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16. Abstract

Texas faces increased freight demands from population growth and economic success, with little prospect of adding substantial capacity to the Texas Department of Transportation (TxDOT) principal highway networks. In Texas's truck-dominated intrastate corridors, can railroads offer competitive service and reduce truck volumes? Current mode choice models do not capture the effects of weight, speed, engine power, grade, or curvature—key elements of any mechanistic approach. Moreover, they are incapable of fully internalizing external or social costs into their calculations. Therefore, in two critical areas for transportation planners—fuel costs and emissions—existing models are deficient. This project combines mechanistic models for both trucks and rail into a PC model, calibrated for Texas and implemented through a series of study workshops for TxDOT and metropolitan planning organization (MPO) planning staff. The output of the toolkit allows planners to compare truck and rail service over a series of corridors in terms of overall cost, fuel costs, emissions per ton-mile, and related secondary costs such as pick-up and delivery costs for rail freight. It provides truck and rail operating cost comparisons that should strengthen corridor analysis—an important component of the MAP-21 legislation.

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Evaluating Truck and Rail Movements along Competitive Multimodal Corridors

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Chapter 1. Introduction

Historically, a major strength of the US economy has been the ability to move freight—imports, exports, and domestic—efficiently and competitively using a variety of modes. The importance of transportation multimodal planning was explicitly recognized at the federal level two decades ago with the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA, 1991[1]) and more recently in the 2013 Moving Ahead for Prosperity in the 21st Century (MAP-21[2]) legislation. The range and complexity of freight transportation gave rise to a designated sector—logistics—which helps shippers select the most efficient routing and mode choice for the commodities moved and the markets served. These mode/route choices, termed *supply chains*, are dynamic and change when costs or service needs substantially alter. Higher fuel costs, for example, have resulted in steamship companies offering services which operate at 15 knots, rather than 20, allowing steamship companies to share the lower costs with those shippers willing to accept a longer trip time. It has also encouraged shippers and large trucking companies to use rail rather than trucks for some long-distance US domestic routes.

Federal and state departments of transportation are embracing freight planning at a critical time if US economic strength is to be maintained. Highway corridors continue to dominate U.S freight transportation flows and in 2012 trucks moved 9.4 billion tons or 69% of the US domestic freight[3] even as highway funding rapidly falls behind needs. Maintenance and replacement needs—for example, replacing interstate bridges built in the early 1970s—when combined with legislative reluctance to raise fuels taxes, make it unlikely that additional lane miles, even on heavily used highway corridors, will be funded over the next decade. In addition, freight routes pass through metropolitan areas that are merging with cities to form megaregions[4] like the Texas Triangle or the Corpus Christi to Louisiana petro-chemical corridor. Metropolitan transportation planning has tended to focus on passenger movements (personal mobility) and the needs of freight companies were secondary. Now, transportation planners recognize that providing for multimodal freight transportation is a crucial step in supporting a strong economy.

Rail is playing an increasingly important role for moving all types of commodities—exports, imports, and internal long-haul intermodal business. Rail demand is estimated to increase at least 37% by tonnage and 86% by value (FAF 3, 2012) between now and 2040. The railroads can handle this demand if investment to remove various bottlenecks is undertaken in combination with longer trains and sidings, and track improvements (Cambridge Systematics, 2007). In addition, further modal shifts to rail on shorter routes are expected, as a result of environmental and energy benefits (TRBNRC, 1998). Finally, some studies have indicated that "a truck-rail container movement can yield much greater cost savings compared with truck alone if the cost of the transfer is offset by rail's lower cost per ton mile" (TRBNRC, 1998; Resor et al., 2007; Seedah et al., 2011). Transportation planners, when considering a greater role for rail in state and regional transportation freight flows, currently face difficulties estimating the point where rail is more economically efficient than trucks on key corridors.

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[1] http://ntl.bts.gov/DOCS/istea.html

[2] http://www.fhwa.dot.gov/map21/

[3] http://www.truckline.com/

[4] http://www.america2050.org/megaregions/archive/

This study was designed to provide those planners evaluating freight corridor options with a planning tool that would identify a truck-competitive rail service over key Texas corridors. A variety of factors impact mode choice but studies show that operating cost and delivery times (Prozzi et al., 2011; Cottrell, 2008; Harrison et al., 2011; Lubis et al., 2003) are prime outputs of any planning model that estimates shipper choice. Current mode choice and other planning models do not capture the effects of weight, speed, engine power, grade changes, and curvature—key elements of any mechanistic approach—on operating cost and delivery times. Furthermore the literature review revealed that (a) cost variables are incorporated in an aggregate manner resulting in poor predictions of the effects of cost-related policies, (b) none of the current models considered the dynamics of fuel cost, (c) most of the input data is out-of-date and/or proprietary, and finally (d) most model applications are confined to larger-scale study areas. This study was designed to address and correct these deficiencies.

Rail costs are influenced by handling costs that increase the route mileage at which rail costs can compete with trucking. Researchers have estimated this breakeven point and, although it is falling, in the literature[5] it remains in the 500-to-700 mile range depending on fuel costs. However, events are changing in favor of rail. Recently, rail has benefited from rail profitability, track investment (double tracking and longer sidings), longer and heavier trains, and terminal efficiencies. These have made rail more competitive and profitable over their entire network. Moreover, rail is much cleaner in terms of ton-mile emissions, which, although not currently valued in the price of rail service, does beneficially impact air quality. This study enables planners—at both the DOT and MPO levels—to accurately evaluate proposals that constitute opportunities for short haul rail service designed to take trucks off the highway. The non-linearity of speed-volume flows shows that modest levels of freight moving from a highway to a rail corridor would substantially benefit the remaining highway users. It would also contribute to decreasing air shed pollution. The study integrates truck and rail mechanistic models in the form of a calibrated toolkit that planners can use to accurately determine costs and social benefits. It was developed with assistance from trucking and rail companies and users of the model at TxDOT as detailed in the work plan.

This report is structured as follows. Chapter 2 presents a detailed literature review of freight movement in Texas, and the variables that need to be considered when estimating intermodal truck and rail costs. Chapter 3 provides background information on the vehicle operating cost model used in the development of the truck-rail intermodal toolkit. Chapter 4 describes the current state of rail modeling and improvements that can be made to existing models in order to satisfy the needs of this study. Chapter 5 explains the methodology of the newly developed rail model. Chapter 6 discusses rail alignments as well as Hay's (1982) method of the location process and how it can be used in rail modeling. Chapter 7 describes a methodology used in accounting for rail capacity at the subdivision level. Chapter 8 is dedicated to examining the sensitivity of key variables used in the toolkit, and this is followed by an example case study of the Houston to Dallas/Fort Worth Interstate 45 freight corridor in Chapter 9. Chapter 10 presents key discussions from workshops hosted as part of this study and provides recommendations on how the toolkit can be integrated into the TxDOT freight planning processes.

[5] See Resor R. and J.R. Blaze (with comment by E. Morlock), "Short-Haul Rail Intermodal: Can It Compete with Trucks?" Transportation Research Record: Journal of the Transportation Research Board. No. 1873, Washington D.C. 2004

Chapter 2. Literature Review

Freight moves in a variety of ways, often involving multiple modes. The focus of the logistics industry has expanded from regional routing optimization in the 1960s to embrace global supply chains covering the efficient movement of traded commodities. There are, of course, a variety of factors behind mode choice but the leading one, for most non-airborne commodities, is cost per ton-mile. Ships, by definition, monopolize the waterborne element of global trade and costs are influenced by route length, speed, vessel size, and possible tolls, such as those for passage through the Suez and Panama canals. Goods landed at marine terminals must be delivered and delivery is carried out in the US by truck and rail modes, often working together. They compete on routes that link all major markets and freight flows on both modes use high density corridors. Rail companies use double-tracked transcontinental routes to move goods across the country; in Texas, however, less than 20% of the on-system highway network carries over 70% of the truck ton-miles. If existing funding mechanisms remain unchanged, then it is unlikely that additional miles, even on heavily used highways, can be easily funded over the next decade. So can rail operations offer a truck-competitive service over key Texas corridors?

Rail costs are influenced by handling costs that increase the route mileage at which rail costs can compete with trucking. Researchers have estimated this breakeven point and, although it is falling, in the literature it remains in the 500-to-700 mile range depending on commodity value and increased fuel costs. However, events are changing in favor of rail. Recently, rail has benefited from rail profitability, track investment (double tracking and longer sidings), longer and heavier trains, and terminal efficiencies. These have made rail more competitive and profitable. Moreover, rail is much cleaner in terms of ton-mile emissions, which, although not currently valued in the price of rail service, does beneficially impact air quality.

2.1 Freight Movement in Texas

A comprehensive study by Prozzi et al. (2011) documented freight movement in Texas. The study found that freight movement is a necessity for the economy in order for products and goods to be safely, reliably, and efficiently moved between markets. For Texas this includes production and consumption centers as well as products in the energy industry. Freight movements in Texas have shown strong increases due to population and economic growth. Texas also contains extensive trade corridors that make the freight movement structure and infrastructure critical. The Texas economy must be further discussed and explained to better understand freight movements (Prozzi et al., 2011).

Texas is usually known for the dominance in the energy industry, in particular oil and gas. Although this is a large part of the economy, Texas is diverse in many other areas that continue to grow. The economy can be broken down into four major goods sectors including construction, mining and logging, manufacturing, and trade and transportation. Trade and transportation represent the largest portion of the Texas economy, which is expected to more than double by 2035 (Prozzi et al., 2011). Freight movement will be a large factor in the growth of the economy as well as its sustainability.

Determining freight demand flows across a state network is challenging. It is necessary to evaluate where and how these flows are distributed in order to “determine the impact of freight on the infrastructure, improve freight mobility, forecast system performance, and improve safety” (Prozzi et al., 2011). In particular, evaluating both truck and rail modes provide good insight to the freight systems performance and characteristics especially in Texas where these modes dominate the market.

Texas has an extensive transportation system that facilitates the movement of freight. This system includes port facilities, railways, highways, pipeline infrastructure, and airports. There are also 11 direct land ports of entry between Texas and Mexico for international ground trade (Prozzi et al., 2011). Over 64% of the total freight tonnage was moved by rail, truck, or some combination of the two modes for all freight movement in Texas in 2007 (Prozzi et al., 2011).

Some of the main highways of Texas, including IH 35, IH 10, IH 20, IH 37, and IH 45, are the most used routes for truckers. Between now and 2040, it is estimated that truck tonnage within Texas will increase by 60% (Prozzi et al., 2011). Any increase in freight transportation could impact traffic congestion, safety, and infrastructure deterioration on these highways (Prozzi et al., 2011). Other possible impacts include security, environmental issues, and quality of life. With increase in truck volumes and an unchanging highway capacity, it can be assumed that the level of service (LOS) of these highways will decrease. Although the current Texas highway system is vast, capacity issues will continue to be a challenging problem for trucks in the state. Trucks are an essential part of the system because trucks are involved in most rail and air supply chains.

