL 2012).

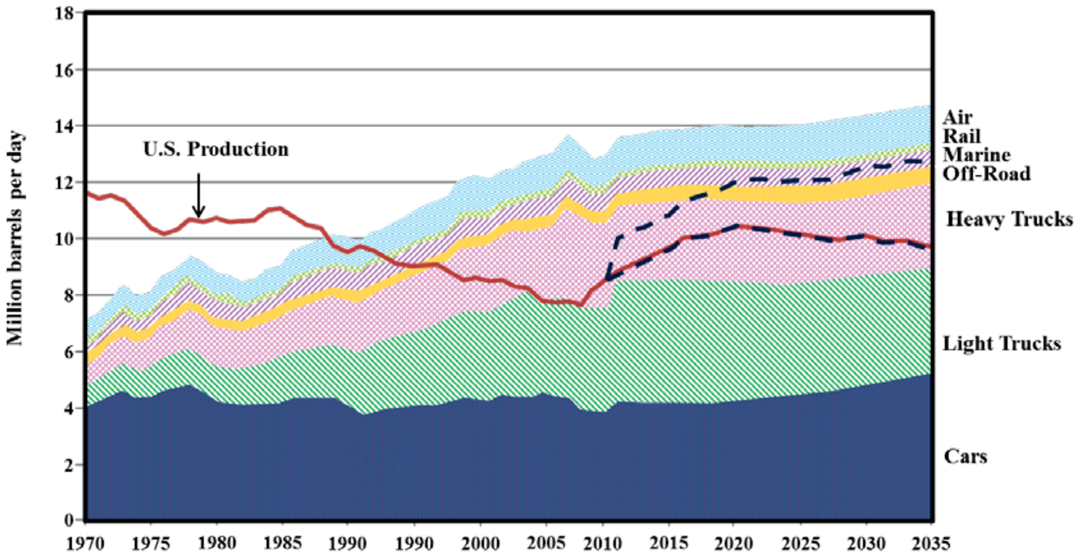


Figure 50. United States Petroleum Production, and Transportation Consumption, 1970–2035.

Figure 51 shows the fuel consumed in the transportation sector by surface modes, excluding pipeline, in 2011 (FHWA 2014). Highway, water, and rail modes combined used just under 265 billion gallons of fuel in 2011. Highway vehicles used about 253 billion of them, roughly 96% of the total. Freight trucks accounted for 25.1% of total highway gallons consumed, just over 63 million gallons (Cobb 2015). The combustion of gasoline and diesel, primarily by transportation sectors, are producing alarmingly increasing CO_2 emissions.

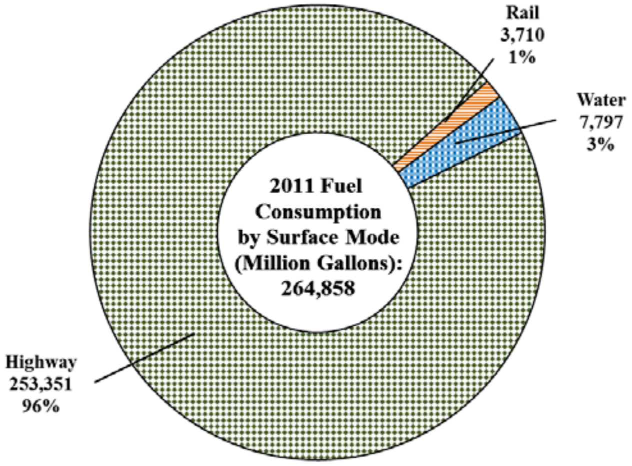


Figure 51. Fuel Consumption in Transportation Sector by Surface Mode (Million Gallons), 2011

These statistics are showing signs that there will be a continued increase in fossil fuel consumption and CO_2 emissions in the upcoming years. As the population and economic prosperity continue to grow, an increase in GHG emissions will continue to occur in the energy and transportation categories. More vehicles will be placed on the U.S. highway system, increasing congestion, idle time of the vehicles, and creating more emissions. Diesel is used as a fuel in the traditional transport technologies of truck, rail and barge traffic. Burning of diesel fuel during combustion process produces a large amount of CO_2 (22.2 lb/gallon). Depending on the transport technology and fuel efficiency, less CO_2 emissions are produced by rail and barges and other waterborne transport. In comparison, a highway freight truck produces about four to five times more CO_2 emissions per ton-km freight (Figure 52).

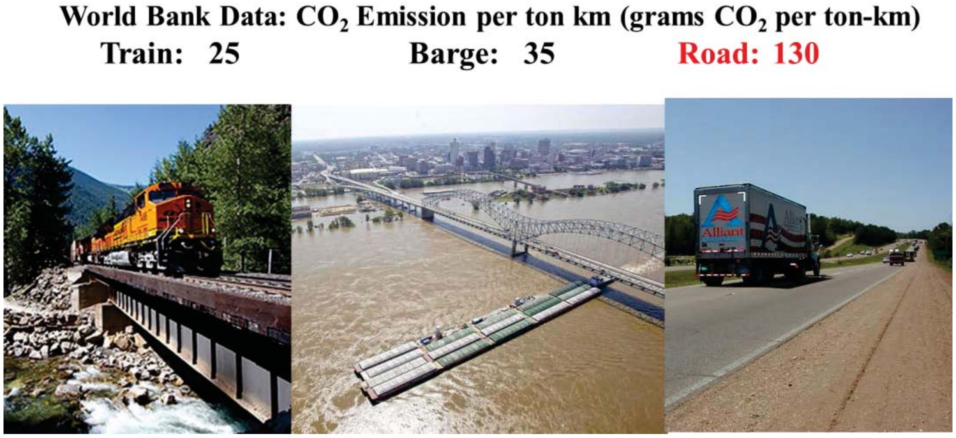


Figure. 52 Rate of CO2 Emission per ton-km for Freight Transportation Modes

The CO_2 emissions, being released by transportation vehicles, are major contributors to global warming. Because CO_2, once emitted, stays in the atmosphere for a very long time, it can have a major effect on global warming if the emissions continue to increase. The increasing concentration of CO_2 in the atmosphere causes the average temperature of the Earth to increase (EPA, 2005, IPCC 2014, Uddin 2012). The most effective way to reduce CO_2 emissions is to reduce fossil fuel consumption. There are many actions that can be taken to help reduce the amount of CO_2 being emitted in the atmosphere in regards to transportation. Some of these actions include:

- Traveling in more fuel-efficient vehicles
- Reducing the distance traveled in vehicles
- Using alternative fuels with lower carbon content

Transportation Impacts on Sustainability

Energy conservation, reduced CO_2 emission, and use of 4R (Recycle, Reuse, Reclaim, Reduce) policies are the corner stones of a "sustainable" society (Uddin 2012, Uddin et al. 2013). The Sustainability is now one of the major issues surrounding freight transportation and supply chain logistics. For long distance international trade over large bodies of water, there is no alternative for airliners or ocean vessels, although these modes are the largest sources of CO_2 emissions. More can be accomplished by addressing the sustainability needs related to inland domestic freight shipments and freight transport across the land borders, such a NAFTA in the U.S., which is where the opportunity lies. Alternative modes to truck freight transport are primarily rail and waterway ("Marine Highways"). All modes have their own unique issues and limitations. For instance, trucks are currently carrying 70% of freight that moves through the U.S., but railroads do not have the ability to reach 80% of the communities across the country. Although this is the case, rail boasts at its ability to transport freight in a more environmentally friendly and fuel efficient way at relatively less shipping costs. As shown in this research project that inventory of short-haul trucks can be increased while long-haul truck volume can be reduced by intermodal integration with rail and waterborne transport. It is up to the federal and state highway authorities, trucking industry, rail and ship/barge operators, and supply chain stakeholders to formulate a national policy for intermodal integration to ensure efficiency and sustainability. This requires more willingness to cooperate and collaborate among the different multimodal stakeholders.

Implementing the Results from the Case Studies of Intermodal Integration

This research project investigated three case studies in which intermodal integration is proposed for moving freight from highway to rail and from highway to waterway transport. In these case studies, scenarios are selected based on the analysis of the commodity flow for the region and the opportunity to move freight from highway to rail or waterway. In these scenarios there is enough amount of freight entering and leaving the terminal and port to justify diverting to an alternative mode. The commodity type to be diverted to rail cars or waterway barges must be a bulk, non-perishable item. The following case studies were analyzed, and the costs and benefits were calculated for each study scenario:

- Integration of highway and rail for Colorado freight
- Integration of highway and rail for selected NAFTA corridors
- Integration of highway and Mississippi River corridor

These intermodal integration studies provide data on travel time saving, increased average speed, and reduced fuel consumption and emissions. These case studies show the benefits of moving freight from highways to rail and waterway. For each of the case studies discussed, the travel time savings, ton-mile cost savings, and CO_2 emission reductions were calculated.

The Colorado intermodal freight integration study results for 30% trucks diverted to rail are presented in Figures 29 and 30. The NAFTA truck-rail integration study results for 20% trucks diverted to rail are shown in Figure 36. Final cost reductions and benefits for 30% trucks diverted to barges on Mississippi River are shown in Figure 44. As summarized in Table 23, these case studies demonstrate the following benefits of diverting a portion of truck freight per year to rail or barge.

Table 23. Summary of Benefits Calculated for Three Case Studies of Freight Integration

Freight Intermodal Integration Study	Annual Truck Freight Diverted	Travel Time Reduction	Ton-Mile Cost Savings	CO_2 Reduction	Fuel Cost Saving
Colorado-California (Truck 1,201 to 1,231 miles; Rail 1,353 miles)	30%	98.9%	87.0%	57.7%	$3,737,349
NAFTA Laredo-Detroit (Truck 1594 miles; Rail 1,777 miles)	20%	98.8%	87.2%	58.2%	$84,798,828
Gulfport-St. Louis, (Truck 695 miles - Mississippi River Barge 984 miles)	30%	19.0%	18.0%	11.7%	$ 113,088

These results demonstrate the economic benefits, societal benefits, and environmental benefits from making this transition to alternative freight transportation modes. These three case studies are different scenarios throughout the country, moving different types of freight by different transportation modes. This shows how the benefits differ among modes and which modes provide the most benefit.

Recommendation for Future Research

The following ideas are recommended to pursue for further research:

- As the U.S. population and economy continue to grow, there will be more automobiles and more freight truck traffic on highways. Reducing long-haul truck traffic and increasing short-haul truck traffic for transporting freight to intermodal stations are the keys for achieving a sustainable integrated multimodal freight transportation system.
- Other multimodal integration strategies should involve rail and highway freight trucks such that long haul freight is done through an integrated network of rail with highway interchanges and shipping channel connections. This includes integration alternatives for land based NAFTA corridor and Gulfport/rail/freight truck corridor. One strategy is to consider dedicated freight truck lanes/elevated separation with access/exit points around major freight hub centers and urban areas.
- It is recommended to evaluate the costs and benefits for life cycle assessment and include these in transportation economics methodology (Uddin and Torres-Verdin 1998, Uddin 2013, Uddin et al. 2013, Uddin et al. 2015) with enhancements related to capacity constraints, environmental costs, and societal benefits.
- Comprehensive econometric, demographic, and freight demand forecasting models should be developed and incorporated in a regional demographic and policy analysis framework.

4. RESEARCH PRODUCTS AND IMPLEMENTATION STATEMENT

4.1 Publications, Presentations, Honors, Awards

Publications and Presentations

A paper on traffic microsimulation conducted for the Mississippi DOT project, based on the thesis of a former M.S. student, was published in an international peer-reviewed ATS journal.
(This Miss DOT project won the 2014 AASHTO award of Sweet Sixteen projects.)

Graduate M.S. Report/Thesis and PhD Dissertation

Ahlan, Muhammad. (2014). Geospatial Applications for Mobility, Travel Demand, Transport Infrastructure, and Associated Impacts on the Environment. M.S. Graduate Report, University of Mississippi, December 2014. (Advisor: Dr. W. Uddin)

Cobb, Seth. (2015). Economic Viability and Societal Benefits of Integrated Multimodal Freight Corridors and Sustainable Passenger Transportation. M.S. Thesis, University of Mississippi, August 2015. (Advisor: Dr. W. Uddin)

Additionally, the following publications/papers/conference presentations are related to the goals of this project:
(One book, one book chapter, three journal papers and one refereed published conference book paper, nine papers in conference proceedings, and eight other conference presentations)

Book Published

Uddin, W., W.R. Hudson, and Ralph Haas (2013). *Public Infrastructure Asset Management*. McGraw-Hill, ISBN 0071820116. (Book published, July 2013) This second revised and expanded edition of our 1997 *Infrastructure Management* book includes several new sections on flood disaster examples, rapid flood impact assessment using remote sensing imagery and geospatial technologies, and examples of life cycle benefit cost analysis for flood disaster mitigation and protection of built infrastructure. Other new topics include supply chain management, use of remote sensing imagery and geospatial technologies, asset management practice for transportation and other lifeline public infrastructure, and value engineering applications for investment decision making.

Book blog post. http://infrastructureglobal.com/dr-robert-khayat-ole-miss-chancellor-emeritus-infrastructure-improvement-cannot-be-delayed-if-we-are-to-continue-as-a-vital-nation/

YouTube video: http://youtu.be/LiHqJInrFy0

Book Chapter

Uddin, W. (2014). Chapter 23 “Mobile and Area Sources of Greenhouse Gases and Abatement Strategies,” in *Handbook of Climate Change Mitigation and Adaptation*, edited by Wei-Yin

Chen, John M. Seiner, Toshio Suzuki and Maximilian Lackner, Springer. (Updated Chapter 23 of the 2012 Handbook in December 2014. The reference book will be available in 2016). http://www.springer.com/energy/renewable+and+green+energy/book/978-3-319-14408-5

Journals and Refereed Conference Books

Smith, Robert, and Waheed Uddin. (2016). A Rational Theory of Tire-Pavement Friction. Research Article 4858317, *Advances in Tribology*, Hindawi Publishing Corporation, Volume 2016. http://www.hindawi.com/journals/at/2016/4858317/ Accessed April 7, 2106.

Uddin, W., McCarty, T., and Sharma, J. (2015). Environmental Sustainability and Energy Considerations for Life-Cycle Analysis of Transportation Infrastructure Systems. *International Symposium on Systematic Approaches to Environmental Sustainability in Transportation (ISSAEST)*, University of Alaska Fairbanks, August 2-5, 2015, Fairbanks, Alaska.

Headrick, Jessica and W. Uddin. (2014). Traffic Flow Microsimulation for Performance Evaluation of Roundabouts and Stop-controlled Intersections at Highway Overpass. *ATS - International Journal of Advances in Transportation Studies*, Issue, XXXIV, November 2014, pp. 7-18.

Uddin, W. (2013). Value Engineering Applications for Managing Sustainable Intermodal Transportation Infrastructure Assets. *Production Engineering Review*, Vol. 4, No. 1, March 2013, pp. 74–84.

Conference Proceedings and Presentations

Durmus, A., Q. Nguyen, M.Z. McGrath, M.S. Altinakar, W. Uddin. (2015). Numerical Modeling and Simulation of Extreme Flood Inundation to Assess Vulnerability of Transportation Infrastructure Assets. 94th Annual Meeting of the Transportation Research Board (TRB), The National Academies, Washington DC. TRB Online Proceedings, January 10-14, 2015. (published and presented by Uddin, international conference)

Altinakar, M.S., M. McGrath, V.P. Ramalingam, and W. Uddin. (2015). Two-Dimensional Flood Modeling for the Assessment of Impacts on Critical Infrastructures. University Transportation Center (UTC) Conference for the Southeastern Region, University of Alabama at Birmingham. Birmingham, Alabama, March 26-27, 2015. (presented by Altinakar and Uddin, regional UTC conference)

Durmus, A., Nguyen, Q., McGrath, M.Z., Altinakar, M.S., and Uddin, W. (2015). Numerical Modeling And Simulation of Extreme Flood Inundation To Assess Vulnerability of Transportation Infrastructure Assets. *University Transportation Center (UTC) Conference for the Southeastern Region*, University of Alabama at Birmingham, March 26-27, 2015, Birmingham, Alabama.

Uddin, W., Cobb, S., Sherry, P. and Eksioglu, B. (2015). Economically Viable

Intermodal Integration of Surface and Waterway Freight Transport for Sustainable Supply Chain. *University Transportation Center (UTC) Conference for the Southeastern Region*, University of Alabama at Birmingham, March 26-27, 2015, Birmingham, Alabama.

Uddin, W, Altinakar, M.S. and Durmus, A. (2015). Extreme Flood Simulations to Assess Inundation Impacts and Structural Integrity of Transportation Infrastructure Assets. *The 2015 Critical Infrastructure Symposium*, The Infrastructure Security Partnership (TISP) and the Society of American Military Engineers (SAME), April 20-21, 2015, Baltimore, Maryland.

Uddin, W. (2015). Aircraft Safety on Airfield Pavements with Standing Water and Slush. Workshop 143- Influence of Airfield Surface Irregularity on Aircraft Life, Presented at the *94th Annual Meeting of The Transportation Research Board*, Washington, DC, January 10-15, 2015.

Uddin, W. (2015). Appraisal of Mechanistic-Empirical Pavement Design Guide for Highways Being Implemented in United States and Complimentary Needs for Pavement Asset Management. *6th ICONF BMP, 6th International Conference Bituminous Mixtures and Pavements*, Aristotle University of Thessaloniki (AUTh), June 10-12, 2015, Thessaloniki, Greece.

Uddin, W., Seth Cobb, and David May. (2014). Environmental Sustainability Dimensions of Freight Transport Considering Highway and Waterway Intermodal Integration. *2014 TRB-CMTS Conference*, Transportation Research Board, Washington DC, June 24-26, 2014.

Uddin, W. (2014). Remote Sensing Laser Survey and Imagery Technologies for Expediting Airport Mapping and Asset Management Applications. *E-Proceedings*, *2014 FAA Worldwide Airport Technology Transfer Conference*, Galloway, New Jersey, August 5-7, 2014.

Merighi, and W. Uddin. (2014). Study of Water Pools on Runways Considering The ICAO and Brazilian Civil Aviation Agency Recommendations For Large Aircraft. *E-Proceedings*, *2014 FAA Worldwide Airport Technology Transfer Conference*, Galloway, New Jersey, August 5-7, 2014.

Uddin, W. (2014). An Overview of GPR Applications for Evaluation of Pavement Thickness and Cracking. *E-Proceedings, 15th International Conference on Ground Penetrating Radar (GPR 2014)*, Brussels, Belgium, June 30 - July 4, 2014.

Uddin, W. and M.S. Altinakar. (2013). NCITEC Project 2012-25: Disaster Protection of Transport Infrastructure and Mobility Using Flood Risk Modeling and Geospatial Visualization–Overview and Progress to Date. Presentation of project overview, *First NCITEC Conference*, Starkville, Mississippi, October 31-November 1, 2013. (Attended by the NCITEC consortium partners including UM project PIs, faculty, and students)

Uddin, W. (2013). Geospatial Technologies for Highway Asset Management and Natural Disaster Risk Reduction Planning. keynote lecture, *2013 IJPC - First International Journal of Pavements Conference*, São Paulo, Brazil, December 9-10, 2013. (This trip was at no cost to the project. Dr. Uddin was an invited guest of the conference organizer professors from Mackenzie University, São Paulo, Brazil, who co-chaired the 2013 IJPC conference.)

Uddin, W., R. Haas, and W.R. Hudson. (2013). "Pavement Design or Pavement Management? Good Design Is Not Enough." *Online Proceedings, First Conference, 2013 IJPC - International Journal of Pavements Conference*, São Paulo, SP, Brazil, December 9-10, 2013. http://www.ijpavement.com/2013-ijpc-papers/

Uddin, W. and Zul Fahmi M. Jaafar. (2013). "Achieving sustainability without compromising long-term pavement performance for road infrastructure assets." *Online Proceedings, First Conference, 2013 IJPC - International Journal of Pavements Conference*, São Paulo, SP, Brazil, December 9-10, 2013. http://www.ijpavement.com/2013-ijpc-papers/

Uddin, W. (2012). Models of Freight Transportation and Emissions Costs. Presentation, *NCIT-MTI Freight and Energy Planning Workshop*, Denver University National Center of Intermodal Transportation (NCIT) and Mineta Transportation Institute (MTI), San Jose State University, San Jose, California, October 25, 2012. Invited presentation

Uddin, W. (2012). Value Engineering Applications for Deploying Sustainable Intermodal Transportation Infrastructure Strategies. *Proceedings, NCIT 2012 - National Conference on Intermodal Transportation: Problems, Practices, and Policies*, Hampton University, Hampton, Virginia, October 11-12, 2012.

Uddin, W. (2012). Pavement Evaluation and Structural Strengthening Considering Surface Materials, Environmental Conditions and Natural Disaster Impacts. *Proceedings, MAIREPAV7 - The Seventh International Conference on Maintenance and Rehabilitation of Pavements and Technological Control*, Auckland, New Zealand, August 28-30, 2012. Best paper Award in Theme of Advanced Trends

Commentary

Uddin, W. (2012). Commentary: What is the Value of Infrastructure Maintenance? A Survey by Felix Rioja. In *Landuse and Infrastructure*, Lincoln Institute, Boston, June 5-6, 2012. (Conference book, July 2013)

Honors and Awards

Uddin:

- 2014 Life member, American Society of Civil Engineers (ASCE)
- 2014 inductee of the University of Texas CAEE Academy of Distinguished Alumni
- Mississippi Transportation Institute (MTI), member of Board of Directors since March 2014

- Gulf Region Intelligent Transportation Society (GRITS), member of Board of Directors, 2009-2012
- Invited member of European project COST Action TU1208 "Civil Engineering Applications of Ground Penetrating Radar," coordinated by "Roma Tre" University, Rome, Italy, since 2012.
- Best paper award in international conferences: 2012 (MAIREPAV7, New Zealand)

Students

- Holt, Elizabeth. (2015). Benefits of highway and Rail Intermodal Integration for NAFTA Supply Chain Corridors. Paper for 2015 ITE Paper Competition, Institute of Transportation Engineers District 5, March 2015. Best Undergraduate Paper 1st District Award (certificate and cash award)
- Sims, Haley. (2014). Impacts of Rapid Urbanization on Transport and Energy Demands along the Mississippi River Transportation Corridor. Paper for 2014 ITE Student Paper Competition, Institute of Transportation Engineers District 5, February 2014. Outstanding Undergraduate 1st Place District Award (certificate and cash award).

4.2 Research Products and Technologies

The project objective was accomplished by using spaceborne remote sensing and geospatial technologies for mapping and visualization of freight corridors and connecting major city hubs. Geospatial databases were created by CAIT research team for transportation networks in NAFTA countries and intermodal networks in the U.S. The intermodal freight corridor case studies were used to develop “best practice guide” examples. Pavement-vehicle tire friction studies were conducted to support rational pavement friction mechanisms that develop during the tire-pavement contact. A paper on transportation infrastructure bank proposal was made for consideration by government transportation agencies, private transport operators, and all other supply chain stakeholders. The following research products were created to accomplish project objectives, which can be used for future traffic flow, freight, supply chain, and natural disaster resilience related research projects:

- Geospatial mapping of Mississippi River barge freight, inland surface transportation integration, and highway and rail networks in NAFTA countries:
- Freight intermodal integration of highway truck traffic and barge traffic on the Mississippi River
- Commodity flow by barges for states along the Mississippi River
- Surface freight transportation by rail and highway integration and new intermodal rail routes
- United States-Canada-Mexico databases of highway and rail networks and border ports
- United States and NAFTA highway buffers for integration with freight rail

- Bridges of NAFTA corridors on U.S. and Mexico border and ports on U.S. and Canada border
- Comprehensive analysis of benefits of rail-highway integration and highway-waterway integration for travel time reduction, shipping cost, and lower CO_2 emission

Other products include:

ACCESS Databases created for Intergraph's GeoMediaPro geospatial software: 2014 United States all (including Alaska and Hawaii), US-Mexico-Canada, 2014 World, Buffer-Mississippi-River-States. (These databases include the 2010 population data of states and counties; highway and rail inventory maps of US-Canada, and Mexico; river port inventory maps and commodity maps for 2014 United States.)

Several examples of spatial maps created on the project are included on the following pages.

4.3 Overall Benefits of Integrating Multimodal Freight Systems

The project is likely to make an impact on the public and society beyond the bounds of science, engineering, and the academic world on areas such as:

- Enhancing public understanding of supply chain transport impacts on urban communities and the environment through visualization products which are easy to understand and communicate with government stakeholders, businesses, media, and the general public.
- Adapting the developed approaches for supply chain infrastructure, intermodal corridor integration, and logistics, and traffic demand management.
- Offering geospatial products for landuse planning, traffic flow control policies, and pavement safety evaluation for roads, airports, intermodal pavements, container parking, and ports.
- Implementing the developed methodologies and web-based social networking tools to build a better public understanding of sustainable supply chain management and reduce degrading effects on the environment and communities
- Recommending new approaches of financing resources for infrastructure investments to reduce severe backlogs due to inadequate federal and state funds.

4.4 Recommendations and Future Work

It is recommended that transportation infrastructure agencies and supply chain stakeholders consider the research products developed in this project and benefits outlined to address the funding deficit and reduction in transportation related anthropogenic carbon emissions. The integrated intermodal infrastructure networks can be managed as a public-private enterprise so that each team player works in a complementary spirit and not competing as rail and freight trucks do now for serving national and global supply chain.

5. REFERENCES

Ahlan, Muhammad. (2014). Geospatial Applications for Mobility, Travel Demand, Transport Infrastructure, and Associated Impacts on the Environment. M.S. Graduate Report, University of Mississippi, December 2014.

AAR. (2011). America's freight railroads. Association of American Railroads. http://www.youtube.com/watch?NR=1&feature=endscreen&v=HpN0mnJn0NY Accessed May 13, 2011.

Advocates. (2015). Truck Driver Fatigue. Advocates for Highway & Auto Safety. http://www.saferoads.org/~saferoad/truck-driver-fatigue Accessed June 26, 2015.

ASCE. (2013). 2013 Report Card for America's Infrastructure. American Society of Civil Engineers. http://www.asce.org/infrastructure/ http://www.infrastructurereportcard.org/a/#p/home Accessed January 15, 2015.

ASTM. (2011). ASTM E274/E274M –11, Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire. ASTM International.

BTS. (2012). Table 3-21: Average Freight Revenue per Ton-Mile. U.S. Department of Transportation, Bureau of Transportation Statistics (BTS), 2012. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_03_21.html Accessed February 23, 2015.

BTS. (2013). North American Transborder Freight Data: Main Page Search. U.S. Department of Transportation, Bureau of Transportation Statistics (BTS), 2013. http://transborder.bts.gov/programs/international/transborder/TBDR_QA.html Accessed May 21, 2015.

BTS. (2014). Passenger Travel Facts and Figures 2014. Bureau of Transportations Statistics. U.S. Department of Transportation, Washington, DC, 2014. http://www.rita.dot.gov/bts/publications/passenger_travel/chapter2 Accessed October 3, 2014.

BTS. (2015a). Chapter 3: Moving Goods. U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts /files/ch3_tsar2012.pdf Accessed May 21, 2015.

BTS. (2015b). Chapter 1: Transportation System Characteristics: An Overview. U.S. Department of Transportation, Office of the Assistant Secretary for Research and Technology. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/ch1_tsar2012_0.pdf Accessed May 21, 2015.

BTS. (2016). Table 2-1: Transportation Fatalities by Mode. Bureau of Transportation Statistics (BTS), Office of the Assistant Secretary for Research and Technology, U.S. Department of Transportation, Washington, DC, Updated July 2016. http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_02_01.html_mfd Accessed July 31, 2016.

CAIT. (2014). Center for Advanced Infrastructure Technology. The University of Mississippi, http://www.olemiss.edu/projects/cait, Accessed May 10, 2014.

CEC. (2011). *Destination Sustainability*. Commission for Environmental Cooperation (CEC), Montreal, Canada, 2011. http://www.cec.org/ Accessed February 15, 2013.

Census. (2007). 2007 Commodity Flow Survey Standard Classification of Transported Goods (SCTG). U.S. Department of Commerce, U.S. Census Bureau. 2007. https://www.census.gov/svsd/www/cfsdat/cfs071200.pdf Accessed June 8, 2015.

Cobb, Seth. (2015). Economic Viability and Societal Benefits of Integrated Multimodal Freight Corridors and Sustainable Passenger Transportation. M.S. Thesis, University of Mississippi, August 2015.

Durmus, A., Q. Nguyen, M.Z. McGrath, M.S. Altinakar, W. Uddin. (2015). Numerical Modeling and Simulation of Extreme Flood Inundation to Assess Vulnerability of Transportation Infrastructure Assets. TRB 94th Annual Meeting, The National Academies, Washington DC. Online Proceedings, January 10-14, 2015.

Durmus, Alper. (2016). Flood Disaster Resilient Bridge Structures for Sustainable Bridge Management Systems. Ph.D. Dissertation. University of Mississippi, August 2016.

EIA. (2015). Today in Energy: U.S. energy-related CO2 emissions up 1% in 2014 as buildings, transport energy use rises. The U.S. Energy Information Administration (EIA), Department of Energy, November 24, 2015. http://www.eia.gov/todayinenergy/detail.cfm?id=23892 Accessed December 15, 2015.

EPA. (2005). Calculating Emissions of Greenhouse Gases: Key Facts and Figures. U.S. Environmental Protection Agency (EPA), 2005. http://nepis.epa.gov/Adobe/PDF/P1001YTV.PDF Accessed October 29, 2014.

EPA. (2013). U.S. Greenhouse Gas Emissions by Economic Sector, 2012. U.S. EPA, 2013. http://www.epa.gov/climatechange/ghgemissions/inventoryexplorer/#allsectors/allgas/econsect/current Accessed October, 27, 2014.

EPA. (2014). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012. U.S. EPA, 2014. http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2014-Main-Text.pdf Accessed October, 28, 2014.

EPA. (2015). U.S. Greenhouse Gas Inventory Report: 1990-2013. U.S. Environmental Protection Agency. 2015. http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html Accessed June 15, 2015.

FHWA. (2014). Assessing the Effects of Freight Movement on Air Quality at the National and Regional Level. U.S. Department of Transportation, Federal Highway Administration. 2014. http://www.fhwa.dot.gov/environment/air_quality/publications/effects_of_freight_movement/chapter01.cfm Accessed June 11, 2015.

FHWA. (2015). Highway History. Federal Highway Administration, United States Department of Transportation, Washington, DC, November 18, 2015. https://www.fhwa.dot.gov/infrastructure/gastax.cfm Accessed March 20, 2015.

FHWA. (2016). Freight Analysis Framework. Freight Management and Operations, Federal Highway Administration, United States Department of Transportation, Washington, DC, Updated August 16, 2016. http://www.ops.fhwa.dot.gov/freight/freight_analysis/faf/ Accessed August 25, 2016.

Gulfport. (2014). Gulfport’s Advantages. Port of Gulfport, 2014. http://shipmspa.com/carriers-customers/gulfports-advantages/#sthash.EVDGSLIR.5PWa8fzV.dpbs Accessed June 8, 2015.

IPCC. (2014). The Fifth Assessment Report (AR5). The Intergovernmental Panel on Climate Change, November 2014. http://www.ipcc.ch/report/ar5/index.shtml Accessed May 10, 2015.

ICC. (2013). Skid Test Description. Manual. International Cybernetics Corporation North Largo, Florida. http://www.intlcybernetics.com/

Infra. (2011). Thailand’s Post-Flood Seminar: Lessons Learned from 2011 Great Flood Disaster and Future Directions for Flood Prevention. InfrastructureGlobal, 2011. http://infrastructureglobal.com/?p=1834, Accessed July 14, 2014.

Kong, Hoi L. and L. Kinvin Wroth. (2015). NAFTA and Sustainable Development: History, Experience, and Prospects for Reform. Cambridge University Press, 2015.

Melillo, J. M., T. C. Richmond and G. W. Yohe, Eds.(2014). Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 2014. http://nca2014.globalchange.gov Accessed 23 May 2014.

Mitchell, Kenneth Ned. (2013) .Waterway Navigation Systems R&D with the US Army Corps of Engineers. Presentation at University of Mississippi Civil Engineering Department, U.S. Army Engineer Research and Development Center Coastal and Hydraulics Lab Vicksburg, MS, April 25, 2013.

MODOT. (2012). Freight Equivalent Units by Mode. Missouri Department of Transportation (MODOT), 2012. http://www.modot.org/othertransportation/freight/documents/FreightEquivalentUnitsbyMode062608.pdf Accessed February 23, 2015.

Murad, Maher M. (2006). Modeling Asphalt Pavement Friction and Wet-Pavement Traffic Accidents for Two-Lane Rural Highways. *IJP-International Journal of Pavements*, Vol. 5, No. 1-2-3, January-May-September 2011, pp. 175-187.

NAFTA. (2012). North American Free Trade Agreement”. NAFTA Now, 2012. http://www.naftanow.org/facts/default_en.asp Accessed June 9, 2015.

NCFRP. (2012a). Guidebook for Understanding Urban Good Movement. Report 14, National Cooperative Freight Research Program (NCFRP), Transportation Research Board, The National Academies, Washington, DC, 2012.

NCFRP. (2012b). Preserving and Protecting Freight Infrastructure and Routes. Report 16, National Cooperative Freight Research Program. Transportation Research Board, The National Academies, 2012.

NCFRP. (2012c). Dedicated Revenue Mechanisms for Freight Transportation Investment. Report 15, National Cooperative Freight Research Program. Transportation Research Board, The National Academies, 2012.

NCHRP (2016). Public Perception of Mileage Based User Fees. Synthesis 487, National Cooperative Highway Research Program, Transportation Research Board, The National Academies, 24 February 2016.

NOAA. (2012). Global Sea Level Rise Scenarios for the United States National Climate Assessment. NOAA Climate Program Office (CPO), National Oceanic and Atmospheric Administration (NOAA), December 6, 2012. http://cpo.noaa.gov/AboutCPO/AllNews/TabId/315/ArtMID/668/ArticleID/80/Global-Sea-Level-Rise-Scenarios-for-the-United-States-National-Climate-Assessment.aspx Accessed April 22, 2016.

NOAA. (2015). The Global Greenhouse Gas Reference Network. NOAA's Earth System Research Laboratory, Boulder, Colorado. http://www.esrl.noaa.gov/gmd/ccgg/trends/ Accessed April 11, 2015.

NPR. (2016). 2015 Traffic Fatalities Rose By Largest Percent In 50 Years, Safety Group Says. NPR Mississippi Public Broadcasting, February 18, 2016. http://www.npr.org/sections/thetwo-way/2016/02/18/467230965/2015-traffic-fatalities-rose-by-largest-percent-in-50-years-safety-group-says Accessed April 15, 2016.

NYT. (2014). Truckers Resist Rules on Sleep, Despite Risks of Drowsy Driving. The New York Times (NYT), 2014. http://www.nytimes.com/2014/06/17/business/truckers-resist-rules-on-sleep-despite-risks-of-drowsy-driving.html?_r=0 Accessed June 26, 2015.

ORNL. (2012).Stacy C. Davis , Susan W. Diegel , and Robert G. Boundy. Transportation Energy Data Book: Edition 31—2012." Oak Ridge National Laboratory, Oak Ridge, Ten., July 2012

ORNL. (2015a). (FAF^3) Summary Statistics, 2007. Center of Transportation Analysis (CTA), Oak Ridge National Laboratory (ORNL), Updated 2015. http://faf.ornl.gov/fafweb/FUT.aspx Accessed March 10, 2015.

ORNL. (2015b). Freight Analysis Framework Data Tabulation Tool. Center of Transportation Analysis (CTA), Oak Ridge National Laboratory (ORNL), Updated 2014. http://faf.ornl.gov/fafweb/Extraction2.aspx Accessed March 12, 2015.

ORNL. (2016). Center of Transportation Analysis (CTA), Oak Ridge National Laboratory (ORNL), Updated 2016. http://faf.ornl.gov/fafweb/ Accessed August 15, 2016.

PNWA. (2015). The Inland Waterways Trust Fund. Pacific Northwest Waterways Association (PNWA), 2015. http://www.pnwa.net/new/Articles/IWTF.pdf

Roll Call. (2015). Port, Waterways Funds May Have Surplus Next Year. March 25, 2015. http://www.rollcall.com/news/port_waterways_funds_may_have_surplus_next_year-240920-1.html#sthash.G88rCwmS.dpuf Accessed July 16, 2015.

Smith, Robert H. and Timothy W. Neubert. (2011). Calculating Tire/Pavement Friction Forces. *IJP-International Journal of Pavements*, Vol. 10, No. 1-2-3, January-May-September 2011, pp. 1-12.

Smith, Robert, and Waheed Uddin. (2016). A Rational Theory of Tire-Pavement Friction. Research Article 4858317, *Advances in Tribology*, Hindawi Publishing Corporation, Volume 2016. http://www.hindawi.com/journals/at/2016/4858317/ Accessed April 7, 2106.

Smith, Robert H. (2008). *Analyzing Friction in the Design of Rubber Products and their Paired Surfaces*. CRC Press, Boca Raton, Florida, U.S.A., 2008

Sweet, James Stouder. (1993). The federal gasoline tax at a glance: A history. Publisher - Bybee House, 23 pages.

Tax. (2016). State Gasoline Tax Rates in 2016. Tax Foundation, Mar 3, 2016. http://taxfoundation.org/blog/state-gasoline-tax-rates-2016 Accessed May 10, 2016.

Uddin, W. and M.S. Altinakar. (2015). Final Report: Project 2012-25 Disaster Protection of Transport Infrastructure and Mobility Using Flood Risk Modeling and Geospatial Visualization. University of Mississippi Report UM-CAIT/2015-01, National Center for Intermodal Transportation for Economic Competitiveness (NCITEC), May 2015.

Uddin, W. and Kanok Boriboonsomsin. (2005). Air Quality Management Using Vehicle Emission Modeling and Spatial Technologies. *Proceedings, Environment 2005 International Conference: Sustainable Transportation in Developing Countries*, Abu Dhabi, UAE, January 30- February 2, 2005, (Published , 2007).

Uddin, W., Seth Cobb, and David May. (2014). Environmental Sustainability Dimensions of Freight Transport Considering Highway and Waterway Intermodal Integration. 2014 TRB-CMTS Conference, Transportation Research Board, Washington DC, June 24-26, 2014. http://onlinepubs.trb.org/onlinepubs/conferences/2014/MTS2014/Uddin.pdf

Uddin, W., S. Cobb, T. McCarty, and J. Sharma. (2015). Environmental and Energy Concerns for Life Cycle Analysis of Transportation Systems. ASCE Special Publication International Symposium on Systematic Approaches to Environmental Sustainability in Transportation, Center for Environmentally Sustainable Transportation in Cold Climates (CESTiCC), Fairbanks, Alaska, August 2-5, 2015.

Uddin, W., W.R. Hudson, and Ralph Haas. (2013). *Public Infrastructure Asset Management*. McGraw-Hill, New York, ISBN 0071820116.

Uddin. W. and V. Torres-Verdin. (1998). Service Life Analysis for Managing Road Pavements in Mexico. Proceedings, Fourth International Conference on Managing Pavements, Durban, South Africa, May 1998, Vol. 2, pp. 882-898.

Uddin, W. (2006). Air Quality Management Using Modern Remote Sensing and Spatial Technologies and Associated Societal Costs. *International Journal of Environmental Research and Public Health*, ISSN 1661-7827, MDPI, Vol. 3, No. 3, September 2006, pp. 235-243.

Uddin, W. (2007). Assessment of Transportation Related Safety and Public Health Impacts Using Remote Sensing and Geospatial Analysis Technologies. *Proceedings, 7th Malaysian Road Conference*, Kuala Lumpur, Malaysia, July 17-19, 2007, pp. 1-16.

Uddin, W. (2012). Mobile and Area Sources of Greenhouse Gases and Abatement Strategies. Chapter 23, *Handbook of Climate Change Mitigation*, (Editors: Wei-Yin Chen, John M. Seiner, Toshio Suzuki and Maximilian Lackner), Springer, 2012, pp 775-839.

Uddin, W. (2013). Value Engineering Applications for Managing Sustainable Intermodal Transportation Infrastructure Assets. *Management and Production Engineering Review*, MPER, Vol. 4, No. 1, March 2013, pp. 74–84.

Uddin, W. (2015). Aircraft Safety on Airfield Pavements with Standing Water and Slush. Workshop 143- Influence of Airfield Surface Irregularity on Aircraft Life, Presented at the 94th Annual Meeting of The Transportation Research Board, Washington, DC, January 10-15, 2015.

USACE. (2014).Tons by Commodity. Navigation Data Center, U.S. Army Corps of Engineers (USACE), 2012. http://www.navigationdatacenter.us/wcsc/webpub12/Part2_Ports_tonsbycommCY2012.HTM. Accessed July 27, 2014.

USDOT. (2002). Transportation, Air Quality, and Remote Sensing Laser Measurements of Air Pollutants Related to Highway Traffic in Mississippi – Oxford and Tupelo. "Achievements of the USDOT-NASA Joint Program on Remote Sensing and Spatial Information Technologies Application to Multimodal Transportation 2000-2002," April 2002.

US Trust. (2016). Rebuilding America: The Road Ahead. Bank of America Corporation, 2016. http://www.ustrust.com/UST/Pages/rebuilding-america.aspx Accessed June 27, 2016.

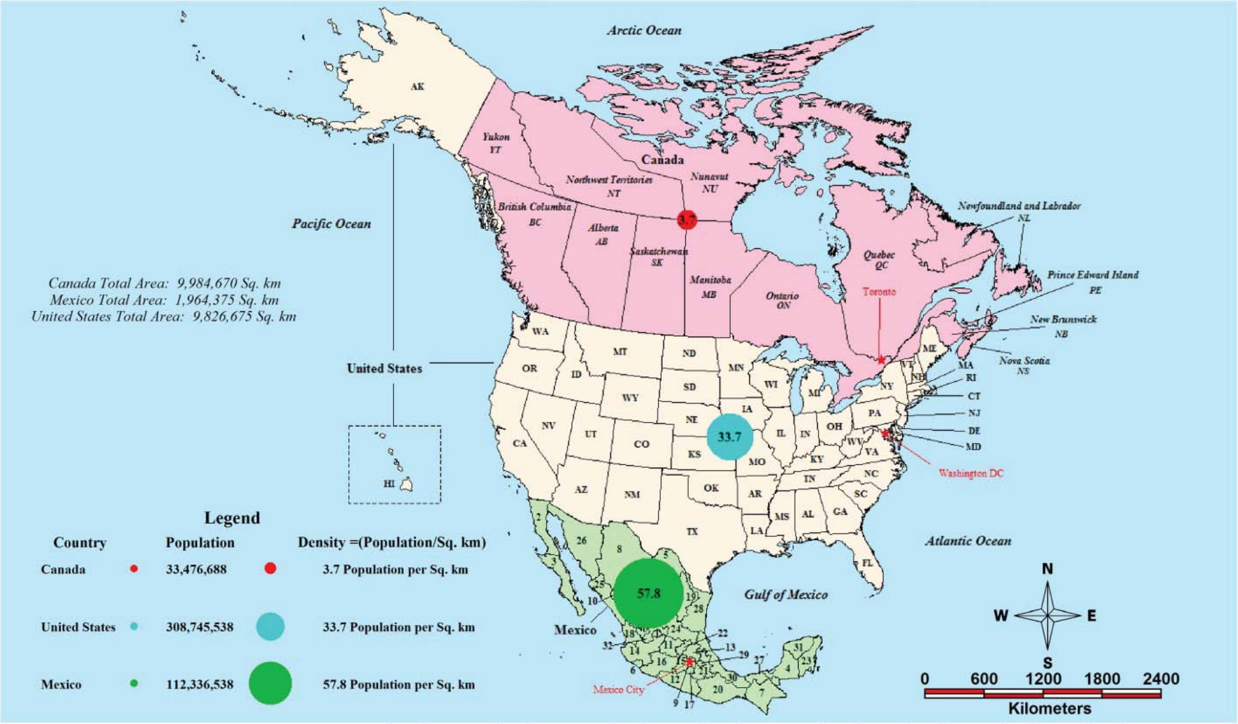
Vector. (2009). Critical Issues Impacting the Freight Transportation Industry in the Southeast Region. Vector, Vanderbilt University, 2009. http://www.vanderbilt.edu/vector/research/ StrategicFreightScan-Final.pdf Accessed June 26, 2015.

White House. (2014). Fact Sheet: The President's Climate Data Initiative: Empowering America's Communities to Prepare for the Effects of Climate Change, 2014, http://www.whitehouse.gov/the-press-office/2014/03/19/fact-sheet-president-s-climate-data-initiative-empowering-america-s-comm Accessed March 28, 2014.

Wilson Center. (2014). Is Geography Destiny? A Primer on North American Relations. (Editors: Christopher Wilson and David Biette), Woodrow Wilson International Center for Scholars, One Woodrow Wilson Plaza, 1300 Pennsylvania Avenue, NW, Washington, DC 2004-3027, Febrauary 2014. https://www.scribd.com/document/207949920/Is-Geography-Destiny-A-Primer-on-North-American-Relations Accessed May 20, 2014

More Examples of Geospatial Databases and Spatial Maps

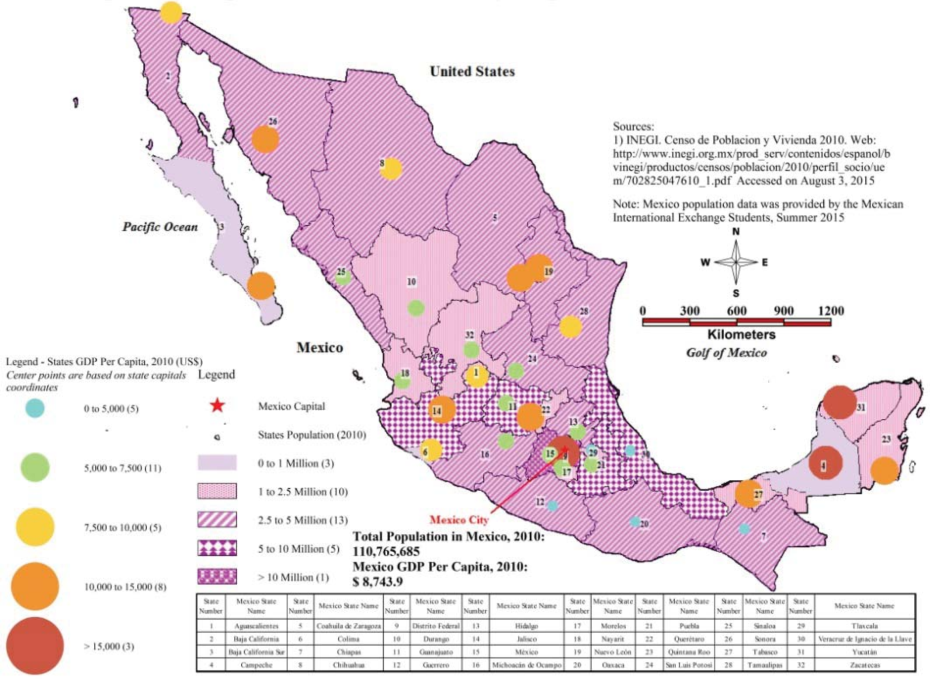
Population Density for NAFTA Countries (2010)



Sources:
CIA World Fact, www.cia.gov, Accessed: 10/10/2014
INEGI, http://www.inegi.org.mx, Accessed: 10/6/2014
Statistics Canada, http://www12.statcan.gc.ca, Accessed: 10/6/2014
US Census Bureau, http://www.census.gov/2010census, Accessed: 10/3/2014

State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name
1	Aguascalientes	5	Coahuila de Zaragoza	9	Distrito Federal	13	Hidalgo	17	Morelos	21	Puebla	25	Sinaloa	29	Tlaxcala
2	Baja California	6	Colima	10	Durango	14	Jalisco	18	Nayarit	22	Querétaro	26	Sonora	30	Veracruz de Ignacio de la Llave
3	Baja California Sur	7	Chiapas	11	Guanajuato	15	México	19	Nuevo León	23	Quintana Roo	27	Tabasco	31	Yucatán
4	Campeche	8	Chihuahua	12	Guerrero	16	Michoacán de Ocampo	20	Oaxaca	24	San Luis Potosí	28	Tamaulipas	32	Zacatecas

Spatial Map of Mexican States By Population and GDP (US$), 2010



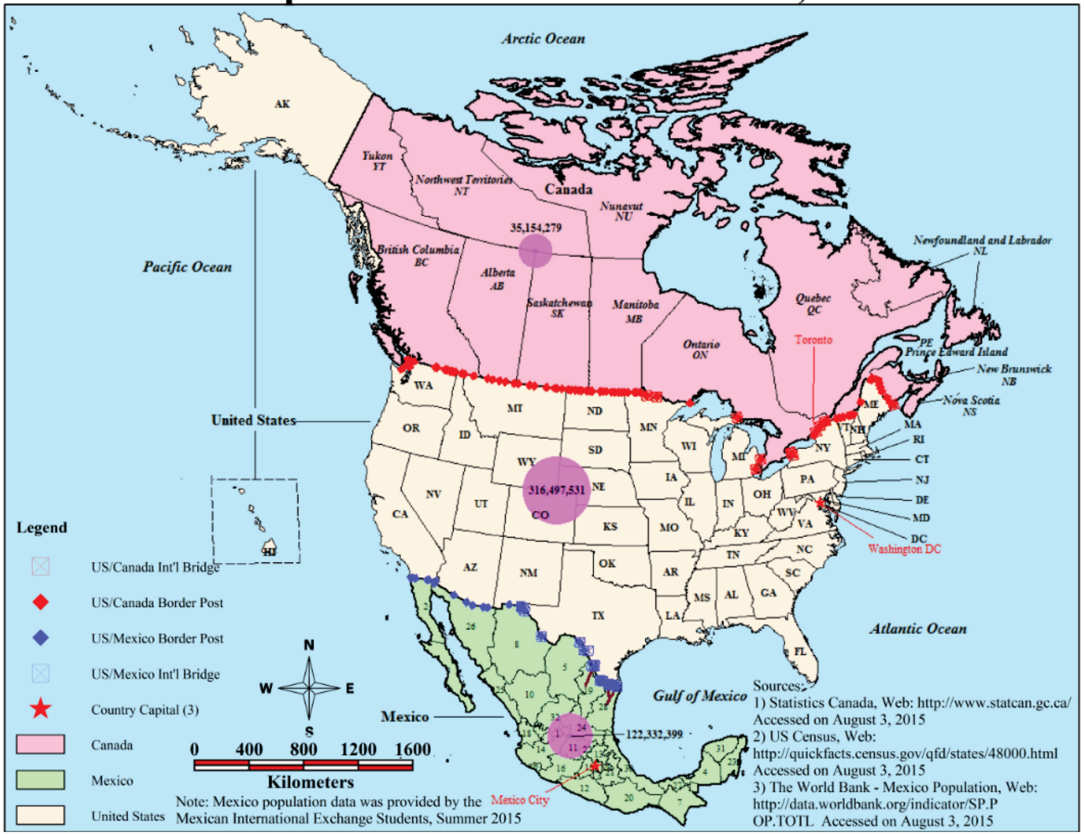
Sources:
1) INEGI. Censo de Poblacion y Vivienda 2010. Web: http://www.inegi.org.mx/prod_serv/contenidos/espanol/bvinegi/productos/censos/poblacion/2010/perfil_socio/uem/702825047610_1.pdf Accessed on August 3, 2015

Note: Mexico population data was provided by the Mexican International Exchange Students, Summer 2015

Total Population in Mexico, 2010: 110,765,685
Mexico GDP Per Capita, 2010: $ 8,743.9

State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name	State Number	Mexico State Name
1	Aguascalientes	5	Coahuila de Zaragoza	9	Distrito Federal	13	Hidalgo	17	Morelos	21	Puebla	25	Sinaloa	29	Tlaxcala
2	Baja California	6	Colima	10	Durango	14	Jalisco	18	Nayarit	22	Querétaro	26	Sonora	30	Veracruz de Ignacio de la Llave
3	Baja California Sur	7	Chiapas	11	Guanajuato	15	México	19	Nuevo León	23	Quintana Roo	27	Tabasco	31	Yucatán
4	Campeche	8	Chihuahua	12	Guerrero	16	Michoacán de Ocampo	20	Oaxaca	24	San Luis Potosí	28	Tamaulipas	32	Zacatecas

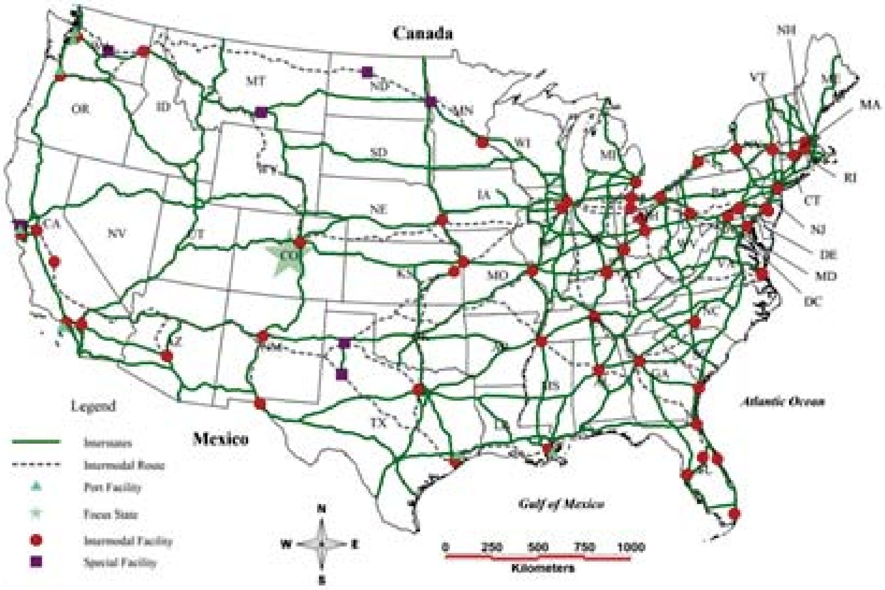
Total Population of NAFTA Countries, 2013



Note: Mexico population data was provided by the Mexican International Exchange Students, Summer 2015

Sources:
1) Statistics Canada, Web: http://www.statcan.gc.ca/ Accessed on August 3, 2015
2) US Census, Web: http://quickfacts.census.gov/qfd/states/48000.html Accessed on August 3, 2015
3) The World Bank - Mexico Population, Web: http://data.worldbank.org/indicator/SP.POP.TOTL Accessed on August 3, 2015

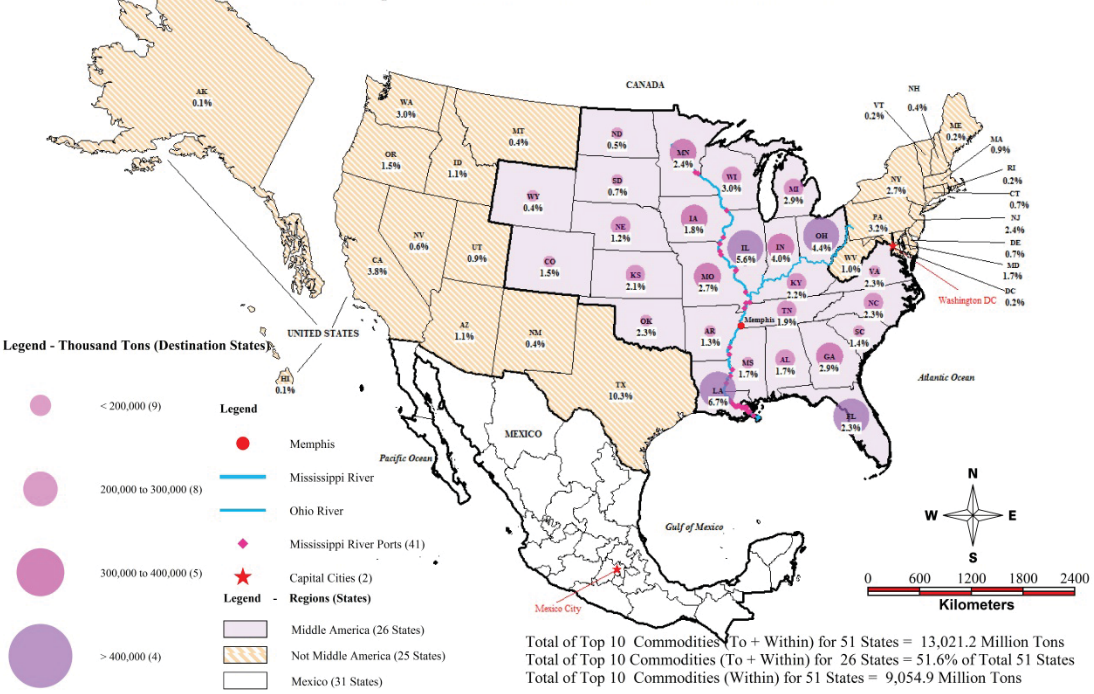
Integrated Freight Truck – Intermodal Rail



Top 10 Commodities Freight Data, Thousand Tons, 2011

(Total for Each Destination State from 26 States Including Within State Freight)

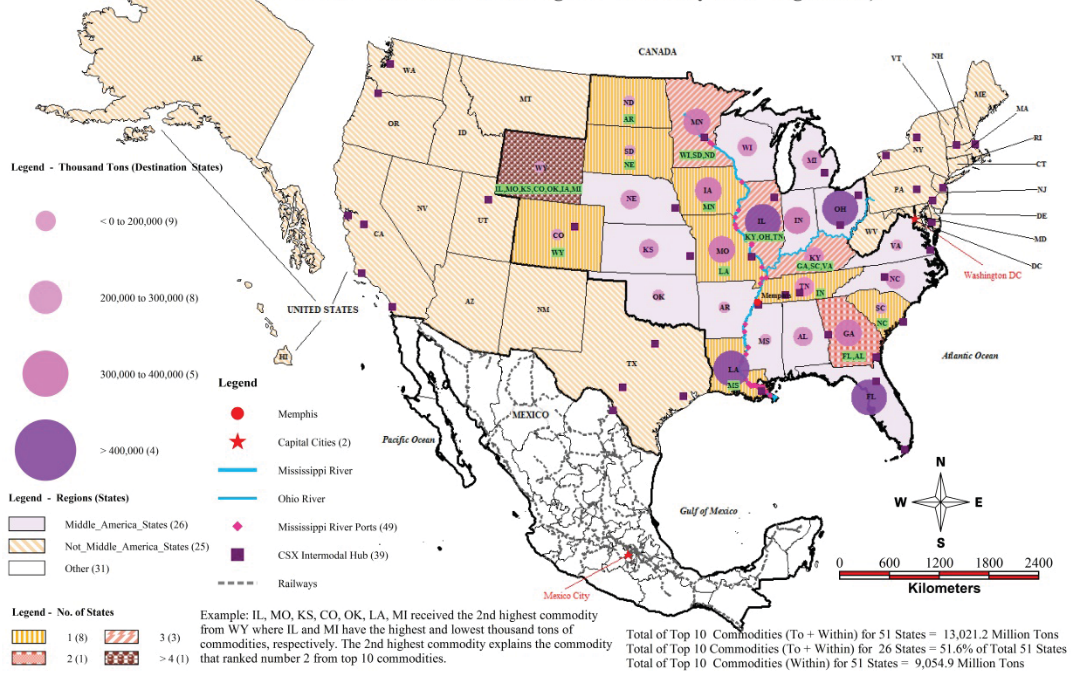
Destination State Top 10 Commodities Shown as % of Destination for All 51 U.S. States



Total of Top 10 Commodities (To + Within) for 51 States = 13,021.2 Million Tons
Total of Top 10 Commodities (To + Within) for 26 States = 51.6% of Total 51 States
Total of Top 10 Commodities (Within) for 51 States = 9,054.9 Million Tons

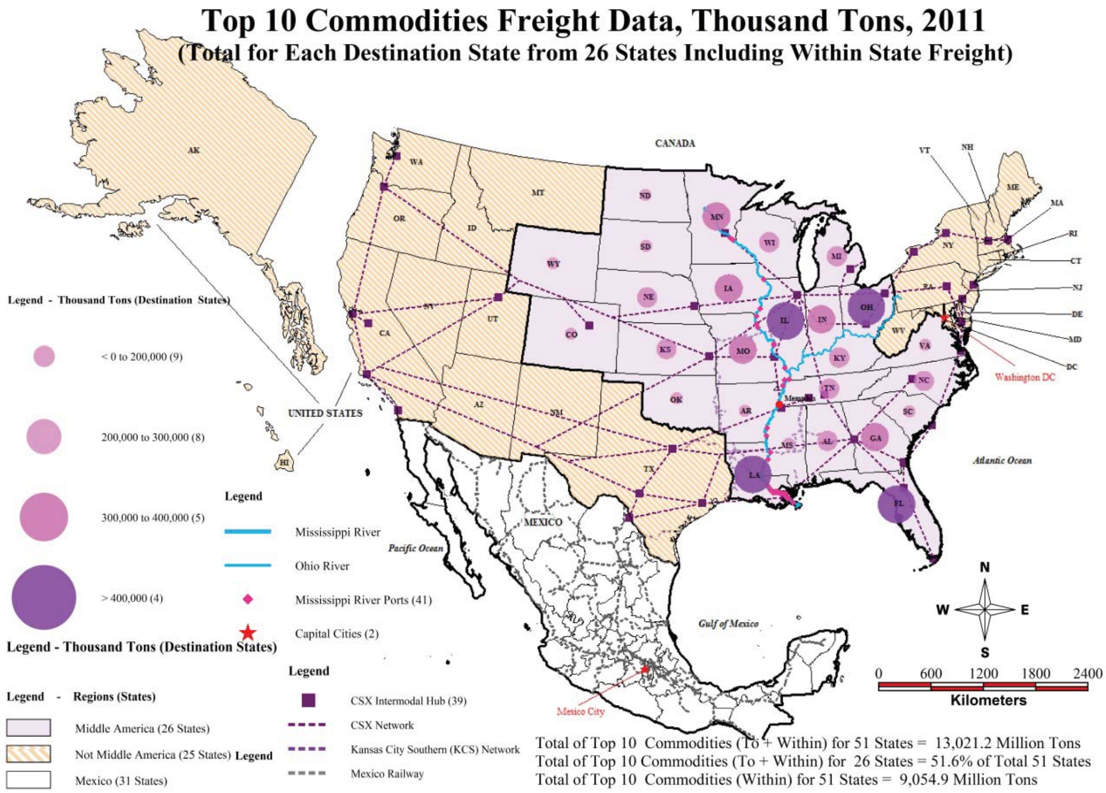
Top 10 Commodities Freight Data, Thousand Tons, 2011

(Total for Each Destination State from 26 States Including Within State Freight and No. of States that Received 2nd Highest Commodity from Origin State)



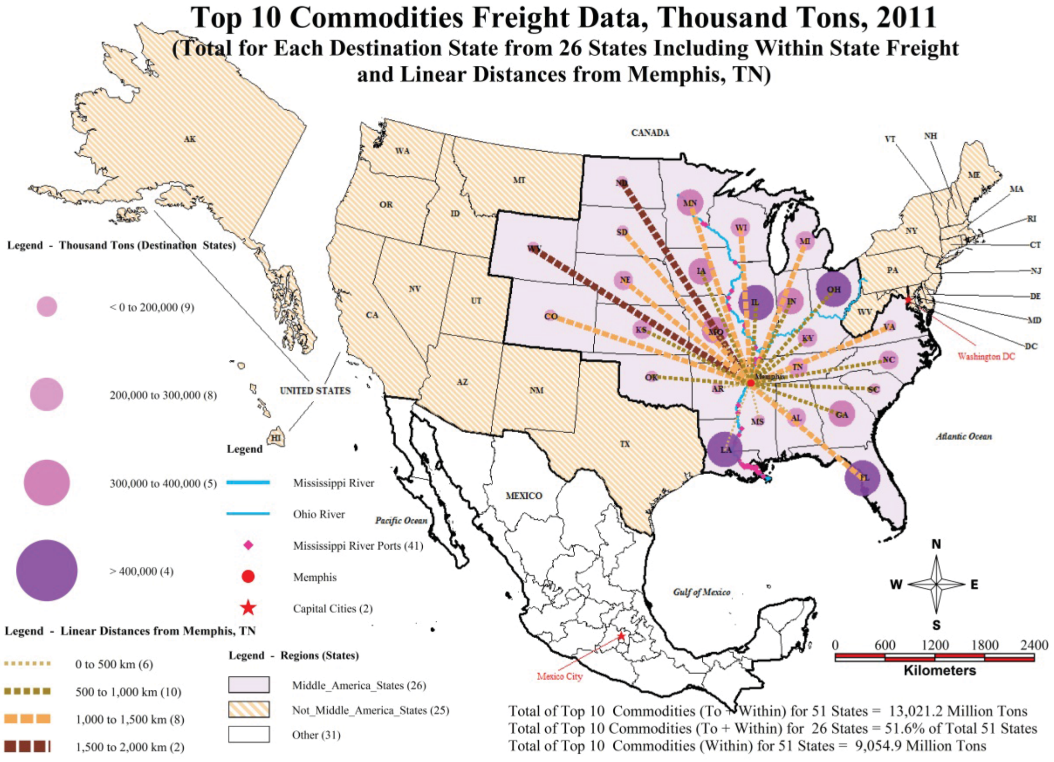
Example: IL, MO, KS, CO, OK, LA, MI received the 2nd highest commodity from WY where IL and MI have the highest and lowest thousand tons of commodities, respectively. The 2nd highest commodity explains the commodity that ranked number 2 from top 10 commodities.

Total of Top 10 Commodities (To + Within) for 51 States = 13,021.2 Million Tons
Total of Top 10 Commodities (To + Within) for 26 States = 51.6% of Total 51 States
Total of Top 10 Commodities (Within) for 51 States = 9,054.9 Million Tons



Top 10 Commodities Freight Data, Thousand Tons, 2011
(Total for Each Destination State from 26 States Including Within State Freight)

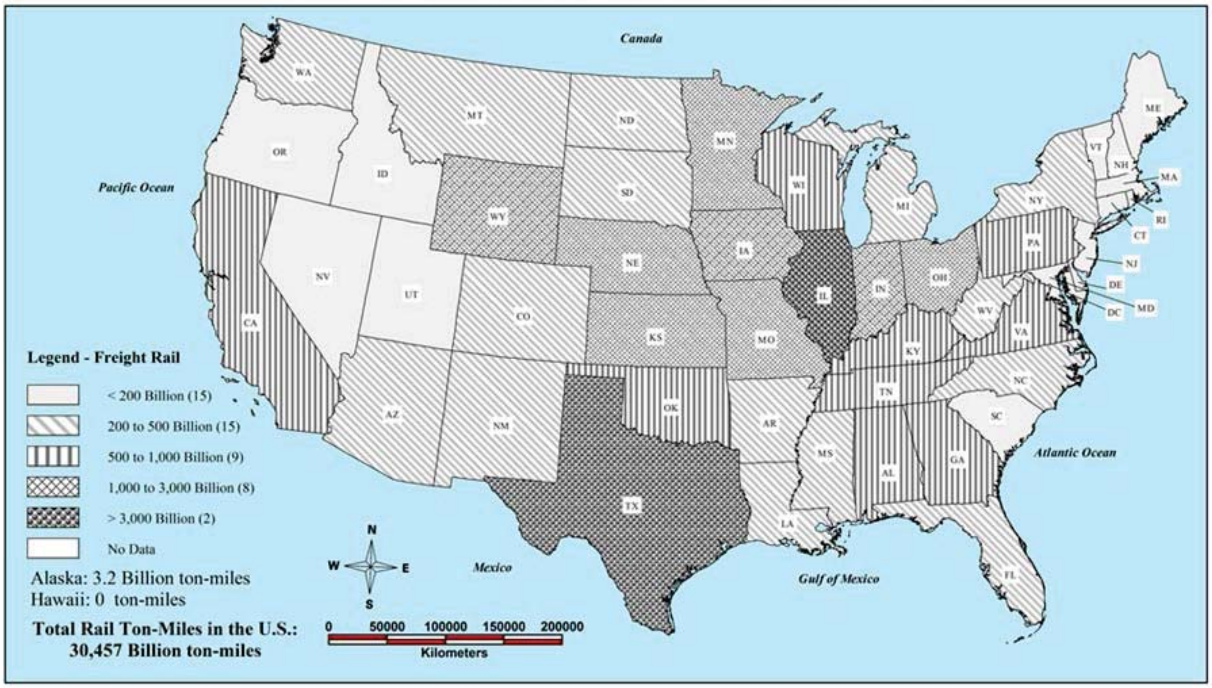
Total of Top 10 Commodities (To + Within) for 51 States = 13,021.2 Million Tons
Total of Top 10 Commodities (To + Within) for 26 States = 51.6% of Total 51 States
Total of Top 10 Commodities (Within) for 51 States = 9,054.9 Million Tons



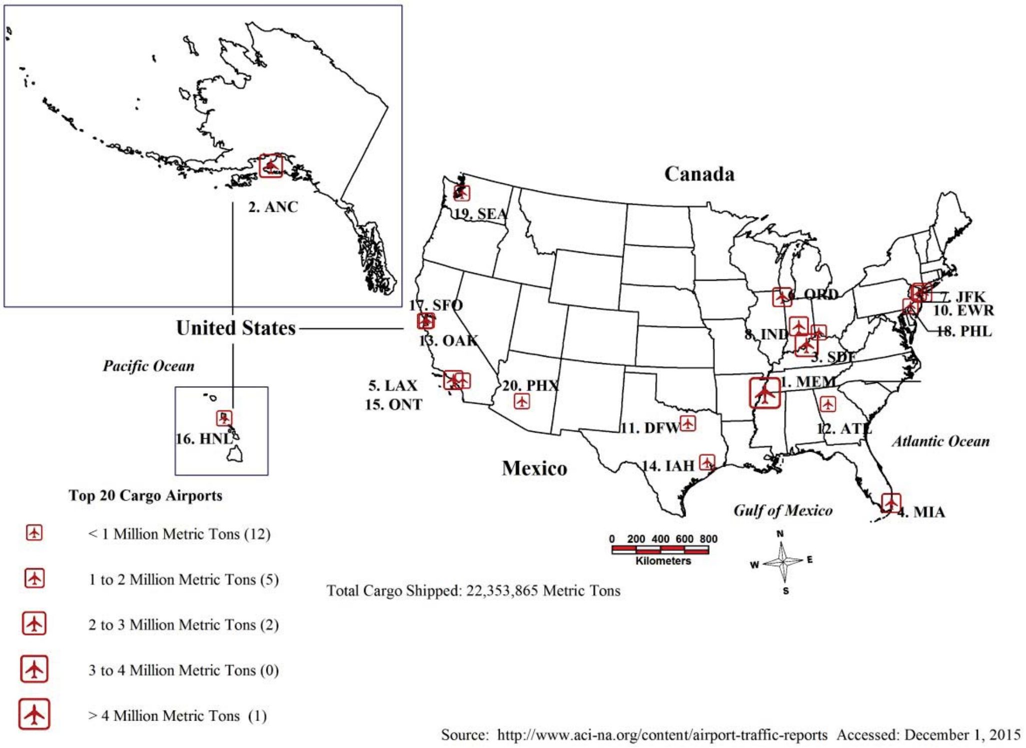
Top 10 Commodities Freight Data, Thousand Tons, 2011
(Total for Each Destination State from 26 States Including Within State Freight
and Linear Distances from Memphis, TN)

Total of Top 10 Commodities (To + Within) for 51 States = 13,021.2 Million Tons
Total of Top 10 Commodities (To + Within) for 26 States = 51.6% of Total 51 States
Total of Top 10 Commodities (Within) for 51 States = 9,054.9 Million Tons