The rail system in Texas plays a key role in linking the economy to other states and getting products to and from the ports. International and interstate economic business depends on the rail system and infrastructure of Texas. Between now and 2040 it is estimated that rail tonnage within Texas will increase by 75% (Prozzi et al., 2011). The rail infrastructure is most important for interstate trade because of the efficiency of rail over long hauls. Chemicals and coal are the two products that are transported the most by rail, first because of safety and second because of cost (Prozzi et al., 2011). Three rail companies—Union Pacific (UP), Burlington Northern Santa Fe (BNSF), and Kansas City Southern (KCS)—own and operate the major Class I rail lines in Texas. Houston has the busiest rail hub in Texas, accounting for most of the rail activity in the region (Prozzi et al., 2011). Freight rail demand is also expected to exceed the capacity on many of the corridors in Texas if the infrastructure remains the same. However, possible modal shifts can be expected toward rail in freight transportation because of the benefit in environmental and energy challenges.

The desire for connectivity of goods through supply chains has increased with globalization. The role of shippers has especially increased to the point where they are the predominant decision-makers in the global market. Freight transportation is continuously evaluated by shippers who monitor and modify these supply chains. The ability of a freight mode to be fast, safe, reliable, and inexpensive are all key components of freight transportation. Most of these characteristics can be a function of the capacity of the infrastructure, and the different technologies of the specific modes. Depending on the goods needed to be shipped and the shipping distance, shippers decide which mode to use. Prozzi et al.'s (2011) study showed that service availability, on-time reliability, minimal loss and damage, and prompt pick-up and delivery are some of the most important factors to shippers. This study concluded that the focus should be simply the characteristics of the commodity instead of which mode would work best for them. Sometimes multi-modal options is best suited the shipper's needs.

2.2 Review of Factors Influencing Intermodal Truck Costs

The Transportation Research Board National Research Council in 1998 discussed and researched policy for intermodal freight transportation in the US. It was found that “a truck-rail container movement can yield much greater cost savings compared with truck alone if the cost of the transfer (the cost of the added handling of the container plus the costs of the difference in speed and reliability between truck and intermodal) is offset by rail’s lower cost per ton mile” (TRBNRC, 1998). In addition, the report also underscored the environmental benefits of intermodal transportation because rail generates lower emissions per ton mile than trucking. “Some state departments of transportation have been attracted by the potential of truck-rail intermodal for relieving pressure on state highway systems and have considered state investments in intermodal facilities as possibly cheaper alternatives to highway expansion” (TRBNRC, 1998). The Council concluded that four areas to improve intermodal freight policy include principles for government involvement, federal surface transportation programs affecting freight, regulatory and operations issues, and public finance of intermodal freight (TRBNRC, 1998).

Further studies by Prentice (2003) and Harrison et al. (2010) also address the importance of intermodal connectivity and bottleneck elimination. Prentice (2003) observed that efficiency and accessibility are two of the main challenges of intermodal freight transportation. Transportation by rail when considering intermodal freight movement helps shippers compete in cost and time. However, bottlenecks can be an issue for intermodal transport, which make scheduling and the logistics much more complex and therefore costly. Congestion and queues that stem from bottlenecks are not only an infrastructure problem but an operational problem as well. If enough time and money is spent, most bottlenecks can be at least relieved or moved (Prentice, 2003). Prentice recommends that supply chain dysfunctions are to be researched to solve these bottleneck issues instead of spending resources only improving infrastructure.

Harrison et al.’s (2010) intermodal traffic study of Texas and the Southwest also identified rail bottlenecks as one of the causes of stifled intermodal growth in the region (Harrison et al., 2010). Rail intermodal service in Texas has many strengths, weaknesses, opportunity, and threats associated with it. The type of products that are being shipped by both rail and truck are important to the intermodal service. However, other factors, including annual growth rates, tonnage, and revenue, are also important to this growing industry and the outcome of the future of rail (Harrison et al., 2010).

Operating cost estimates of transportation modes provide a realistic approach to determine how shippers and freight movers make decisions concerning route choice, mode choice, delivery times, and frequency of delivery. Shippers are rational and will make decisions that lower operating cost and raise profits. Conditions of the transportation network such as congestion may influence which routes are used and the time of delivery. Key components such as weight, speed, engine power, grade, or curvature—key elements of any mechanistic approach—which influences operating cost and travel time of both trucking and rail modes (Cottrell, 2008; Harrison et al., 2011; Lubis et al., 2003). Moreover, they are incapable of fully internalizing external or social costs into their calculations.

Harrison et al. (2010) therefore recommend that it is necessary “to link the modal components together in a single cost model which would allow planners to replicate, at the basic level, the operations of logistical departments and companies who manage the supply chains of companies that use the services provided by the various modal providers.” Using this approach will enable planners to accurately identify problem areas and effectively allocate scarce resources to these areas to relieve bottlenecks in the system.

2.3 Factors Influencing Rail Costs

Transportation-research-related studies by Cambridge Systematics (2007), Morgan et al. (2007) and Fekpe (2010) address freight rail mobility constraints. Cambridge Systematics (2007) identifies the need for new rail tracks, signals, bridges, tunnels, terminals, and service facilities to enable the US rail infrastructure handle growth over the next few years. “The U.S. DOT estimates that the demand for rail freight transportation, measured in tonnage, will increase 88 percent by 2035” (Cambridge Systematics, 2007). Thus, in order to attract truck movements to rail, further work needs to be done to determine the capacity and investment that is needed to increase the tonnage moved by rail, and reduce the rate of growth of truck traffic on highways (Cambridge Systematics, 2007). Morgan et al. (2007) examined rail systems in the US to determine good practices for relocating, expanding, and developing rail and their associated policies in the urban areas of Texas. Rail relocation proved to be a vital part of the long-term strategy to address urban transportation system changes and provide economic opportunities. Alternative corridors or improvements in existing corridors can also highly benefit congestion problems especially in urban areas (Morgan et al., 2007).

Fekpe’s (2010) study addressed freight mobility constraints for the rail system including low-cost improvements. Fekpe (2010) states that railroads are beginning to encounter capacity constraints especially when freight is shared with a passenger rail system. This issue has been seen in areas of the US where high speed rail is desired. Certain upgrades such as track improvements, communication systems, pairing mainlines, and the joint uses of facilities are a necessity to maintain the current mobility of trains (Fekpe, 2010). Variables affecting these recent constraints and capacity issues include speed, length of trains, idle time, LOS, terminal dwell time, and on-time customer pickup or delivery (Fekpe, 2010).

A recent update from the American Association of Railroads (2011) suggests that the current weights of costs in the rail industry are changing. While labor continues to dominate the majority of the costs for rail, fuel is increasing rapidly. Just in 2010, the percentage spent on fuel increased from 14.9% to 18% while labor decreased by over 1% (AAR, 2011). Other smaller factors include materials/supplies, equipment rentals, depreciation, and interest (AAR 2011). All of these other factors still only contribute about 45% of the total costs. Each quarter these numbers are updated, allowing trends to be observed and recorded.

Table 2.1: Current Weights of Costs in the Rail Industry (AAR, 2011)

	2008	2009	2010
Labor	30.2%	34.7%	33.3%
Fuel	25.2%	14.9%	18.0%
M&S	5.1%	5.1%	5.0%
Equipment Rents	6.3%	7.1%	6.2%
Depreciation	10.4%	13.9%	12.8%
Interest	2.3%	3.0%	2.9%
Other	20.5%	21.3%	21.8%
Total	100.0%	100.0%	100.0%

In a study by Seedah et al. (2010) many variables were found to contribute to the costs of transportation by rail and must be accounted for when performing any cost analysis. According to Seedah et al. (2010), rail costs can be divided into eight categories: cargo weight, locomotive selection, "train in motion" calculations, fuel consumption, locomotive emissions, crew labor costs, maintenance costs, and capital/investment costs. These variables were found to be essential to accurately estimating rail costs. An initial 2009 case study performed in the study demonstrated the economic benefits of different levels of intermodal rail service in competition with direct highway truck movement. The study determined that high terminal loading and drayage costs for a corridor trailer truck type intermodal rail movement can be partially offset by the line haul economics of double-stacking container even at higher train speeds.

Another study conducted by Resor et al. (2004) involving short-haul rail movement included costs breakdown consisting of crew, locomotive, car, fuel, and track maintenance cost. A cost of movement per twenty-foot equivalent unit was then developed for specified routes in the study. Resor et al. (2004) found that track maintenance cost was the largest portion of total line haul cost at 35%. Furthermore, it was also determined that high terminal costs prevented the rail industry from being competitive with trucks and therefore should be the focus of any research or improvement (Resor et al., 2004).

In a paper by DeSalvo (1969), it was recommended that rail freight transportation be divided into various processes, including assembly, line-haul, and loading and unloading. The line haul process, further studied in this paper, showed vast variances in costs depending on the locomotive, route, and tonnage. It was determined that long hauls and short hauls can be very different and should be evaluated in a separate manner (DeSalvo, 1967).

Track design factors—comprised of grade, curvature, and rise and fall—are found to influence track resistance, grade resistance, curve resistance, and train resistance, and consequently fuel consumption and cost. These factors are further explained and discussed by Hay (1980). Grade resistance is probably the most important factor in most route designs (Hay, 1980). "This can have an impact on the number of trains, locomotive units, and horsepower to move a given tonnage, on speed and schedule time, on locomotive utilization, and consequently, on costs" (Hay, 1980). Curvature is also important when designing curves because minimizing the curve resistance will increase the train efficiency and reduce the amount of energy required to move through the curve. This resistance is developed by friction between the flanges and the treads of the wheels (Hay, 1980). Rise and fall gradients can be divided into classes in which the gradient either forces the operator to apply acceleration or braking, or only minor variation in speed results (Hay, 1980). When designing a new track, these factors must be considered in order to achieve long term efficiency and cost effective rail transportation.

In addition, Hay (1980) suggests that tonnage rating[6] is the most important factor when deciding the appropriate locomotive to use on a haul. Not only can the tonnage rating help decide which locomotive to choose but also which route to take. Tonnage rating gives an estimate of the horsepower which will then give an insight to the size of locomotive required, and the maximum and minimum speeds that can be travelled over a specific route (Hay, 1980). All of these factors consequently affect the costs of the trip.

Information regarding pollution by locomotives has been gathered by the Environmental Protection Agency (EPA). According to the agency, the engines are only required to meet modest regulations set in 1997 (EPA, 1997). The Clean Air Nonroad Diesel Rule set in 2004 has

[6] Tonnage rating is the tonnage which can be hauled at a specified minimum speed over a given territory. (Hay, 1980)

helped tremendously with reducing particulate matter. Standards will continue to be set and enforced to improve the public health and reduce air emissions.

Technological advancements are also making intermodal transportation of freight to become more efficient and viable while achieving the lowest costs and most beneficial environmental impact (TRBNRC, 1998). Machalaba (2011) discusses the impact that technology is having on the freight rail community as well as the possible upsides it can have for the future. Digital technology is becoming more prevalent in rail and soon will be able to ensure the safety of the train as well as keeping a tight schedule (Machalaba, 2011). Two of the more recent technological breakthroughs have been the development of positive train control (PTC) and electronic controlled pneumatic (ECP) brakes. PTC allows a central control system where the control station can remotely control the train if necessary (Machalaba, 2011). ECP is a brake system that is controlled by electronic signals instead of air pressure, which can improve handling and shorten braking distance (Machalaba, 2011). As technology develops, rail systems will become more efficient and much more reliable.

In the area of rail planning, complex models have been developed to determine the benefits and costs associated with rail investments. For example, Lubis et al. (2003) researched a freight network plan that could be utilized for a complex multimodal system. Using decision-based models and non-decision-making models, flows and capacity issues were evaluated for both rail and highway networks in Indonesia. It was determined that it was more beneficial to expand the rail system than continue to expand the road network (Lubis et al., 2003). Another study by Arnold et al. (2003) addressed the modeling aspect of a rail/road intermodal transportation system using a "linear programing formulation to the hub-type problem based on multi-commodity fixed charge network design problems," and focused specifically on comparing rail to truck (Arnold et al., 2003). The authors suggest that the location of the intermodal terminal is the most important factors when determining which modes are more efficient (Arnold et al., 2003). Multimodal transportation is also very sensitive to the transfer or transshipment costs and can easily affect the modes feasibility (Arnold et al., 2003). Chen et al. (2010) assessed the performance of intermodal transfers at cargo terminals using a model that coordinates cargo transfers to improve efficiency and reduce total transportation costs (Chen et al., 2010). Advantages of using this type of model are the ability to concentrate cargo on faster routes, use the existing infrastructure, and reduce the requirements for warehouses and storage areas with poor connections. Some of the variables considered are total system costs, operating costs, cargo dwell time, loading and unloading costs, cargo processing costs, and cargo transfer costs (Chen et al., 2010). This model is able to further assess efficiency advantages in the terminals and during transfers. Further development and case studies with this model should improve efficiency of intermodal freight terminals making intermodal transportation much more viable and cost effective.

A study by Southworth et al. (2000) explains the need for intermodal and international freight network modeling. Integrating multimodal and transcontinental networks can be useful when evaluating the freight network. Recent geographical information system (GIS) technology can be used to improve logistics not only in a corridor but for international freight transportation (Southworth et al., 2000). A case study with tens of thousands of origins and destinations both within and across US borders was conducted. Another model developed by Lai et al. (2009) evaluates capacity and is able to consider future demand, compute line capacity, and even budget investment costs. This tool utilizes subdivisions characteristics to evaluate different impacts (Lai et al., 2009). After running some test cases, this model showed very good cost estimates of capacity expansion alternatives and also gives an output of delay vs. volume, total delay, average delay, and LOS. This model can help planners with capacity for developing rail alternatives based on network characteristics, demand, and budget.

Based on reviewed literature, elements identified to influence rail movements and costs include the following:

- Track Design
- Grade
- Curvature
- Rise and Fall
- Tonnage
- Train Speed
- Length of Train
- Idling at sidings
- Terminal Dwell Time
- Trip Delays
- Terminal Operations Costs
- Fuel
- Labor
- Capital investment costs
- Cost of maintenance
- Bottlenecks
- Annual growth rates
- Emissions
- Track Capacity
- Overhead Costs
- Scheduling
- Empty car traffic
- Switching
- Freight Car Rental

Table 2.2 shows a breakdown of the literature and the variables associated with freight rail. Tonnage, terminal costs, capacity, and cost of expansion are the variables of highest interest to the rail industry and considerable research has been performed in those areas. Out of all 18 sources, at least 6 of them discussed these variables. Both track design and bottlenecks were also common, with five sources for each of these variables. Having a variety of sources discussing each of these variables gave many perspectives and methods of considering these variables and helped decide which factors are necessary to consider for the rail mode.

Table 2.2: Rail Variables and the Associated Literature

	Track design (grade, curvature, rise and fall)	Tonnage	Train speed	Length of train	Idling at sidings	Terminal dwell time	Total trip delay	Terminal operations costs
AAR (2011)								
Arnold et al. (2003)						✓		✓
Cambridge Systematics (2007)		✓		✓				✓
Chen et al. (2010)						✓		✓
DeSalvo (1967)	✓	✓						✓
Fekpe (2010)			✓	✓	✓	✓		
General Accounting Office (2003)								
Harrison et al. (2010)		✓						
Hay (1980)	✓	✓	✓	✓				✓
Lai et al. (2009)							✓	
Lubis et al. (2003)								
Machalaba (2011)								
Morgan et al. (2007)	✓							
Prentice (2003)								
Prozzi et al. (2006)		✓						
Resor et al. (2004)	✓							✓
Seedah et al. (2010)	✓							
TRB National Research Council (1998)		✓						

Table 2.2 continued: Rail Variables and the Associated Literature

	Fuel	Labor	Capital investment costs	Costs of expansion	Cost of maintenance	Bottlenecks	Annual growth rates	Emissions	Track capacity
AAR (2011)	✓	✓							
Arnold et al. (2003)									
Cambridge Systematics (2007)				✓	✓		✓		✓
Chen et al. (2010)									
DeSalvo (1967)									
Fekpe (2010)				✓	✓				✓
General Accounting Office (2003)			✓						
Harrison et al. (2010)						✓	✓		
Hay (1980)	✓	✓	✓	✓	✓				✓
Lai et al. (2009)			✓	✓					✓
Lubis et al. (2003)				✓			✓		✓
Machalaba (2011)									
Morgan et al. (2007)				✓		✓			✓
Prentice (2003)						✓			✓
Prozzi et al. (2006)				✓		✓		✓	
Resor et al. (2004)	✓	✓							
Seedah et al. (2010)	✓	✓	✓		✓				
Transportation Research Board National Research Council (1998)						✓		✓	

2.4 Chapter Summary

Creating a planning tool to evaluate the interplay of key variables is essential if planners are expected to understand the role that freight rail can play in supplementing economic growth (since much of rail operations are privately owned). A publicly available tool to easily analyze rail freight is essential. These operations are extremely difficult to model and can change vastly over time, making it necessary to create a user-friendly and highly adjustable tool that can account for changes in prices, technology, and other variables.

Finally, an implementation of the concept to corridor planning will be a great improvement to the current freight movement system. Examining freight movement from this perspective allows planners to see the system as a whole and improve it along specific corridors. This will also give insight into the strengths and advantages of shipping by rail as opposed to other modes such as trucking. US freight is moved on both domestic and global supply chains, through which international ports and gateways which connect origins to destinations in the most efficient manner. These connections and corridors must be evaluated and planned to maximize the efficiency of shipping freight.

The next chapter provides background information on the vehicle operating cost model used in the development of the truck-rail intermodal toolkit.

Chapter 3. Development of Vehicle Operating Cost Model and the Highway Improvement Model

As part the earlier TxDOT project 0-5974, "Estimating Texas Motor Vehicle Operating Costs," a truck operating cost model was developed to examine the impact of travel speeds, grades, fuel costs, financing, insurance, maintenance, and other fixed costs on truck movements along specified routes. This chapter of the report discusses the components that make up the vehicle operating cost model developed as part of the 0-5974 study, and discusses how methodologies presented in the 2010 Highway Capacity Manual (HCM) can be used in examining the influence of highway improvement strategies such as roadway expansion on travel conditions that subsequently affect trucking operations and costs.

3.1 Vehicle Operating Cost Model

In 2012, researchers at the Center for Transportation Research (CTR) at The University of Texas at Austin finalized a comprehensive vehicle operating cost toolkit, termed *CT-Vcost*, that allows planners to simulate truck movements over a specified corridor given factors such as truck weight, speed, grade, equipment depreciation, financing, insurance, maintenance costs, fuel cost, driver costs, road use fees (e.g., tolls), and other fixed costs—factors that influence truck operating costs and delivery time (Matthews et al., 2012). CT-Vcost is a comprehensive vehicle operating cost toolkit capable of producing an array of results that allows planners to better estimate the economic consequences of various engineering strategies. It provides operating cost estimates for specific representative vehicles or vehicle fleets and utilizes a unique vehicle identifier algorithm for data storage, cost calculations, and user interactions via its graphical user interface (Matthews et al., 2012).

The unique ID property also enables vehicles to retain their unique identities and data values when dealing with multiple vehicles, vehicle classes, and vehicle fleets (Matthews et al., 2012). Using default data from verified secondary vehicle cost data and certified vehicle databases such as the EPA's Fuel Economy database and Annual Certification Test Results databases, the model allows users to change parameters so that cost calculations are specific to any particular situation, and can be updated as the economic or technological landscape changes (Matthews et al., 2011).

Six main cost categories are included in CT-Vcost model: depreciation, financing, insurance, other fixed costs, repair and maintenance, and fuel. These costs fall into two categories: fixed and variable costs. The model provides operating cost estimates for each specific representative vehicle as well as fleets of vehicles. The model allows the user to change key parameters so that the cost calculation is specific to any particular situation, and can be updated as the economic or technological landscape changes. In addition, the impact of pavement roughness and traffic speeds (free flow and congestion) on vehicle operating costs is included in the CT-Vcost model. CT-Vcost also contains drive cycles of some of the major Texas corridors (e.g., IH-35) (Matthews et al., 2012).

The researchers developed a lightweight version of CT-Vcost for the intermodal truck-rail toolkit, limiting it to only truck movements. Data was stored in the toolkit's spreadsheet interface and transmitted to a CT-Vcost Lite executable file, and the output retransmitted back to the spreadsheet. Various components that make up the lite version of CT-Vcost are discussed in the following sections.

- **Diesel Price:** Users can specify the base diesel fuel price and this value is used in the calculation of the fuel cost accumulated for the route.
- **Diesel Tax:** Users can specify the current tax rate on a gallon of diesel fuel.
- **Annual Utilization:** The number of miles driven by the vehicle each year.
- Vehicle Maintenance Cost: This is the estimated annual maintenance cost incurred by the vehicle. It includes tire replacement, oil change, and both scheduled and unscheduled maintenance activities.
- **New Vehicle Price:** The user specifies the actual cost of purchasing the new vehicle. This is used in calculating the financing cost of truck as a percentage of the overall truck operating cost.

3.1.1 Depreciation

New vehicles are known to depreciate more in the first year of ownership than in subsequent years. For heavy-duty vehicles (HDVs), a constant 15% depreciation value is used as the default although this may vary substantially for different truck models and miles driven annually. The values for both first year and subsequent yearly depreciation can be edited by the user if empirical values are available.

Vehicle depreciation is calculated in two stages: 1) first-year depreciation, and 2) subsequent-year depreciation. The declining-balance method (reducing-balance method) is used. First-year depreciation is calculated as

$$Depreciation_1 = NewVehiclePrice \times Depreciation\ Rate_{first\ years} \quad \text{(Eq. 3.1)}$$

Subsequent year depreciation is calculated annually (i) as

$$Depreciation_i = Residual\ Value_{i-1} \times Depreciation\ Rate_{subsequent\ years} \quad \text{(Eq. 3.2)}$$

The following vehicle parameters are used: New Vehicle Price (MSRP), First Year Depreciation, and Subsequent Years Depreciation.

3.1.2 Finance

The cost of financing a vehicle is dependent on the cost of the new vehicle, the interest rate, the down payment amount, the term of the loan, and the credit score of the individual or group financing the vehicle (Welter et al., 2009). For HDVs, a 48-month lease term is used as large trucking companies tend to heavily use their new trucks (they can accumulate between 140,000 miles and 300,000 miles annually[7]) before selling them to smaller carriers.