2010 Rail Ton-Miles in the United States

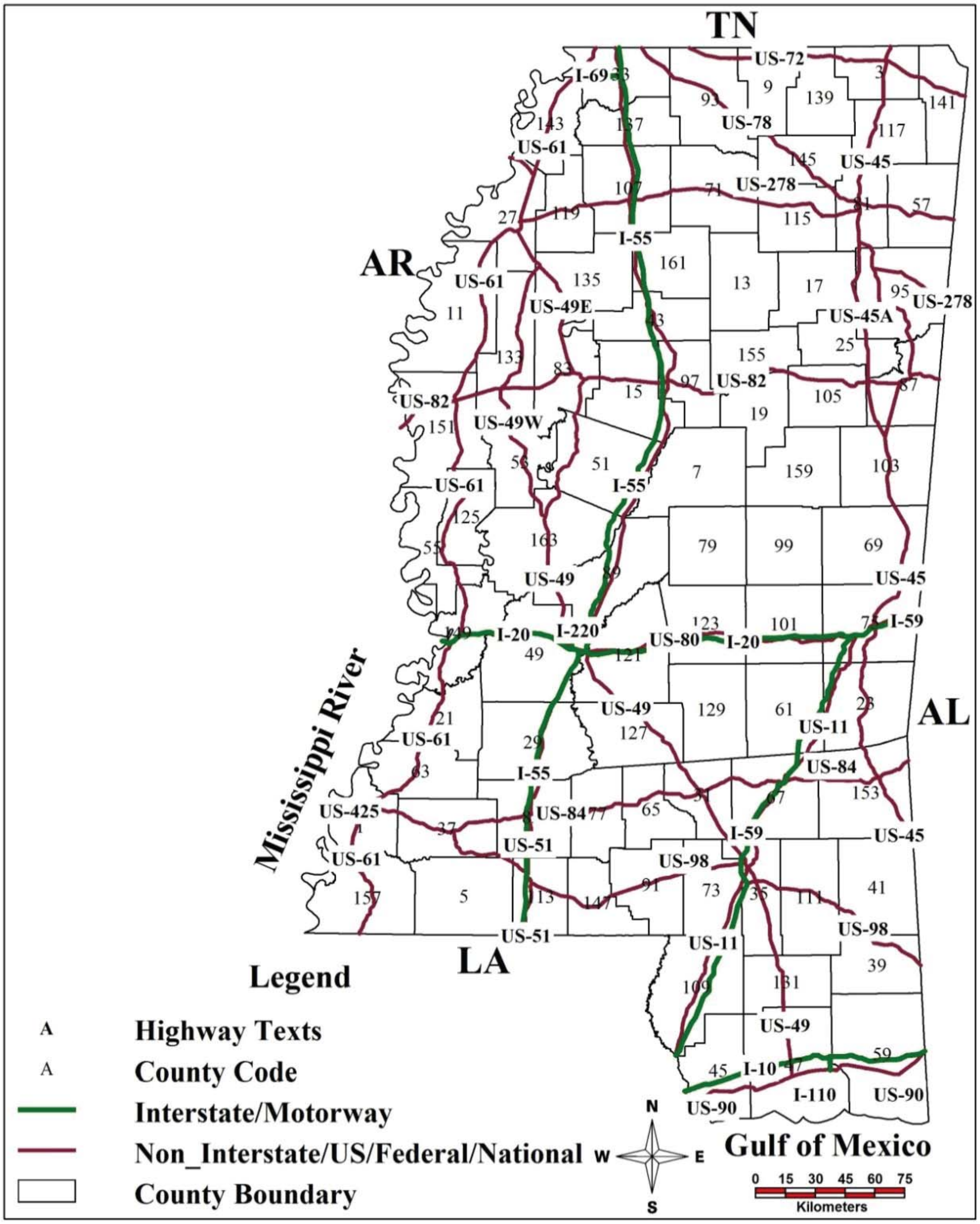


Top 20 Cargo Airports by Metric Tons, 2014

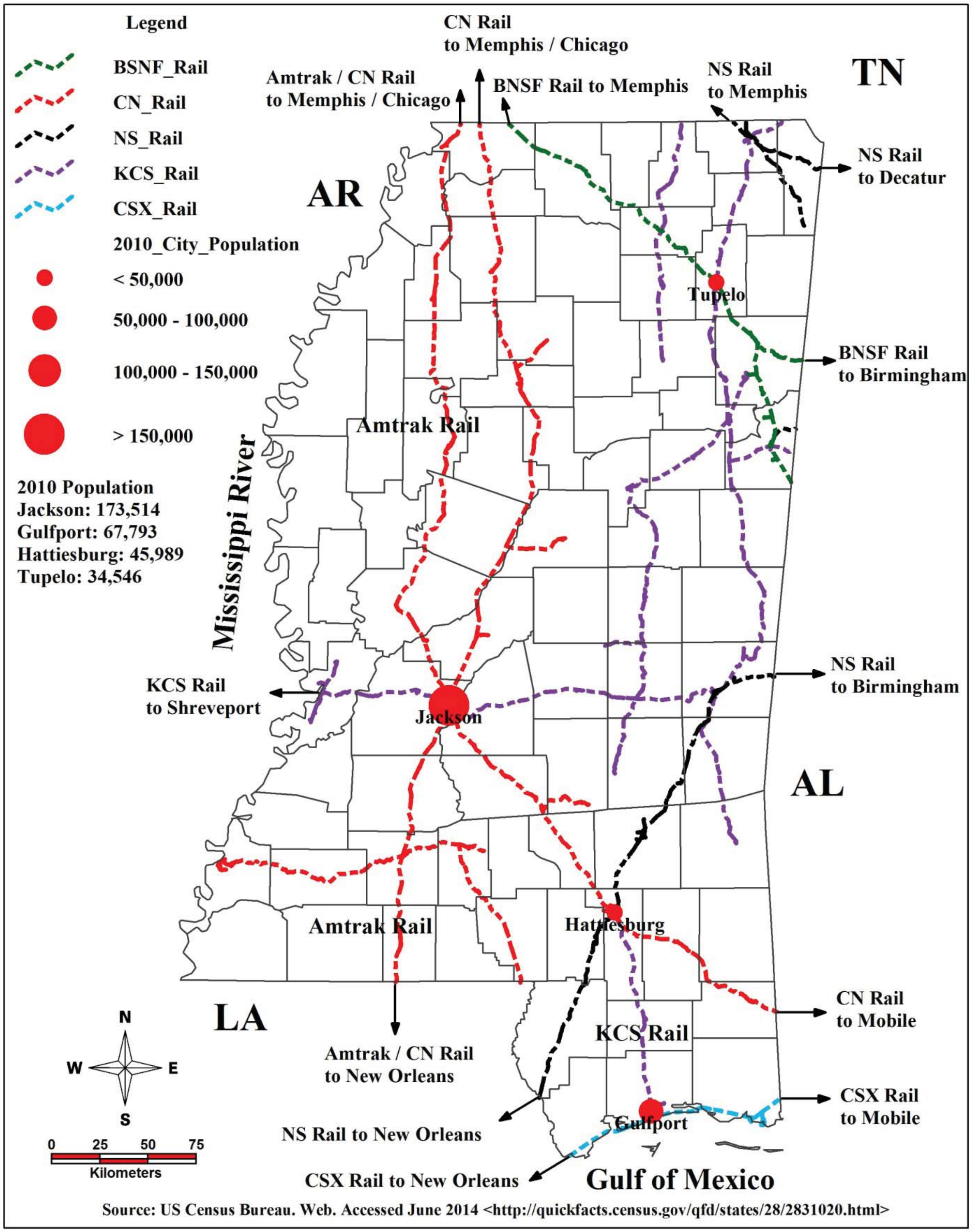


Source: http://www.aci-na.org/content/airport-traffic-reports Accessed: December 1, 2015

Mississippi Highway Map



Map of Major Freight Rails in Mississippi



Source: US Census Bureau. Web. Accessed June 2014 <http://quickfacts.census.gov/qfd/states/28/2831020.html>

APPENDIX

Supply Chain Stakeholder Form

Infrastructure Bank Proposal (White Paper)

Pavement Friction and Skid Test Research (Consultant's Report)

NAFTA Freight and Infrastructure Data from Mexico (Consultant's Report)

Information about the Survey Study

Study Sponsor: US Department of Transportation (USOT) RITA / National Center for Intermodal Transportation for Economic Competitiveness (NCITEC)

Investigators: Dr. Waheed Uddin, Professor of Civil Engineering, University of Mississippi
Voice 662-915-5363 662-915-1939 cvuddin@gmail.com

Dr. Patrick Sherry, University of Denver (DU) (303) 871-2495 psherry@du.edu
Program Director, Department of Counseling Psychology

Dr. Burak Eksioglu, Mississippi State University (MSU), (662) 325-7625
beksioglu@ise.msstate.edu NCITEC Director and Associate Professor, Department of Industrial & Systems Engineering

Project Title: Integrated Intermodal Transportation Corridors for Economically Viable and Safe Global Supply Chain

Project Summary: The global supply chain can be seriously disrupted by natural disasters. For example the earthquake and tsunami disaster that stuck Japan in March 2011 even had an effect on car manufacturing facilities in the U.S. that lasted for several months. This problem of disruption in the supply chain can seriously hurt local economies which depend on distribution through surface transportation modes. As recently reported at National Press club on July 17, 2009 and discussed in a report of the National Academies that U.S. companies collectively spend a trillion dollars a year on freight logistics. This is nearly 10% of the nation's gross domestic product (GDP). A recent Commodity Flow Survey (CFS) indicates that, on average, 42 tons of freight worth $39,000 was delivered per person in the U.S. in 2007. These statistics are indicative of the importance of the lifeline supply chain to support our society and everyday life. The four transportation modes (shipping port, aviation, rail, and highway) are owned and operated by different entities in the U.S. Unlike federal and state funded highway infrastructure freight railroads are privately owned. All these modal networks operate within their own policy frameworks and profit motivations with little or no real operational integration. Financing for preserving and upgrading intermodal infrastructure for both freight and rail is being handled very differently. Transport infrastructure funding crisis is evident on all levels.

The overall objective of this tri-university applied research project is to identify major transportation corridors involving waterways (marine and inland river system), highway network, and rail infrastructure networks and to evaluate the economic viability, safety, disaster resiliency, and revenue/funding aspects of integrating selected segments of the candidate corridors.

Purpose of Survey: The survey of supply chain stakeholders is being conducted to learn their dependence on multimodal transportation needs and assess their willingness to consider the intermodal integration and innovative funding strategies to improve the intermodal infrastructure and economic competitiveness.

The intermodal freight corridor case studies and supply chain survey results will be used to develop a "best practice guide" and intermodal infrastructure bank proposal for consideration by government transportation agencies, private transport operators, and other stakeholders.

(Note: The preliminary results of spatial freight data analysis within the United States and NAFTA corridor, computer modeling of selected highway/waterway/rail corridors, and intermodal integration strategies show: improved freight flow performance with respect to increased average speed on highways, reduced overall travel time, decreased greenhouse gas emissions, and less wastage of fuel.)

Conduct of Survey: This is an anonymous opinion survey where personal info is not used in data analysis. The survey should be completed within 15 minutes. Names, personal data, or physical contact info are solely for the purpose of follow up and sharing the results of the research study. There is no payment and any material benefit for helping us in this study. We are seeking volunteer participation to learn supply chain stakeholders' opinions so that we can formulate our recommendations for implementing intermodal integration strategies.

Drs. Sherry, Uddin, and Eksioglu can be reached by e-mail/phone to answer any queries. We thank you for your time and feedback. Please email the completed two survey pages to Dr. W. Uddin. cvuddin@gmail.com

Supply Chain Infrastructure and Intermodal Freight
Survey Questionnaire

IRB Approval: *This study has been reviewed by The University of Mississippi's Institutional Review Board (IRB). If you have any questions, concerns, or reports regarding your rights as a participant of research, please contact the IRB at (662) 915-7482 or irb@olemiss.edu.*

The survey of supply chain stakeholders is being conducted to learn their dependence on multimodal transportation needs and assess their willingness to consider the intermodal integration and innovative funding strategies to improve the intermodal infrastructure and economic competitiveness. This is an anonymous opinion survey. It should be completed within 15 minutes. *(No personal info will be used in data analysis.)*

1. What type of supply chain business is conducted by your organization? (Please circle only one.)
   a. Manufacturing b. Wholesale/Retail c. Transport d. Other
   If other, describe briefly (e.g., agriculture, fuel/crude oil/coal…) ____________________

2. What percentage of transportation mode does your organization utilize, compared to all modes?
   a. Truck (Please circle below)
      i. 0-25%
      ii. 26-50%
      iii. 51-75%
      iv. 76-100%
   b. Rail (Please circle below)
      i. 0-25%
      ii. 26-50%
      iii. 51-75%
      iv. 76-100%
   c. Maritime/waterway (Please circle below)
      i. 0-25%
      ii. 26-50%
      iii. 51-75%
      iv. 76-100%
   d. Air (Please circle below)
      i. 0-25%
      ii. 26-50%
      iii. 51-75%
      iv. 76-100%

3. What percentage of your inbound/outbound freight shipments is containerized?

Inbound	Outbound
a. 0%-25%	a. 0%-25%
b. 26%-50%	b. 26%-50%
c. 51%-75%	c. 51%-75%
d. 76%-100%	d. 76%-100%

4. Do you have manufacturing or supply chain operations outside country (a, b)?
   a. Yes (What percentage of your outbound shipments is containerized?)
      i) less than 25% ii) 25 – 50% iii) more than 50 to 75% iv) 75 – 100%
   b. No
   c. If yes, how much percent of your total ton-mile freight originates from outside country?
      i) less than 25% ii) 25 – 50% iii) more than 50 to 75% iv) 75 – 100%
   d. If yes, how much percent of total ton-mile freight is shipped to the country by each mode?
      i) Truck ii) Rail iii) Maritime/Waterway iv) Air

5. Based on the following map, in the blocks below please indicate what percentage of your freight is shipped to the specific region of the country?

Northwest Region: ☐
Southwest Region: ☐
Northeast Region: ☐
Southeast Region: ☐
Total: 100%

6. Do you currently believe the freight infrastructure needs improvement by integrating road/rail/waterway & marine transportation modes?
   a. Yes
   b. No
   c. If yes, which area of intermodal integration improvement (such as intermodal terminals) will help your business and increase economic competitiveness?
      i) Rail/Road ii) Road/Waterway & Port iii) Rail/Road/Waterway & Port iv) None
      Comment:____
      ____

7. Circle the outcomes that may occur from these suggested intermodal integration improvements (referring to Question 6).

a. Improved commercial operations	b. Greater Speed
c. More reliability	d. Lower transportation cost
e. Changing routings	f. Changing capacity or scale of service
g. Induced service or new competition	h. Declining traffic
i. Reduced overall travel time	j. Reduced vehicle emissions
k. Nothing	l. Other (write):

8. As a private sector stakeholder/participant of the transportation network, would your agency / organization / company be willing to partner with public/government agencies to invest in particular types of infrastructure improvements, such as intermodal terminals for integration of road/rail and road/waterway (barge & ship) transport operations? (Same question to public/government agencies for investment sharing with private transport entities such as PPP, Public-Private-Partnership.)
   a. Yes
   b. No

9. Will you support “dedicated truck lane” initiative on major busy segments of the “National Highway System" and highway bottlenecks in and around congested urban areas?
   a. Yes
   b. No

10. Will you support additional “user fee” based on a just and equitable formula applicable across all transportation modes to preserve and improve freight transport infrastructure?
    a. Yes
    b. No
    c. If Yes and an “infrastructure bank” is established to handle the “user fee” revenue, how will you prefer to benefit from this “infrastructure bank”?
       i. Take loan on easy terms and competitive interest rates.
       ii. Waive federal business income tax or part of it instead of paying “user fee”.
       iii. Other _*For example: Grant* ____

11. Other comments:

Public-Private Partnerships and a National Infrastructure Bank: A Policy Tool for the Future of Intermodalism

Jody Holland, PhD

Department of Public Policy Leadership

University of Mississippi

June 2013

Contents

Introduction

The notion of replacing today's deteriorating transportation infrastructure has become paramount for transportation officials. Even recent economic policy focused attention to "shovel-ready" projects. For example, The American Recovery and Reinvestment Act of 2009 (ARRA) funded hundreds of infrastructure projects and highlighted the negative impact of the "substructure or underlying foundation or network used for providing goods and services..."[i] to the people of the country due to its deterioration. At present, public entities manage a vast majority of the transportation infrastructure that is due for replacement. Many of these entities are not suited financially to replace or to repair the deteriorated infrastructure systems. With the current economic climate in this country, one of the tools in the policymaker's arsenal is public-private partnerships (PPPs). Currently, federal, state, and local government officials are exploring the further use of PPPs to offset the expense of public entities replacing the infrastructure singlehandedly.[ii]

The concept of PPPs is not clear or consistent. However, the characteristics of public-private partnerships have emerged in the literature. "These characteristics are: (a) two or more partners, with at least one public entity, (b) partners with the ability and authority to bargain, (c) a continuing relationship, (d) an arrangement in which each partner brings genuine value, and (e) shared responsibility for the outcome of actions taken via the public-private partnerships.[iii]

As this document explores the utilization of PPPs for funding the development and rehabilitation of transportation infrastructure, a clear understanding of the difference between PPPs versus privatization is needed. Although the mechanisms for implementation have some similarities, they are vastly different. Both are crouched in the philosophy that private participation in the "delivery of public projects or services can result in operational and fiscal benefits for a public agency"[iv]. However, asset ownership is one key difference between the PPPs and privatization. For example, privatization involves selling and transferring operational arrangements of public assets to private industry. By contrast, under a public-private partnership arrangement, the public partner owns the asset or infrastructure, directs the management of the asset or infrastructure, and establishes user rates."[v] Another difference between the two is structure. For instance, "in the privatization scenario, government involvement is minor, except possibly in a regulatory role. Also, traditional privatization features no ongoing contract or formal agreement between the public entity and private industry. In contrast, in most PPPs arrangements, the public entity retains a substantial role in the arrangement and exerts control and oversight of the asset or infrastructure."[vi] Finally, risk is another distinction between privatization and PPPs. In the public-private partnership arrangement, both public and private partners allocate risk between themselves; conversely, when an asset is privatized, the public entity assumes no responsibility for all assets and infrastructure.

The intent of this research is to explore the utilization of PPPs for infrastructure development and rehabilitation and provide recommendations that can further enhance the utilization of PPPs. As transportation officials continue to struggle with developing a planning strategy for the national transportation system, the author suggests that the usage of PPPs coupled with a national infrastructure banking institution can enhance national transportation planning by leveraging seamless intermodal systems into the planning process. To tell this story, first, this document presents the current transportation funding tools. Then, the author provides a brief history of PPPs and highlight different arrangements as well as presents legislation that impacts public-private partnerships. Next, a discussion regarding the integration of an intermodal and PPPs through a national infrastructure bank is highlighted. Finally, in the conclusion, the author argues for better solutions for infrastructure financing and provides policy recommendation for transportation planners and pertinent stakeholders.

Current Transportation Funding Mechanisms

Trust funds for transportation infrastructure development have been the main policy tool for financing the expansion of the transportation system. The money that pays for capital improvement are mostly generated from user taxes. However, many pundits claim that the solvency of the transportation trust funds is in question. In this section, the author will provide a brief overview of the current transportation trust funds that are being utilized to finance the transportation systems in America.

Aviation Trust Fund

Airport and Airway Trust Fund (AATF) was created from The Airport and Airway Revenue Act of 1970. This law enabled the federal government to charge excise taxes paid by users of the national airspace system. The purpose of the fund was twofold. First, it provided a dedicated source of funding for the aviation system, which was independent of the General Fund. Second, this funding source would develop and expand as the aviation transportation system increased. At present, the Trust Fund revenues are derived from: domestic airline passenger tickets, domestic airline passenger flight segments, international passenger arrivals and departures, air cargo waybills, aviation fuels, and amounts paid for the right to provide mileage awards[vii]. Currently, the Federal Aviation Administration's Office of Aviation Policy and Plans (APO) monitors the Trust Fund. The agency collects and forecasts the overall health of the fund. As of 2012, the Trust Fund has a balance of $10.3 billion. Although a substantial amount, in 2011, the United States Government Accountability Office (GAO) released a report titled, "Airport and Airway Trust Fund: Declining Balance Raises Concerns over Ability to Meet Future Demands". The balance has steadily decreased since 2011 and there is a "poor forecast of future funds.[viii]"

Harbor Maintenance Trust Fund

The Harbor Maintenance Trust Fund (HMTF) was created in 1986 to fund the operation and maintenance of ports and harbors in the United States. Mostly, the funds are utilized for dredging, dredged material disposal areas, jetties, and breakwaters. The maintenance of the ports and harbors is expensive. Currently, the Trust Fund has a surplus. As revenues have exceeded appropriations, the surplus has increased to $7 billion. Although the surplus provides, mostly, the U.S. Army Corps of Engineers with the funds to maintain the infrastructure, problems arise due to inadequate appropriations. According to the U.S. Army Corps Engineers almost 30 percent of commercial vessel calls at U.S. ports are constrained due to inadequate channel depths.[ix] As inadequately maintained harbors are becoming like "block arteries", policy makers and stakeholders should understand the boost to the economy that would be experienced if the appropriations matched the revenue.

Moreover, as international trade continues to increase, harbor maintenance and infrastructure development must keep up the rate of growth. The problem of not having adequate appropriations was addressed by in H.R. 335 and S.218, which ties HMTF appropriations to HMTF revenue. Finally, inequality has become a problem within the Trust Fund. For example, the larger ports, such as the Ports of Los Angeles and Long Beach generate the largest percentage of revenue to the HMTF. However, due to the natural design, the ports require little maintenance. Conversely, ports and harbors in the Deep South and on the east coast require significant maintenance, which requires immense expenditures.

Inland Waterways Trust Fund

Inland waterway navigation has been made possible by the U.S. Army Corps of Engineers since 1824. Before the Inland Waterway Trust Fund, maintenance and infrastructure improvements were financed through the national general fund. However, in 1978, the Inland Waterways Trust Fund (IWTF) was created as part of the Inland Waterways Revenue Act of 1978[x]. According to the nonprofit group, Taxpayers for Common Sense,

> The IWTF was established to finance construction and major rehabilitation on the nation's inland waterways. Under the IWTF, commercial users of waterways contribute to the trust fund through a modest tax on fuel they use on the waterway system. The fund is then tapped to cove 50 percent of the costs for construction of new the costs of construction of new dams and navigation locks and major rehabilitation (major maintenance work costing over $8 million) of existing facilities. The other 50 percent of project costs is covered by taxpayers. Once these projects are completed, taxpayer- not users- also pick up 100 percent of the tab for operations and maintenance of the system, currently costing roughly $600 million annually. The aggregate federal expenditures result in a more than 90 percent taxpayer subsidy[xi].

However, projects do not automatically get funded from the IWTF. Congress must authorize projects and appropriate funds for each project. Again, like other trust funds, this has led to a major problem of excessive revenue without appropriating any funds to the projects. It was only after passage of the Water Resources Development Act of 1986 (WRDA 1986) that required cost sharing mandates. The Act created the Inland Waterways Users Board (IWUB), which is a congressional advisory committee that is task with prioritizing projects and spending from the fund.

The Highway Trust Fund

Before the Highway Trust Fund (HTF) and the 1956 Highway Revenue Act, roads, in the United States, were funded from the General Fund. However, the Federal-Aid Highway Act of 1956 increased the technical and political feasibility of supporting a national highway system in America. The HTF is the source that funds of the national highway system. The revenue is generated from a gas tax, which is currently 18.4 cents per gallon. 15.44 cents are directed to the Highway Account, 2.86 cents are directed to the Mass Transit Account, and .1 cent is directed to the Leaking Underground Storage Tank Trust Fund (a separate trust fund set up for certain environmental cleanup purposes, which is financed with a small portion of the motor fuel taxes)[xii].

Although the HTF has accomplished many of the objectives set before the financial mechanism, solvency issues are on the horizon, which is rising rapidly. Moving Ahead for Progress in the 21st Century or MAP-21, the recently transportation bill, projects that there will be growing division between the amount of revenue generated and the expenditures needed to sustain the highway network. At current spending levels, the five-year highway reauthorization bill requires $258 bill in funding. However, the Congressional Budget Office projects only $201 revenues over the five year period[xiii].

Other Transportation Funding

National Railroad Passenger Corporation

Amtrak is a national commuter train that is financed from the General Fund. For FY 2014, Amtrak is seeking $373 in federal operating support or about 17 percent less than it requested in FY 2013. This is made possible by an improved financial position where last fiscal year Amtrak covered 88 percent of its operating costs with ticket sales and other non-federal revenue sources, up from 85 percent the prior year. In addition, if current service levels are maintained, Amtrak's state revenues in FY 2014 should increase by approximately $85 million as Amtrak and the states implement a Congressional requirement on cost allocation for short-distance routes. Also, for FY 2014, Amtrak is requesting $2.065 billion in federal capital support to: maintain the Northeast Corridor and other Amtrak-owned or maintained infrastructure and equipment. Finally, Amtrak is requesting $212 million for debt service.

State Transportation Funding

Although there are federal funds to support transportation infrastructure, state expenditures for transportation, including transit and airports are significant. For states to accomplish transportation goals, a myriad of financing mechanisms have been established to fund transportation project. Most often, this revenue is coupled with federal funding from the aforementioned trust funds[xiv]. Table 1 highlights the various funding approaches.

Table 1: Funding Approaches

Fuel Taxes	All states have some kind of motor fuel tax. In 2009, state motor fuel taxes averaged 21.72 cents per gallon of gasoline (ranging from 7.0 to 32 cents per gallon). Approximately, one-third of state generated transportation funds are derived from these fuel tax receipts, which totaled $36.6 billion in 2008.
Sales or Additional Taxes	In addition to state fuel taxes, some states add a sales tax to gasoline purchases or tax fuel distributors or suppliers.
Vehicle Registration	All states collect some form of vehicle registration fee. In 2008, $20 billion was collected in total.
Bonds	Every state except South Dakota, Tennessee, and Wyoming has authority to issue state transportation bonds. State and local governments issue general obligation transportation bond to finance transportation projects whose costs exceed available revenue for a given year.
Tolls	There are approximately 150 toll roads, bridges, and tunnels in the United States, operating in 27 states. Tolls are collected by a variety or entities, including state departments of transportation; special tollway, bridge, tunnel, or port authorities, and federally approved interstate agencies and international agencies.
General Funds	Thirty-two states have general fund revenues that collectively account for approximately 7 percent of total state highway funding.
Other Traditional Funding Sources	Twenty states use one or more other sources of funding, including inspection fees, driver license fees, advertising, a rental car tax, state lottery/gaming funds, oil company taxes, vehicle excise taxes, vehicle weight fees, investment income, and other licenses, permits and fees revenue.

This section highlighted current funding mechanism for both federal and state governments. Over the past decades, Trust Funds have institutionalized user tax mechanisms to support the operation and maintenance of the transportation system. However, even though some of the current funds show a surplus, it’s artificially because the rehabilitations of the system is currently needed, but Congress will not agree on the priority of appropriating the funds. Hence, a surplus is created. The next section of this report introduces public-private partnerships and presents various PPPs arrangements.

Public-Private Partnerships

Since 1792, private parties have been involved in highway projects. “The first turnpike was chartered and became known as the Philadelphia and Lancaster Turnpike in Pennsylvania”[xv]. As transportation policy emerged in the United States, the importance of the role of each state became paramount for designing, financing, and implementing the development of the nation's transportation system. For example, under the Federal Aid Highway Act of 1916, which funded highway construction primarily in rural areas, each state was required to create a "state highway agency with engineering professionals to carry out the federal-aid highway program."[xvi] Furthermore, it wasn't until the late 1970s that states and the "federal government considered public-private partnerships involvement in state highway construction projects as a current structure as a means of maintaining the quality of highways and reducing the impacts on highways users."[xvii]

Moreover, the evolution of public-private partnerships has been used significantly for transportation facilities since the 1990s, especially for procurement.

> Prime examples are the Dulles Greenway, SR-91 in California, the new international air terminal (Terminal 4) and its recent expansion at JFK International Airport, the Port of Miami Tunnel, the North Tarrant Expressway and I-635/LBJ Freeway in Texas, Denver's FasTracks commuter and light rail project, and the Presidio Parkway in California. The well-publicized monetization of the Chicago Skyway toll bridge, the Indiana Toll Road and, most recently, the PR-22 and PR-5 toll roads in Puerto Rico have similarly highlighted the prominent role that the private sector can play in improving and operating transportation infrastructure. Each of these projects has served to illustrate the public private partnerships procurement compels all parties to plan and budget for the full life cycle costs of maintaining and operating-not just building- the project in question. This is a significant change from traditional procurement model, under which the life cycle costs to be incurred years and decades into the future are neither considered not budgeted for at the time of procurement. Aside from leaving state and local governments with a potentiality significant overhang of unfunded operations and maintenance obligations, the traditional procurement model has not always focused parties' attention on the fact that design decisions at inception can have important effects on life cycle costs.[xviii]

In addition, there has been success with public-private partnerships where the private entity has the capacity to construct projects that users are willing to pay for enhanced services, and attempt to operate and maintain transportation traffic flows that meet a higher standard, compared to low quality, congested travel patterns.

Types of Public-Private Partnerships in Transportation Projects

As seen above, PPPs have been utilized in many transportation projects. However, PPPs can be structured in a variety of methods and arrangements. It's important for policymakers and transportation officials to understand the various approaches. The narrative in Table 1 demonstrates five types of PPPs arrangements for delivering transportation projects[xix].

Table 2: Public-Private Partnerships Arrangements[xx]

Private Contract Service Approach	It is the most common form of private sector involvement in surface transportation projects and service delivery in which a public partner (Federal, State, and Local government) contracts with a private partner to operate, maintain and manage the system providing a service. There are two types of contract services: Operation and Maintenance; Operations, Maintenance, and Management.
Alternative Project Delivery Approach	The Associated General Contractors (AGC) defines project delivery method as "The comprehensive process of assigning the contractual responsibilities for designing and constructing a project. A delivery method identifies the primary parties taking contractual responsibility for the performance of the work". The alternative project delivery approach has several combinations based on the phases in which the private partner takes responsibility. The following are the primary combinations: Design-Bid-Build (DBB) Construction Manager-at-Risk (CM@Risk) Design-Build (DB) Design-Build with a Warranty (DBW) Design-Build-Operate-Maintain (DBOM) Design-Build-Finance-Operate (DBFO) Build-Operate-Transfer (BOT) Build-Own-Operate (BOO)
Multimodal Partnerships	Multimodal Partnerships are increasing in the United States because of the potential benefits not only in highway applications but also in other transportation modes including transit, rail, and airports. Some public and quasi-public agencies are involved with the PPPs and multimodal partnership projects.
Joint Development	Joint development means public agencies like transit agencies provide private developers the right to design and construct a residential, commercial, or mixed use building on or above the transit property in return for negotiated payment. There are many advantages of mixed use development such as increased revenue for transit agencies, aesthetics, and safer environment for the public. The improved environment may in turn allow increased fares in the transit system.
Long-term Lease or Concession Agreements	Long-term lease agreements involve publicly financed projects. The governmental agency engages the private sector for developing and delivering the project, and for maintenance and operation of that project for a specific time period. In that concession period, the private sector collects the revenue for the facility and pays a lease fee. Examples of this type of project include toll roads, parking garages, etc.

Understanding the various arrangements of PPPs can benefit transportation officials as they continue to utilize these mechanisms for implementation.

In addition, scholars have explored the characteristics of successful PPPs. For example, Zhang's work[xxi] indicates that regarding construction projects in general, the most important aspects of success include: project characteristics, contractual arrangements, project participants, and interactive processes. The characteristics of a project include both internal and external aspects. For example, internally, the success factors include constructability, pioneering status, and project size. Externally, the success factors include political and economical risks, impact on public efficiency of technical approval authorities, adequacy of funding, and site limitation and location. In addition, Tiong[xxii] suggests that many studies indicate that winning PPPs contracts are successful due to: entrepreneurship and leadership, right project identification, strength of the consortium, technical solution advantage, financial package differentiation, and differentiation in guarantees. Finally, Merna and Smith[xxiii] suggest that PPPs should consider critical success factors that include identifying environments that are favorable for investing.

Finally, economic viability is important for the success for PPPs. Being able to determine long-term demands for the products and services as well as establishing barriers for competition is important for the vitality of PPPs. Moreover, the authors indicate that sound financial packages with excellence analysis as well as developing investment, payment, and drawdown schedules are important for public and private entities to understand the direction of successful PPPs. Lastly, the appropriate risk allocation per a reliable contract is important for successfully implementation.

Examples of Public-Private Partnerships in Transportation

Even with many obstacles, public-private partnerships are playing a significant role in transportation infrastructure projects in the United States. Below are examples of different infrastructure projects in various states.

- The California Department of Transportation and a Meridiam / Hochtief-led consortium agreed on a 30-year concession of a $1billion Presido Parkway project that will refashion the south access to the Golden Gate Bridge. Under California's PPP-enabling legislation, which was enacted in 2009, this has become the first project of significance[xxiv].

- In Colorado, the beginning phase of a $6.5 billion FasTracks commuter rail system reached a closing with a package that included $400 million of public funds, $52.3 million of PPP sponsor equity, in addition to roughly $1.15 billion in debt financing from the Denver Regional Transportation District[xxv].
- Georgia is also engaging PPPs. The Georgia Department of Transportation is engaging in bids for a 50-year concession for the construction and operation of a new, $1.3 billion managed lane system. This project has been pre approved for $275 of TIFIA assistance, and Georgia Department of Transportation has submitted an application for $700 million of private assisted bonds (PABs)[xxvi].
- In Texas, new legislation is enabling the Interstate Highway 35E in Denton county, which is a $1.8 billion project to expand. This 52 year- concession for the managed lane system was financed by $615 million PABs, $498 million loan from TxDOT, $665 million of sponsor equity and an $850 million TIFIA loan[xxvii].
- Virginia Department of Transportation (VDOT) and Macquarie/Skanska consortium achieved close on a $1.9 billion Midtown tunnel project. The concessionaire has committed $1.2 billion in financing, comprised of $318 million in equity, $495 million of bank loans and $422 million of TIFIA funding[xxviii].

In addition, the University Transportation Center for Alabama examined the successes and failures of public-private partnerships. With this data, policymakers can begin to develop a deeper understanding of the policy tools.

First, Route 895, the Pocahontas Parkway, in Virginia was examined. Originally, this was not intended to utilize private funds for development. This parkway was developed under a joint venture between Virginia Department of Transportation, Flour Daniel, and Washington Group International. The private entities utilized the Design/Build method, which was based on VDOT suggestions.

> The Pocahontas Parkway was financed through the Pocahontas Parkway Association (PPA), a private entity created by Flour Daniel and the Commonwealth Transportation Board. The PPA's primary task was to administer PPA bonds to VDOT to use for the project. While the bulk of the risk fell on the PPA to return their bondholders money, decision were primarily made by Flour Daniel and VDOT. In this way, VDOT limited their risk by transferring it to the PPA. A clear example is VDOT's decision to build the Parkway in one phase. The initial recommendation was to build the project in two phases,

> with the second phase being built only as traffic allowed. Traffic levels did not meet expectations, staying between 25% and 50% lower than predicted for the first year. The result of the decision was more infrastructures for VDOT, more construction work for Fluor Daniel, and a bigger development fee from the single phase approach[xxix].

In addition, the Tim Kaine, Governor, shifted the operational of the Parkway to Transburan of Melbourne, Australia, which shifted the risks from both private and public entities to just a private entity. With this action, Transburan paid PPA debt and reimbursed VDOT for operational costs, maintain, and repairs. This transaction was deemed a success because Transurban increase tolls, which reflected inflation, and the organization advertized the utilization of the Parkway as well as contracted with additional private entities to complete additional interchanges.

Second, the Indiana Toll Road is an example of a scenario were a PPPs has successfully maintained an infrastructure project. In 2006, Governor Mitch Daniels transferred the Indiana Toll Road to a private group, Cintra Concensiones de Infraestructuras de Transporte SA (Centra) of Mexico for $3.8million. This consortium is known as Statewide Mobility Partners (SMP), which agreed to 75 year lease. Under this contract, the group retained revenue, which derived from the toll. They were two camps of opinion regarding this transfer. First, proponents argued that immense profit could be made from the transaction. However, opponents of the project were concerned with increased traffic and the fact that the state would lose revenue due the toll lease.

The rationale for selling was based on the notion that the toll road would be profitable for many years. Therefore, the state could capture years of revenue up for additional projects. In addition, the interest on debt was terminated due to the transfer, saving the state even more money. This transfer was deemed successful due to SMP ability to keep tolls low, while maintaining and developing additional lanes to relieve congestion.

Another example of PPPs in action is the Dulles Greenway. This is a joint venture project between Bill Allen and John Miller. In this venture, the two developed Municipal Development Corporation (MDC) to secure the operation and maintenance of the Dulles Greenway. This project is unique due to the strength of the oversight of the government. For example,

> The commonwealth has agencies at hand to ensure that the private entity makes sound decisions. One such agency is the State Utility Commission with is in place to facilitate road development. Another agency is the State Corporation Committee, which has the power to deny toll raises set by private entity. These agencies limit the state's risk by helping the private sector return to the state a successful project[xxx].

In addition, this project repay the debt services as well as operations, while paring $2 million annually property taxes and $175,000 to regulatory service.

In this section, the author provided a synopsis of the types of PPPs. As the progress of PPPs continue to support the development and rehabilitation of infrastructure, transportation officials must understand the various structures of implementing these policy tools. The next section begins to explore financing solutions that would enable PPPs to work within an integrated, centralize systems that could enhance national transportation planning.

Integrating Intermodal Systems and Public-Private Partnerships

The nation's transportation system, which includes highways, railways, airways, and waterways, is suffering from neglect. Due to the dependence on the system to sustain the economic competitiveness of the nation, transportation officials and transportation stakeholders need to understand the negative impacts associated with the deteriorating transportation system. As a country, the government has failed to maintain the health of the system, which now is literally falling apart before us[xxxi]. According to the American Society of Civil Engineers, $186 billion will need to be spent annually to substantially improve the roads system. However, this dollar amount is not being appropriated.

Moreover, as the population in America increases and demanding more goods, the infrastructure is not growing with the demands. For example, according to American Association of State Highway and Transportation Officials, "between 1980 and 2006, traffic on the Interstate Highway System grew by 150 percent, while interstate capacity grew by only 15 percent." [xxxii] Yet, many policymakers are unaware of what is at stake. Pete Rhan, Leader National Transportation Practice, claims, "our railroads are under increasing strain", yet underfunded. In 2012, our nation's railroads, highways and ports will receive $527 million from the U.S. Department of Transportation's Transportation Investment Generating Economic Recovery program. However, that investment was insignificant compared to the $14 billion sought through applications for TIGER funds. There is a clear problem with the current transportation infrastructure system, and a bold plan should be formulated to implement decisive action to rectify the problems.

The Moving Ahead for Progress in the 21st Century Act (MAP-21) attempts to move the country forward. Regarding national transportation planning, in MAP-21,

> The metropolitan and statewide transportation planning processes are continued and enhanced to incorporate performance goals, measures, and targets into the process of identifying needed transportation improvements and project selection. Public involvement remains a hallmark of the planning process. Requirement for a long-term plan and a short-term transportation improvement plan (TIP) continue, with the long-range plan to incorporate performance plans required by the Act for specific programs. The long-range plan must describe the performance measures and targets used in assessing system performance and progress in achieving the performance targets and include a description of the anticipated achievements. In the Statewide and nonmetropolitan planning process, selection of projects in nonmetropolitan areas, except projects on the NHS or funded with funds remaining from the discontinued Highway Bridge Program, must be made in cooperation with affected nonmetropolitan officials or any regional transportation planning organization. The Secretary is required to establish criteria for the evaluation of the new performance-based planning processes. The process will consider whether States developed appropriate performance targets and made progress toward achieving the targets. Five years after enactment of MAP-21, the Secretary is to provide to the Congress reports evaluating the overall effectiveness of performance-based planning and the effectiveness of the process in each State and for each MPO[xxxiii].

As transportation policy focuses on planning for a national transportation that is continuing to deteriorate and is underfunded, policymakers need to seek alternatives for future funding. Utilizing an intermodal transportation planning approach along with a national transportation banking system is a viable alternative that should be explored. Intermodalism has been defined, “as the use of two or more modes to move a shipment from origin to destination”[xxxiv] The approach provides a flexible response to the changing supply chain management that is require in a global market.

Intermodalism

Over the past decades, there have been a lot of opportunities and obstacles regarding in Intermodal Freight Transportation. The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) presented an innovative vision of regarding the future of transportation. This notion replaced the traditional view of silo mode approaches that are costly and not integrated. However, the concept of intermodalism concentrates on seamless, efficient integration. According to the 1991 policy, “It is the policy of the

United States to develop a National Intermodal Transportation System that is economically efficient and environmentally sound, provides the foundation for the Nation to compete in the global economy and will move people and goods in an energy efficient manner” [xxxv]

This vision encompasses a systems approach, which includes logistics, institutional/organizational, and information components. As this document concentrates on the institutional and organizational component, which is a framework that explains how actors develop and improve infrastructure and how these actions influence public and private entities, it is important to understand how the development of an infrastructure banking system can assist in developing an seamless, efficient financing mechanism for the future of transportation.

National Infrastructure Banking

In recent years, the development of more fuel-efficient vehicles coupled with the sharp downturn in the United States’ economy has led to a depleted tax revenue source via the gasoline tax. This transformation has forced the federal government to start thinking about new ways to generate the revenue necessary to maintain the expansive infrastructure system. Due to these concerns, the most logical and efficient mechanism for creating infrastructure, while enjoying the benefits of higher employment, is the chartering and creation of a National Infrastructure Bank.

Across the United States there is currently an extremely large[xxxvi] system of transportation infrastructure”[xxxvii]. In order to preserve and maintain an uninterrupted flow of commerce, “The United States spends approximately billions each year on building, operating, and maintaining this system”[xxxviii]. In order to address the ever-growing transportation network, The United States Senate proposed Senate Bill (S. 1926) or the “National Infrastructure Bank Act of 2007”, sponsored by Senators Chris Dodd (D-Conn), Chairman of the Senate Committee on Banking, Housing and Urban Affairs and Chuck Hagel (R-Neb), with the primary purpose of “establish[ing] the National Infrastructure Bank to provide funding for qualified infrastructure projects, and for other purposes”[2]. The bill will create a National Infrastructure Bank that will operate as an individual entity of the United States Government, which will be headed by “a Board of Directors consisting of 5 members, appointed by the President, by and with the advice and consent of the Senate, from among individuals who are citizens of the United States”[xxxix]. Infrastructure projects that come under the bank's consideration are publicly owned mass transit

---

systems, housing properties, roads, bridges, drinking water systems, and wastewater systems"[xl]. The requirements for holding a position on the Board of Directors is thus: "Not less than 1 member of the Board shall have demonstrated expertise in transit infrastructure, public housing infrastructure, road and bridge infrastructure, water infrastructure, or public finance"[xli]. "The Chairperson and Vice Chairperson of the Board shall be appointed and shall serve in the same manner as is provided for members of the Federal Deposit Insurance Corporation under section 2(b) of the Federal Deposit Insurance Act (12 U.S.C. 1812(b))", and both the Chairperson and Vice Chairperson will be appointed to six year terms, with the remaining chairmen serving staggered terms with one member serving for five years, one member serving for four years, and the last member serving for three years[xlii]. In order to be eligible for a loan from the bank, a private entity must file an application on behalf of the project, which "the Bank shall, upon application and otherwise in accordance with this section, designate infrastructure projects as qualified projects for purposes of assistance under this Act"[xliii]. The bill grants the board the authority to:

> (1) to act as a centralized entity to provide financing for qualified infrastructure projects; (2) to issue general purpose infrastructure bonds, and to provide direct subsidies to qualified infrastructure projects from amounts made available from the issuance of such bonds; to issue project-based infrastructure bonds for the financing of specific qualified infrastructure projects; to provide loan guarantees to State or local governments issuing debt to finance qualified infra- structure projects, under rules prescribed by the Board, in a manner similar to that described in chapter 6 of title 23, United States Code; (3) to issue loans, at varying interest rates, including very low interest rates, to qualified project sponsors for qualified projects; (4) to leverage resources and stimulate public and private investment in infrastructure; and (5) to encourage States to create additional opportunities for the financing of infrastructure projects[xliv].

Projects considerable under the act must follow the following stipulations: "The Bank shall accept applications for the designation of qualified infrastructure projects under this section from among public sponsors, for any infrastructure project having—(1) A potential Federal commitment of an amount that is not less than $75,000,000;(2) a public sponsor; and (3) regional or national significance"[xlv]. After the application process the chair will evaluate the following:

> In making a determination as to a designation of a qualified infrastructure project, the Board shall evaluate and rate each applicant based on the factors appropriate for that type of infrastructure project, which shall include—(A) for any transit project— (B) regional or national significance; (C) promotion of economic growth; (D) reduction in traffic

> congestion;(E) environmental benefits, including reduction in pollution from reduced use of automobiles from direct trip reduction and indirect trip reduction through land use and density changes; (F) urban land use policies, including those that promote smart growth; and (G) mobility improvements" with the same requirements befalling any highway, bridge, or road project[xlvi].

The final steps for approving a candidate for infrastructure development must fall under the following criteria under the heading:

> "DETERMINATION AMONG PROJECTS OF DIFFERENT INFRASTRUCTURE TYPES. The Bank shall establish, by rule, comprehensive criteria for allocating qualified status among different types of infrastructure projects for purposes of this Act—(1) including— (A) a full view of the project benefits, as compared to project costs; (B) a preference for projects that have national or substantial regional impact; (C) a preference for projects which leverage private financing, including public-private partnerships, for either the explicit cost of the project or for enhancements which increase the benefits of the project; (D) an understanding of the importance of balanced investment in various types of infrastructure, as emphasized in the current allocation of Federal resources between modes; and (E) an understanding of the importance of diverse investment in infrastructure in all regions of the country; and (2) that do not eliminate any project based on size, but rather allow for selection of the projects that are most meritorious.[xlvii]"

The bill states that after a project is approved by the bank, it will start "receiving financial assistance from the bank under this section shall comply with applicable provisions of Federal law and regulations", which applies to highways, roads, bridges, and waterworks[xlviii].

After the establishment of the bank and subsequent establishment of private-public partnerships, infrastructure development will commence. The bill then addresses the faults of the current infrastructure and offers recommendations and dollar amounts to correct the current abysmal United States' infrastructure system. The bill references current findings from the American Society of Civil Engineers that state United States roads are in such poor condition—an overall average of a "D"—they represent a sizable impediment for the creation and continued "prosperity and quality of life" in the United States with expenditures requiring "approximately $15,800,000,000 each year for a period of not less than 20 years to maintain the operational capacity of the transit systems of the United States; and approximately $21,800,000,000 each year for a period of not less than 20 years to improve the operational capacity of the transit systems of the United States to meet the growing demands of passengers in a safe and adequate manner[xlix]. Additionally, the Federal Highway Administration maintains, "33 percent of all urban and rural roads in the United States are in poor, mediocre, or fair condition", which will require "approximately $131,700,000,000 [to] be expended each year for a period of not less than 20 years to improve the conditions of those urban and rural roads"[l]. The bill also lays limitations and regulations regarding National Infrastructure Bank issued bonds: "General purpose and project-based infrastructure bonds issued by the Bank under this Act shall be subject to such terms and limitations as may be established by rules of the Bank, in consultation with the Secretary of the Treasury" as well prohibiting issuing out more than $60,000,000,000 in bonds for a single project at a time[li]. After the loans are paid back to the bank with interest, "not more than 1 percent of funds resulting from the issuance of bonds under this Act may be used to fund the operations of the Bank"[lii]. In order to maintain the efficiency and gauge the effectiveness of the resulting PPPs, the board will convene "no later than 2 years after the date of enactment of this Act, and every 3 years thereafter, the Board shall conduct a study evaluating the effectiveness of each Federal financing mechanism that is used to support an infrastructure system of the United States" by "evaluat[ing] the economic efficacy and transparency of each financing mechanism used by (A) the Bank to fund qualified infrastructure projects; and (B) each agency and department of the Federal Government to support infrastructure systems, including—(i) infrastructure formula funding; (ii) user fees; and (iii) modal taxes", and will also include "recommendations for improving each funding mechanism to increase the economic efficacy and transparency of the Bank, and each agency and department of the Federal Government, to finance infrastructure projects in the United States[liii]. The bill has numerous recommendations for instituting a federally funded and chartered National Infrastructure Bank, which aim to right the current infrastructure failures and deficiencies.

Opportunities for a National Infrastructure Bank

Due to increased balanced sheets and heightened national debt, governments are sitting in limbo regarding the infrastructure development. Having PPPs, the government can attacked large sums of new capital in the market. The success of this type initiate depends on collaboration and establishing structures of transparency as well as control. The challenges that emerge for government and PPPs expose great opportunities for creating a national infrastructure bank. As PPPs emerge as a policy tool, government need prepare for an increasing capacity to access, structure, and the ability to oversee projects. In addition, interagency coordination and improving relations between federal agencies and state and local governments, private firms, and nonprofits must be addressed if governments and PPPS attempt to increase capital for infrastructure projects[liv].

Therefore, a national infrastructure bank would provide policy makers an institution for decision making that would be divorced from partisan politics. This type funding mechanism, which would manage user fees and additional revenues, would be independent and allow the bank to survive political transitions. Moreover, a national infrastructure bank would have more financial flexibility. It should not have complete budgetary freedom. Due to the Government Corporate Control Act, "it would be required to submit a budget to the President, who in turn is required to include that budget with the executive branch budget he submits to Congress"[lv].

Barriers for a National Infrastructure Bank

While the presence of a national infrastructure bank is indeed paramount in creating jobs, maintaining quality of life and American prosperity, and redeveloping structurally poor roads and bridges, while simultaneously creating new roads and bridges, there remain a few problems, which will impede the implementation and chartering of a national infrastructure bank. Critics point to cronyism as one of the main deterrents in creating a national bank. The National Infrastructure Bank Act of 2007 counters this criticism with the adage, "No member of the Board may, during service on the Board be an officer or director of, or otherwise be employed by, any entity engaged in or otherwise associated with an infrastructure project assisted or considered under this Act; hold stock in any such entity", with the adage of "No member of the Board may hold any office, position, or employment in any entity engaged in or otherwise associated with an infrastructure project assisted under this Act during the 2-year period beginning on the date on which such member ceases to serve on the Board" [lvi]. However, there still remains the likely possibility of a chairman selling off stock and resigning from his respective private entity in order to accept a nomination to a chairmanship. This leaves various possible chances for cronyism and corruption, as a chairman with previous backgrounds in private financial institutions will always look out for his previous company's best interest, which will lead to unfair advantages for said companies in receiving government bids for infrastructure development.

Moreover, another problem with a national infrastructure bank lies in its structure, with much criticism stemming from arguments that “some would make the NIB entirely self sustaining, and so compel it to prioritize projects with a revenue stream, for instance from tolls, that would go to paying back the loan”, which would incentivize a bank with this structure to be more selective for projects “with greater social benefits, but less ability to repay funds quickly: it might fund construction of a toll road to a wealthy suburb rather than an upgrade to a municipal water system despite the latter's greater benefit”[lvii]. The bank, similar to the Federal Reserve Bank of the United States, is intended to be an apolitical institution, yet this is misleading because the sitting President of the United States will surely appoint directors whose political affiliation is similar to that of the President and after passing the President’s personal litmus test.

Another source of contention lies in American mistrust in federal lending of American taxpayers, especially after the failed subsidizations of clean energy companies—a primary example being the solar energy company Solyndra’s $535 million loss and subsequent bankruptcy. Perhaps one of the largest obstacles facing the National Infrastructure Bank is the lack of a clear definition or mission purpose. Currently, the bank’s purpose is: “Building, improvement, or increase in capacity of a basic installation, facility, asset, or stock that is associated with a mass transit system that meets the criteria in subparagraph; a public housing property that is eligible to receive funding under section 24 of the United States Housing Act of 1937 (42 U.S.C. 1437v) and that meets the criteria in subparagraph (B); a road or bridge that meets the criteria in subparagraph (B); or a drinking water system or a wastewater system that meets the criteria in subparagraph (B)”, which ignores the development of airports, shipping ports, railways, and expanding internet availability—primarily in rural areas[lviii].

Also, laws impacting PPP financing can be an issue around the implementation of a National Infrastructure Bank. As the Transportation Infrastructure Finance and Innovation Act (TIFIA) established state infrastructure banks (SIBs) and The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users of 2005 (SAFETEA-LU) attempted to establish state infrastructure banks (SIBs) and encourage the PPPS, there still needs to be a strong legal foundation for PPPs before potential public and private partners will be willing to enter into partnerships. Table 3 highlights relevant legal issues addressed by the Federal Highway Administration.

Table 3: Legal Issues for PPPs

- Legal capacity of parties and legal requirement of sponsor to provide services
- Ability of private firms to be more involved in infrastructure development and control, including the nature and extent of participation by foreign firms
- Existence and legal basis of cost recovery and tolling (if applicable)
- Authority to regulate toll rates, exemptions to tolling, and services
- Dispute resolution and liability provisions
- Competition and anti-trust regulations
- Avoiding conflicts of interest among private and public parties to a PPP
- Special provisions associated with use of Federal funds-Davis-Bacon, Buy-America, Section 13c of Federal Transit Act, Etc.
- Public sector borrowing restrictions/ debt limitations
- Tax and accounting liabilities
- Adequacy of procurement and selection procedures
- Contract provisions and surety requirements
- Property and intelligent property laws protecting propriety technologies and know-how
- Authority of other government entities over infrastructure assets and access rights
- Property issues of land acquisitions-condemnation, use and disposal

Finally, a National Infrastructure Bank is an institution for which the United States is exploring as policy tool that would support PPPs to develop or rehabilitate the infrastructure systems. Senate Bill 1926 has laid a solid foundation for the most progressive and feasible plan towards job creation, tax revenues, and the expansion of the national infrastructure system. The current legislation is being debated and accepted by both Democrats and Republicans, but it is only a matter of time before it will come to the forefront of American politics.

Conclusion and Recommendations

For decades, the United States has underinvested in its transportation infrastructure. Due to this negligence, commuter and businesses alike are losing billions of dollars on congested highways and deteriorating waterways, locks, and dams are stalling growth of commerce. As global competition continues to increase, the United States economy will be faced with ramping up infrastructure investment as well as developing a national transportation plan that integrates intermodalism.   Therefore, for the United States to remain internationally competitive, a significant investment into the transportation infrastructure is paramount. This report explored PPPs are a policy tool for increase capital for infrastructure development. As highlighted, these public-private partnerships arrangements are being utilized throughout the nation. However, this research proposes that creating a national infrastructure bank would better facilitate planning and financing needed to increase investments in the nation.

Although there is significant barriers to creating a national infrastructure bank, proponents suggest that creating this type of institution will send clear message to investor and the global economy that the United States is prepare make smarter choices regarding the infrastructure that support a significant global supply chain. In addition, this institution would have a foundational mission to connect private sector investors and infrastructure projects.

Finally, the creation of a national infrastructure bank would have many positive attributes that could have propel American’s competitive advantage. However, the politics are not so simple. Attempts to create a national infrastructure bank during a time when trust is government is at an all time low will be extremely difficult. Today’s political complexities will pose a challenge for the most formidably policy entrepreneur. Nonetheless, these complexities that derive from the American government system are causing the gridlock that is affect the current transportation system. Therefore, it time for policymakers to explore different alternatives. This reports suggestion that a national infrastructure bank is one alternative that should be explored.

Endnotes

---

[i] U.S Envt'l Protection Agency Off. Grants &Debarment, Definition of "Infrastructure" for Purposes of the American Recovery and Reinvestment Act of 2009. www.epa.gov/odg/definition_of_infrastructure_for_ARRA.pdf.

[ii] O'Steen, C., and Jenkins, J.(2012). We built it, and they came! Now what? Public-Private Partnerships in the replacement era. Local Government Law Symposium.

[iii] Mullin, S. (2002). Public-Private Partnerships and State and Local Economic Development: Leveraging Private Investment. www.eda.gov/PDF/econsul/final.pdf.

[iv] Cal. Debt & Inv. Advisory Comm'n, Issue Brief, Privatization vs. Public-Private Partnerships: A Comparative Analysis 12 (2012) www.treasurer.ca.gov/cdiac/publications/privatizaitons.

[vv] Water P'ship Council, Establishing Public-Private Partnerships for Water and Wastewater Systems. A Blueprint for Success. www.nawc.org/uploads/documents-and-publications/documents/documents_567764ad-b69f-4715-bc5d-eaa32c304fdd.pdf

[vi] Palmer, G (2009). Public-Private Partnership Literature Review. Dpwg-lgd.or/cms/upload/pdf/publicprivatepartnership_lit_review.doc)

[vii] www.faa.gov/about/office_org/headquarters_offices/apl/aatf/.com

[viii] GAO-11-358T

[ix] Realize America's Maritime Promise: Harbor Maintenance Trust Fund Fairness Coalition. www.ramphmtf.com

[x] The Inland Waterways Trust Fund. Taxpayers for Common Sense: Making Government Work. www.Taypayer.net

[xi] Ibid

[xii] http://www.fhwa.dot.gov/map21/htf.cfm

[xiii] Heritage Foundation calculations based on data from Congressional Budget Office, "Projections of the Highway Trust Fund Accounts Under CBO's February 2013 Baseline," February 5, 2013,http://www.cbo.gov/sites/default/files/cbofiles/attachments/43884_HighwayTrustFundAccounts_0.pdf(accessed April 22, 2013)

[xiv] How States and Territories Fund Transportation: An Overview of Traditional and Nontraditional Strategies.

[xv] U.S. Dept Transportation (2004), Report to Congress on Public-Private Partnerships, www.fhwa.dot.gov/reports/pppdec2004.pdf

[xvi] Id.

[xvii] Id.

[xviii] Mattei, I., McGuigan, M (2012) The Road Ahead for US PPP.

[xix] Cui, Q. & Lindly, J. (2010). Evaluation of Public Private Partnership Proposals. UTCA Report # 08402

[xx] Ibid 11.

[xxi] Zhang, X (2005). Critical Success Factors for Public-Private Partnerships in Infrastructure Development. *Journal of Construction Engineering and Management. January.*

[xxii] Tiong, R. L. K. (1996) CSFs in competitive tendering and negotiation model for BOT Projects, *Journal of Construction Engineering and Management.*

[xxiii] Merna, A. and Smith, N.J. (1996). Guide to the preparation and evaluation of build-own-operate-transfer (BOOT) project tenders. Asia Law and Practice, Hong Kong.

[xxiv] The Current Catalysts for US PPP Development. Project Finance. , November 15th, 2011.

[xxv] Ibid.

[xxvi] Ibid.

[xxvii] Ibid.

[xxviii] Ibid.

[xxix] Cui, Q . & Lindly J. (2010). Evolution of Public Partnership Proposals. UTCA Report # 08402.

[xxx] Ibid.

[xxxi] NTSB: Washington State Bridge Collapse Should Be A Wake-Up Call, Huffington Post, May 26, 2013

[xxxii] Improving Our Nation's Transportation Bill of Health, Viewpoint, http://news.hntb.com/viewpoints/improving-our-nations-transportation-bill-of-health.htm

[xxxiii] www.Fwha.dot.gov/map21/summaryinfo.com

[xxxiv] DeWitt W, & Clinger, J. Intermodal Freight Transportation, Committee of Intermodal Freight Transport. Transportation Research Board.

[xxxv] Toward a National Intermodal Transportation System, Final Report. National Commission on Intermodal Transportation., Pg. 6, Washington, D.C., 1994.

[xxxvi] Transportation Infrastructure Investment. (2012). *Congressional Digest*, *91*(7), 193.
[xxxvii] Senate Bill 1926 (2007)
[xxxviii] Ibid.
[xxxix]Ibid.
[xl]Ibid.
[xli] Ibid.
[xlii] Ibid.
[xliii] Ibid
[xliv]Ibid
[xlv] Ibid
[xlvi] Ibid
[xlvii] Ibid
[xlviii] Ibid
[xlix] Ibid.
[l] Ibid.
[li]Ibid.
[lii] Ibid.
[liii] Ibid
[liv] Likosky, M., Ishmatsu, J., & Miller, J. (2011) Rethinking 21st- Century Government: Public-Private Partnerships and The National Infrastructure Bank, An SSRC Report.
[lv] Galston, W, & Davis, K. (2012). Setting Priorities, Meeting Needs: The Case for a National Infrastructure Bank,
[lvi] Ibid.
[lvii] GARRETT-PELTIER, H. (2010). The Case for a National Infrastructure Bank. *Dollars & Sense*, (291), 8.
[lviii] Senate Bill 1926 (2007).

TECHNICAL MEMORANDUM

TECH MEMO: TM-RS-1 **DATE: August 3, 2013**
Revised: December 31, 2013
PROJECT: CAIT – NCITEC 2012-27, Global Supply Chain
TO: Waheed Uddin, NCITEC Project Director
Center for Advanced Infrastructure Technology (CAIT), University of Mississippi

AUTHOR: Robert H. Smith, CAIT Consultant

SUBJECT: Field Testing for a Tire-Loading-Based Theory of Pavement Traction in Place of the Traditional Coefficient of Friction

---

1. BACKGROUND OF NCITEC PROJECT, OBJECTIVE AND RESEARCH TASKS

The U.S Department of Transportation (DOT) Research and Innovative Technology Administration (RITA) has awarded funding in 2012 to the National Center for Intermodal Transportation for Economic Competitiveness (NCITEC) at the University of Mississippi to conduct research. The general theme of the project is to promote the development of an integrated, economically competitive, efficient, safe, secure, and sustainable national intermodal transportation network by integrating all transportation modes for both freight and passenger mobility.

1.1 Background on Pavement-Tire Friction Properties

In keeping with the CAIT – NCITEC 2012-27 project objective of improving transportation safety, this project evaluates a new approach to understanding roadway and airport runway traction by focusing on the friction forces generated when portions of a tire are sliding on asphalt and concrete pavements in both wet and dry conditions. An associated hypothesis concerns the indicated existence of a fourth rubber friction force, surface deformation hysteresis (F_{Hs}), which is theorized to be independent of tire loading during such sliding. In 1966, Kummer proposed[1] a unified engineering theory of sliding-tire friction to be the sum of tire/pavement adhesion, or F_A, macrohysteretic bulk deformation of the tire tread on rough roads, or F_{Hb}, and physical wear of the tire, or F_C. This theory will be augmented with the F_{Hs} term.

Although the introduction of passenger auto antilock brake systems (ABS) with slip-ratio tolerances in the range of approximately 0.10 to 0.30 has considerably reduced braking sliding in these vehicles, frequent tire sliding occurs in braked commercial vehicles. In addition, changes in auto steering (slip) angles during routine turning can develop lateral friction forces. Regarding segments of the tire tread experiencing such sliding, Haney[2] states:

> “At higher slip angles portions of the tire patch are sliding, and you can get less increase in lateral force with an increase in slip angle…After [a] peak…, lateral forces can fall off 30% within a few degrees of extra slip angle. At these high slip angles most of the contact patch is sliding, producing a lot of heat and wear.”(p.94)

Thus, significant sliding of the tire in the contact patch during vehicle turning is a routine occurrence, and the friction forces developed should be understood as thoroughly as possible.

In addition to this issue, safety aspects of pavement/tire interaction revealed by a tire-loading-based approach as an advantageous replacement to the traditional use of the coefficient of friction (CoF) and skid number (SN) are also considered. The CoF is not a material property of rubber, and, as is sometimes assumed, it is not always constant under varying tire loads. Quantifying the actual friction forces generated in given conditions should assist in determining the adequacy of currently assumed safety factors.

1.2 Study Objective

The objectives of this study are: (1) to review and discuss measurement of the traditional friction coefficient and a variable-loading-based theory for determining pavement-tire friction characteristics, (2) to conduct a field testing program to validate the variable loading-based theory, and (3) to evaluate the field test results using the loading-based data analysis and compare them with the results of traditional pavement-tire friction parameters, (4) and to propose the use of a sliding friction index (SFI) as a replacement for the use of the coefficient of friction and skid number.

Locked-wheel skid testing is used in field tests to validate the loading-based theory and illustrate use of the associated data analysis approach.

1.3 Research Needs

As discussed in the author's book, *Analyzing Friction in the Design of Rubber Products and Their Paired Surfaces*[3], use of the CoF-approach arose during the important studies of metallic machinery in industry. The initial scientific investigation focused on contacting metal surfaces. Presently accepted metallic friction theory developed from research begun in the 1940s and 1950s. Introductory physics courses in technical institutions utilized the CoF when illustrating practical applications of metallic friction theory. Unfortunately for engineers, however, many such courses did not emphasize that the CoF (defined as $f = F_T/F_N$, where F_T equals total developed friction force and F_N equals the applied vertical load) does not rationally apply to rubber as it is not a material property of elastomers. Similarly, neither does the Skid Number (SN), which is defined as the f value multiplied by 100.

1.4 Consultant's Tasks

The consultant's tasks included:

- developing a field testing plan involving both asphalt and concrete road pavements,
- identifying and recruiting a competent and well-equipped pavement-testing organization,
- conducting traction measurements on dry and wet concrete and asphalt pavements, and
- interpreting the results as related to the loading-based hypothesis and comparing them with the traditional CoF and SN values.

Each test was conducted at standard speed using eight F_N loads (883, 930, 984, 1034, 1084, 1132, 1188, and 1242 lb). Temperatures of the tested pavements were recorded.

Application of the theoretical considerations in the variable loading-based data analysis and the results of the associated field studies provide transportation asset management professionals and road designers with a greater understanding of the friction mechanisms that develop in the tire/pavement contact patch. A later section will illustrate and discuss limitations of the traditional *f* and SN terms. Specific guidelines for application of the study's findings and an implementation statement are presented in section 8.5.

2. ALTERNATIVE THEORY AND TEST TECHNOLOGY APPLICABLE TO THE RESEARCH APPROACH

By looking at standard skid test results in a manner different from the traditional CoF approach, an improved understanding of the mechanisms of rubber friction can be revealed. The field testing plan specified use of a tire/pavement friction tester able to produce and control sliding of a full-scale tire needed to illustrate these mechanisms. This sliding requirement has been demonstrated in Smith's 2008 book[3] on *Analyzing Friction* and a paper[4] coauthored by R.H. Smith and T.W. Neubert, detailing the tire/pavement loading-based approach. The approach and theory detailed in *Analyzing Friction*[3] are based on analysis of more that 100 dry and wet rubber-friction tests carried out by others on macroscopically smooth and rough surfaces. A large proportion of these tests were conducted by scientists under controlled laboratory conditions, thereby demonstrating data accuracy through repeatability of results. The present research study generated the rubber microhysteretic friction force by use of a standard, full-scale ASTM ribbed tire in locked-wheel testing[5] and so indicates its existence to within engineering accuracy.

The 2011 Smith/Neubert paper[4] serves as a summary of that portion of Smith's 2008 book[3] on *Analyzing Friction* applicable to the present tire/pavement friction investigation, as well as exemplifying a number of techniques that illustrate how to calculate sliding friction forces developed when tires are loaded to F_N values greater than those used in the present testing.

2.1 Generation of the Rubber Microhysteretic Friction Force in Locked Wheel Skid Tests

Generation of the microhysteretic friction force can be exemplified by analysis of previously conducted locked-wheel testing. In 1974, the Transportation Research Board (TRB) published the results[5] of its extensive investigation concerning correlation and calibration of locked-wheel pavement skid testing in wet conditions. Of the approximately 70 figures presented in the TRB report, one concerned the effects of test-wheel loading. The report stated, "The direct effect of test wheel load changes on skid resistance is relatively small…This was confirmed in recent tests and Figure A-41 shows the load dependence of skid resistance as computed from seven tests on different pavements, each test being the mean of 10 lockups." Loads of 800 lb, 1000 lb, and 1200 lb were applied.

Figure 1 presents a plot of the TRB Figure A-41 data[5], exemplifying the loading-based approach in which the ordinate axis represents the total measured friction force (F_T) in lbf, and the abscissa represents the normal load (F_N) in lb, applied to the tire. The three TRB data points are shown. It may be noted that a straight-line connects these points. When this straight-line is extrapolated to the F_T axis, an intercept value of 150 lbf is indicated.

In addition, it is seen that the Figure 1 plot conforms to the elementary algebraic expression y=mx + b, where "y" is the ordinate value, "x" is the abscissa value, "m" is the slope of the straight-line, and "b" is a constant component in all F_T values encompassed by the testing range. The "b" value is considered to quantify the magnitude of F_{Hs}, 150 lbf.

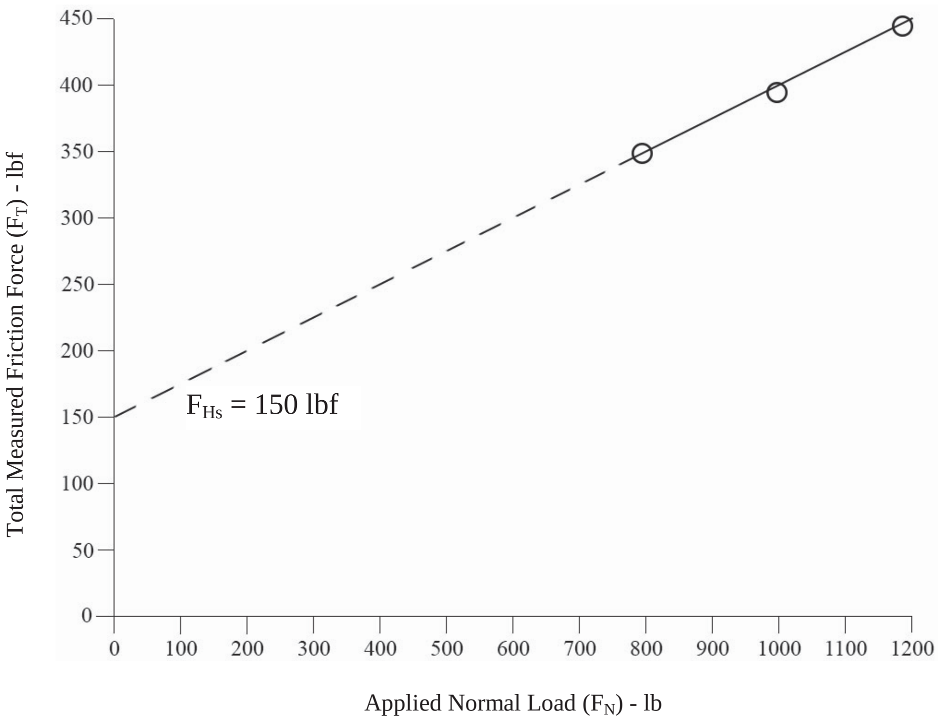


Figure 1. Transportation Research Board [5] Figure A-41 data replotted in accordance with the tire-loading-based approach to sliding-tire-friction-force calculations showing generation of a 150 lbf microhysteretic friction force (F_{Hs}), and the direct effect of increasing F_T with increasing $F_{N.}$

Generation of surface deformation hysteresis is theorized to occur when sliding rubber self-adhesively envelops at least some of the microroughness of a rigid contacted substrate. This microroughness is characterized by the microtexture depth and pavement surface free energy (γ). The adhesion mechanism is indicated to arise from the combined surface free energies (γ) of the pavement and contacting tire tread. As illustrated in *Analyzing Friction*[5] and the Smith/Neubert paper[4], if the combined surface free energies (γ) are insufficient to produce at least some envelopment of the contacted microroughness, F_{Hs} does not develop.

Figure 2 illustrates a means for checking the existence and accuracy of the determined F_{Hs} force – by subtracting the quantified F_{Hs} value, in this case[5] 150 lbf, from the associated F_T values. Plotting the resultants versus the same applied F_N loads as in Figure 1 should yield a straight-line, which extrapolates to the origin, as shown in Figure 2.

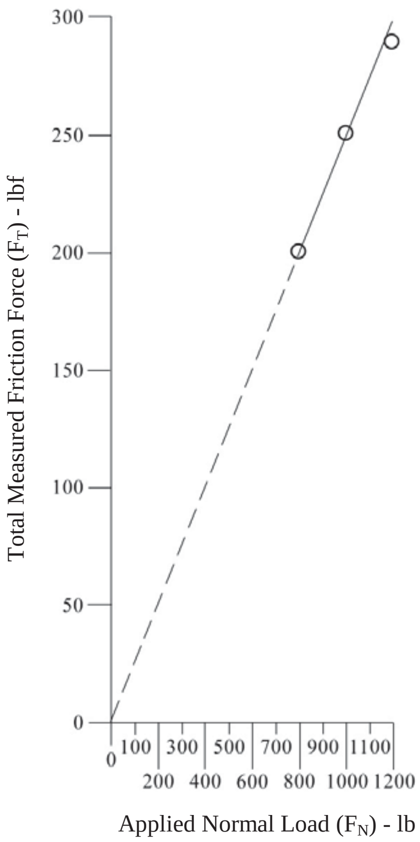


Figure 2. Checking for the existence and accuracy of the 150 lbf microhysteretic friction force, F_{Hs}, by extrapolation of the TRB data points to the origin

2.2 Scientific Data Support for the Existence of the Rubber Microhysteretic Friction Force

A mechanism for the production of a microhysteretic rubber friction force (i.e., involving the microtexture of a rigid surface paired with sliding rubber) was theorized by Persson in 1998[6]. While Persson did not opine that this force would be constant under different applied loads, its characteristics appear to be consistent with those exhibited by the constant F_{Hs} value, as seen in Figure 1 and shown later in the present testing results.

Persson[6] applied viscoelasticity theory to rubber sliding at a low velocity (V) on a clean, hard, macroscopically rough substrate having a microtexture on its surface of approximately 100 Å. Considering the free surface energies (γ) of the paired materials, Persson concluded that at room temperature and with a sufficient combined γ value, the rubber surface could deform and self-adhesively cover the contacted microroughness with sliding rubber. Persson further calculated that a microroughness approaching 1000 Å could be covered by this mechanism.

Figure 3 depicts rubber sliding at velocity V on plate glass, which typically exhibits a microroughness of about 100 Å. The elastomer is compressed into the microtexture and densified by an applied normal load of F_N. Persson's mechanism[6] is also at work, considered to be a stratum of rubber self-adhering to portions of the glass surface and thereby generating a distinct frictional resistance force.

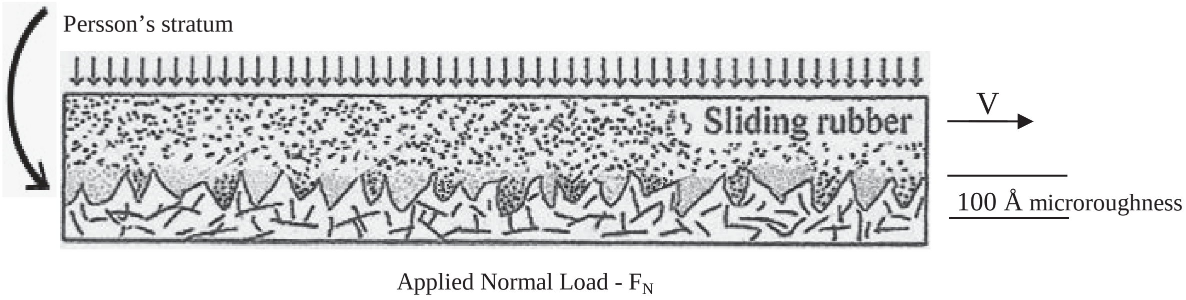
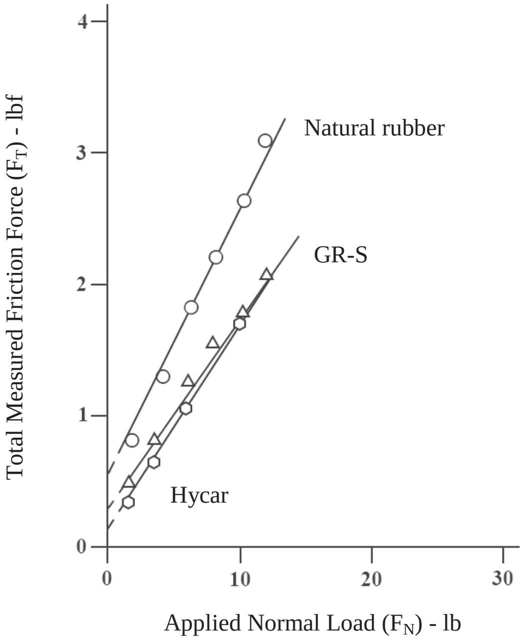


Figure 3. Rubber sliding at velocity V on plate glass having a microroughness of 100 Å. The elastomer is compressed into the microstructure and densified by a normal load of F_N. Persson's mechanism [6] is also depicted, considered to be a stratum of rubber self-adhering to portions of the glass surface and thereby generating a distinct frictional resistance force.