Vehicle finance is calculated using the amortization formula:

$$A = P\frac{r(1+r)^n}{(1+r)^n - 1} \quad \text{(Eq. 3.3)}$$

[7] Depending on the utilization (sleeper cab, day cab, sleeper cab team, day cab with terminal switching)

where *A* is the payment amount per period (monthly), *P* is the initial principal (MSRP minus down payment), *r* is the interest rate per period (monthly), and *n* is the total number of payment periods (finance term in months). The following vehicle parameters are used in the code: *New Vehicle Price* (MSRP), *Down Payment, Interest Rate* (APR), and *Finance term.*

3.1.3 Insurance and Other Fixed Annual Costs (Registration and Permit Fees)

Insurance and other fixed annual cost (e.g., registration and permit fees) are calculated annually for each year in the analysis period, and included in the vehicle's annual operating cost. Users can specify the insurance cost associated with owning a truck. The HDV insurance cost based on industry estimates ranged from $4,000 to $7,500 annually.

3.1.4 Fuel Economy

Fuel consumption is calculated as a function of speed using at least two known points: city fuel economy (FE_{city}) and highway fuel economy (FE_{hwy}). The user specifies a vehicle speed that yields optimum fuel economy (v_o). Then, using Equations 3.2 and 3.3, the possible miles per gallon (MPG) estimates are derived. As illustrated in Figure 3.1, the slope-based approach, though simple and replicable for most vehicles, is not entirely accurate as the vehicle speed that yields optimum fuel economy varies between 25 to 55 miles per hour (MPH) when using actual fuel economy data[8].

$$\mathrm{FE}(V) = \begin{Bmatrix} (v * m) + mpg_{city} & if\ v \leq v_o \\ f(v_o) - m * (v - v_o) & if\ v > v_o \end{Bmatrix} \quad \text{(Eq. 3.4)}$$

where the slope (m) is defined as

$$m = \frac{mpg_{hwy} - mpg_{city}}{\bar{v}_{hwy} - \bar{v}_{city}} \quad \text{(Eq. 3.5)}$$

3.1.5 Driver Costs

CT-Vcost provides users with two alternatives for capturing driver cost: Hourly Driver Cost and Per Mile Driver Cost. Hourly driver cost is useful for capturing the cost of delay during congested conditions. This is useful for time-sensitive deliveries such as perishable and high value commodities. An industry average value in 2010 of 40.4¢ a mile is used for the per-mile driver cost[9].

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[8] B.H. West, R.N. McGill, J.W. Hodgson, S.S. Sluder, D.E. Smith, Development and Verification of Light-Duty Modal Emissions and Fuel Consumption Values for Traffic Models, Washington, DC, April 1997, and additional project data, April 1998. (Additional resources: www.fhwa-tsis.com)

[9] American Transportation Research Institute, "An Analysis of the Operational Costs of Trucking: A 2011 Update". Prepared by the American Transportation Research Institute, June 2011.

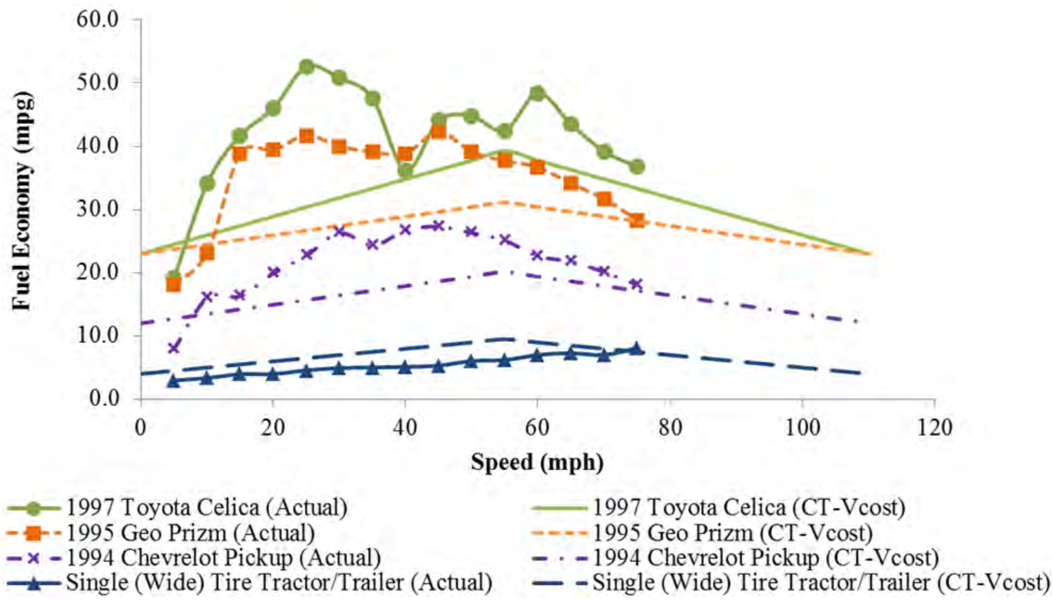

Figure 3.1: Comparison of Slope-Based Approach with Reported Fuel Economy Data (Matthews et al., 2011)

3.1.6 Route Cost Calculations

CT-Vcost calculates the route cost in two segments: 1) time-based route cost, and 2) route-conditions-based cost. The total per mile cost is the sum of the time-based route cost and the route-conditions-based cost. The following subsections further explain these two cost types.

3.1.7 Time-Based Route Cost

Time-based route costs are costs that do not vary despite the type of route used. These annual costs are paid by the driver, determined by the number of miles driven annually, and not necessarily the condition of the routes. Annual costs categorized as time-based per-mile include depreciation, finance, insurance, maintenance, and other costs (registration and permit fees). The per-mile costs of these are calculated by dividing the total cost of each item over the life of the vehicle by the total distance driven over the life of the vehicle. This results in a per-mile cost estimate over the life of the vehicle.

3.1.8 Route-Conditions-Based Cost

Route-conditions-based costs are determined by factors such as traffic congestion, traffic speeds, route distance, toll charges, pavement condition, and hourly and per-mile drive costs. Each cost item is independently determined for each section in the route for each vehicle, and the per-mile cost of the route is the weighted average of all the sections in that route (see Equation 3.6).

$$Item\ Cost_{per\ mile} = \frac{\sum_{i=section}^{Number\ of\ Sections}\left(Item\ Cost_{section\ cost\ per\ mile_{model}} \times Vehicle\ Count_{model}\right)}{Number\ of\ Sections} \quad \text{(Eq. 3.6)}$$

As discussed earlier in the Route Analysis module section of this report (Subsection 3.3.5), traffic congestion and traffic speeds determine fuel consumption (in MPG). Per mile fuel cost and fuel tax are determined by dividing the fuel price (or tax) by the calculated fuel economy at that travel speed for each section.

$$Fuel\ Cost_{section\ cost\ per\ mile} = \frac{Fuel\ Price}{MPG_{section}} \quad \text{(Eq. 3.7)}$$

$$Fuel\ Tax_{section\ cost\ per\ mile} = \frac{Fuel\ Tax}{MPG_{section}} \quad \text{(Eq. 3.8)}$$

Carbon footprint (CO_2 emissions) is calculated by multiplying fuel consumption by 19.4 lb (or 22.2 lb), the amount of CO_2 in every gallon of gasoline (or diesel).

Hourly driver cost is determined by traffic speeds and travel time. A user-specified hourly driver cost is multiplied by the travel time and divided by the distance travelled to determine the per-mile for each section.

$$Hourly\ Driver\ Cost_{section\ cost\ per\ mile} = \frac{Hourly\ Drive\ Cost \times Travel\ Time_{section}}{Distance_{section}} \quad \text{(Eq. 3.9)}$$

The per-mile driver drive cost is the same as the user-specified per-mile driver cost. Toll charges are applied on a per-mile basis by dividing the user-specified section toll by the length of the section.

$$Toll\ Cost_{section\ cost\ per\ mile} = \frac{Toll_{section}}{Distance_{section}} \quad \text{(Eq. 3.10)}$$

The total route cost is finally determined by summing the product of the per-mile route cost by the total route distance of each cost item.

$$Total\ Route\ Cost = \sum_{i\ =\ item}^{Number\ of\ Items} (Item\ Cost_{per\ mile} \times Total\ Route\ Distance) \quad \text{(Eq. 3.11)}$$

3.2 Highway Improvements Model

Based on the review of selected truck and highway improvement models, FREEVAL 2010 was chosen as the base model for the development of the highway improvement model. It provides a simple and straight forward methodology that can be employed by the research team in developing the Intermodal Toolkit. Though FREEVAL-2010 cannot be used as the final decision-maker for future roadway planning, it provides an opportunity for easier integration into the Toolkit for preliminary comparison of truck and rail intermodal flows.

3.2.1 Introduction to FREEVAL

FREEVAL (FREeway EVALuation) is a computerized, worksheet-based environment designed based on the HCM and used to perform operational analysis computations for Undersaturated and Oversaturated Directional Freeway Facilities (HCM, 2010[10]). HCM methodologies can be applied to various operations, design, preliminary engineering, and planning levels of analysis. FREEVAL-2010 is however limited to only basic freeway segments.

[10] HCM Chapter 10 and 25

FREEVAL-2010, the most recent version of the application allows users to define freeway segments and specify vehicle volumes at 15-minute time intervals. Vehicle speeds are then computed and the facility's volume-to-capacity ratio, demand-to-capacity ratio, segment speed, segment density, and LOS are given as output. Changes can then be made to the facility segments and rerun to determine new roadway measures of effectiveness.

It accounts for freeway weaving and merge and diverge segments (on-ramps and off-ramps). Below is a summarized description of the methodology used in FREEVAL-2010 as outlined in the HCM for evaluation of basic freeway segments, freeway weaving segments, and freeway merge and diverge segments.

3.2.2 HCM Methodology used in FREEVAL

The methodologies defined by the HCM and used in FREEVAL 2010 involve the following steps:

1. Demand, geometry, and time-space domain data must be specified by the user.
2. Demand is then adjusted according to spatial and time units established.
3. Segment capacities are then computed based on methodologies for basic freeway segments, weaving segments, and merge and diverge segments.
4. Segment capacities are then adjusted to account for rare conditions such as capacity changes caused by construction work zones, major maintenance operations, and weather and environmental conditions.
5. Undersaturated/oversaturated service measures and other performance measures are then computed.
6. The final step computes freeway facility service measures and other performance measures by time interval. Freeway facility LOS is defined for each time interval included in the analysis and an average density for each time interval, weighted by length of segments and number of lanes in segments, is calculated.

The Truck-Rail Intermodal Toolkit (TRIT) follows a similar methodology with variations based on expected availability of data by users of the toolkit. The following sections of this report outline the steps involved in highway improvement analysis of TRIT.