Further scientific support for the existence of the F_{Hs} force is seen in laboratory testing arising from the experience gained during World War II with the use of synthetic rubber tires. It was realized that such tires were more likely to slip on ice than were those made from natural rubber (NR). Pfalzner[7] carried out reproducible laboratory testing in a cold room comparing the sliding frictional resistance of NR to formulations of synthetic Hycar (acrylonitrile butadiene) and GR-S (styrene butadiene). Pfalzner prepared 1 inch^2 x 0.25 inch samples and applied normal loads to them in the range of 42 psi to 100 psi while mounted on an ice-covered, electrically driven turntable rotating at a constant speed of 50 rpm. The testing was carried out at 20º F. Freezing to produce ice was done in such a manner that it was both dry and macroscopically smooth. Figure 4 presents results from Pfalzner's testing[7].

Figure 4. Results of Pfalzner's [7] sliding friction testing of natural rubber and synthetic Hycar and GR-S on dry, macroscopically smooth ice showing generation of a microhysteretic friction force in each elastomer



(From [3], CRC Press, 2008. With permission.)

Generation of the microhysteretic friction force in natural rubber, having a magnitude of about 0.6 lbf, is evidenced in the Figure 4 results from Pfalzner's testing[7]. The GR-S and Hycar plots indicate generation of the F_{Hs} force having magnitudes of approximately 0.30 lbf and 0.25 lbf, respectively. These results are consistent with the tire slipperiness observations made during World War II. In addition to providing an indication of the existence of F_{Hs}, the test results suggest that its slip-resistance contribution on ice should not be overlooked.

The 1994 research of Mori et al[8] also supports the existence of F_{Hs}. Their laboratory-controlled studies focused on clarifying the role of surface free energy (γ) on the adhesion forces generated in a sliding configuration when rubber is paired with different, macroscopically smooth surfaces under varying applied load. The vulcanized specimens were formed in specially fabricated molds which possessed different surface free energies, thereby imparting different surface free energies to the surfaces of the rubber specimens. This technique allowed each sample to retain the inherent deformational properties of its bulk material. The various specimens tested included styrene butadiene rubber (SBR), having been molded to possess both high-adhesion and low-adhesion surfaces. The SBR was paired with macroscopically smooth Teflon®.

One SBR sample was molded on macroscopically smooth Teflon® to yield a low surface free energy material. Another SBR specimen was molded on macroscopically smooth chrome to yield a high surface free energy SBR. Both of these were put in sliding contact with a Teflon® surface and a load was applied.

Figure 5 presents the Mori et al[8] results, plotted in accordance with the loading-based theory to reveal indication of the rubber microhysteretic friction force, if present. It is seen that extrapolation of the high-adhesion (chrome mold) SBR-Teflon® pairing plot evidences production of an F_{Hs} force having a magnitude of approximately 0.2 lbf. The low-adhesion SBR-Teflon® pairing plot extrapolates to the origin, however, indicating the absence of F_{Hs}.

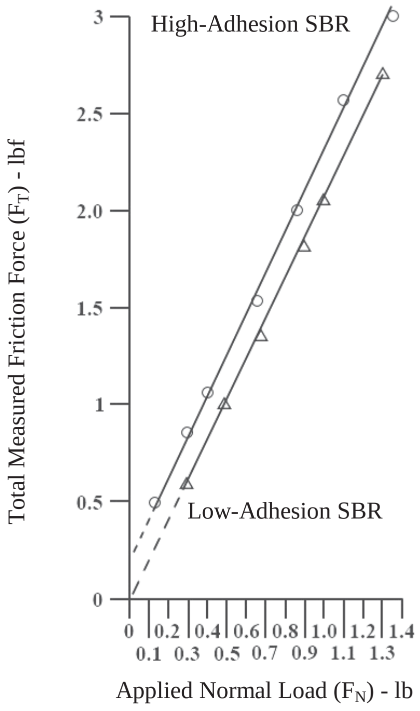


Figure 5. Plots of the Mori et al [8] test results from high-adhesion and low-adhesion SBR sliding on Teflon®, indicating generation of the microhysteretic rubber friction force (F_{Hs}) and its absence, respectively

3. RECONSIDERATION OF THE COEFFICIENT OF FRICTION AND SKID NUMBER

3.1 The 1974 TRB Report

The 1974 TRB report[5] stated, “The direct effect of test wheel load changes in skid resistance is relatively small…This was confirmed in recent tests and Figure A-41 (Figure 6 below) shows the load dependence of skid resistance as computed from seven tests on different pavements, each being the mean of 10 lockups.” Reference to Figure 1, however, shows that, opposite to the stated belief, the direct effect of changes in wheel load when the tire is sliding is significant, as illustrated on the F_T axis. The largest F_T force was produced by the largest F_N load. Increases in F_N can increase the real area of tire/pavement contact. Such contact growth can produce greater adhesion[3], a principal tire/pavement friction force. Greater adhesion can also increase tire contact area with pavement macroroughness, adding to macrohysteretic (F_{Hb}) friction force development through greater bulk deformation of the tire tread.

Figure 6 expresses SN vs. applied normal load. A moderately decreasing hyperbolic curve for the three applied loads of 800 lb, 1000 lb, and 1200 lb is seen, indicating that the frictional resistance decreases with increasing load when the opposite is true. Application of the variable loading-based approach in sliding-friction data analysis can enhance interpretation of skid test results.

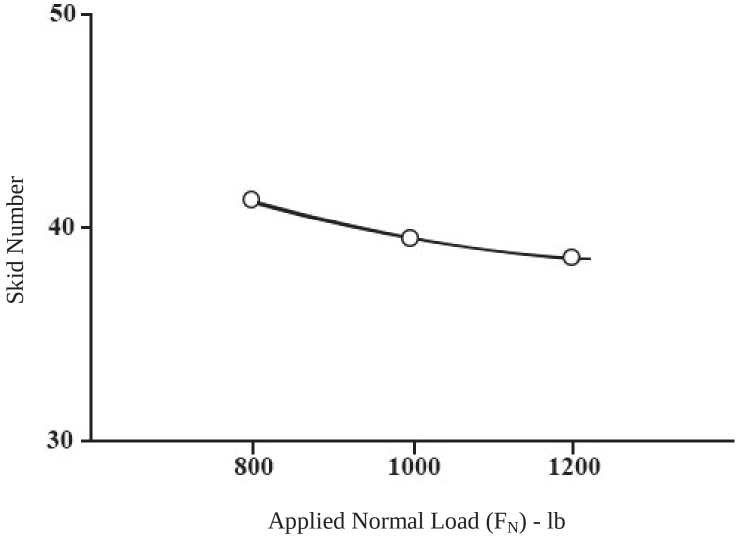


Figure 6. Transportation Research Board [5] Figure A-41 data replotted as skid number vs. applied normal load (F_N). As shown in Figure 1, the largest friction force developed, approximately 445 lbf, corresponds to the largest applied load, 1200 lb, in wet conditions

3.2 Use of CFMEs to Assess Airport Pavement Traction

Airport pavement traction is also assessed using the CoF. At present it is common practice to use the so-called CFMEs, or Continuous Friction Measuring Equipment, for this purpose[4]. Such equipment is approved by the Federal Aviation Administration (FAA), and can comprise instrumented autos, pickups, or trailers. These smooth-tire tests are conducted at a fixed percent slip, rather than locked-wheel sliding. They are carried out in accordance with an ASTM standard[9]. Because these tests involve slipping, the theorized microhysteretic friction force, F_{Hs}, is not generated. As a consequence, the microhysteretic friction contribution to traction is not determined.

Figure 7 presents the results of such CFME testing carried out in 2009 on an ‘almost polished’, ungrooved, concrete runway taxiway in dry conditions at 17 percent tire slip using a towed trailer incorporating the testing tire in straight-line operation at a velocity of 30 mph at 86ºF ambient temperature. The CoF data points were obtained by varying the F_N loads applied to the tire. As shown, the plot extrapolates to the origin indicating that the F_{Hs} force was not generated.

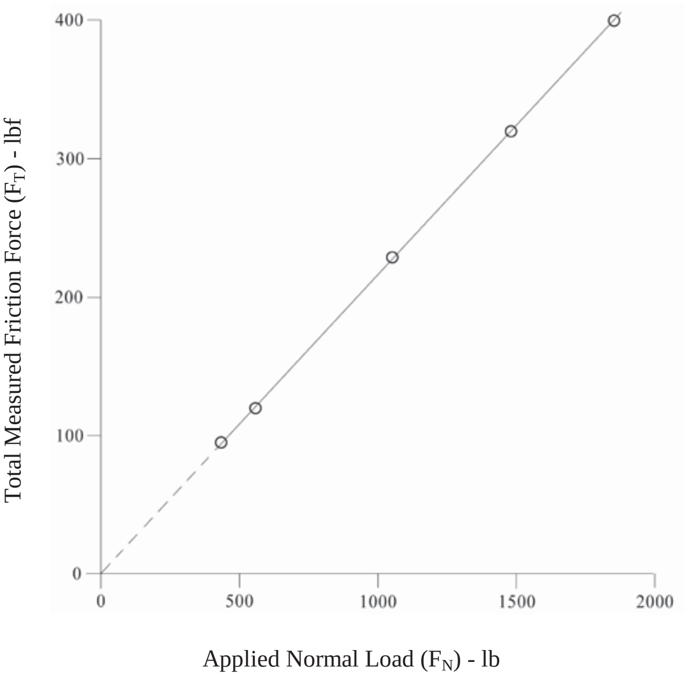


Figure 7. Results of CFME testing[4] on an ungrooved concrete runway taxiway at 17 percent tire slip in dry conditions illustrating the inability to generate the microhysteretic friction force
(Reproduced with permission from the International Journal of Pavements©, 2011)

3.3 Examining the Reported START Program Results

Yager et al[10] reported results obtained in the Surface Traction and Radial Tire (START) Program conducted by the American aircraft industry, the National Aeronautics and Space Administration (NASA), and the FAA. The program’s particular focus was on the evaluation of tire rolling resistance, braking, and cornering performance in dry conditions on concrete. Three full-size commercial aircraft tire types – radial-belted, bias-ply, and H-type – were investigated.

The studies were carried out at NASA Langley’s Aircraft Landing Dynamics Facility, which provided a 2,800-ft long textured concrete test track runway. The runway’s macrotexture was measured using the NASA grease sample technique[11] and found to have an average depth of 0.0051 in. Cornering performance was assessed by use of a 60 ton tire-carriage operating at a velocity of 100 knots and applying normal loads (F_N) on freely rotating tires of up to 25,000 lb. The carriage was instrumented to measure the total side friction force, F_{TS}, generated at different tire slip angles of interest, and reported values of the side friction coefficient, F_{TS}/F_N.

Figure 8 presents the side coefficient of friction (F_{TS}/F_N) results reported[10] by the START Program for the bias-ply tire tested at five slip angles of interest. It is seen that each plot yields a straight-line having a pronounced downward slope. Conventional interpretation of rubber friction coefficients would conclude that lateral resistance to sliding was decreasing with increasing F_N at all slip angles. As seen in Figure 9, however, in which the same data are plotted in accordance with the loading-based approach (previously explained in Figure 1) to quantify F_{Hs} values, the side friction force is increasing. This is another example of improved data interpretation for analyzing the coefficient of friction. Table A presents the approximate values of the F_{Hs} force at each tire slip angle.

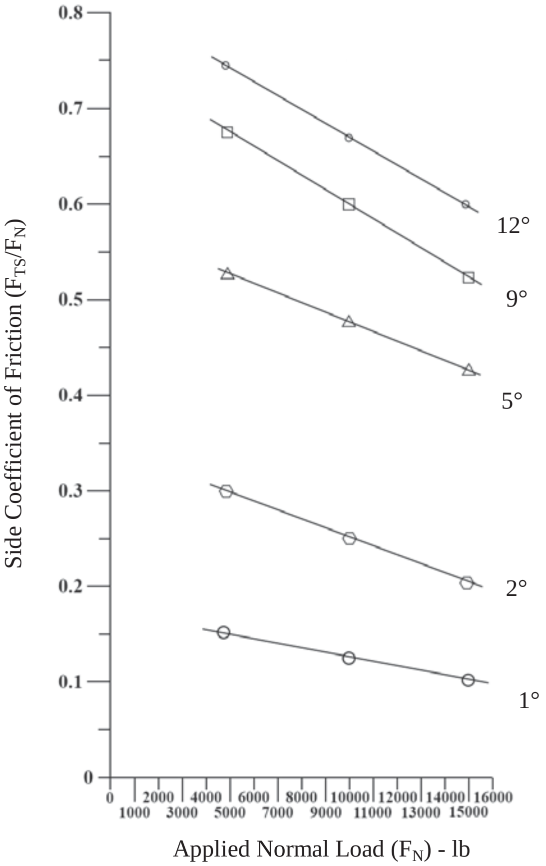


Figure 8. Side coefficient of friction results reported by the START[10] Program indicate that lateral frictional resistance to sliding in the tire contact patch decreases with increasing applied load

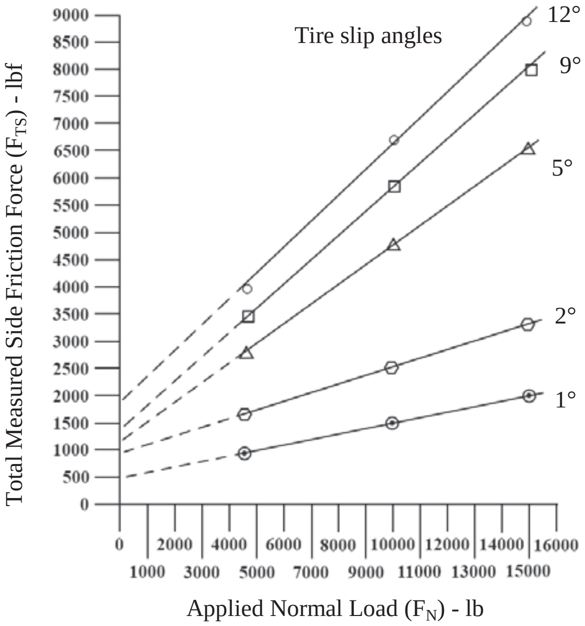


Figure 9. Yager et al[10] side friction force results from tests of full-scale, freely rotating aircraft tires on textured concrete at five different slip angles, replotted in accordance with the tire-loading-based approach illustrating quantification of the load-dependent side friction force (F_{TS}) and values of the associated constant microhysteretic friction force, F_{Hs}, shown in Table A, obtained by extrapolation to the side-friction-force axis

Table A. Approximate Values of the Microhysteretic Rubber Friction Force, F_{Hs}, generated during the Yager et al[10] sliding, side friction force tests of full-scale, rotating, bias-ply aircraft tires at five different slip angles

Tire Slip Angle	Value of Microhysteretic Force	Side CoF at 10,000 lb Load
1º	450 lbf	0.125
2º	900 lbf	0.25
5º	1,100 lbf	0.475
9º	1,300 lbf	0.6
12 º	1,600 lbf	0.675

The above side friction test results on an airport-like test track pavement indicate generation of F_{Hs} forces at all slip angles. These forces are produced due to good pavement microtexture depth and sufficient combined surface free energies of the tire and pavement. The conventional quantification of slip resistance values expressed as side CoF is shown in Table A. Its use simply ignores these F_{Hs} forces arising in the tire contact patch and the presence of a microtexture on the pavement surface.

4. METHODOLOGY AND FACTORS FOR FIELD TESTS IN CURRENT STUDY

In the current NCITEC 2012-27 project controlled sliding-tire friction testing of asphalt and concrete pavement was accomplished by using a locked-wheel skid trailer device fitted with a standard, full-scale tire. Instead of the conventional single-load, locked-wheel testing, however, eight different loads were applied to the tire sliding on both asphalt and concrete pavements in wet and dry conditions, as presented in section 1.4.

4.1 Pavement Friction Testing Equipment and Standards

Tire/pavement-friction testing was carried out using an instrumented locked-wheel device provided and operated by International Cybernetics Corporation (ICC) of Largo, Florida. This tester is capable of producing and controlling sliding of a previously conditioned, standard, full-scale ribbed tire (ASTM E501 – 08)[12] while measuring the total friction force generated. It was operated in accordance with ASTM E274/E274M–11[13], the current standard for such testing, except that the standard-specified applied load of 1085 ± 15 lb was replaced by the loads listed in section 1.4 The individual, level pavement test sections were of uniform age, material composition, and wear and were free from major defects and obvious surface contamination. ICC has served governmental and consultancy clients since 1975, and has received testing contracts from the United States and around the world. It supplies both hardware and software to meet friction test data-collection and analysis needs. Contact information regarding ICC is provided in the Appendix.

4.2 Factors and Variables of Test Program

The following two factors were considered for conducting field tests: (1) pavement type at two levels (asphalt surfaced and concrete surfaced pavements) and (2) pavement surface condition (dry and wet). Both pavement types were tested using the eight loads listed in section 1.4. Five lockups were carried out for each load in the dry condition. Five sets of three lockups were carried out for each different tire load in the wet condition. This sampling resulted in four sets of test data collected at each of the eight normal test loads.

In accordance with ASTM E274/E274M – 11[13] , the locked-wheel tester slid the test tire at a constant 40±1 mph velocity. The eight different vertical loads ranging from 883 to 1,242 lb were applied to the tire's centerline under the different test conditions. In accordance with Section 4.7 of this standard concerning pavement wetting, the quantity of water applied in the simulated wet tests at 40±1 mph was 4.0 gal ± 10 %/min·in. of wetted width, amounting to 28 gal/minute.

4.3 Data Collection and Interpretation of Results

Each of four sliding locked-wheel tests generated eight mean values of measured friction force vs. applied normal load for the asphalt and concrete pavements in wet and dry conditions. These results have been plotted on conventional rectangular coordinates providing a visual depiction of changes in the magnitude of the developed friction forces as tire loading changes.

The eight different F_N tire loads used in the asphalt and concrete testing were obtained by placing individual steel slab loads in the loading box located at the rear of the test trailer. The load applied to the tire was controlled by the selected weights placed in this box.

5. LOCKED-WHEEL TESTING

5.1 Dry Asphalt Pavement Testing

Dry testing of asphalt using the ICC tester, always operated by the same experienced engineer, began on Belcher Road in Largo, Florida on March 18 and was completed on March 22, 2013, during daylight hours. Traffic on Belcher Road was moderate; no significant interference with traffic took place during the testing at 40 ±1 mph. Figure 10 depicts the starting point of these tests. Although some clouds were present, no rain fell during the dry asphalt study.

The asphalt pavement was 18 to 20 months old with no significant polishing. Figure 11 depicts a close-up of the Belcher Road pavement on which the skid testing was done. A U.S. quarter placed on the pavement has been included to assist in depicting the lack of polishing.

Figure 10. Starting point for the Belcher Road asphalt testing in Largo, Florida

Figure 11. Close-up of the Belcher Road asphalt pavement depicting the lack of polishing and presence of microtexture

A new, run-in, full-scale ASTM E501 – 08 ribbed tire mounted on the left side of the tester with the standard 24 ± 0.5 psi inflation pressure was used. Three preliminary lockups with the same tire loading were done for quality control purposes.

Five lockup cycles of five individual tests were done for each of the eight applied loads. The results were averaged to obtain a mean value for the total measured friction force, F_T, generated by each load. These test data were always obtained in the same lateral roadway position in the same operating lane, recorded for 1 sec. Figure 12 presents the dry Belcher Road results plotted in accordance with loading-based approach. When compared to the CoF vs. load plot seen in Figure 6, the test-data plots provide superior insight into the friction-generating mechanisms active in the tire/pavement contact patch. Table B presents the normal loads and their associated F_T friction-force values.

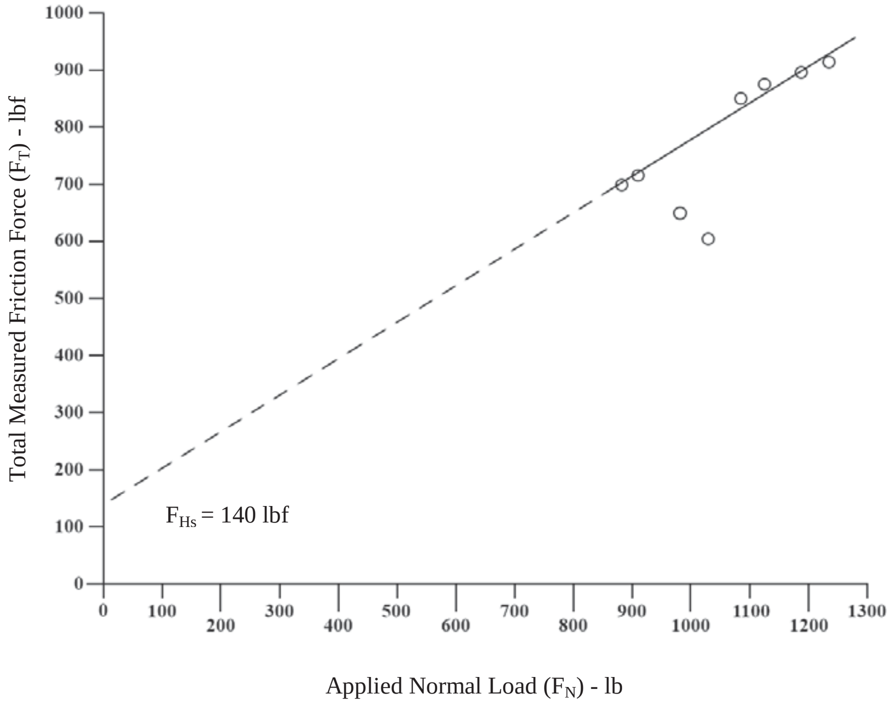


Figure 12. Dry Belcher Road test results

Table B. Individual Weights Selected for Use in Controlling the Dynamic Load (F_N) Applied to Test Tire During Lockups and Measured F_T Values Dry Asphalt Pavement Testing

#	F_N Normal Load	Increase in Load, %	F_T lbf
1	883 lb	-	693
2	930 lb	5.3	705
3	984 lb	11.4	650
4	1034 lb	17.1	597
5	1084 lb	22.8	850
6	1132 lb	28.2	879
7	1188 lb	34.5	890
8	1242 lb	40.7	923

It is seen that six of the eight F_T values, when connected by a straight line and extrapolated to the Y-axis, indicate generation of the microhysteretic friction force, F_{Hs}, having a magnitude of about 140 lbf. The plotted points for two of the applied loads, 984 lb and 1034 lb, however, are considered outliers. These may be associated with puffs of white smoke which emanated from the tire/pavement contact patch during all dry lockups.

Examination of the pavement at the dry lockup locations revealed that soft spots had developed on the tire, as indicated by black streaks of rubber on the pavement surface. Smoke production may have resulted from the presence of the mechanism which is common in tires during aircraft landings. Heat degradation of the tires and rubber vaporization can cause white smoke to be generated. A professional commercial pilot has stated[14], “The smoke is the result of a wheel which is not turning in flight making contact with a stationary runway. The wheel must accelerate to the landing speed very quickly. During that acceleration, there is a short time when the tire is skidding, which produces the smoke.”

While tire softening occurred during all dry lockups as a result of friction, the 984 lb and 1034 lb load testing of Belcher Road was also subjected to the highest continuous pavement temperatures arising from solar radiation, potentially resulting in additional tire softening with consequent reduction in the generated friction force. The pavement temperature during these two test cycles was 119ºF. Pavement temperatures during application of the other six applied loads averaged a continuous 82ºF.

5.2 Wet Asphalt Pavement Testing

Wet testing of the same asphalt pavement using the ICC tester, always operated by the same experienced engineer, took began on Belcher Road in Largo, Florida on March 18, 2013 and was completed on March 22, 2013, both during daylight hours. Traffic on Belcher Road was moderate; no significant traffic interference took place with the testing at 40 ±1 mph.

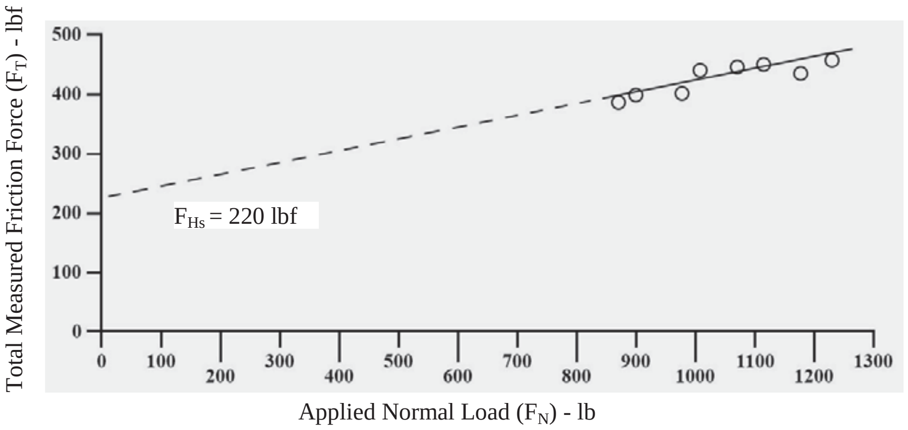


Figure 13. Wet Belcher Road test results

A loading-based plot of the resulting test data is presented in Figure 13. Generation of an F_{Hs} friction force of about 220 lbf is indicated. Table C presents the individual F_N weights utilized and the resulting associated F_T values produced.

Table C. Individual Weights Selected for Use in Controlling the Dynamic Load (F_N) Applied to Test Tire During Lockups and Measured F_T Values Wet Asphalt Pavement Testing

#	F_N Normal Load	Increase in Load, %	F_T lbf
1	883 lb	-	395
2	930 lb	5.3	384
3	984 lb	11.4	402
4	1034 lb	17.1	455
5	1084 lb	22.8	449
6	1132 lb	28.2	452
7	1188 lb	34.5	431
8	1242 lb	40.7	449

The new, run-in, full-scale ASTM E501 – 08 ribbed tire mounted on the left side of the tester with the standard 24 ± 0.5 psi inflation pressure[5] was used.

Five lockup cycles of three individual tests were done for each of the eight applied loads. The results were averaged to obtain a mean value for the total measured friction force, F_T, generated by each load. These test data were always obtained in the same lateral roadway position in the same operating lane, recorded for 1 sec.

It is seen that seven of the F_T values fall on or very near a straight-line which, when extrapolated, indicates generation of the microhysteretic friction force, F_{Hs}, having a magnitude of about 220 lbf. The 1,188 lb data point, however, which is slightly below the straight-line, could be considered an outlier. Drawing on the experience of ICC from their routine locked-wheel testing in wet conditions likely revealed the apparent discrepancy. The friction data for the 1,188 lb and 1,242 lb loads were collected three days after the friction data for the other loads. It had been noticed that friction data obtained on different days could show such different results, probably associated with pavement temperature variations during such periods.

5.3 Dry Concrete Pavement Testing

Dry testing of concrete pavement using the ICC tester, always operated by the same experienced engineer, began on Tyrone Boulevard in St. Petersburg, Florida on March 18, 2013 and was completed on March 22, 2013, both during daylight hours. Traffic on Tyrone Boulevard was moderate; no significant interaction took place between it and tester as 40 ± 1 mph. Figure 14 depicts the starting point of these tests, as well as the ICC truck and trailer. Although some clouds were presents, no rain was experienced during the dry concrete study.

Figure 14. Starting point for the Tyrone Boulevard testing in St. Petersburg, Florida

Figure 15. Close-up of the polished Tyrone Boulevard pavement showing the longitudinal tining

Figure 15 presents a close-up of the polished Tyrone Boulevard pavement. A U.S. dime has been placed on the pavement to assist in depicting the surface condition and its treatment. The Florida Department of Transportation requires that all concrete roads undergo tining, a process in which metal prongs are dragged on semi-hardened concrete to create grooves transversely or longitudinally[15]. The longitudinal grooves in the otherwise polished Tyrone Boulevard pavement in the area of testing are readily apparent. Figure 16 presents the dry Tyrone Boulevard test results.

It is seen that seven of the eight F_T values, when connected by a straight-line and extrapolated to the Y-axis, indicate generation of the microhysteretic friction force F_{Hs}, having a magnitude of about 200 lbf. As with the dry asphalt testing, however, an outlier is present, in this case at the 883 lb load. The continuous pavement temperature for the 883 lb testing was 116ºF, while the pavement temperature during testing at the other loads averaged 74ºF. Puffs of smoke emanating from the tire/pavement contact patch were also observed during the dry concrete testing. These conditions are consistent with greater softening of the tire and a reduced F_T value at the 883 lb load, as reported. A F_{Hs} value 200 lbf was measured. Table D presents the applied loads and the associated F_T values.

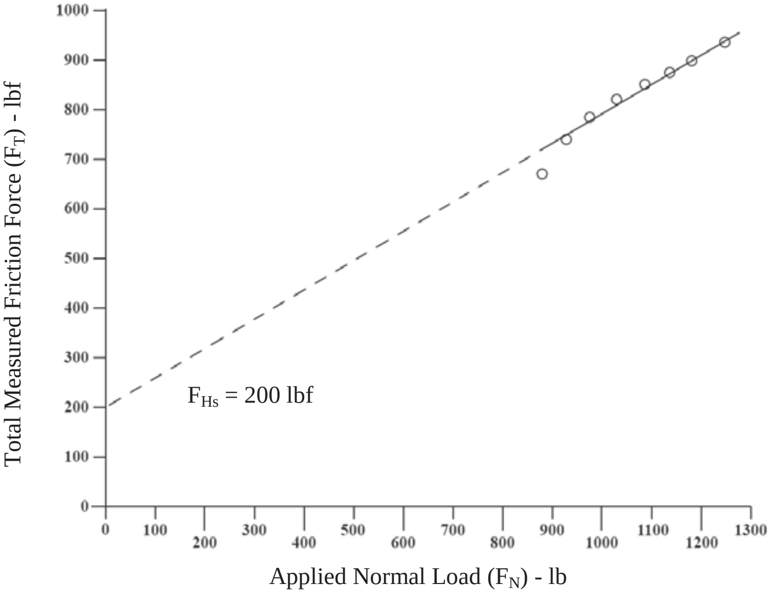


Figure 16. Dry Tyrone Boulevard test results

Table D. Individual Weights Selected for Use in Controlling the Dynamic Load (F_N) Applied to Test Tire During Lockups and Measured F_T Values Dry Concrete Pavement Testing

#	F_N Normal Load	Increase in Load, %	F_T lbf
1	883 lb	-	666
2	930 lb	5.3	743
3	984 lb	11.4	786
4	1034 lb	17.1	824
5	1084 lb	22.8	848
6	1132 lb	28.2	878
7	1188 lb	34.5	903
8	1242 lb	40.7	931

5.4 Wet Concrete Pavement Testing

Wet testing of concrete using the ICC tester, always operated by the same experienced engineer, began on Tyrone Boulevard in St. Petersburg, Florida on March 18, 2013 and was completed on March 22, 2013, both during daylight hours. Traffic on Tyrone Boulevard was moderate; no significant interaction took place between it and the testing at 40 ±1 mph.

The new, run-in, full-scale ASTM E501 – 08 ribbed tire mounted on the left side of the tester with the standard 24 ± 0.5 psi inflation pressure was used.

Five lockup cycles of three individual tests were done for each of the eight applied loads. The results were averaged to obtain a mean value for F_T, generated by each load. These test data were always obtained by the same engineer in the same lateral roadway position in the same operating lane, recorded for 1 sec. Figure 17 presents the wet Tyrone Boulevard results. Table E presents the normal tire loads and their associated F_T values.

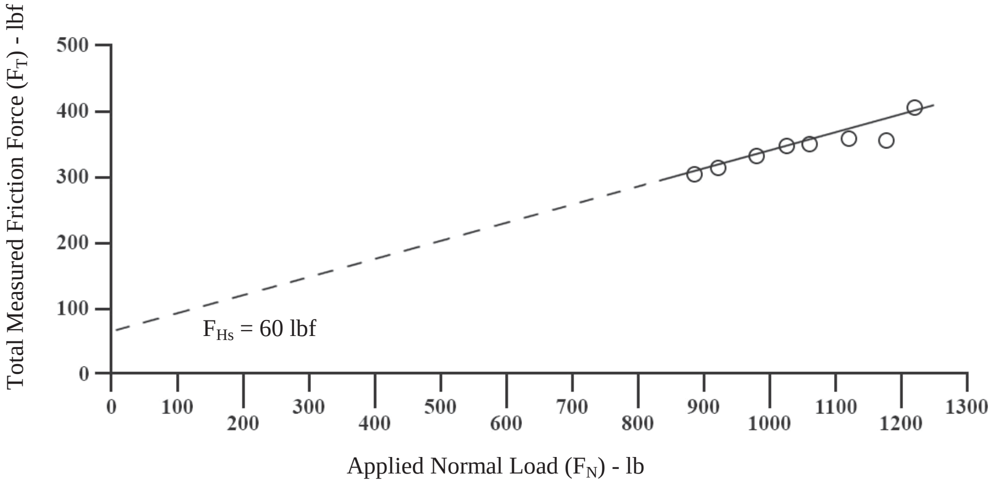


Figure 17. Wet Tyrone Boulevard test results

Table E. Individual Weights Selected for Use in Controlling the Dynamic Load (F_N) Applied to Test Tire During Lockups and Measured F_T Values Wet Concrete Pavement Testing

#	F_N Normal Load	Increase in Load, %	F_T lbf
1	883 lb	-	314
2	930 lb	5.3	322
3	984 lb	11.4	339
4	1034 lb	17.1	352
5	1084 lb	22.8	351
6	1132 lb	28.2	363
7	1188 lb	34.5	362
8	1242 lb	40.7	426

It is seen that seven of the F_T values fall on or in contact with the straight-line which, when extrapolated, indicates generation of the microhysteretic friction force, F_{Hs}, having a magnitude of about 60 lbf

The 1188 lb data point, however, could be considered an outlier. The ICC experience with their routine locked-wheel testing in wet conditions on different days likely provides the explanation for the discrepancy.

5.5 Summary of Test Results and Proposed Sliding Friction Index Values

Table F summarizes the loading-based-interpretation results with F_{Hs} values for all four sets of the friction test data. Higher values of the microhysteretic force for the unpolished asphalt indicates superior microtexture characteristics at the time of testing compared to the polished concrete pavement.

Using the loading-based approach, a “Sliding Friction Index” (SFI) is proposed as an improved metric for sliding-tire friction calculations resulting from variable F_N values, presented in section 8.3

Table F. Summary of Friction Test Results from the Four Tests Reporting Values of Their Associated Sliding Friction Index.

#	Pavement Type	Test Condition	$F_{Hs,}$ lbf	Sliding Friction Index
1	Asphalt	Dry	140	0.60
2	Asphalt	Wet	220	0.60
3	Concrete	Dry	200	0.58
4	Concrete	Wet	60	0.58

5.6 Coefficient of Friction Values for all four Locked-Wheel Tests

Table G presents the *f* values for all four locked-wheel test results. These are reported here for comparison to the use of the tire-loading-based approach, which allows separate quantification of the F_{Hs} force. Each calculation used the mean value of the corresponding F_T measurement, and unavoidably has an F_{Hs} force component.