Step 1: Input Data

TRIT provides a graphical user interface that enables the user to specify the roadway geometry (segment type), segment length, number of lanes, entering and exiting flow rates, and expected traffic demand in 15-minute intervals (see Figure 3.2 and Tables 3.1 and 3.2). Available segment types include basic freeway segment, on-ramp segment, off-ramp segment, and weaving segments. Other data that need to be specified by the user include the following:

- Percentage of heavy vehicles: trucks and recreational vehicles (all movements)
- Unfamiliar driver populations (f_p)
- Free flow speed (FFS) (in MPH): all mainline segments
- Ramp FFS (in MPH): all ramps

- Acceleration lane length (in feet): all ramps
- Deceleration lane length (in feet): all ramps
- Jam density (D_{jam}): (in passenger cars per miles per lane)
- c_{IFL}: capacity of a basic freeway segment at FFS under equivalent ideal conditions (in passenger car per hour per lane): for FFS = 60 MPH
- Length of weaving segment (Ls) (in feet)
- Total ramp density (TRD) (in ramps per mile)
- Terrain type: level, mountainous, rolling
- Duration of analysis (in minutes): divided into a number of 15-minute intervals

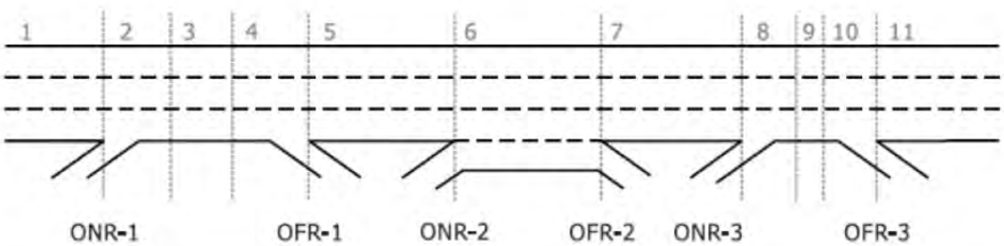

Figure 3.2: Sample Input Data Showing Roadway Geometry (HCM, 2010)

Table 3.1: Sample Input Data for Roadway Lengths and Number of Lanes (HCM, 2010)

Segment No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Segment type	B	ONR	B	OFR	B	B or W	B	ONR	R	OFR	B
Segment length (ft)	5,280	1,500	2,280	1,500	5,280	2,640	5,280	1,140	360	1,140	5,280
No. of lanes	3	3	3	3	3	4	3	3	3	3	3

Note: B = basic freeway segment, W = weaving segment, ONR = on-ramp (merge) segment, OFR = off-ramp (diverge) segment, R = overlapping ramp segment.

Table 3.2: Sample Traffic Demand Data in 15-Minute Increments (HCM, 2010)

Time Step (15 min)	Entering Flow Rate (veh/h)	Ramp Flow Rates by Time Period (veh/h)						Exiting Flow Rate (veh/h)
		ONR1	ONR2*	ONR3	OFR1	OFR2	OFR3	
1	4,505	450	540 (50)	450	270	360	270	5,045
2	4,955	540	720 (100)	540	360	360	270	5,765
3	5,225	630	810 (150)	630	270	360	450	6,215
4	4,685	360	360 (80)	450	270	360	270	4,955
5	3,785	180	270 (50)	270	270	180	180	3,875

*Numbers in parentheses indicate ONR-2 to ORF-2 demand flow rates in Weaving Segment 6.

Volumes in Table 3.2 represent the 15-minute demand flow rates on the facility as determined from field observations or other sources (HCM, 2010).

Step 2: Demand Adjustments

If the traffic flows provided in Table 3.2 are already actual demands, there is no need for adjustments. According to the HCM, demand adjustments are necessary only if field-measured volumes are used that may be affected by upstream congestion (bottleneck) on the facility (HCM, 2010).

Step 3: Compute Segment Capacities

Segment capacities in TRIT are computed using methodologies outlined in HCM Chapter 11 for basic freeway segments, Chapter 12 for weaving segments, and Chapter 13 for merge and diverge segments. Below is a summarized description of capacity is calculated in each of the segments.

Basic Freeway Segments

The first step is to estimate FFS using Equation 3.12, where $\boldsymbol{f_{LW}}$ is adjustment for land width (in MPH), $\boldsymbol{f_{LC}}$ is adjustment for right-side lateral clearance (in MPH), and TRD is total ramp density (ramps/mile).

$$\text{FFS} = 75.4 - f_{LW} - f_{LC} - 3.22TRD^{0.84} \quad \text{(Eq. 3.12)}$$

Adjustment for lane widths is determined using Table 3.3 and adjustment for lateral clearance is determined using Table 3.4. TRD is defined as the number of ramps (on and off, one direction) located between 3 miles upstream and 3 miles downstream of the midpoint of the basic freeway segment under study, divided by 6 miles (HCM, 2010). It is found to be a measure of the impact of merging and diverging vehicles on FFS (HCM, 2010).

Table 3.3: Adjustment to FFS for Average Lane Width (HCM, 2010)

Average Lane Width (ft)	Reduction in FFS, f_{LW} (mi/h)
≥ 12	0.0
≥ 11–12	1.9
≥ 10–11	6.6

Table 3.4: Adjustment to FFS for Right Side Lateral Clearance, f_{LC}, (mi/h) (HCM, 2010)

Right-Side Lateral Clearance (ft)	Lanes in One Direction			
	1	2	3	4
≥ 6	0.0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.0	2.0	1.0	0.5
0	3.6	2.4	1.2	0.6

The maximum service flow rate (MSFi) for the target LOS (LOS E is selected as it reflects the maximum capacity of the segment) is them determined from Table 3.5. Using the$\boldsymbol{MSF_i}$, the service flow rate (SFi) is determined as

$$\mathrm{SF}_i = MSF_i * \mathrm{N} * f_{HV} - f_p \qquad \text{(Eq. 3.13)}$$

where N is the number of lanes of the segment, $\boldsymbol{f_{HV}}$ is the heavy-vehicle adjustment factor (which is determined using Equation 3.14) and $\boldsymbol{f_p}$ is the adjustment factor for unfamiliar driver populations.

$$\mathrm{f}_{HV} = \frac{1}{1+P_T(E_T-1)+P_R(E_R-1)} \qquad \text{(Eq. 3.14)}$$

where $\boldsymbol{f_{HV}}$ = heavy-vehicle adjustment factor, P_T = proportion of trucks and buses in traffic stream, P_R = proportion of RVs in traffic stream, E_T = passenger-car equivalent (PCE) of one truck or bus in traffic stream, E_R = PCE of one RV in traffic stream

Table 3.5: Target LOS (HCM, 2010)

FFS (mi/h)	A	B	C	D	E
75	820	1,310	1,750	2,110	2,400
70	770	1,250	1,690	2,080	2,400
65	710	1,170	1,630	2,030	2,350
60	660	1,080	1,560	2,010	2,300
55	600	990	1,430	1,900	2,250

Note: All values rounded to the nearest 10 pc/h/ln.

The service flow rate ($\boldsymbol{SF_i}$) is then converted to service volume ($\mathbf{SV}_{\boldsymbol{i}}$) by applying a peak hour factor (PHF) as shown in Equation 3.15.

$$\mathbf{SV}_{\boldsymbol{i}} = \boldsymbol{SF_i} * \mathbf{PHF} \qquad \text{(Eq. 3.15)}$$

The service volume ($\mathbf{SV}_{\boldsymbol{i}}$) is equivalent to the capacity of the basic freeway segment.

On-Ramp and Off-Ramp Segments

For on-ramp and off-ramp segments, the user-specified demand volumes are first converted to demand flow rates using Equation 3.16:

$$\boldsymbol{v_i} = \frac{\boldsymbol{V_i}}{\boldsymbol{PHF * f_{HV} * f_p}} \qquad \text{(Eq. 3.16)}$$

where $\boldsymbol{v_i}$= demand flow rate for movement I (pc/h), $\boldsymbol{V_i}$ = demand volume for movement I (veh/h), PHF = peak hour factor, $\boldsymbol{f_{HV}}$ = adjustment factor for heavy vehicle presence, and $\boldsymbol{f_p}$ = adjustment factor for driver population. If demand data or forecasts are already stated as 15-minute flow rates, PHF is set at 1.00. Adjustment factors are the same as those used in Chapter 11, Basic Freeway Segments. These can also be used when the primary facility is a multilane highway or a C-D roadway in a freeway interchange.

The approaching flow rates in Lanes 1 and 2 of the freeway immediately upstream of the Ramp Influence Area (see Figure 3.3) are also estimated using Equations 3.17 and Equations 3.18.

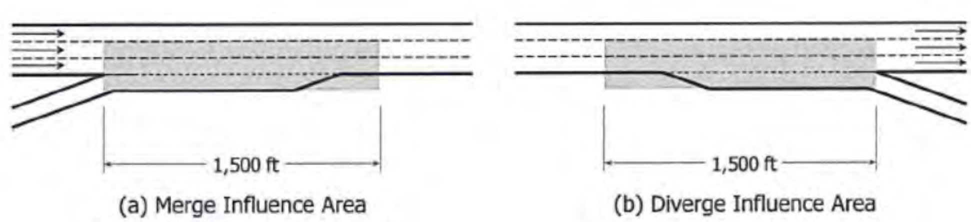

Figure 3.3: Ramp Influence Areas Illustrated (HCM, 2010)

$$\boldsymbol{v_{12} = v_F * \mathrm{P}_{FM}} \qquad \text{(Eq. 3.17)}$$

where $\boldsymbol{v_{12}}$= flow rate in Lanes 1 and 2 (pc/h), $\boldsymbol{v_F}$= total flow rate on freeway immediately upstream of the on-ramp (merge) influence area (pc/h), and P_{FM} proportion of freeway vehicles remaining in Lanes 1 and 2 immediately upstream of the on-ramp influence area.

$$\boldsymbol{v_{12} = v_R + (v_F - v_R)v * P_{FD}} \qquad \text{(Eq. 3.18)}$$

where $\boldsymbol{v_{12}}$ = flow rate in Lanes 1 and 2 of the freeway immediately upstream of the deceleration lane (pc/h), $\boldsymbol{v_R}$ = flow rate on the off-ramp (pc/h), and P_{FD} = proportion of diverging traffic remaining in Lanes 1 and 2 immediately upstream of the deceleration lane. A detailed description of how $\boldsymbol{P_{FM}}$ and $\boldsymbol{P_{FD}}$ is determined can be found in pages 14 to 17 of HCM Chapter 13 – Freeway Merge and Diverge Segments.

According to the HCM, these are the three major checkpoints for the capacity of a ramp-freeway junction:

1. The capacity of the freeway immediately downstream of an on-ramp or immediately upstream of an off-ramp,

2. The capacity of the ramp roadway, and

3. The maximum flow rate entering the ramp influence area.

In most cases, option 1—the freeway capacity—is the controlling factor and the capacity of the ramp roadway is rarely a factor at on-ramps though a problem for off-ramps. For off-ramps, total flow rate entering the ramp influence area is stated as the estimated value of v12. However, for on-ramps, the total flow entering the ramp influence area is a sum of v12 and the on-ramp flow (see Equation 3.19).

$$\boldsymbol{v_{R12} = v_{12} + v_R} \qquad \text{(Eq. 3.19)}$$

where $\boldsymbol{v_{R12}}$ is the total flow rate entering the ramp influence area at an on-ramp (pc/h) and all other variables are as previously defined.

Table 3.6 shows capacity values for ramp-freeway junctions. Table 3.7 shows capacity on high-speed ramps on multilane highways and C-D roadways within freeway interchanges. Table 3.8 shows the capacity of ramp roadways.

Table 3.6: Capacity of Ramp-Freeway Junctions (pc/h) (HCM, 2010)

FFS (mi/h)	1	2	3	>4	Max. Desirable Flow Rate (v_{R12}) Entering Merge Influence Area[b]	Max. Desirable Flow Rate (v_{12}) Entering Diverge Influence Area[b]
≥70	4,800	7,200	9,600	2,400/ln	4,600	4,400
65	4,700	7,050	9,400	2,350/ln	4,600	4,400
60	4,600	6,900	9,200	2,300/ln	4,600	4,400
55	4,500	6,750	9,000	2,250/ln	4,600	4,400

Notes: [a] Demand in excess of these capacities results in LOS F.
[b] Demand in excess of these values alone does not result in LOS F; operations may be worse than predicted by this methodology

Table 3.7: Capacity of High-Speed Ramp Junctions on Multilane Highways and C-D Roadways (pc/h) (HCM, 2010)

FFS (mi/h)	1	2	>3	Max. Desirable Flow Rate (v_{R12}) Entering Merge Influence Area[b]	Max. Desirable Flow Rate (v_{12}) Entering Diverge Influence Area[b]
≥60	4,400	6,600	2,200/ln	4,600	4,400
55	4,200	6,300	2,100/ln	4,600	4,400
50	4,000	6,000	2,000/ln	4,600	4,400
45	3,800	5,700	1,900/ln	4,600	4,400

Notes: [a] Demand in excess of these capacities results in LOS F.
[b] Demand in excess of these values alone does not result in LOS F; operations may be worse than predicted by this methodology

Table 3.8: Capacity of Ramp Roadways (pc/h) (HCM, 2010)

Ramp FFS S_{FR} (mi/h)	Capacity of Ramp Roadway	
	Single-Lane Ramps	Two-Lane Ramps
>50	3,540	1,974
>40–50	4,536	2,970
>30–40	5,584	4,018
≥20–30	6,681	5,115
<20	7,826	6,260

Note: Capacity of a ramp roadway does not ensure an equal capacity at its freeway or other high-speed junction. Junction capacity must be checked against criteria in Table 3.6 and Table 3.7.

Weaving Segments

TRIT only deals with one-sided weaving segments (see Figures 3.4 and 3.5) and follows the methodology as defined in the HCM 2010.

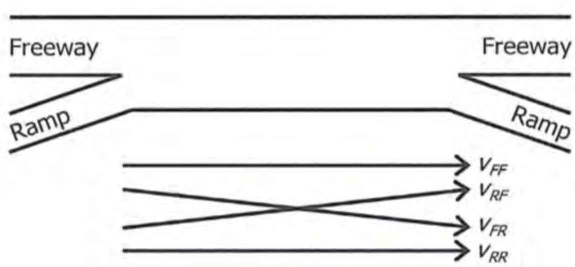

Figure 3.4: Weaving Variables for One-Sided Weaving Segments (HCM, 2010)

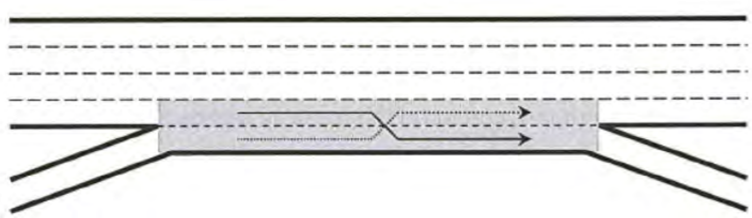

Figure 3.5: Weaving Segment for a Five-Lane Ramp (HCM, 2010)

Variables used in the determination of weaving segment capacities include the following:

$\boldsymbol{v_{FF}}$ = freeway-to-freeway demand flow rate in the weaving segment in passenger cars per hour (pc/h);

$\boldsymbol{v_{RF}}$ = ramp-to-freeway demand flow rate in the weaving segment (pc/h);

$\boldsymbol{v_{FR}}$ = freeway-to-ramp demand flow rate in the weaving segment (pc/h);

$\boldsymbol{v_{RR}}$ = ramp-to-ramp demand flow rate in the weaving segment (pc/h);

$\boldsymbol{v_W}$ = weaving demand flow rate in the weaving segment (pc/h), $\boldsymbol{v_W = v_{RF} + v_{FR}}$;

$\boldsymbol{v_{NW}}$ = nonweaving demand flow rate in the weaving segment (pc/h), $\boldsymbol{v_{NW} = v_{FF} + v_{RR}}$;

$\boldsymbol{v}$ = total demand flow rate in the weaving segment (pc/h), $\boldsymbol{v = v_W + v_{NW}}$;

VR = volume ratio, $^{v_W}/_{v}$;

N = number of lanes within the weaving section;

$\boldsymbol{N_{WL}}$= number of lanes from which a weaving maneuver may be made with one or no lane changes;

$\boldsymbol{S_W}$ = average speed of weaving vehicles within the weaving segment (mi/h);

$\boldsymbol{S_{NW}}$ = average speed of nonweaving vehicles within the weaving segment (mi/h);

S = average speed of all vehicles within the weaving segment (mi/h);

FFS = free-flow speed of the weaving segment (mi/h);

D = average density of all vehicles within the weaving segment in passenger cars per mile per lane (pc/mi/ln);

W = weaving intensity factor;

$\boldsymbol{L_S}$ = length of the weaving segment (ft), based on the short length definition of Exhibit 12-2 of the HCM;

$\boldsymbol{LC_{RF}}$ = minimum number of lane changes that must be made by a single weaving vehicle moving from the on-ramp to the freeway;

$\boldsymbol{LC_{FR}}$ = minimum number of lane changes that must be made by a single weaving vehicle moving from the freeway to the off-ramp;

$\boldsymbol{LC_{MIN}}$=minimum rate of lane changing that must exist for all weaving vehicles to complete their weaving maneuvers successfully, in lane changes per hour (lc/h), $\boldsymbol{LC_{MIN} = (LC_{RF} * v_{RF}) + (LC_{FR} * \ v_{FR})}$

$\boldsymbol{LC_W}$ = total rate of lane changing by weaving vehicles within the weaving segment (lc/h);

$\boldsymbol{LC_{NW}}$= total rate of lane changing by nonweaving vehicles within the weaving segment (lc/h);

$\boldsymbol{LC_{ALL}}$= total rate of lane changing of all vehicles within the weaving segment (lc/h), $\boldsymbol{LC_{ALL} = LC_W + LC_{NW}}$

ID = interchange density, the number of interchanges within ± 3 mi of the center of the subject weaving segment divided by 6, in interchanges per mil (int/mi); and

$\boldsymbol{I_{LC}}$ = lane-changing intensity, $^{\boldsymbol{LC_{ALL}}}/_{\boldsymbol{L_S}}$, in lane changes per fool (lc/ft).

First off, demand flow rates for freeway to freeway (FF), freeway to ramp (FR), ramp to freeway (RF) and ramp to ramp (RR) flows are determined using Equation 3.20.

$$v_i = \frac{V_i}{PHF * f_{HV} * f_p} \qquad \text{(Eq. 3.20)}$$

where v_i= flow rate under ideal conditions, V_i = hourly volume for flow i under prevailing conditions in vehicles per hour (veh/h), PHF = peak hour factor, f_{HV} = adjustment factor for heavy vehicle presence, and f_p = adjustment factor for driver population. Flow rates are computed for freeway to freeway flows (FF), freeway to ramp flows (FR), ramp to freeway flows (RF), ramp to ramp flows (RR), weaving traffic (W) and nonweaving traffic (NW).

For one-sided weaving segments, the minimum rate at which weaving vehicles must change lanes to complete all weaving maneuvers successfully, LC_{MIN}, in lc/h is then determined using Equation 3.21.

$$LC_{MIN} = (\mathbf{LC_{RF}} * \ v_{\mathbf{RF}}) + (\mathbf{LC_{FR}} * \ v_{\mathbf{FR}}) \qquad \text{(Eq. 3.21)}$$

where LC_{RF} = minimum number of lane changes that must be made by one ramp-to-freeway vehicle to execute the desired maneuver successfully, and LC_{FR} = minimum number of lane changes that must be made by one freeway-to-ramp vehicle to execute the desired maneuver successfully. For one-sided weaving segments, the value of N_{WL} is either 2 or 4. The determination is made by a review of the geometric design and the configuration of the segment, as illustrated in Exhibit 12-5 of the HCM.

The maximum weaving length (L_{MAX}) is then determined using Equation 3.22.

$$L_{MAX} = [5,728(1 + \mathbf{VR})^{1.6} - [1,566N_{WL}] \qquad \text{(Eq. 3.22)}$$

where N_{WL} = number of lanes from which weaving maneuvers may be made with either one or no lane changes. VR is the variation of weaving length versus volume ratio and number of weaving lanes (ft). VR is determined from Equation 3.23 and Table 3.9.

$$\text{VR} = v_W/v \qquad \text{(Eq. 3.23)}$$

Table 3.9: Variation of Weaving Length versus Volume Ratio and Number of Weaving Lanes (HCM, 2010)

VR	Number of Weaving Lanes	
	N_{WL} = 2	N_{WL} = 3
0.1	3,540	1,974
0.2	4,536	2,970
0.3	5,584	4,018
0.4	6,681	5,115
0.5	7,826	6,260
0.6	9,019	7,453
0.7	10,256	8,690
0.8	11,538	9,972

The value of $\boldsymbol{L_{MAX}}$ is then used to determine whether continued analysis of the configuration as a weaving segment is justified or not:

If $\boldsymbol{L_S} < \boldsymbol{L_{MAX}}$, then the segment should be analyzed as a weaving segment
If $\boldsymbol{L_S} \geq \boldsymbol{L_{MAX}}$, then the segment should be analyzed as separate merge and diverge junctions using the methodology described earlier for on- and off- ramps.

If the segment is determined to be a weaving segment, then capacity can be determined based on one of the two conditions:

1. Breakdown of a weaving segment is expected to occur when the average density of all vehicles in the segment reaches 43 pc/mi/ln; or
2. Breakdown of a weaving segment is expected when the total weaving demand flow rate exceeds 2,400 pc/h for cases in which $\boldsymbol{N_{WL}}$ = 2 lanes, or 3,500 pc/h for cases in which $\boldsymbol{N_{WL}}$ = 3 lanes.

Weaving Segment Capacity Determine by Density: The capacity of a weaving segment, based on reaching a density of 43 pc/mi/ln, is estimated using Equation 3.24.

$$C_{IWL} = C_{IFL} - [438.2(1 + \mathrm{VR})^{1.6}] + [0.0765L_S] + [119.8N_{WL}] \qquad \text{(Eq. 3.24)}$$

where C_{IWL} = capacity of the weaving segment under equivalent ideal conditions, per lane (pc/h/ln), and C_{IFL} = capacity of a basic freeway segment with the same FFS as the weaving segment under equivalent ideal conditions, per lane (pc/h/ln).