Table G. Calculated *f* Values for All Locked-Wheel Tests

Dry Belcher Road Asphalt	
F_N Values	*f* Values
883 lb	0.78
930 lb	0.76
984 lb	0.66
1034 lb	0.58
1084 lb	0.78
1132 lb	0.78
1188 lb	0.75
1242 lb	0.74
Wet Belcher Road Asphalt	
883 lb	0.45
930 lb	0.41
984 lb	0.41
1034 lb	0.44
1084 lb	0.41
1132 lb	0.40
1188 lb	0.36
1242 lb	0.36
Dry Tyrone Boulevard Concrete	
883 lb	0.75
930 lb	0.80
984 lb	0.80
1034 lb	0.80
1084 lb	0.78
1132 lb	0.77
1188 lb	0.76
1242 lb	0.75
Wet Tyrone Boulevard Concrete	
883 lb	0.34
930 lb	0.35
984 lb	0.34
1034 lb	0.34
1084 lb	0.32
1132 lb	0.32
1188 lb	0.31
1242 lb	0.34

6. A UNIFIED, LOADING-BASED ENGINEERING THEORY OF TIRE/PAVEMENT FRICTION

As discussed, Kummer proposed[1] a unified theory of sliding tire/pavement friction in 1966, expressing the total friction force produced as the sum of its components. These included adhesion, F_A, associated with the combined surface free energies of the paired materials. He considered that bulk deformation of the tire tread on rough pavements produces a macrohysteretic frictional contribution, F_{Hb}. He also included tire wear, or cohesion loss, F_C. Kummer's purpose for proposing the theory was to "improve the frictional coupling between tires and wet road surfaces, particularly at high speeds."

Building on Kummer's approach, an expanded, unified, loading-based engineering theory of tire/pavement friction has been proposed[3,4]. The theory incorporates the microhysteretic rubber friction force, the evidence for which has now been indicated by locked-wheel testing:

$F_T = F_A + F_{Hb} + F_C + F_{Hs}$, where,

F_T = total frictional sliding resistance of the tire on pavement surfaces,

F_A = adhesion force arising from the combined surface free energies of the paired materials,

F_{Hb} = bulk deformation of the tire tread,

F_C = cohesion loss component from tire wear, and

F_{Hs} = contribution from the constant microhysteretic friction force.

It should be noted that Kummer[1] included the F_C term for completeness, but opined that its magnitude in particular short-term circumstances could be negligible. It should also be noted that F_A and F_{Hb} are not necessarily independent. Adhesion-assisted macrohysteresis can increase F_{Hb} force development in some circumstances by adhering tire rubber to rough pavement surfaces more closely[3].

7. PRACTICAL APPLICATIONS OF THE LOADING-BASED APPROACH

7.1 Contributions to Vehicle Dynamics Analysis

As shown in Figure 1 and other plots presenting test results reported here as F_T vs. F_N, increasing the applied normal load increases the resulting tire/pavement friction force. As discussed in section 3, use of the coefficient of friction and skid number can inadvertently result in misinterpreting developed friction-force assessments. This can be illustrated by considering a simple example in vehicle dynamics.

When a two-axle motor vehicle decelerates during straight-ahead braking on a horizontal pavement, dynamic load transfer from the rear axle to the front axle can occur. During this process, loads on the rear tires decrease while the front tires can experience increased loading. Because the CoF is not generally constant under varying load, a larger coefficient can therefore seemingly apply to the rear tires as the vehicle slows while a smaller friction ratio would apparently be associated with the front tires, *opposite* indications of actual friction-force generation.

Use of the loading-based approach can allow calculation of the actual F_{TS} forces generated at desired slip angles and F_N values of interest. When drivers make routine intersection turns or steering adjustments to follow roadway curvature, lateral friction forces are produced. Knowledge of such data would appear valuable to vehicle dynamists for use when quantifying the lateral sliding resistance needed to overcome inertial forces arising during such maneuvers, thereby keeping vehicles on the road.

7.2 Monitoring the Microtexture Depth Variation of Pavement Surfaces

It has been previously recognized that the study of tire traction should include pavement microtexture. Bond et al conducted investigations regarding the importance of wet pavement microtexture, reported in 1974[16]. They found that microroughness plays a significant role in tire traction in wet conditions. Their research encompassed seasonality issues and discovered that wet traction increased to a maximum in winter and fell to a minimum in summer. Examination of photomicrographs of in-service pavements revealed that pavement microroughness increased to a maximum in winter due to frost and other natural weathering effects on road aggregate during this period. It was also found that traffic polishing dominated during the summer, thereby removing the aggregate's microtexture to a considerable extent. These findings correlated well with the frequency of traffic incidents, fewer in winter and a greater number in summer.

Bond et al[16] further determined that the wet traction indicated to be provided by the pavement microroughness was minimal unless the aggregates' topographical depth was greater than a critical value, on the order of 1.95×10^{-4} in. Above this value, wet-roadway skid resistance increased rapidly.

Williams reviewed[17] the then state-of-the-art of tire/pavement traction in 1992, with a particular interested in a tire's roadholding ability in wet conditions. Recognizing the importance of an adequate pavement microtexture, he stated:

> "There is no substitute for the appropriate level of microtexture for aggregates in the new and traveled condition. The most desirable level of microtexture relates to its ability to remove the remaining thin film of water to create real areas of contact with the tread compound. Levels of microtexture below this minimum fail to generate high levels of wet friction." (p. 132)

Figures 13 and 17 present test results allowing quantification of the microhysteretic rubber friction force, F_{Hs}, in wet conditions, obtained by routine use of a locked-wheel tester. The F_{Hs} measurements of unpolished Belcher Road (220 lbf) and polished Tyrone Boulevard (60 lbf) are consistent with the findings of Bond et al[16] and Williams[17]. These results, which were obtained in a few days of testing, reveal significant differences in the magnitudes of the respective F_{Hs} forces. The ability of routine locked-wheel testing, the results of which were likely influenced, at least in part, by pavement microtexture characteristics, suggests that higher frictional resistance is measured on pavements with greater microtexture depth. An improved loading-based data interpretation was used to develop a "Sliding Friction Index" discussed below in Section 7.5. Seasonal testing and testing on other road pavements with different microtexture characteristics should help to demonstrate broad applicability of the proposed friction index model. It would provide a reliable indication of the variation of friction index arising from varying F_N.

7.3 A Lateral Friction Tester in Current Use

Investigation has revealed that there is at least one mobile side friction device in routine use – the fleet of SCRIM® testers operated by the Transportation Research Laboratory (TRL) in the UK. The Sideway-force Coefficient Routine Investigation Machine, or SCRIM®, measures the lateral friction produced in controlled wet conditions by use of a freely rotating smooth rubber tire fixed at a slip angle of 20º to the direction of travel of the testing vehicle. While not presently used in accordance with the tire-loading-based approach, plotting the reported data as shown in Figure 9 would reveal the true F_{TS} vs. F_N relationship, and quantify the value of F_{Hs}.

Using the SCRIM® data at the 20º slip angle in this manner appears suitable for monitoring the microtexture depth variation of roadway pavement surfaces discussed in section 7.2. In fact, the stated purpose of SCRIM® testing is, “to determine the need to treat the [test] site to restore skid resistance.” Contact information for TRL may be found in the Appendix.

7.4 Alternative Approach to the Coefficient of Friction in the Geometric Design of Roads

Section 3 discussed and illustrated (Figures 1 and 6) how the use of the coefficient of friction and skid number can lead to inadvertent misassessments when analyzing locked-wheel test results. At present there is no accepted, verifiable, comprehensive, rational theory of rubber friction incorporating the CoF term, which itself is not a material property of elastomers. For safety reasons, application of the validated tire-loading-based approach and the sliding friction index in appropriate transportation segments is recommended instead.

The coefficient of friction, designated as *f*, is widely used in equations presented in the Green Book[18], the basic American roadway geometric design manual. This manual, under continuing development over many decades and involving the participation of numerous skilled engineers and experienced designers, has made an enormous and lasting contribution to the practice of transportation safety and efficiency[18]. The practice, when involving *f*, however, does not consider contributions of the microhysteretic force (F_{Hs}) arising from sliding tire contact with the pavement’s microtexture.

7.5 Sliding Friction Index

By accepting the existence of the microhysteretic friction force (F_{Hs}) and accounting for it in the analysis of locked-wheel testing, it is possible to generate a rational number quantifying the variable frictional sliding resistance produced when different values of applied tire loads (F_N) are used in such testing.

The process involves subtraction of the constant F_{Hs} value from the total measured friction force (F_T) generated from each such applied load. This may be illustrated using the locked-wheel testing data published by the Transportation Research Board[5] in 1974 and shown in Figure 1, in which a F_{Hs} force of 150 lbf was produced using three different applied loads of 800 lb, 1000 lb, and 1200 lb. In this testing, the corresponding F_T values were 350 lbf, 400 lbf, and 450 lbf, respectively. Table H presents the appropriate calculations. It is seen that subtraction of the 150 lbf F_{Hs} force from the three F_T values yields 200 lbf, 250 lbf, and 300 lbf, respectively. Division of these resultants by their respective F_N quantities yields the dimensionless sliding friction index (SFI) value of 0.25 for all three loads. Figures 18, 19, 20, and 21 present SFI values for the present wet and dry locked-wheel test results. The outlier values were not included in these SFI calculations.

Table H. Calculation of the Sliding Friction Index (SFI) Using Data from TRB Locked-Wheel Testing

F_N Value	F_T Value	F_{Hs} Value	Difference	Division BY F_N	SFI
800 lb	350 lbf.	150 lbf.	200 lbf.	200 lb./800 lb.	0.25
1000 lb.	400 lbf.	150 lbf.	250 lbf.	250 lb./1000 lb.	0.25
1200 lb.	450 lbf.	150 lbf.	300 lbf.	300 lb./1200 lb.	0.25

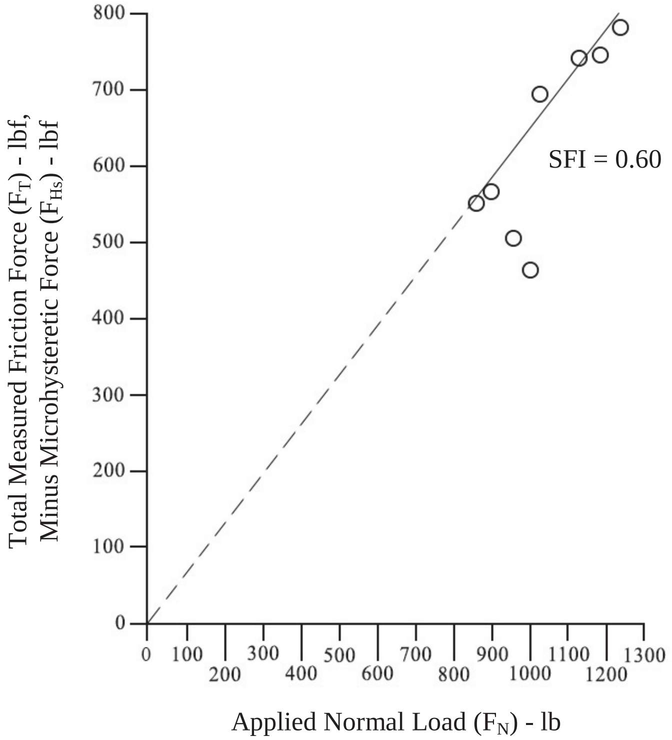


Figure 18. Dry Belcher Road Test Results Showing the Sliding Friction Index (SFI) Value

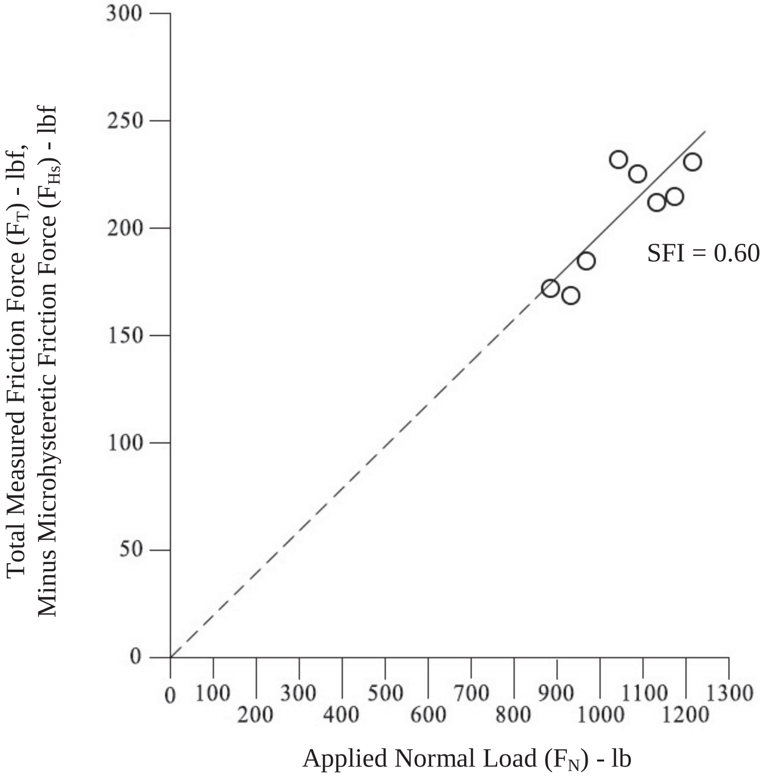


Figure 19. Wet Belcher Road Test Results Showing the Sliding Friction Index (SFI) Value

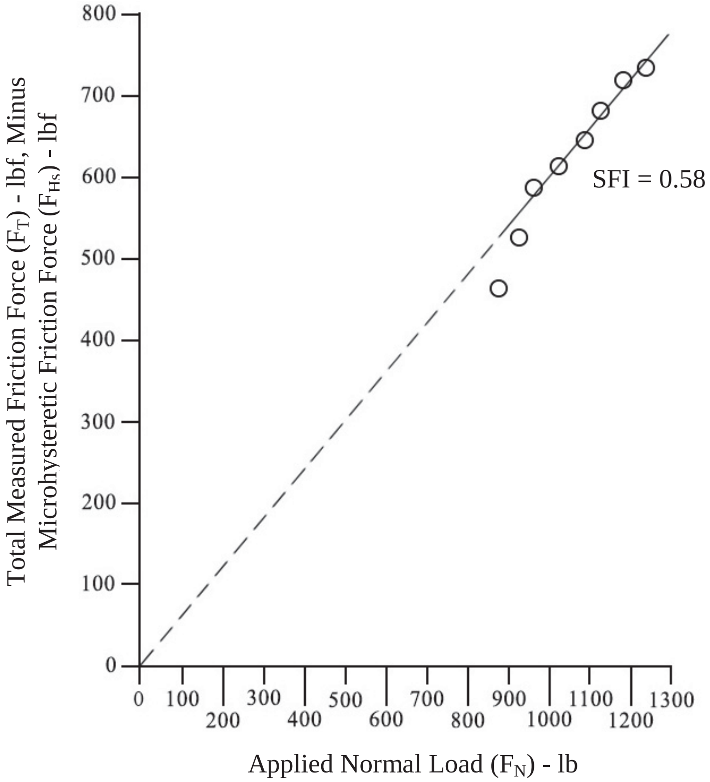


Figure 20. Dry Tyrone Boulevard Test Results Showing the Sliding Friction Index (SFI) Value

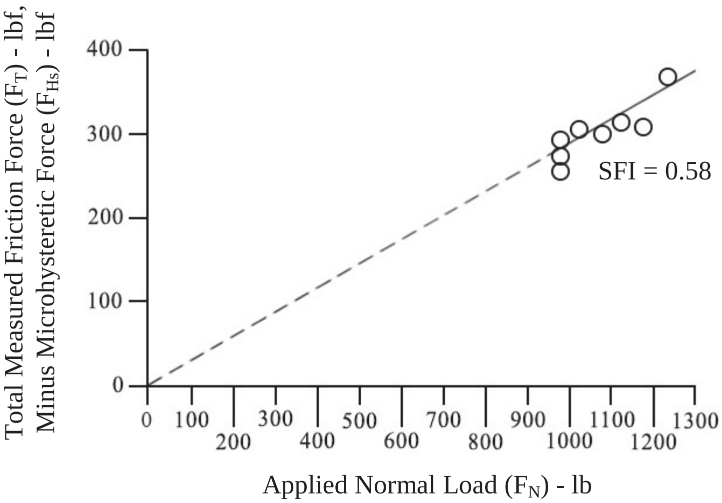


Figure 21. Wet Tyrone Boulevard Test Results Showing the Sliding Friction Index (SFI) Value

8. CONCLUSIONS

8.1 Role of Pavement Microtexture in Sliding Resistance

The importance of pavement microtexture was discussed in Section 7.2. It had been realized in 1974[16] from tests on in-service roadways that pavement microroughness plays a significant role in tire traction in wet conditions. These roads included those that were highly polished by summer driving and others that had experienced microroughness enhancement from winter frost. Photomicrographic studies revealed that the usefulness of pavement microtexture in wet conditions is minimal unless it exceeds about 1.95×10^{-4} in. in depth. These findings correlated well with the frequency of traffic incidents, fewer in winter and a greater number in summer.

It was subsequently discovered that[17] an adequate depth of pavement microtexture plays a role in contributing to a tire's roadholding ability in wet conditions. The most desirable microtexture roughness is one that assists the tire in removing any surface water film present so as to create real areas of contact with the tread.

Figures 13 and 17 present wet test results obtained by routine use of a locked-wheel tester allowing quantification of the microhysteretic rubber friction force, F_{Hs}, as a metric for assessment of pavement microroughness and its component contribution to the total potentially available F_T force, along with the tire loading component.

The F_{Hs} measurements of unpolished Belcher Road (220 lbf) and polished Tyrone Boulevard (60 lbf) may be used as an example in this regard. The identical F_N loadings contributed a mean of 52 percent of the total Belcher Road F_T value, while the F_{Hs} component in the Tyrone Boulevard testing contributed a mean of 17 percent of total F_T. Diamond grinding of concrete pavement is known to increase surface macrotexture. Locked-wheel ASTM testing to measure F_{Hs} would be required to determine if surface microtexture is also enhanced. Testing of asphalt pavement after milling would similarly need such testing for the same purpose.

In short:

- Routine locked-wheel testing can be used to quantify the F_{Hs} value of a roadway segment.
- F_{Hs} values can be used as a metric for assessing pavement microroughness.
- Locked-wheel testing of diamond ground concrete pavement would be needed to determine if F_{Hs} increased.
- Locked-wheel testing of asphalt pavement after milling would be required for the same purpose.

8.2 The Sliding Friction Index in Practical Application of Locked-Wheel Test Data

The importance of the sliding friction index (SFI) was discussed in section 7.5. Measuring values of the F_{Hs} force can be readily accomplished through routine use of ASTM locked-wheel testing. Subtracting these values from the total measured friction force (F_T) quantifies the sliding resistance produced by application of the tire loads, F_N. This technique permits determination of the dimensionless SFI, which accurately quantifies this second, distinct loading component of F_T.

8.3 The two-pronged approach needed to utilize the total sliding resistance force measured in standard ASTM locked-wheel testing

Because the SFI value is tire-load-dependent, and the F_{Hs} force is tire-load-independent, a two-pronged approach is needed for application of these two distinct sliding friction forces measured in standard ASTM locked-wheel testing. This may be readily accomplished by use of a simple force-combining equation:

$F_F = F_{Hs} + SFI \times F_N$, where,

F_F = total frictional sliding resistance force measured by standard ASTM locked-wheel testing obtained through use of the loading-based approach to quantify F_{Hs} by extrapolation of the straight-line data plot to the Y-axis, expressed as lbf,

F_{Hs} = value of the microhysteretic force measured by standard ASTM locked-wheel testing, expressed in lbf,

SFI x F_N = the calculated SFI value obtained from the results of standard ASTM locked-wheel testing multiplied by the applied tire load of interest, expressed as lbf.

Table I exemplifies application of the force-combining equation to the wet and dry asphalt and concrete test data at the F_N value of 1242 lb. It may be noted that the value of the wet Belcher Road F_{Hs} force was significantly larger (220 lbf) than the value of the dry Belcher Road F_{Hs} force (140 lbf). It may be recalled that generation of smoke was observed during the dry asphalt testing. The diminished F_{Hs} value appears consistent with this production of smoke. Perhaps the heat associated with the smoke also reduced the rigidity of the asphalt microtexture, and/or led to diminished depth during the locked-wheel procedure.

TABLE I

Calculating Values for the Force-Combining Equation

$$F_F = F_{Hs} + SFI \text{ x } F_N$$

Dry Belcher Road F_F = 140 lbf + (0.60 x 1242 lb) = 745 lbf + 140 lbf = 885 lbf
Wet Belcher Road F_F = 220 lbf + (0.60 x 1242 lb) = 745 lbf + 220 lbf = 965 lbf
Dry Tyrone Boulevard F_F = 200 lbf + (0.58 x 1242) = 720 lbf + 200 lbf = 920 lbf
Wet Tyrone Boulevard F_F = 60 lbf + (0.58 x 1242) = 720 lbf + 60 lbf = 780 lbf

8.4 Use of the Force-Combining Equation to Predict Skid Resistance and Braking Distance

Development of a testing data base comprising typical asphalt and concrete F_{Hs} and SFI values obtained by standard ASTM locked-wheel testing, and analyzed by use of the force-combining equation in combination with stopping-distance testing, will be needed to allow reliable prediction of skid resistance and braking distance.

In short:

- Routine use of locked-wheel testing can measure the F_{Hs} values in pavement sections of interest.

- These F_{Hs} values can be used to determine the rational, dimensionless SFI quantifying the sliding resistance attributable to tire loading.

- Use of the loading-based approach for analysis of ASTM locked-wheel testing data permits measurement of the F_{Hs} force attributable to pavement microroughness, pavement surface free energy, and surface free energy of the sliding tire tread.

8.5 Implementation Statement

Considering the evidence developed from the analysis of testing results involving data from both wet and dry asphalt and concrete pavements, together with the supporting matter discussed above, it is recommended that use of the skid number and coefficient of friction be reconsidered.

9. NEEDED RESEARCH

As shown in Figure 2 by the straight-line plot, when the F_{Hs} force is subtracted from F_T, the associated CoF values are directly proportional to applied load in the commonly used locked-wheel F_N range. As shown by the straight-line plots in Figures 18, 19, 20, and 21 – when the outlier points are ignored – the sliding friction index values are also directly proportional to applied load. Further research is needed in order to understand the underlying mechanism giving rise to this directly proportional characteristic. Such knowledge may prove valuable in practical application of the sliding friction index.

Archard[20, 21] has scientifically investigated the direct proportionality issue using macroscopically smooth materials sliding on macroscopically smooth surfaces. When using this approach only F_A friction forces are generated. Archard investigated pairings of smooth brass and pairings of smooth, non-elastomeric plastic, poly (methyl-methacrylate), or PMMA, all in the elastic loading range. He found that, as F_N increases, new real areas of contact between the paired surfaces can be established. He theorized that that the additional friction forces generated would be directly proportional to the increased load if the primary result of such loading is to create new real areas of contact. Persson recently reexamined[22] Archard's theory and concurred with it.

ACKNOWLEDGEMENT AND DISCLAIMER

The study was a part of a USDOT funded National Center for Intermodal Transportation for Economic Competitiveness (NCITEC) project on global supply chain management. The contents of this paper reflect the views of the author who is responsible for the facts, findings, and data presented herein. The contents do not represent the views of the agencies cited in this document. The author received remuneration for his consulting involvement.

REFERENCES

[1] Kummer, H.W., *Unified Theory of Rubber and Tire Friction*, Engineering Research Bulletin B-94, The Pennsylvania State University, 1966.

[2] Haney, P., *The Racing & High Performance Tire*, SAE International, 2003.

[3] Smith, Robert H. *Analyzing Friction in the Design of Rubber Products and their Paired Surfaces*, CRC Press, Boca Raton, Florida, U.S.A., 2008.

[4] Smith, Robert H. and Timothy W. Neubert. Calculating Tire/Pavement Friction Forces. IJP-International Journal of Pavements, Vol. 10, No. 1-2-3, January-May-September 2011, pp. 1-12.

[5] Meyer, W.E., Hegmon, R.R., and Gillespie, T.D., *Locked-Wheel Pavement Skid Tester Correlation and Calibration Techniques, Report 151*, Transportation Research Board, National Cooperative Highway Research Program, National Research Council, Washington, D.C., 1974.

[6] Persson, B.J.N. On the theory of rubber friction. Surface Science, No. 401, 1998, pp. 445-454.

[7] Pfalzner, P.M., On the friction of various synthetic and natural rubbers on ice, Canadian Journal of Research, Vol. 28, Section, F., 1949, pp. 468-487.

[8] Mori, K., Kaneda, S., Kanae, K., Hirahara, H., Oishi., Y., and Iwabuchi, A. Influence on friction force of adhesion force between vulcanizates and sliders. Rubber Chemistry and Technology, Vol. 67, No.5, 1994, pp. 797-805.

[9] ASTM International, *ASTM E1551-08, Standard Specifications for Special Purpose, Smooth-Tread Tire, Operated on Fixed Braking Slip Continuous Friction Measuring Equipment*.

[10] Yager, T.J., Stubbs, S.M., and Davis, P.M., Aircraft radial-belted tire evaluation, Paper 901931, in *Emerging Technologies in Aircraft Landing Gear*, Tanner, J.A., Ulrich, P.C., Medzorian, J.P., and Morris, D.L., Eds., SAE International, Warrendale, PA, 1997, pp. 243-250.

[11] Leland, T.J.W., Yager, T.J., and Joyner, U.T., Effects of pavement texture on wet-runway braking performance, NASA publication TN D4323, January 1968.

[12] ASTM International, *ASTM E501–08, Standard Specifications for Standard Rib Tire for Pavement Skid-Resistance Tests*.

[13] ASTM International, *ASTM E274/E274M –11, Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire*.

[14] *USA Today*, Interview with aircraft Captain Cox, April 8, 2013.

[15] Minnesota's Astro-Turf Drag Technique Texturing Concrete Pavements, in, *Minnesota Department of Transportation Concrete Research and Development in Smooth, Quiet, Safe and Durable Pavements*, 2005, p.1.

[16] Bond, R., Lees, G., and Williams, A.R., An approach towards the understanding of the tyre, in *The Physics of Tire Traction-Theory and Experiment*, Hays, D.F. and Browne, A.L. Eds., Plenum Press, 1974, Chapter IV.

[17] Williams, A.R., A review of tire traction, in *Vehicle, Tire, Pavement Interface*, Henry, J.J. and Wambold, J.C., Eds., ASTM, 1992, p. 132.

[18] American Association of State Highway and Transportation Officials, *A Policy on Geometric Design of Highways and Streets*, 6th Edition, 2011.

[19] Randall, N., Anderson, R.N., and Smith, R.H., paper 60, A unified theory of rubber friction; presented at the fall 178th Technical Meeting of the Rubber Division, American Chemical Society, Inc., Milwaukee, WI, October 12-14, 2010.

[20] Archard, J.F., Elastic deformation and the contact of solids, in *Nature*, 172, 918, 1953.

[21] Archard, J.F., Elastic deformation and the laws of friction, in *Proceedings of the Royal Society, A*, 243, 190, 1957.

[22] Persson, B.N.J., *Sliding Friction, Physical Principals and Applications*, Springer, Berlin, 2000, p.51.

APPENDIX

Contact information for the International Cybernetics Corporation:

International Cybernetics Corporation
10630 75th Street, North
Largo, Florida, 33777, United States; 727-547-0696 (Phone); 727-546-8633 (Fax)
Web Site: http://www.intlcybernetics.com/
e-mail: marketing@internationalcybernetics.com

Contact information for the Transportation Research Laboratory:

Transportation Research Laboratory, Crowthorne House, Nine Mile Ride, Wokingham, Berkshire, RG40 3GA, United Kingdom; Tel: +44 (0)1344 773131; Fax: +44 (0)1344 770356; Email: enquiries@trl.co.uk

INTEGRATED INTERMODAL TRANSPORTATION CORRIDORS FOR ECONOMICALLY VIABLE AND SAFE GLOBAL SUPPLY CHAIN

MEXICO - NAFTA CORRIDOR TRANSPORTATION INFRASTRUCTURE AND FREIGHT/PASSENGER DATA RESEARCH

FINAL REPORT

FOR:

UNIVERSITY OF MISSISSIPPI

DOCUMENT PREPARED BY:

DR. VÍCTOR TORRES-VERDÍN

TORRES, CONSULTORES EN INGENIERÍA, S.A. DE C.V.

December 2014.

Calculistas Núm. 19.
Col. Sifón
09400 México, D.F.
Mexico

Tel.: +52 55 5634-0049
Fax: +55 55 5633-1062
vtorres@torrestci.com

ABSTRACT

As part of the study entitled “Integrated Intermodal Transportation Corridors For Economically Viable And Safe Global Supply Chain”, it was required to analyze the impacts of the North American Free Trade Agreement (NAFTA) on Mexico’s transportation Infrastructure, and freight/passenger demand. NAFTA came into force in January 1994, and it has generated some benefits to Mexico’s economy, which has resulted in growing exports between the US, Canada and Mexico.

In this report, a summary of freight, and passenger data along the US-Mexico border is provided, along with several GIS files. Several aspects of Mexico’s international trade are also covered.

TABLE OF CONTENTS

INTEGRATED INTERMODAL TRANSPORTATION CORRIDORS FOR ECONOMICALLY VIABLE AND SAFE GLOBAL SUPPLY CHAIN

MEXICO - NAFTA CORRIDOR TRANSPORTATION INFRASTRUCTURE AND FREIGHT/PASSENGER DATA RESEARCH

FINAL REPORT

1. INTRODUCTION

1.1. Study Background

We live in the time of the “global economy”. The global supply chain can be seriously disrupted by natural disasters, as it has been evidenced in recent years. This, in turn, can significantly hurt local economies, which depend to a large extent on surface transportation modes for distribution of most products. A transport infrastructure funding crisis has been detected on all levels.

The overall objective of this study is to identify major transportation corridors involving shipping ports (marine and inland river system), highway network and rail infrastructure and to evaluate the economic viability, safety, disaster resiliency, and revenue/funding aspects of integrating selected segments of the candidate corridors. The intermodal freight corridor case studies have been used to develop a “best practice guide” and intermodal infrastructure bank proposal for consideration by government transportation agencies, private transport operators, and all other stakeholders. The economic competitiveness, safety, security and disaster resilience of freight transport can be significantly enhanced if owners, operators, and users of all transportation modes understand the importance of operational integration of these modes. Similarly, integration of passenger services can reduce wastage of millions of hours of travel time of single occupancy vehicle commuters that will result in cost avoidance of billions of gallons of fuel wastage on congested highway corridors and reduce transportation related emissions of carbon dioxide and other harmful pollutants

1.2. Objectives and Scope

(1) Review and synthesize NAFTA corridor related freight and passenger traffic data for Mexico-US border for the past 3-5 years or whatever available. Data shall be prepared in Excel files with all references and date accessed inside the Excel file and separate sheets for the in-bound (to Mexico) and outbound (from Mexico). Provide high resolution raster imageries (jpg digital files or .shp shapefile) of road and rail corridors in Mexico connecting with NAFTA corridors along the Mexico-U.S. border.

(2) Assist in life cycle assessment of benefits & costs of proposed intermodal integration scenarios (such as highways and rails). This activity shall provide the latest city/region population data, annual average daily traffic volume and traffic mix data, and a raster imagery showing locations of the major cities along the freight/passenger corridors in Mexico connecting to NAFTA corridors along the Mexico-U.S. border. Use the overall project title: Integrated Intermodal Transportation Corridors for Economically Viable and Safe Global Supply Chain. Subtitle shall be: Mexico-NAFTA Corridor Transportation Infrastructure and Freight/Passenger Data Research.

(3) Prepare and submit a draft report in electronic Word file. The draft report shall include full documentation of all activities completed, including the literature review, summary tables and representative plots of both passenger and freight data along each major corridor, summary of passenger/freight transport infrastructure assets, raster imageries showing major road and rail corridors in Mexico, and conclusions. Finalize the report and submit electronic Word files by the agreement termination date.

1.3. Data Provided to CAIT

During the first weeks the Consultant participated in the Study, the following GIS maps and tables were submitted to CAIT:

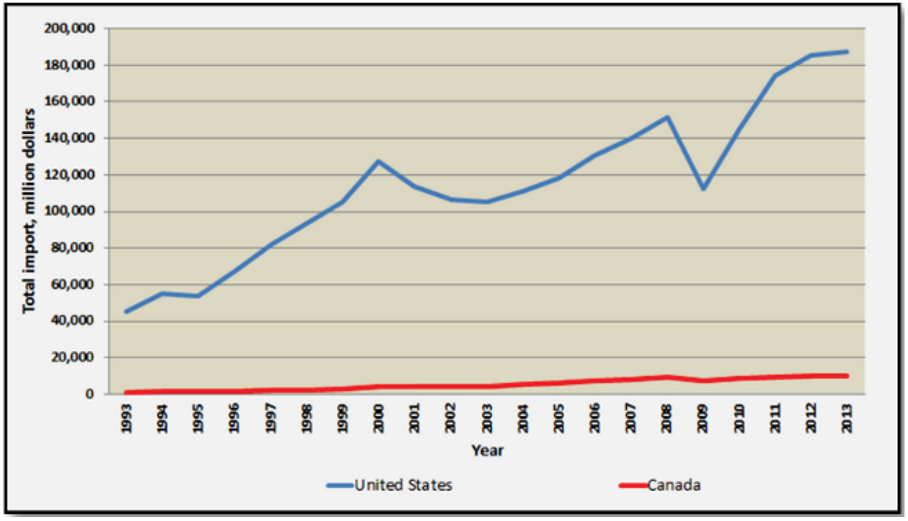
1. Location of cities with more than 50,000 inhabitants (map, and table).
2. Main highways of Mexico (map), indicating “free” and toll highways.
3. International ports of entry along the Mexico - U.S. border (map, and table).
4. Population of main Mexican cities (map).
5. Main maritime ports of Mexico (map, and table).
6. Railway network of Mexico, coverage and current operating condition (maps).
7. Mexican airports.
8. Boundaries of Mexican states (map).
9. AADT, all vehicle types, at international ports of entry (map).
10. AADT, buses, at international ports of entry (map).
11. AADT, cars, at international ports of entry (map).
12. AADT, trucks, at international ports of entry (map).

Copies of these deliverables are presented in this report’s Appendix.

2. MEXICO’S NAFTA TRADE AND FREIGHT TRANSPORT

Mexico’s imports from the US have increased significantly since NAFTA was implemented, as shown in Figure 1. Imports from Canada have also augmented but they stay at a relatively low level, as compared to imports from the US.

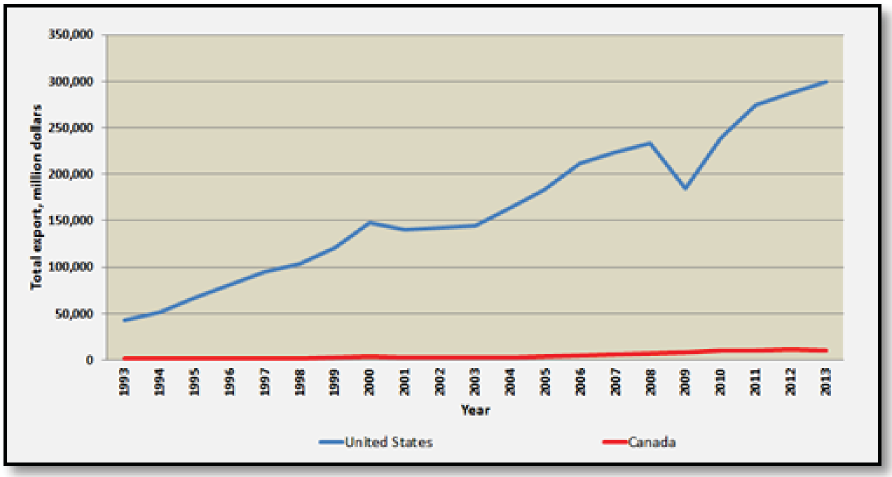
Figure 1. Historical trend of Mexican imports from the U.S., and Canada.



Source: Ref. 1

Exports from Mexico have also increased steadily, as observed in Figure 2.

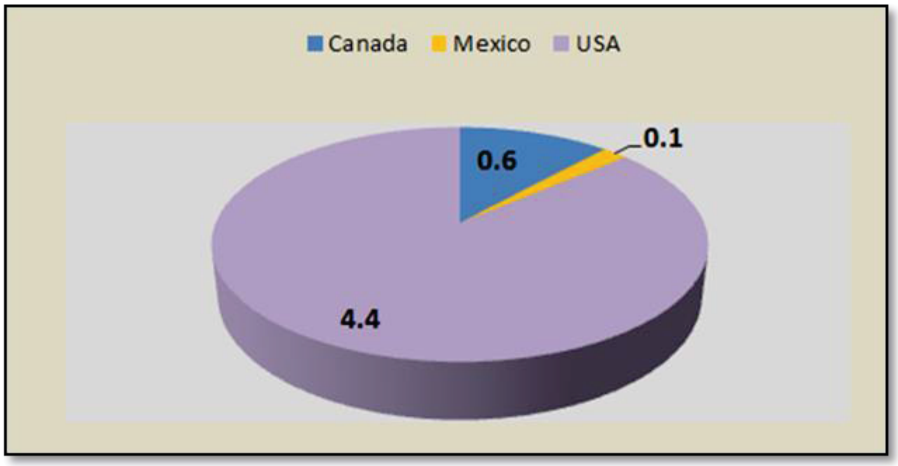
Figure 2. Historical trend of Mexican exports to the U.S., and Canada.



Source: Ref. 1

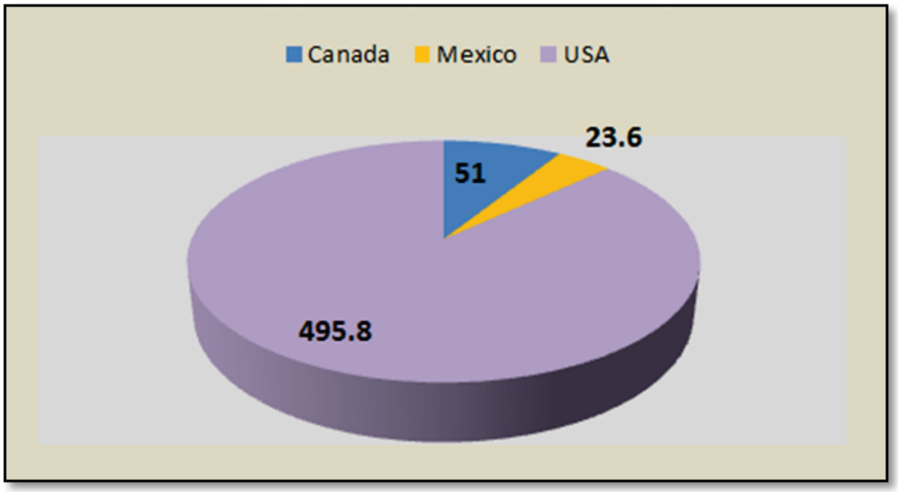
As far as domestic freight activities in the three countries, for year 2011, Figs. 3 to 6 show in ton-kilometers commodities transported in different modes. Despite Mexico's population being much larger than that of Canada, the latter shows higher activity than Mexico in some transportation modes.

Figure 3. Air transport domestic freight activity in Mexico, the U.S., and Canada.



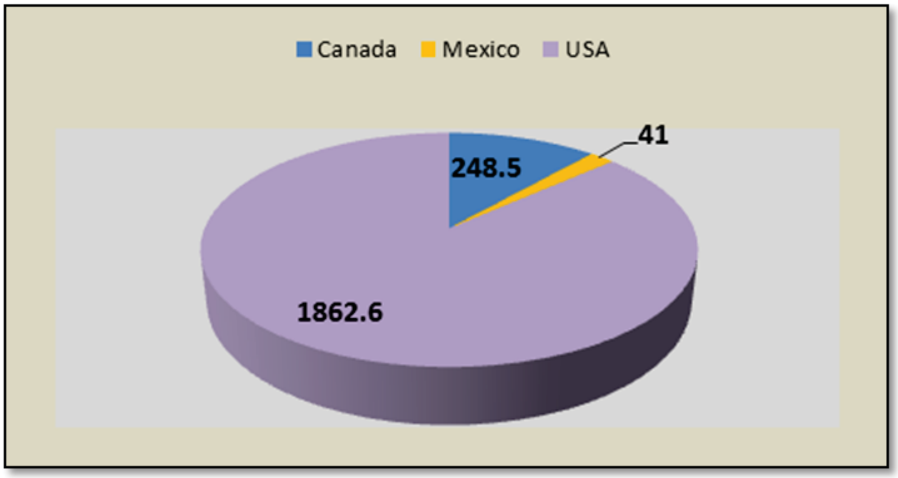
Source: Ref. 2
Note: figures in billions U.S. dollars.

Figure 4. Water transport domestic freight activity in Mexico, the U.S., and Canada.



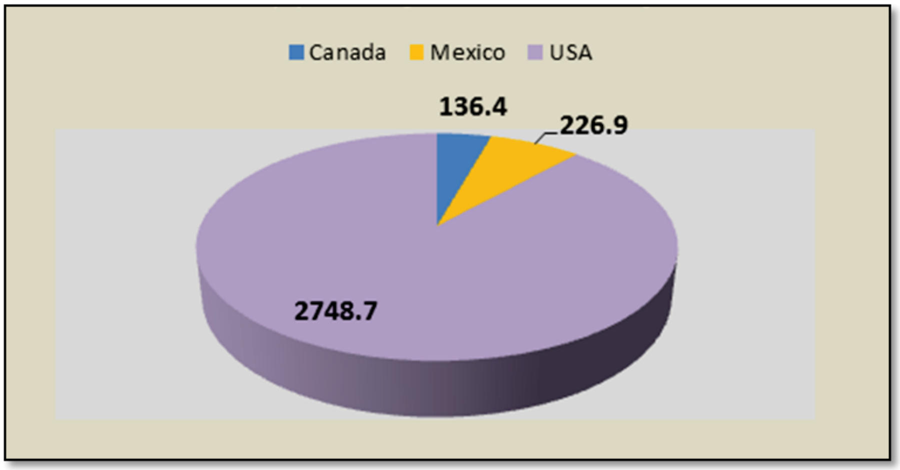
Source: Ref. 2
Note: figures in billions U.S. dollars.

Figure 5. Rail transport domestic freight activity in Mexico, the U.S., and Canada.



Source: Ref. 2
Note: figures in billions U.S. dollars.

Figure 6. Road transport domestic freight activity in Mexico, the U.S., and Canada.



Source: Ref. 2
Note: figures in billions U.S. dollars.

In Fig. 7 main federal highways of Mexico are shown. These roads are used to transport exports to the U.S., and Canada. Some of these primary road links are toll divided highways. Mexico has concessioned to private companies many kilometers of toll roads since the early 1990's.

Figure 7. Main highway corridors in Mexico used for truck freight.

Source: Ref. 3

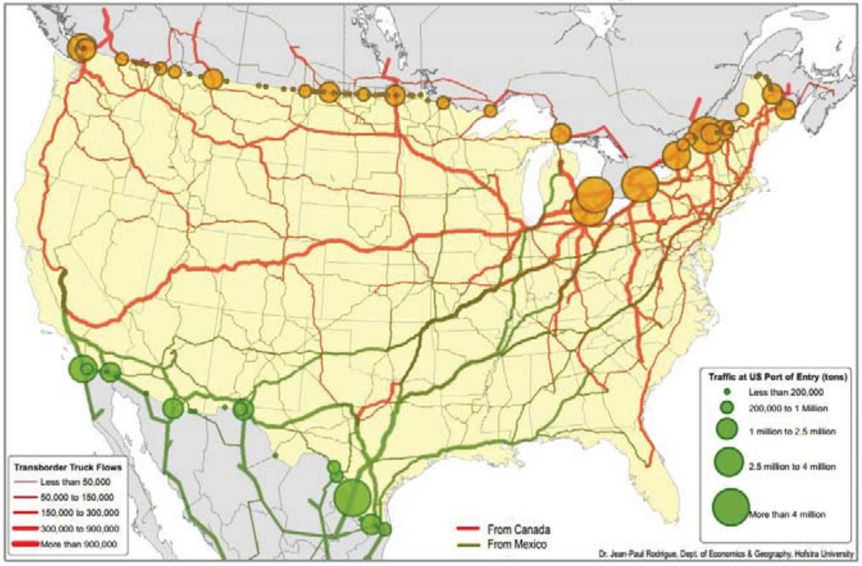
Fig. 8 illustrates freight volumes at major international ports of entry along the U.S. borders with Mexico and Canada. It also shows freight at the most important U.S. maritime ports. Laredo, Ciudad Juárez, and Tijuana are the most important Mexican international ports on the U.S. border.

Figure 8. Main U.S. transportation network for truck, and maritime freight, and connecting primary highways of northern Mexico, and southern Canada.

Source: Ref. 4

Fig. 9 shows traffic at U.S. ports of entry freight on both international borders, as well as the most important highway corridors used by trucks transporting imported and exported goods.

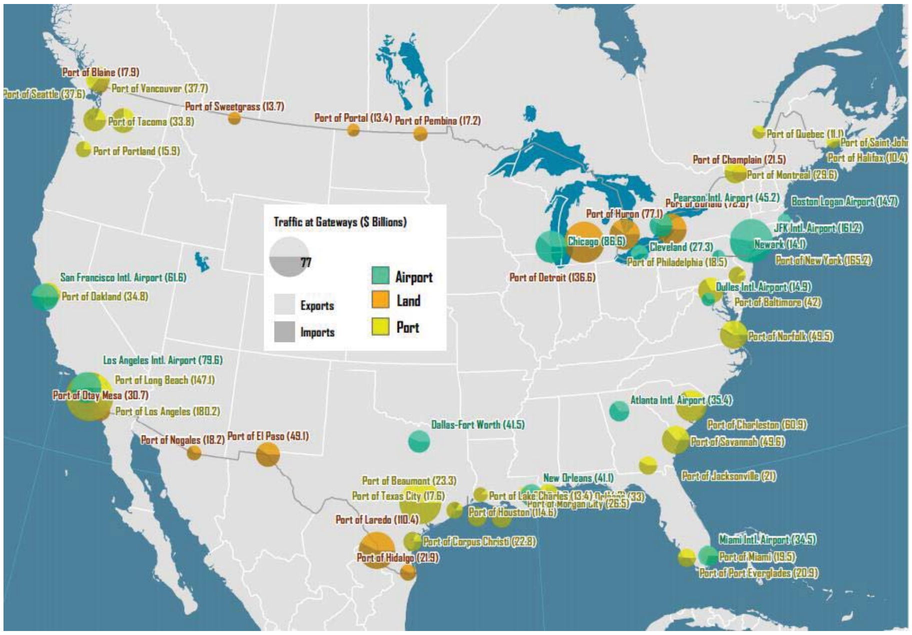
Figure 9. NAFTA transborder truck flows and traffic at U.S. ports of entry, 2002.



Source: Ref. 4

As far as the mode distribution of traffic at U.S. Gateways, Fig. 10 shows airport, land, and port movements.

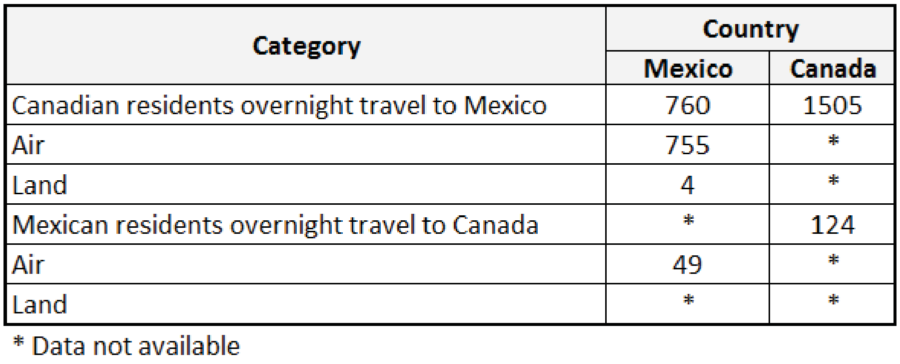
Figure 10. Traffic at U.S. Gateways by Transportation Mode.



Source: Ref. 4

Tables 1-3 summarize passenger flows by air and land between the U.S., Canada, and Mexico.

Table 1. International passenger flows between Canada and Mexico, 2011.

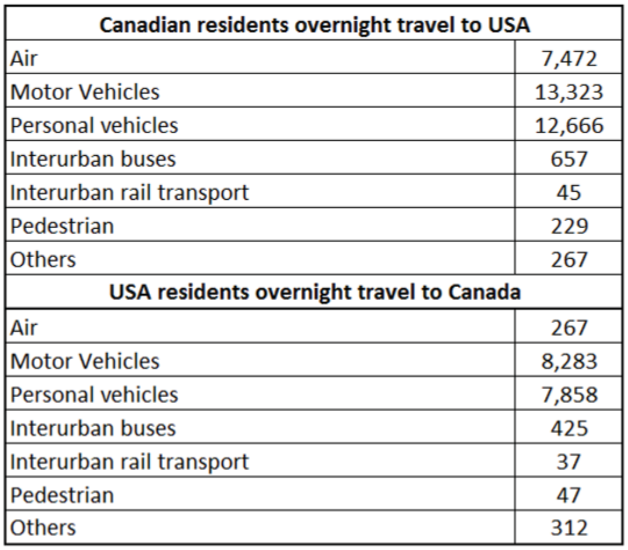


Category	Country	
	Mexico	Canada
Canadian residents overnight travel to Mexico	760	1505
Air	755	*
Land	4	*
Mexican residents overnight travel to Canada	*	124
Air	49	*
Land	*	*

* Data not available

Source: Ref. 5

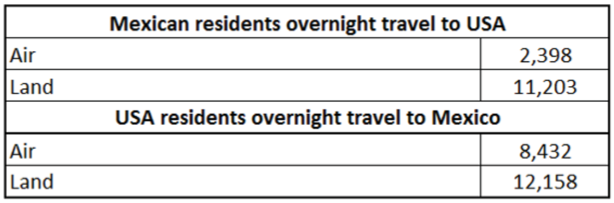
Table 2. International passenger flows between Canada and the U.S.



Canadian residents overnight travel to USA	
Air	7,472
Motor Vehicles	13,323
Personal vehicles	12,666
Interurban buses	657
Interurban rail transport	45
Pedestrian	229
Others	267
USA residents overnight travel to Canada	
Air	267
Motor Vehicles	8,283
Personal vehicles	7,858
Interurban buses	425
Interurban rail transport	37
Pedestrian	47
Others	312

Source: Ref. 5

Table 3. International passenger flows between Mexico and the U.S.



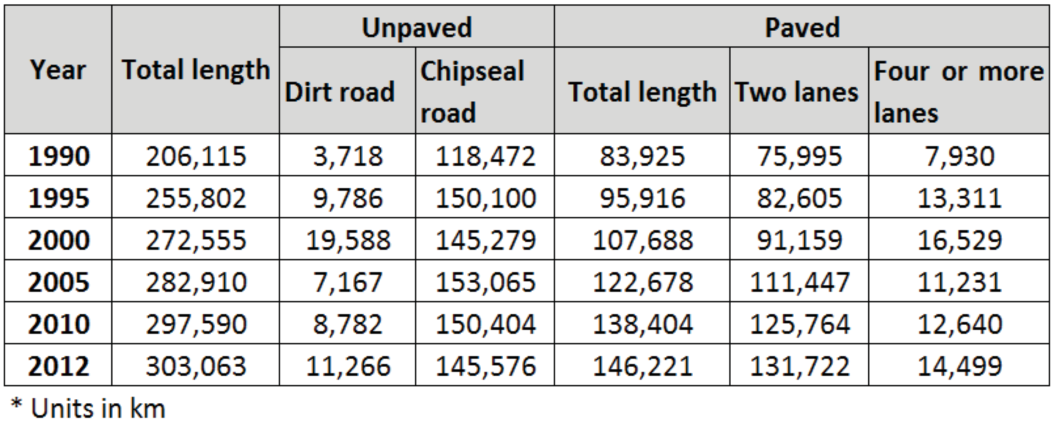
Mexican residents overnight travel to USA	
Air	2,398
Land	11,203
USA residents overnight travel to Mexico	
Air	8,432
Land	12,158

Source: Ref. 5

3. IMPACTS OF NAFTA ON MEXICO'S TRANSPORT INFRASTRUCTURE

Mexico's road network has been growing continuously since 1990, as shown in Table 4.

Table 4. Expansion of Mexico's road network in recent years.



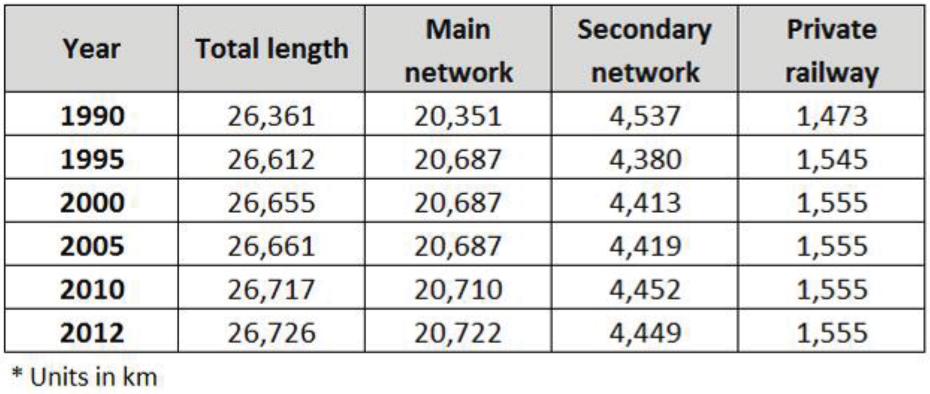
Year	Total length	Unpaved		Paved		
		Dirt road	Chipseal road	Total length	Two lanes	Four or more lanes
1990	206,115	3,718	118,472	83,925	75,995	7,930
1995	255,802	9,786	150,100	95,916	82,605	13,311
2000	272,555	19,588	145,279	107,688	91,159	16,529
2005	282,910	7,167	153,065	122,678	111,447	11,231
2010	297,590	8,782	150,404	138,404	125,764	12,640
2012	303,063	11,266	145,576	146,221	131,722	14,499

* Units in km

Source: Ref. 3

Mexico's rail network has not grown much in the last years, despite the fact that Government-owned infrastructure was concessioned to the private sector in recent years. Table 5 summarizes rail network length divided into several categories.

Table 5. Expansion of Mexico's rail network in recent years.



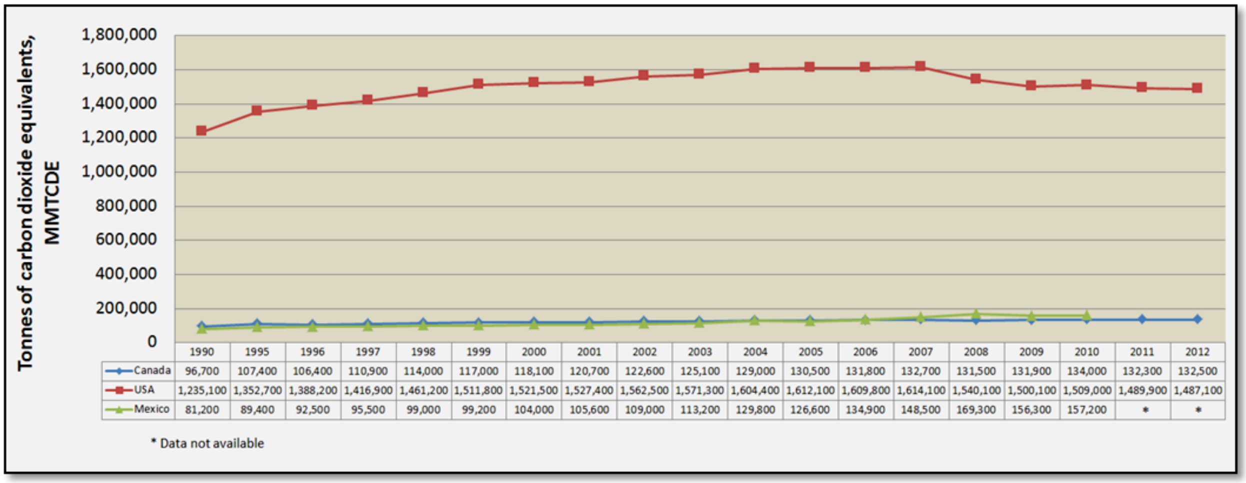
Year	Total length	Main network	Secondary network	Private railway
1990	26,361	20,351	4,537	1,473
1995	26,612	20,687	4,380	1,545
2000	26,655	20,687	4,413	1,555
2005	26,661	20,687	4,419	1,555
2010	26,717	20,710	4,452	1,555
2012	26,726	20,722	4,449	1,555

* Units in km

Source: Ref. 3

Gas emissions attributable to road and rail transport have remained within a certain range in North America, as depicted in Figs. 11-12.

Figure 11. Greenhouse gas emissions generated by road transport in North America.

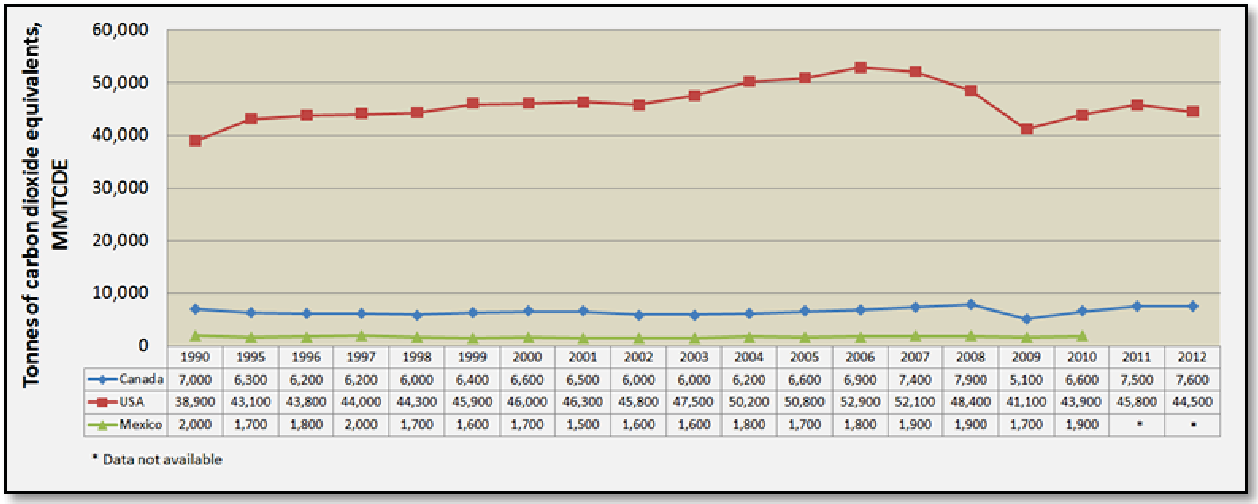


	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Canada	96,700	107,400	106,400	110,900	114,000	117,000	118,100	120,700	122,600	125,100	129,000	130,500	131,800	132,700	131,500	131,900	134,000	132,300	132,500
USA	1,235,100	1,352,700	1,388,200	1,416,900	1,461,200	1,511,800	1,521,500	1,527,400	1,562,500	1,571,300	1,604,400	1,612,100	1,609,800	1,614,100	1,540,100	1,500,100	1,509,000	1,489,900	1,487,100
Mexico	81,200	89,400	92,500	95,500	99,000	99,200	104,000	105,600	109,000	113,200	129,800	126,600	134,900	148,500	169,300	156,300	157,200	*	*

* Data not available

Source: Ref. 2
Note: MMTCDE: million metric tons of carbon dioxide equivalents.

Figure 12. Greenhouse gas emissions generated by road transport in North America.



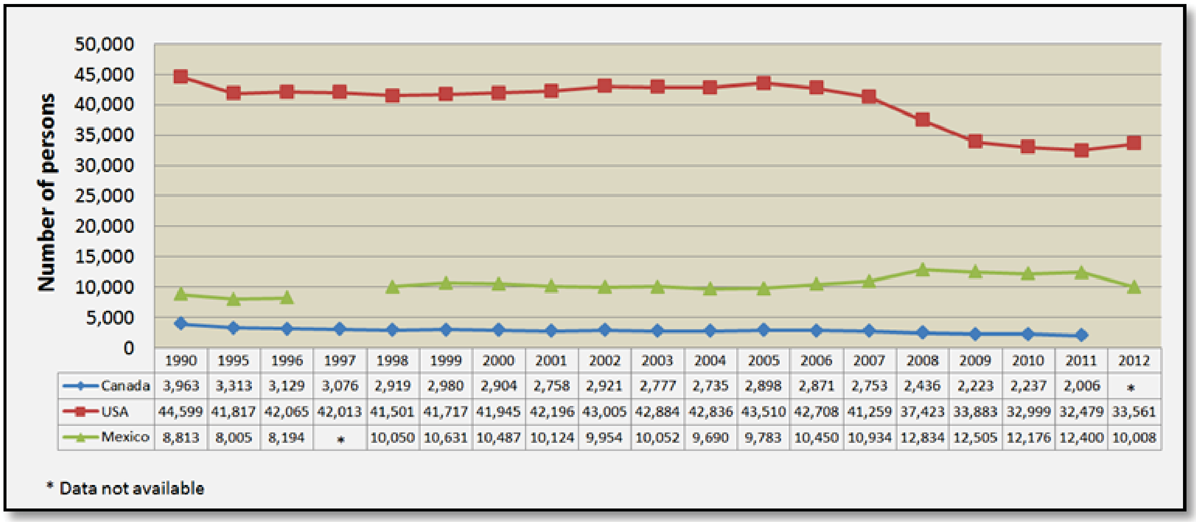
	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Canada	7,000	6,300	6,200	6,200	6,000	6,400	6,600	6,500	6,000	6,000	6,200	6,600	6,900	7,400	7,900	5,100	6,600	7,500	7,600
USA	38,900	43,100	43,800	44,000	44,300	45,900	46,000	46,300	45,800	47,500	50,200	50,800	52,900	52,100	48,400	41,100	43,900	45,800	44,500
Mexico	2,000	1,700	1,800	2,000	1,700	1,600	1,700	1,500	1,600	1,600	1,800	1,700	1,800	1,900	1,900	1,700	1,900	*	*

* Data not available

Source: Ref. 2
Note: MMTCDE: million metric tons of carbon dioxide equivalents.

Fatalities caused by road transport exhibit a decreasing trend in the U.S., and Canada, as shown in Fig. 13.

Figure 13. Fatalities caused by road transport in North America.



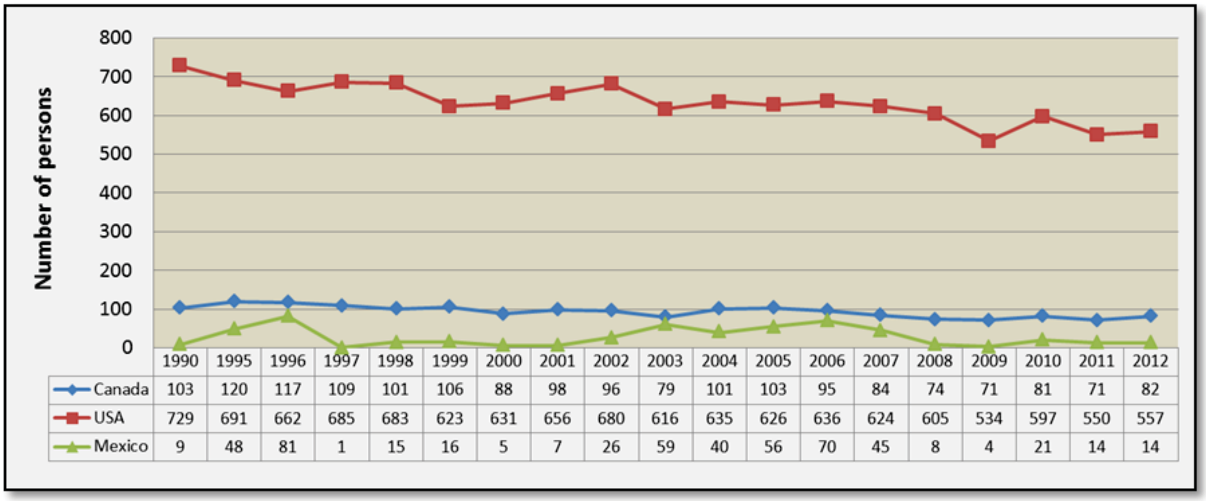
	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Canada	3,963	3,313	3,129	3,076	2,919	2,980	2,904	2,758	2,921	2,777	2,735	2,898	2,871	2,753	2,436	2,223	2,237	2,006	*
USA	44,599	41,817	42,065	42,013	41,501	41,717	41,945	42,196	43,005	42,884	42,836	43,510	42,708	41,259	37,423	33,883	32,999	32,479	33,561
Mexico	8,813	8,005	8,194	*	10,050	10,631	10,487	10,124	9,954	10,052	9,690	9,783	10,450	10,934	12,834	12,505	12,176	12,400	10,008

* Data not available

Source: Ref. 2

Rail transport fatalities also show a decreasing pattern in the U.S., and Canada, according to Fig. 14. In Mexico, this type of fatalities has been reduced significantly in the last five years (2008-2012).

Figure 14. Fatalities caused by rail transport in North America.



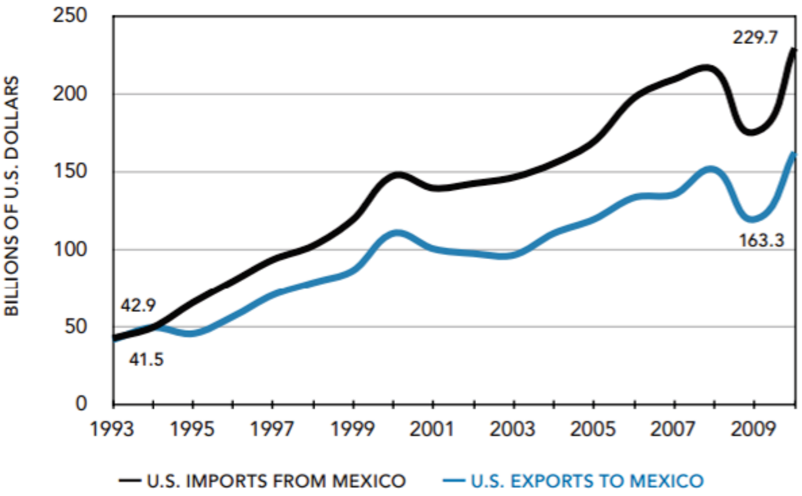
	1990	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Canada	103	120	117	109	101	106	88	98	96	79	101	103	95	84	74	71	81	71	82
USA	729	691	662	685	683	623	631	656	680	616	635	626	636	624	605	534	597	550	557
Mexico	9	48	81	1	15	16	5	7	26	59	40	56	70	45	8	4	21	14	14

Source: Ref. 2

4. IMPACTS OF NAFTA ON MEXICO’S ECONOMY

NAFTA has had a major positive impact on Mexico´s economy. Excluding years with economic depression, trade with the U.S. has been on the rise since NAFTA was implemented, as shown in Fig. 15.

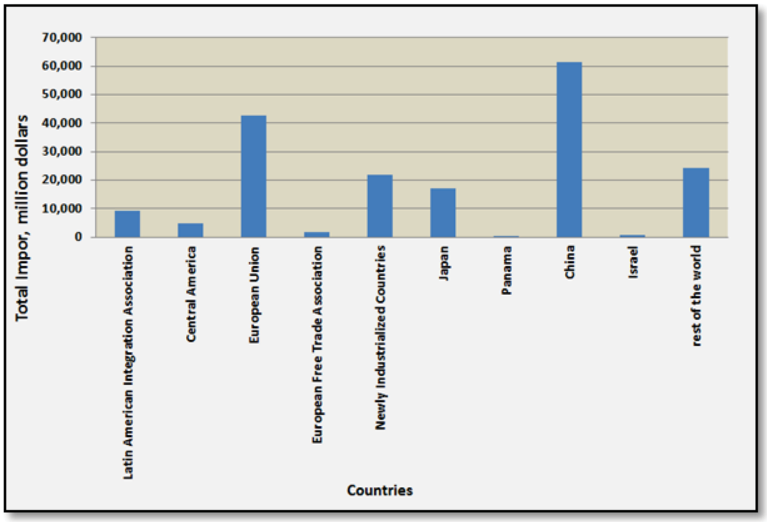
Figure 15. U.S. imports from and exports to Mexico.



Source: Ref. 4

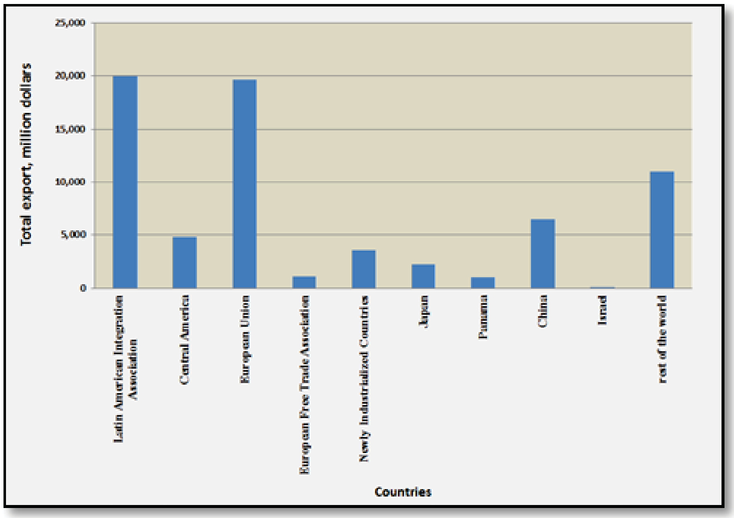
If trade with NAFTA partners is excluded, Mexican imports from China are the most significant, as it can be observed in Fig. 16. As far as exports outside the NAFTA area, Fig. 17 shows that Latin American countries are the most important partner.

Figure 16. Mexican imports from different nations, excluding NAFTA partners, 2013.



Source: Ref. 2

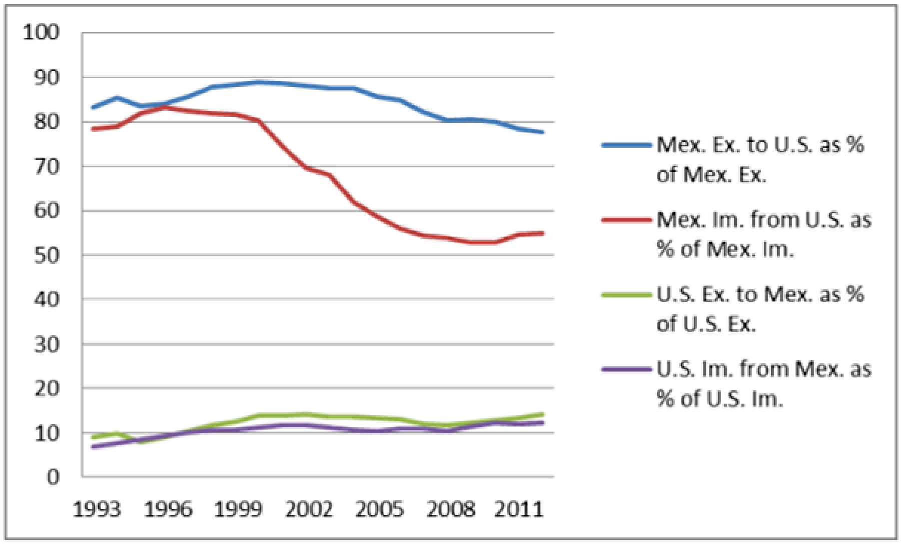
Figure 17. Mexican exports to different nations, excluding NAFTA partners, 2013.



Source: Ref. 2

Undoubtedly, the U.S. is the most important trading partner for Mexico, as clearly depicted in Fig. 18:

Figure 18. Market share as percentage of total trade: Mexico and the U.S. (1993-2012).

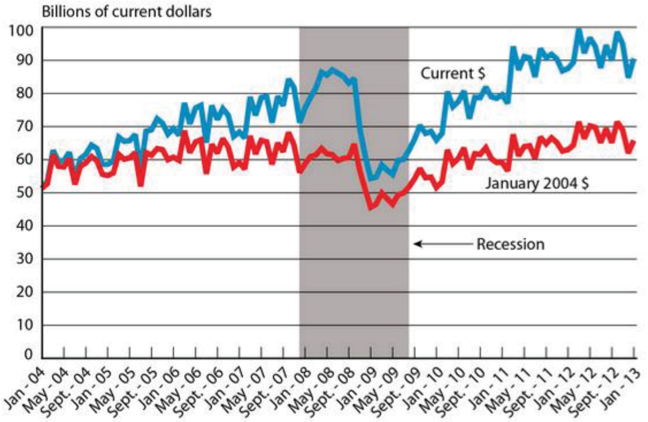


Source: Ref. 6

Notes: Represents exports to and imports from other country as percentage of country's total trade.

If trade between the U.S. and its NAFTA partners is expressed in January 2004 dollars, it has not increased much, although there has been a series of yearly seasonal fluctuations, and a major drop in years 2008-2009, as shown in Fig. 19.

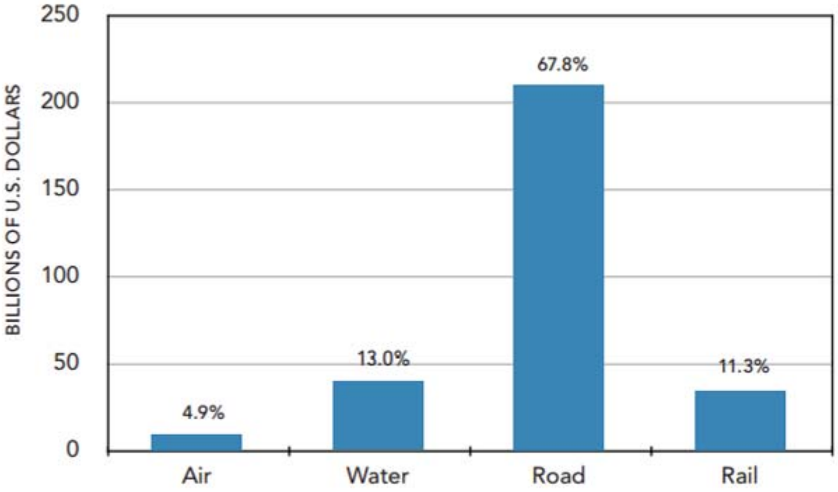
Figure 19. Trade between the U.S. and NAFTA partners (2004-2013).