C_{IWL} is then converted to total capacity under prevailing conditions using Equation 3.25.

$$\boldsymbol{c_W = c_{IWL} * \mathbf{N} * \mathbf{f}_{HV} * \mathbf{f}_p} \qquad \text{(Eq. 3.25)}$$

where c_w is the capacity of the weaving segment under prevailing conditions in vehicles per hour. As with all capacities, it is stated as a flow rate for a 15-minute analysis period.

Weaving Segment Capacity Determine by Weaving Demand Flows: The capacity controlled by the maximum weaving flow rates as defined in Table 3.9 above is found from these equations:

$$\mathrm{c_{IW}} = \frac{2{,}400}{\mathrm{VR}} \text{ for } \mathrm{N_{WL}} = 2 \text{ lanes} \qquad \text{(Eq. 3.26)}$$
$$\mathrm{c_{IW}} = \frac{3{,}500}{\mathrm{VR}} \text{ for } \mathrm{N_{WL}} = 3 \text{ lanes} \qquad \text{(Eq. 3.27)}$$

where $\mathbf{c_{IW}}$ is the capacity of all lanes in the weaving segment under ideal conditions in passenger cars per hour, and all other variables are as previously defined. This value must be converted to prevailing conditions by using Equation 3.28:

$$c_W = c_{IW} * \mathrm{f}_{HV} * \mathrm{f}_p \qquad \text{(Eq. 3.28)}$$

Final capacity is the smaller of the two estimates of Equation 3.25 and 3.28.

Step 4: Adjust Segment Capacities

After segment capacities are determined for all the segments being analyzed, the capacities can be adjusted to account for the effects of short-term work zones, long-term construction, inclement weather conditions, or incidents. This feature is however not included in TRIT.

Step 5: Computed Demand-to-Capacity Ratios

Demand-to-capacity ratios are then determined by dividing the demand volumes by the roadway segment capacities determined in Step 3:

$$Demand\ to\ capacity\ ratio\ = \frac{v_d}{c} \tag{Eq. 3.29}$$

Step 6a: Compute Undersaturated Segment Service Measures

If the facility is globally undersaturated—that is, the v/c ratios are all less than 1.0—then TRIT calculates the speeds on the segment as outlined in Chapters 11, 12, and 13 of the HCM.

Basic Freeway Segments

At capacity, the speed of a basic freeway segment can be determined using the Equation 3.30 and Table 3.10:

$$\boldsymbol{S = FFS - K_f(v_p - Breakpoint)} \tag{Eq. 3.30}$$

Table 3.10: Equations Describing Speed-Flow Curves (speeds in MPH) (HCM, 2010)

FFS (mi/h)	Flow Rate Range		
	Breakpoint (pc/h/ln)	≥0≤ Breakpoint	> Breakpoints ≤ Capacity
75	1,000	75	$75 - 0.00001107(v_p - 1{,}000)^2$
70	1,200	70	$70 - 0.00001160(v_p - 1{,}200)^2$
65	1,400	65	$65 - 0.00001418(v_p - 1{,}400)^2$
60	1,600	60	$60 - 0.00001816(v_p - 1{,}600)^2$
55	1,800	55	$55 - 0.00002469(v_p - 1{,}800)^2$

Notes: FFS = free-flow speed, v_p = demand flow rate (pc/h/ln) under equivalent base conditions. Maximum flow rate for the equations is capacity: 2,400 pc/h/ln for 70 and 75 MPH FFS; 2,350 pc/h/ln for 65 MPH FFS; 2,300 pc/h/ln for 60 MPH FFS; and 2,250 pc/h/ln for 55 MPH FFS

On-Ramp and Off-Ramp Segments

According to the HCM, two types of speeds can be estimated for ramp segments:

- Average speed of vehicles within the ramp influence area (MPH), and

- Average speed of vehicles across all lanes (including outer lanes) within 1,500 ft. length of the ramp influence area (MPH)

Both types of speeds are needed when a freeway facility analysis is conducted. The first type of speed provides a useful companion measure to density within the ramp influence area in all cares. Tables 3.11 and 3.12 provided equations for estimating the average speed of vehicles (a) within the ramp influence area, and (b) in outer lanes of the freeway adjacent to the 1,500-ft ramp influence area. For four-lane freeways (two lanes in each direction), there are no "outer lanes." For six-lane freeways (three lanes in each direction), there is one outer lane (Lane 3). For eight-lane freeways (four lanes in each direction), there are two outer lanes (Lanes 3 and 4) (HCM, 2010).

Table 3.11: Estimating Speed at On-Ramp (Merge) Junctions (HCM, 2010)

Average Speed in	Equation
Ramp influence area	$S_R = FFS - (FFS - 42)M_S$ $M_S = 0.321 + 0.0039e^{(v_{R12/1,000})} - 0.002\ (L_A S_{FR}/1{,}000)$
Outer lanes of freeway	$S_C = FFS \qquad v_{OA} < 500\ pc/h$ $S_C = FFS - 0.0036(v_{OA} - 500) \qquad 500\ pc/h \le v_{OA} \le 2{,}300\ pc/h$ $S_C = FFS - 6.53 - 0.006(v_{OA} - 2{,}300) \qquad v_{OA} > 2{,}300\ pc/h$

Table 3.12: Estimating Speed at Off-Ramp (Diverge) Junctions (HCM, 2010)

Average Speed in	Equation
Ramp influence area	$S_R = FFS - (FFS - 42)D_S$ $D_S = 0.883 + 0.00009v_R - 0.013S_{FR}$
Outer lanes of freeway	$S_O = 1.097FFS \qquad v_{OA} < 1{,}000\ pc/h$ $S_C = 1.097FFS - 0.0039(v_{OA} - 1{,}000) \qquad v_{OA} \ge 1{,}000\ pc/h$

Table 3.13 provides equations to determine the average speed of all vehicles (ramp plus all freeway vehicles) within the 1,500-ft length of the ramp influence area.

Table 3.13: Estimating Average Speed of All Vehicles at Ramp-Freeway Junctions (HCM, 2010)

Value	Equation
Average flow in outer lanes $\boldsymbol{v_{OA}}$ (pc/h)	$v_{OA} = \dfrac{v_f - v_{12}}{N_O}$
Average speed for on-ramp (merge) junctions (mi/h)	$S = \dfrac{v_{R12} - v_{OA}N_O}{(\frac{v_{R12}}{S_R}) + (\frac{v_{OA}N_O}{S_O})}$
Average speed for off-ramp (diverge) junctions (mi/h)	$S = \dfrac{v_{12} - v_{OA}N_O}{(\frac{v_{12}}{S_R}) + (\frac{v_{OA}N_O}{S_O})}$

It is to be noted that the equations in Tables 3.11, 3.12, and 3.13 apply only to cases in which operation is stable (LOS A – E). Analysis of operational details for cases in which LOS F is present relies on deterministic queuing approaches, as presented in the over saturated section of this report. Following are the definitions of the variables presented in Tables 3.11, 3.12, and 3.13:

S_R = average speed of vehicles within the ramp influence area (mi/h); for merge areas, this includes all ramp and freeway vehicles in Lanes 1 and 2; for diverge areas, this includes all vehicles in Lanes 1 and 2;

S_O = average speed of vehicles in outer lanes of the freeway, adjacent to the 1,500-ft ramp influence area (mi/h);

S = average speed of all vehicles in all lanes within the 1,500-ft length covered by the ramp influence area (mi/h);

FFS = free-flow speed of the freeway (mi/h);

SFR = FFS of the ramp (mi/h);

LA = length of acceleration lane (ft);

LD = length of deceleration lane (ft);

v_R = demand flow rate on ramp (pc/h);

v_{12} = demand flow rate in Lanes 1 and 2 of the freeway immediately upstream of the ramp influence area (pc/h);

v_{R12} = total demand flow rate entering the on-ramp influence area, including v_{12} and v_R (pc/h);

v_{OA} = average demand flow per lane in outer lanes adjacent to the ramp influence area (not including flow in Lanes 1 and 2) (pc/h/ln);

v_F = demand flow rate on freeway immediately upstream of the ramp influence area (pc/h);

NO = number of outer lanes on the freeway (1 for a six-lane freeway; 2 for an eight-lane freeway);

MS = speed index for on-ramps (merge areas); this is simply an intermediate computation that simplifies the equations.

Ds = speed index for off-ramps (diverge areas); this is simply an intermediate computation that simplifies the equations.

Weaving Segments

The steps in determining the speeds on weaving segments are described in pages 12-18 to 12-22 of the HCM. A summarized description of those steps is presented below. For further details on the equations used below, please refer to HCM 2010.

To determine vehicle speeds on weaving segments, the lane-changing rates of weaving and nonweaving vehicles need to be determined. Lane changes may be optional or required for weaving vehicles but are only optional for nonweaving vehicles.

Estimating the Total Lane-Changing rate for Weaving Vehicles: Lane-changing rate for weaving vehicles is determined using Equation 3.31:

$$LC_W = LC_{MIN} + 0.39[(L_S - 300)^{0.5} N^2 (1 + ID)^{0.8}] \quad \text{(Eq. 3.31)}$$

where

LC_W = equivalent hourly rate at which weaving vehicles make lane changes within the weaving segment (lc/h);
LC_{MIN} = minimum equivalent hourly rate at which weaving vehicles must make lane changes within the weaving segment to complete all weaving maneuvers successfully (lc/h);
L_S = length of the weaving segment, using the short length definition (ft.) (300 ft. is the minimum value);
N = number of lanes within the weaving segment, and
ID = interchange density (int/mi).

Estimating the Total Lane-Changing rate for Nonweaving Vehicles: Lane-changing rate for nonweaving vehicles is determined using Equations 3.32 where I_{NW} (nonweaving vehicle index) is an index that measures the tendency of conditions to induce unusually large nonweaving vehicle lane-changing rates:

$$I_{NW} = \frac{L_S \times ID \times v_{NW}}{10{,}000} \quad \text{(Eq. 3.32)}$$

If I_{NW} is less than or equal to 1,300—i.e., normal lane-changing characteristics are expected—then the lane changing rate per hour (LC_{NW1}) for nonweaving vehicles is computed as in Equation 3.33:

$$LC_{NW1} = (0.206 v_{NW}) + (0.542 L_S) - (192.6 N) \quad \text{(Eq. 3.33)}$$

For cases in which a combination of high nonweaving demand flow, high interchange density, and long segment length produce extraordinarily high nonweaving lane-changing rates—i.e., I_{NW} is greater than or equal to 1,950—the lane-changing rate per hour (LC_{NW2}) is determined as in Equation 3.34:

$$LC_{NW2} = 2{,}135 + 0.223(v_{NW} - 2{,}000) \qquad \text{(Eq. 3.34)}$$

If the nonweaving index (I_{NW}) is between 1,300 and 1,950, a straight interpolation between the values of LC_{NW1} and LC_{NW2} is used as shown in Equation 3.35, where LC_{NW3} is the lane-changing rate per hour.

$$LC_{NW3} = LC_{NW1} + (LC_{NW2} - LC_{NW1})\left(\frac{I_{NW} - 1{,}300}{650}\right) \qquad \text{(Eq. 3.35)}$$

<u>Total Lane-Changing Rate</u>: Total lane changing rate LC_{ALL} for vehicles in the weaving segment, in lane changers per hour, is determined as in Equation 3.36:

$$LC_{ALL} = LC_W + LC_{NW} \qquad \text{(Eq. 3.36)}$$

<u>Average Speed of Weaving Vehicles:</u> The average speed (S_W) of the weaving vehicles is then determined using Equations 3.37 and 3.38 where *W* is the weaving intensity factor.

$$S_W = 15 + \left(\frac{FFS - 15}{1 + W}\right) \qquad \text{(Eq. 3.37)}$$

$$W = 0.226\left(\frac{LC_{ALL}}{L_S}\right)^{0.789} \qquad \text{(Eq. 3.38)}$$

<u>Average Speed of Nonweaving Vehicles:</u> For nonweaving vehicles, average speed ($\boldsymbol{S_{NW}}$) is determined as in Equation 3.39:

$$S_{NW} = FFS - (0.0072 LC_{MIN}) - \left(0.0048\frac{v}{N}\right) \qquad \text{(Eq. 3.39)}$$

<u>Average Speed of Nonweaving Vehicles: </u>The average speed of all vehicles in the weaving segment is thus:

$$\boldsymbol{S} = \frac{v_W + v_{NW}}{\left(\frac{v_W}{S_W}\right) + \left(\frac{v_{NW}}{S_{NW}}\right)} \qquad \text{(Eq. 3.40)}$$

Step 6b: Compute Oversaturated Segment Service Measures

According to HCM 2010, oversaturated flow condition occurs when the demand on one or more freeway segment cells exceeds the capacity. The methodology for modeling oversaturated flows is more complicated than undersaturated flows because "spatial units become nodes and segments, and the temporal unit moves from a time interval to smaller time steps." This feature is currently is not integrated into TRIT.