Source: Ref. 4

According to Fig. 20, road freight is the predominant transportation mode for U.S. trade with Mexico.

Figure 20. U.S. trade with Mexico by transportation mode, 2009.

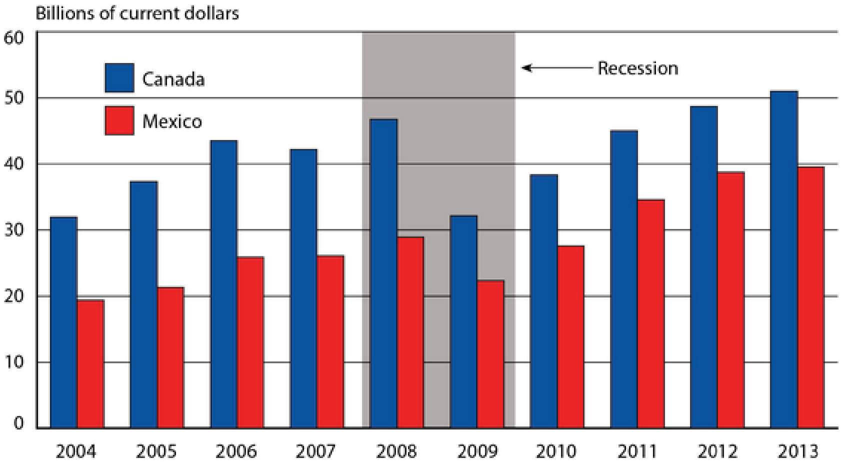


Source: Ref. 6

Notes: Represents exports to and imports from other country as percentage of country's total trade.

If all transportation modes are combined, the value of traded goods of U.S. with NAFTA partners has shown yearly variations, as it can be observed in Fig. 21. Mexico has not displaced Canada yet as the U.S. most important trading partner.

Figure 21. U.S. Trade with NAFTA by all transportation modes (2004-2013).



Source: Ref. 4

5. SUMMARY

For many years, Mexico has been an important trade partner of the U.S. Since NAFTA came into force, in 1994, trade volumes between the U.S., Mexico, and Canada have shown sustained growth. Data provided to CAIT, as part of this consulting agreement, are very useful to understand the transportation infrastructure and modes of Mexico that are a vital part of the NCITEC supply chain. In this case, ports of entry along the U.S. – Mexico border play a major role for road and rail freight, based on the significant import/export trade volumes handled at these international ports.

As a reference, main GIS maps and tables with information on Mexico's NAFTA transportation infrastructure are provided in this report's Appendix. These items were the most important deliverables during the initial phase of this consulting agreement with CAIT.

6. REFERENCES

1. Ministry of Economy, Mexico, 2014. http://www.economia.gob.mx/comunidad-negocios/comercio-exterior/informacion-estadistica-y-arancelaria

2. North American Transportation Statistics, 2014. http://nats.sct.gob.mx/

3. Mexico's Transportation and Communications Ministry, Statistical Yearbook, 2014. http://www.sct.gob.mx/informacion-general/planeacion/estadistica/anuario-estadistico-sct/

4. North American Transborder Freight Data. Bureau of Transportation Statistics, 2014. http://people.hofstra.edu/geotrans/eng/ch2en/appl2en/NAFTA_trade_value.html

5. United States Department of Transportation, 2014. http://www.rita.dot.gov/

6. Wilson, E. (2011). Economic ties between the United States and Mexico. Woodrow Wilson International Center for Scholars.

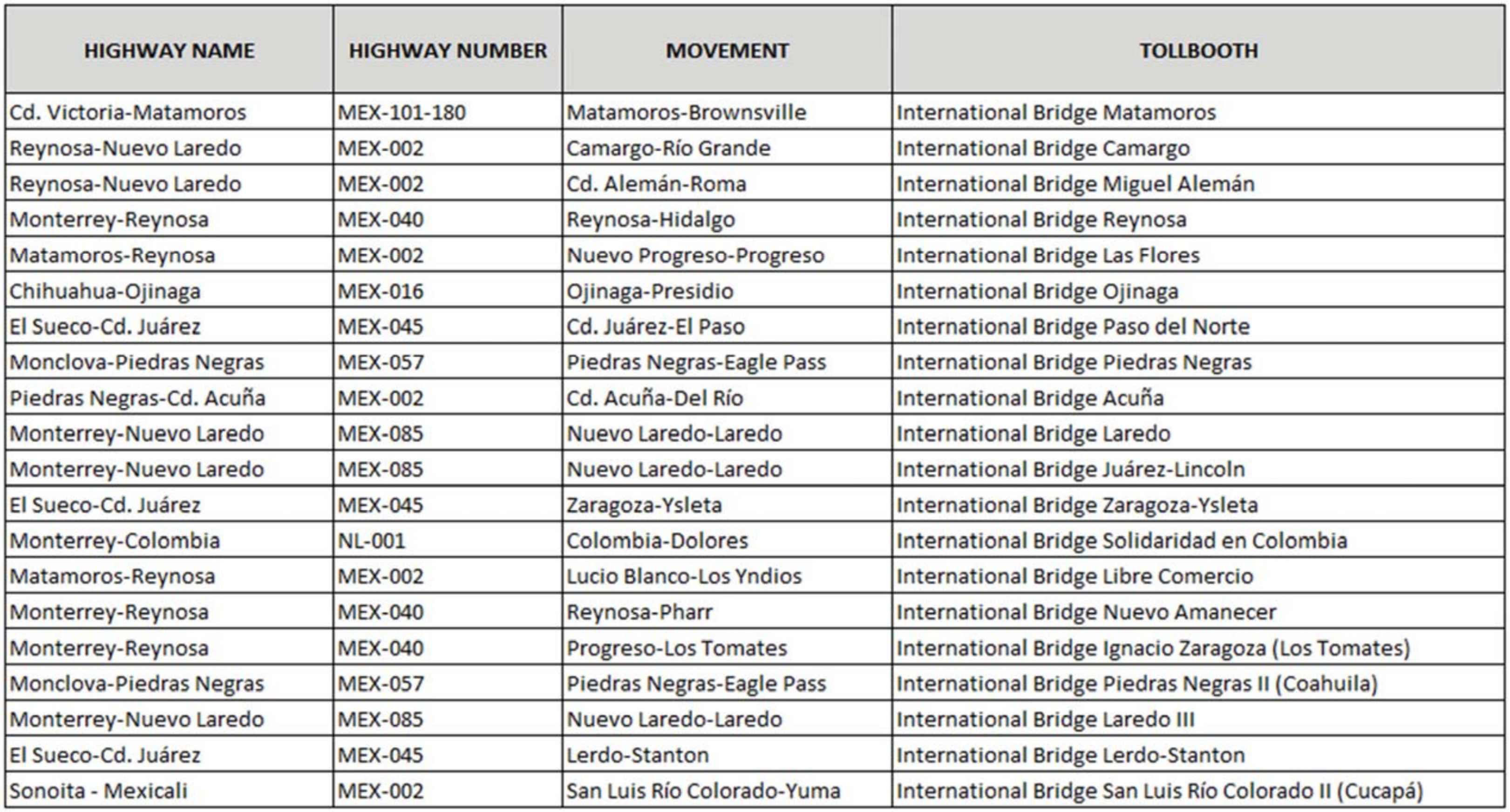
Appendix.

Location of cities with more than 50,000 inhabitants.

Main highways of Mexico.

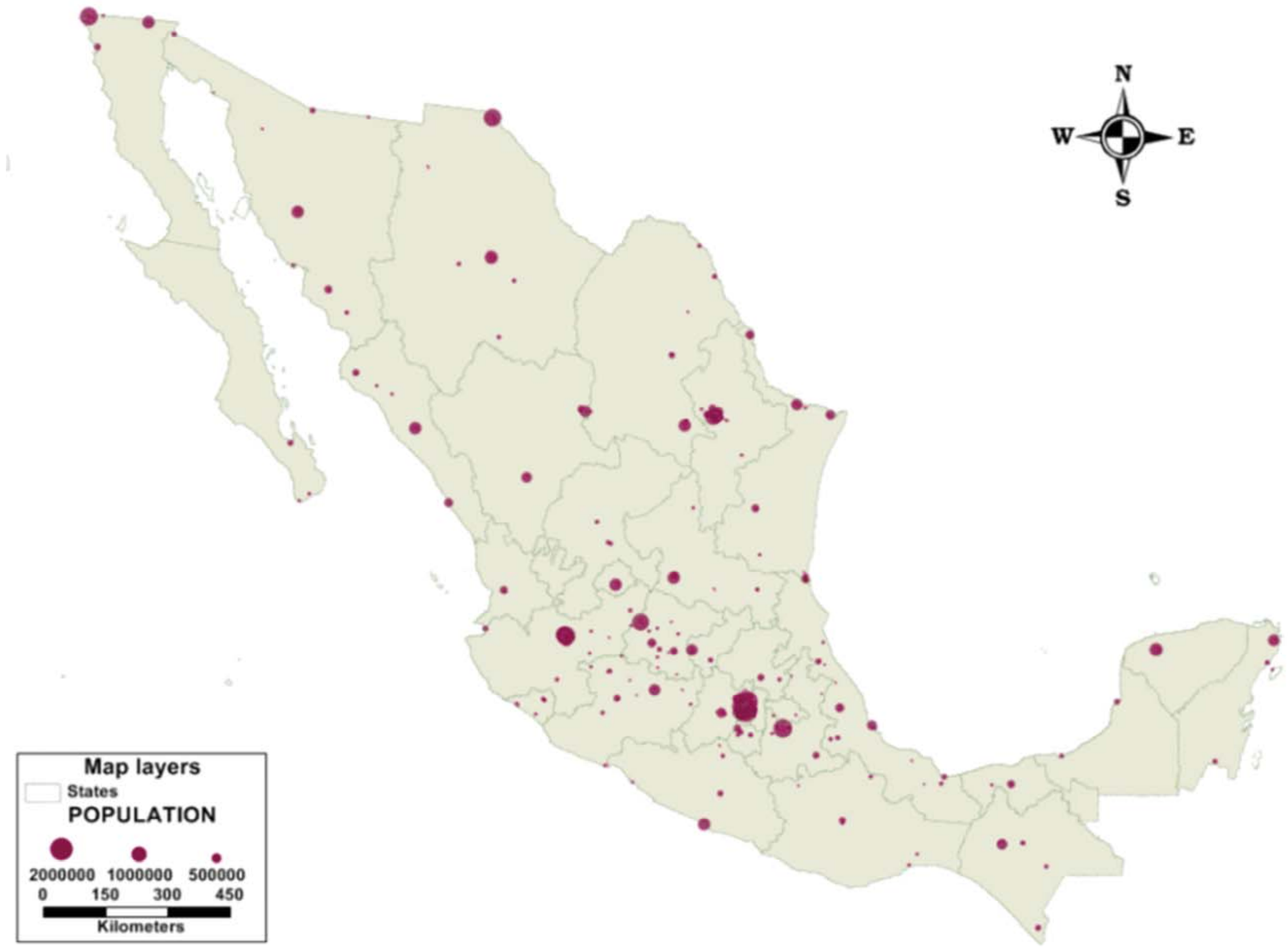
International ports of entry along the Mexico - U.S. border.

International ports of entry along the Mexico - U.S. border.



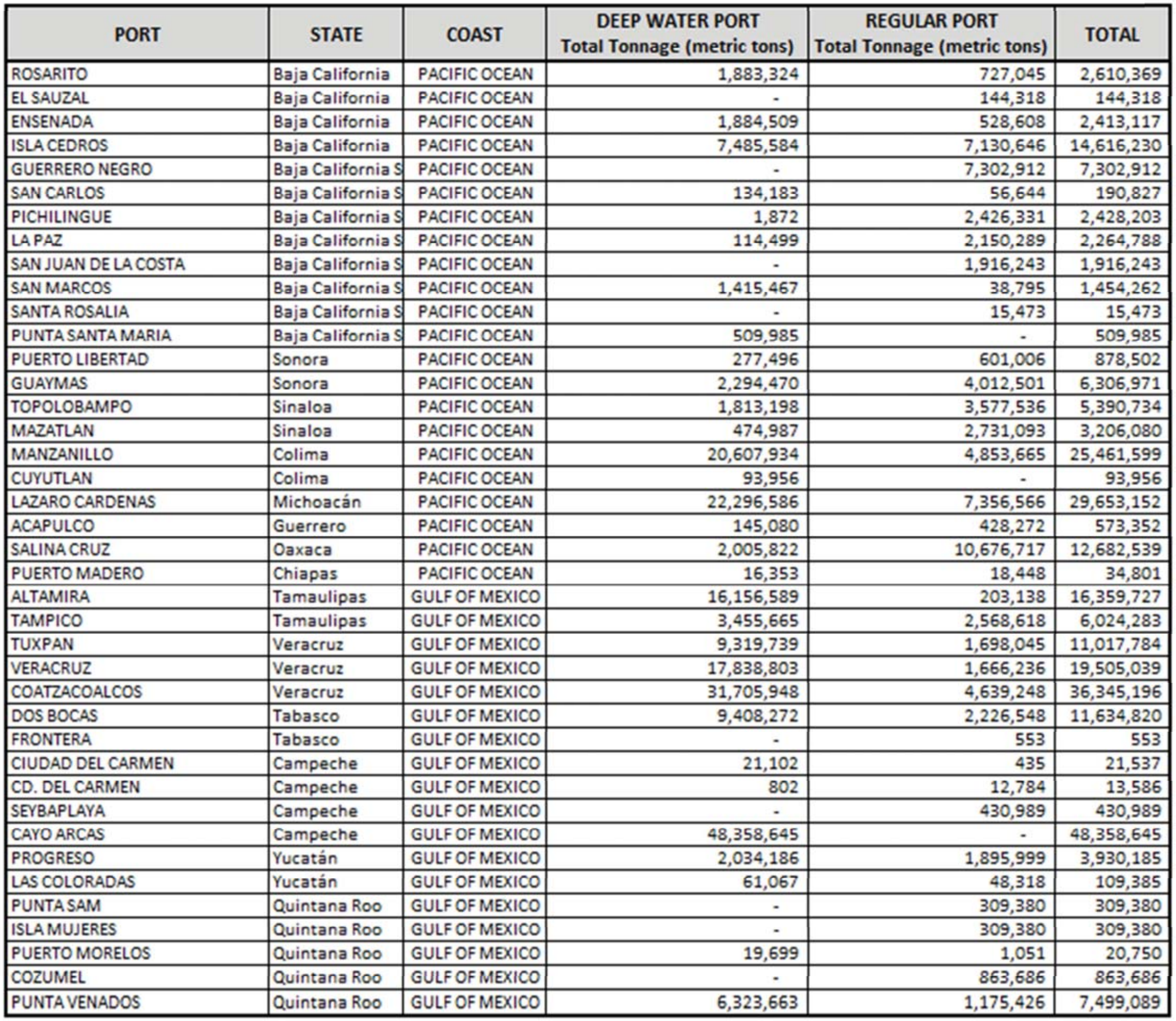
HIGHWAY NAME	HIGHWAY NUMBER	MOVEMENT	TOLLBOOTH
Cd. Victoria-Matamoros	MEX-101-180	Matamoros-Brownsville	International Bridge Matamoros
Reynosa-Nuevo Laredo	MEX-002	Camargo-Río Grande	International Bridge Camargo
Reynosa-Nuevo Laredo	MEX-002	Cd. Alemán-Roma	International Bridge Miguel Alemán
Monterrey-Reynosa	MEX-040	Reynosa-Hidalgo	International Bridge Reynosa
Matamoros-Reynosa	MEX-002	Nuevo Progreso-Progreso	International Bridge Las Flores
Chihuahua-Ojinaga	MEX-016	Ojinaga-Presidio	International Bridge Ojinaga
El Sueco-Cd. Juárez	MEX-045	Cd. Juárez-El Paso	International Bridge Paso del Norte
Monclova-Piedras Negras	MEX-057	Piedras Negras-Eagle Pass	International Bridge Piedras Negras
Piedras Negras-Cd. Acuña	MEX-002	Cd. Acuña-Del Río	International Bridge Acuña
Monterrey-Nuevo Laredo	MEX-085	Nuevo Laredo-Laredo	International Bridge Laredo
Monterrey-Nuevo Laredo	MEX-085	Nuevo Laredo-Laredo	International Bridge Juárez-Lincoln
El Sueco-Cd. Juárez	MEX-045	Zaragoza-Ysleta	International Bridge Zaragoza-Ysleta
Monterrey-Colombia	NL-001	Colombia-Dolores	International Bridge Solidaridad en Colombia
Matamoros-Reynosa	MEX-002	Lucio Blanco-Los Yndios	International Bridge Libre Comercio
Monterrey-Reynosa	MEX-040	Reynosa-Pharr	International Bridge Nuevo Amanecer
Monterrey-Reynosa	MEX-040	Progreso-Los Tomates	International Bridge Ignacio Zaragoza (Los Tomates)
Monclova-Piedras Negras	MEX-057	Piedras Negras-Eagle Pass	International Bridge Piedras Negras II (Coahuila)
Monterrey-Nuevo Laredo	MEX-085	Nuevo Laredo-Laredo	International Bridge Laredo III
El Sueco-Cd. Juárez	MEX-045	Lerdo-Stanton	International Bridge Lerdo-Stanton
Sonoita - Mexicali	MEX-002	San Luis Río Colorado-Yuma	International Bridge San Luis Río Colorado II (Cucapá)

Population of main Mexican cities.



Main maritime ports of Mexico.

Main maritime ports of Mexico.

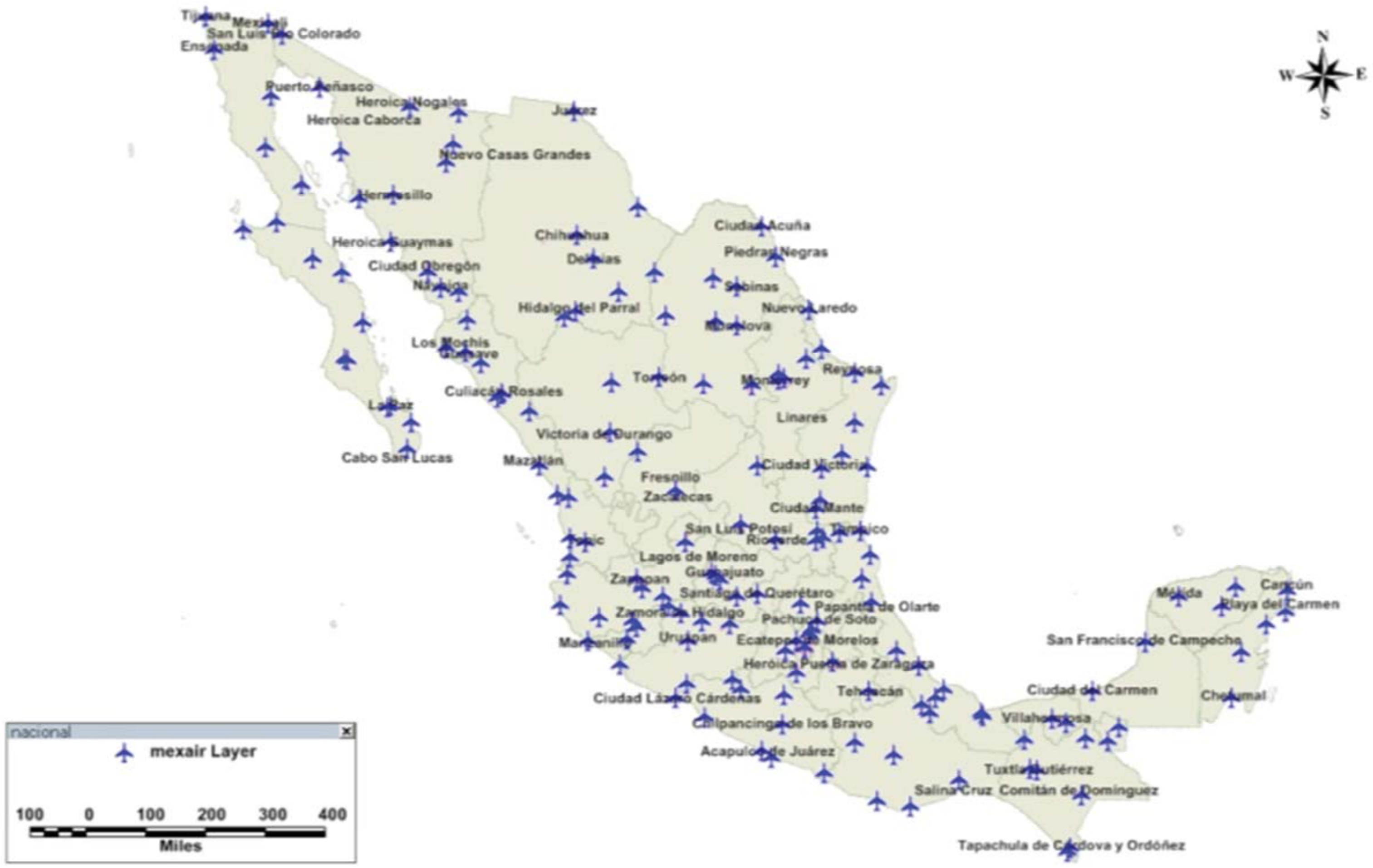


PORT	STATE	COAST	DEEP WATER PORT Total Tonnage (metric tons)	REGULAR PORT Total Tonnage (metric tons)	TOTAL
ROSARITO	Baja California	PACIFIC OCEAN	1,883,324	727,045	2,610,369
EL SAUZAL	Baja California	PACIFIC OCEAN	-	144,318	144,318
ENSENADA	Baja California	PACIFIC OCEAN	1,884,509	528,608	2,413,117
ISLA CEDROS	Baja California	PACIFIC OCEAN	7,485,584	7,130,646	14,616,230
GUERRERO NEGRO	Baja California S	PACIFIC OCEAN	-	7,302,912	7,302,912
SAN CARLOS	Baja California S	PACIFIC OCEAN	134,183	56,644	190,827
PICHILINGUE	Baja California S	PACIFIC OCEAN	1,872	2,426,331	2,428,203
LA PAZ	Baja California S	PACIFIC OCEAN	114,499	2,150,289	2,264,788
SAN JUAN DE LA COSTA	Baja California S	PACIFIC OCEAN	-	1,916,243	1,916,243
SAN MARCOS	Baja California S	PACIFIC OCEAN	1,415,467	38,795	1,454,262
SANTA ROSALIA	Baja California S	PACIFIC OCEAN	-	15,473	15,473
PUNTA SANTA MARIA	Baja California S	PACIFIC OCEAN	509,985	-	509,985
PUERTO LIBERTAD	Sonora	PACIFIC OCEAN	277,496	601,006	878,502
GUAYMAS	Sonora	PACIFIC OCEAN	2,294,470	4,012,501	6,306,971
TOPOLOBAMPO	Sinaloa	PACIFIC OCEAN	1,813,198	3,577,536	5,390,734
MAZATLAN	Sinaloa	PACIFIC OCEAN	474,987	2,731,093	3,206,080
MANZANILLO	Colima	PACIFIC OCEAN	20,607,934	4,853,665	25,461,599
CUYUTLAN	Colima	PACIFIC OCEAN	93,956	-	93,956
LAZARO CARDENAS	Michoacán	PACIFIC OCEAN	22,296,586	7,356,566	29,653,152
ACAPULCO	Guerrero	PACIFIC OCEAN	145,080	428,272	573,352
SALINA CRUZ	Oaxaca	PACIFIC OCEAN	2,005,822	10,676,717	12,682,539
PUERTO MADERO	Chiapas	PACIFIC OCEAN	16,353	18,448	34,801
ALTAMIRA	Tamaulipas	GULF OF MEXICO	16,156,589	203,138	16,359,727
TAMPICO	Tamaulipas	GULF OF MEXICO	3,455,665	2,568,618	6,024,283
TUXPAN	Veracruz	GULF OF MEXICO	9,319,739	1,698,045	11,017,784
VERACRUZ	Veracruz	GULF OF MEXICO	17,838,803	1,666,236	19,505,039
COATZACOALCOS	Veracruz	GULF OF MEXICO	31,705,948	4,639,248	36,345,196
DOS BOCAS	Tabasco	GULF OF MEXICO	9,408,272	2,226,548	11,634,820
FRONTERA	Tabasco	GULF OF MEXICO	-	553	553
CIUDAD DEL CARMEN	Campeche	GULF OF MEXICO	21,102	435	21,537
CD. DEL CARMEN	Campeche	GULF OF MEXICO	802	12,784	13,586
SEYBAPLAYA	Campeche	GULF OF MEXICO	-	430,989	430,989
CAYO ARCAS	Campeche	GULF OF MEXICO	48,358,645	-	48,358,645
PROGRESO	Yucatán	GULF OF MEXICO	2,034,186	1,895,999	3,930,185
LAS COLORADAS	Yucatán	GULF OF MEXICO	61,067	48,318	109,385
PUNTA SAM	Quintana Roo	GULF OF MEXICO	-	309,380	309,380
ISLA MUJERES	Quintana Roo	GULF OF MEXICO	-	309,380	309,380
PUERTO MORELOS	Quintana Roo	GULF OF MEXICO	19,699	1,051	20,750
COZUMEL	Quintana Roo	GULF OF MEXICO	-	863,686	863,686
PUNTA VENADOS	Quintana Roo	GULF OF MEXICO	6,323,663	1,175,426	7,499,089

Railway network of Mexico, coverage.

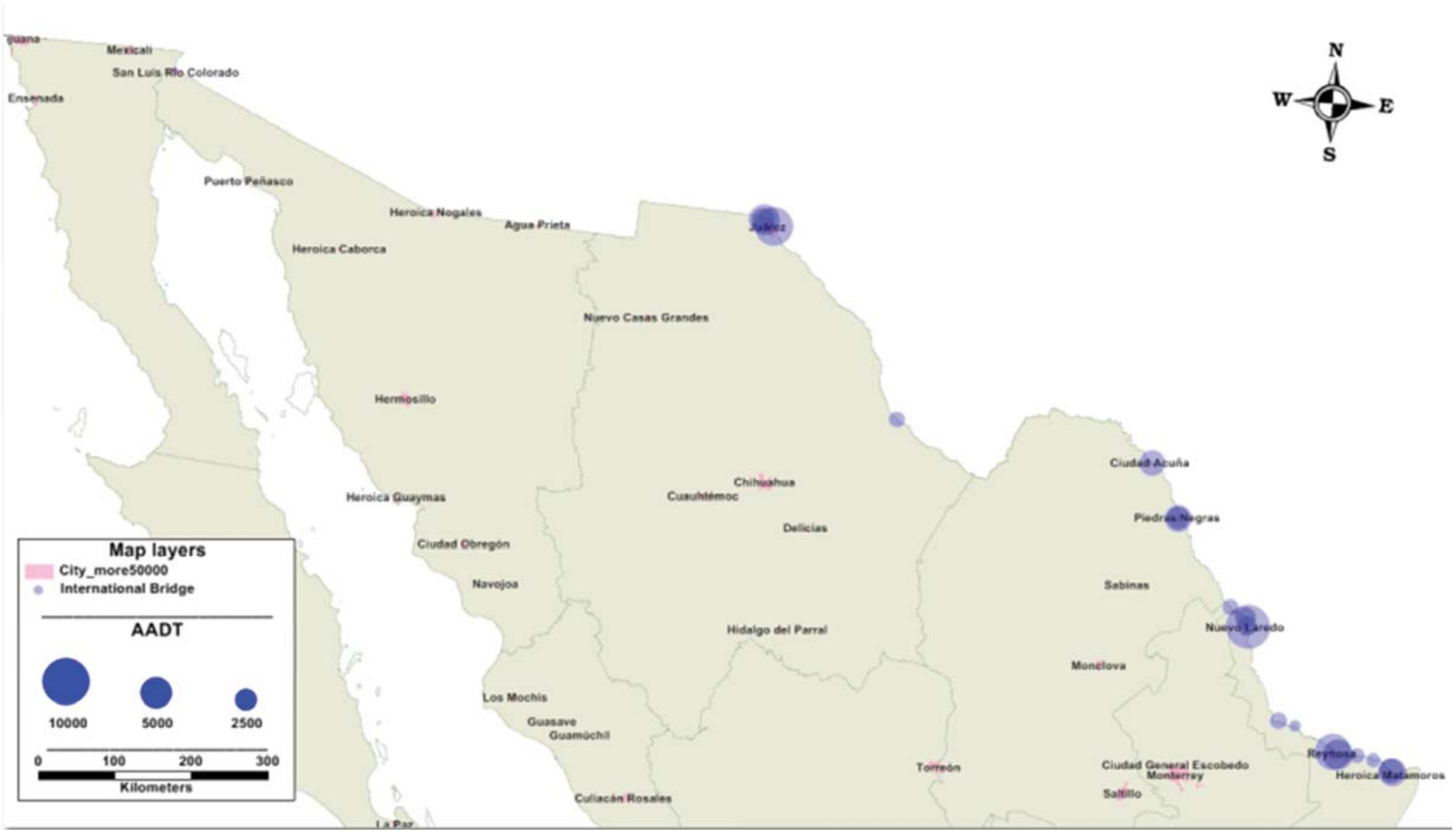
Railway network of Mexico, current operating condition.

Mexican airports.

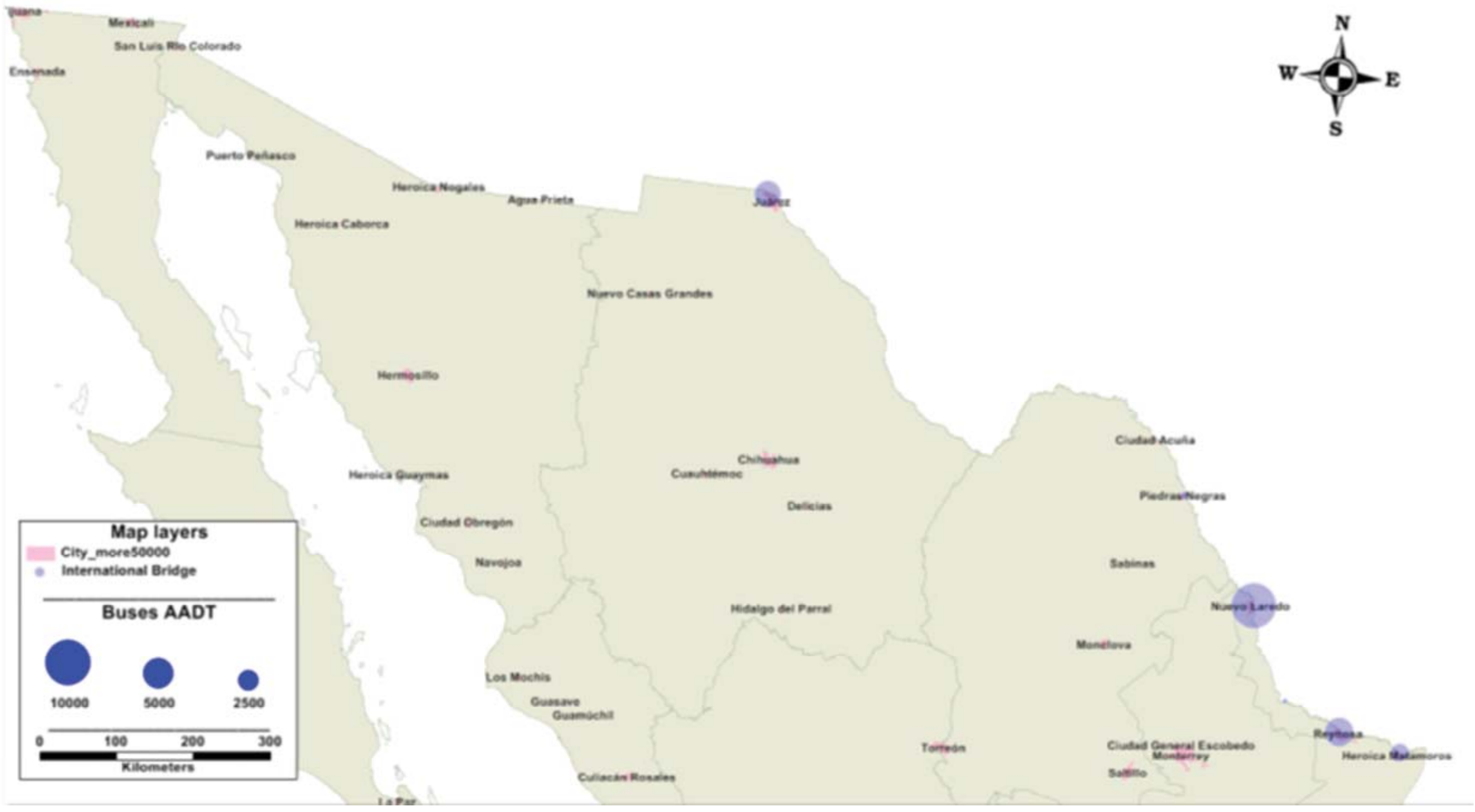


Boundaries of Mexican states.

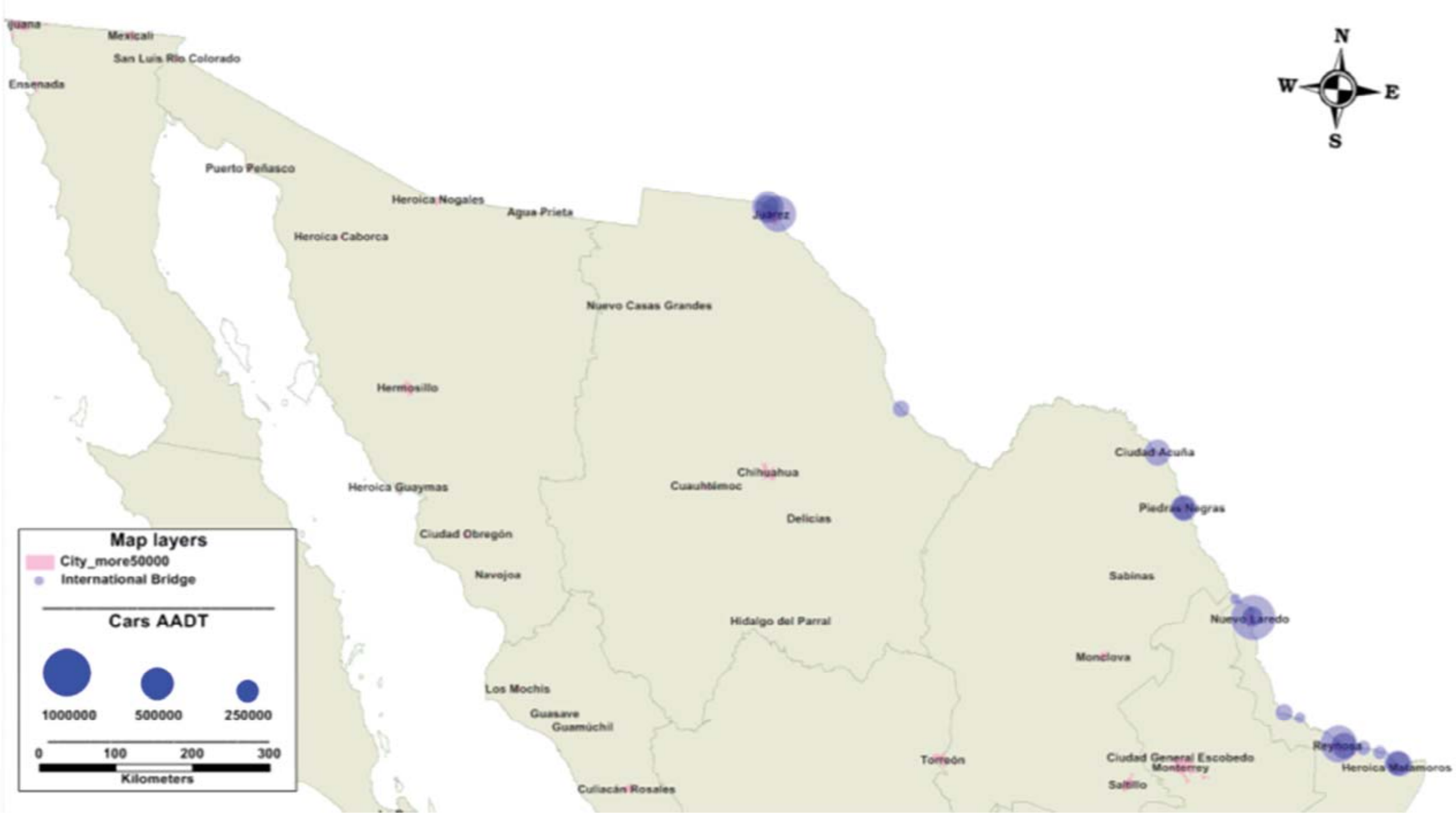
AADT, all vehicle types, at international ports of entry.



AADT, buses, at international ports of entry.



AADT, cars, at international ports of entry.



AADT, trucks, at international ports of entry.