Step 7: Integration into CT-Vcost Lite

After the speeds are determined for the various segments of the roadway, the data is submitted back to TRIT, which in turn sends it to CT-Vcost Lite. CT-Vcost Lite then determines vehicle operating cost parameters for each user-specified 15-minute time interval. The output includes per-mile depreciation, finance, fixed, insurance, commercial truck driver, and fuel costs. Total route cost and the amount of fuel consumed are also calculated.

Methodology Limitations

The HCM analysis of freeway facilities methodology used in TRIT is limited in its scope. As stated in the manual:

1. The methodology does not account for delays caused by vehicles using alternative routes or vehicles leaving before or after the analysis period.
2. Multiple overlapping breakdowns or bottlenecks are difficult to analyze and cannot be fully evaluated by this methodology. [Advanced traffic analysis tools such stochastic, deterministic, static flow and time-varying flow models for simulation can be used for specific applications beyond the capabilities of the methodology.]
3. Spatial, temporal, modal, and total demand responses to traffic management strategies are not automatically incorporated into the methodology. On viewing the facility traffic performance results, the analyst can modify the demand input manually to analyze the effect of user-demand responses and traffic growth. The accuracy of the results depends on the accuracy of the estimation of user-demand responses.
4. The methodology can address local oversaturated flow but cannot directly address system-wide oversaturation flow conditions.
5. The completeness of the analysis will be limited if freeway segments in the first time interval, the last time interval, and the first freeway segment (in all time periods) have demand-to-capacity ratios greater than 1.00…
6. The methodology does not directly address separated HOV facilities and does not account for the interactions between HOV lanes and mixed-flow lanes and the weaving that may be produced.
7. The method does not address conditions in which off-ramp capacity limitations result in queues that extend onto the freeway or affect the behavior of off-ramp vehicles.
8. The method does not address toll plaza operations or their effect on freeway facility operations.

3.3 Chapter Summary

This chapter outlined how CT-Vcost was integrated into TRIT. The researchers developed an abridged version of CT-Vcost (CT-Vcost Lite) that uses input data from the toolkit's spreadsheet interface and transmits it to the model. The output from the model is then transmitted back to the spreadsheet. Output from CT-Vcost includes per-mile costs for depreciation, finance, fixed, insurance, commercial truck driver, and fuel consumption. Total route cost and travel time is also calculated.

In addition, a relatively simple and straight forward methodology developed in the HCM was employed by the research team in developing the highway improvement model. Though the model cannot be used as the final decision-maker for future roadway planning, it provides an opportunity for easier integration into the Toolkit for preliminary comparison of truck and rail intermodal flows. Freeway facility service measures and segment speeds by time interval are computed in the model and this data is then fed into CT-Vcost Lite. CT-Vcost Lite then processes the data and determines truck operating costs for the various time intervals relative to the speeds computed in the highway improvement model. The next chapter describes the current state of rail modeling and improvements that can be made to existing models in order to satisfy the needs of this study.

Chapter 4. Current State of Rail Models

Planners encounter difficulties in estimating rail line haul movement operations for specific corridors due to inadequate data and a limited insight into how railroads function. Actual rail cost models are few in number and can require finesse in deriving good estimates. The following rail models are described in detail, including their limitations as well as improvements that can be made to the models. Descriptions of the models are taken from existing literature and cited accordingly.

4.1 Rail Models

4.1.1 Uniform Rail Costing System[11]

The Uniform Rail Costing System (URCS) is the Surface Transportation Board's (STB) railroad general purpose costing system that is used to estimate variable and total unit costs for Class I US rail lines. It is the official tool used by the STB and serves as its first point of reference for rail operations studies. The URCS model can be used for costing specific traffic with less concern for economic characteristics (Bereskin, 2001). URCS uses system average units based on costs relationships and system data for Class I railroads. The data is updated annually by the STB; however, the basic structure of the model remains as it was when it was developed decades ago and does not reflect modern railroad operations. For example, there is no clear way to delineate double-stack intermodal as this technology was not widespread at the time of the model's development. For several reasons, the cost estimation method used by URCS is not entirely accurate. Four primary problems have been identified by researchers. First, the model uses linear "percent variable" equations to allocate expenses to specific operating activities based on a cross-sectional regression of cost data against traffic data for the Class I railroads of the 1980s, using a several-year time series. The equations therefore do not account for recent industry changes (e.g., mergers, increasing size, and traffic carried) which have affected operational costs of railroads (Bereskin, 2001). Furthermore, the linear nature of the model is contrary to the earlier stated finding that rail costs are non-linear in nature.

Secondly, URCS uses system averages based on data collected from Class I railroads. It "uses an accounting-based approach to costing, relying on annual operating expenses and traffic data reported by the railroads. This approach provides cost estimates on the average cost structure of individual railroads or regionalized groups of railroads. Average data on average railroad moves may not, in all cases, be appropriate for estimating a cost for a given railroad movement" (URCS Manual). System averages may not reflect the actual railroad rates charged by carriers, and may not reflect geographical location, technological improvements, and system performance (AECOM, 2007). However, URCS gives users the flexibility of substituting cost data developed by the STB with user-generated cost.

The third primary problem with URCS is that it does not account for changes in fuel prices. The model does not have an input for fuel cost which we believe has a major influence in freight rail service rates.

Finally, URCS does not have the ability to estimate emissions produced during line-haul operations. This capability is essential for comparison with other transport modes (such as

[11] Taken from Seedah, Dan and Robert Harrison (2010), "Export Growth, Energy Costs, and Sustainable Supply Chains," Southwest Region University Transportation Center Report No. 476660-00069-1.

trucks); having this ability in a single model makes it easier for researchers to test different scenarios. Recently the STB announced its intention to begin the process of replacing the URCS model due to its well-known limitations. This initiative, created under chairman-elect Mulvey, started with a hearing at the STB on April 30, 2009.

4.1.2 Train Energy Model[12]

The Train Energy Model (TEM) developed under the Association of American Railroads (AAR) Energy Program is a train-performance simulator used to predict fuel consumption for any train on any route. It simulates the energy required to run a specific train over a specific route. Route data can be imported into the program and locomotive type, car type, lading weight and operating requirements for a consist can be specified. The program simulates the characteristics of the train over the route and the simulation acts in the role of an engineer by adjusting the throttle and brake applications to keep the train under the speed limit while avoiding unduly large draft and buff forces (Painter, 2004).

According to Painter (2004), train consists and ladings are configurable via a graphical interface and different locomotive and car types can be chosen to replicate the consists seen in service. New car types that are not included in the program can also be created using graphical tools (Painter, 2004).

An additional feature in TEM is the ability to import routes based on actual data that includes speed limits, grades, and curves. These routes can then be used in the simulation of any consist that has also been created (Painter, 2004). The train control can be modified to simulate starts and stops or to limit operation to only a portion of the track segment.

After a simulation has been run, the train speed and track speed limit are displayed as a function of the milepost along the track for the segment simulated (Figure 4.1). Further information about the energy usage of the train and its speed at a given time is available to enable an in-depth analysis. TEM also produces a summary report that includes the "WORK DONE by EACH FORCE" which represents the energy produced by each simulated force acting on the train (Painter, 2004).

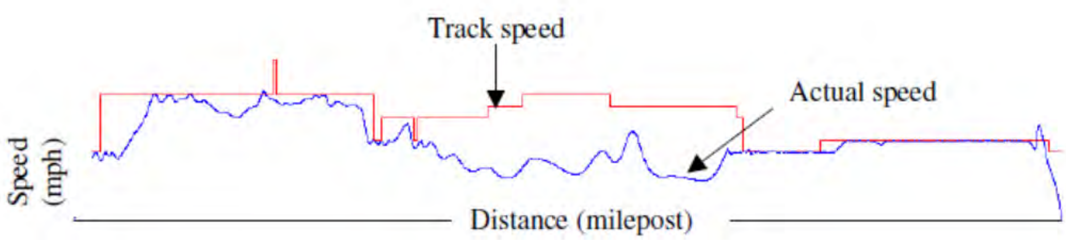

Figure 4.1: Example of Speed Profile Output from TEM (Painter, 2004)

Despite the capabilities of TEM, the software is not publicly available and the research team's efforts to obtain a copy were futile. The developers assert that the model is available only to railroads but can be used to validate new models.

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[12] Recovering Railroad Diesel-Electric Locomotive Dynamic Brake Energy By Travis D. Painter B.S., University Of Illinois At Urbana-Champaign, 2004 Thesis, Urbana, Illinois.

4.1.3 Train Operation and Energy Simulator (TOES™)[13]

The AAR's Train Operation and Energy Simulator (TOES™) simulates the interaction of train air-brake and ECP-brake systems, inter-car coupling behavior, locomotive performance characteristics, and train resistance forces. According to the TOES website, TOES has been validated numerous times in heavy North American freight trains and the software was applied to passenger and transit systems due to its ability to predict braking system response and stopping distance (AAR, 2008). TOES "allows the user to predict and analyze the response from various throttle and brake commands, and may be used to evaluate a vehicles response to in-train forces. The software applies a set of two complex operations: A non-linear fluid dynamics model of automatic and independent air brake systems and non-linear models of friction draft gear and end-of-car cushioning units. TOES is therefore very useful in derailment prevention and analysis work."

Typical TOES applications as listed on the website (http://www.aar.com/toes/) include accident or incident investigation; stopping distance investigations; coupler force monitoring; prediction of vehicle longitudinal accelerations; evaluation of train make-up strategies; evaluation of train handling studies; comparison of new track layouts; prediction of car fatigue damage; evaluation of new equipment; and examination of train make-up (AAR, 2008).

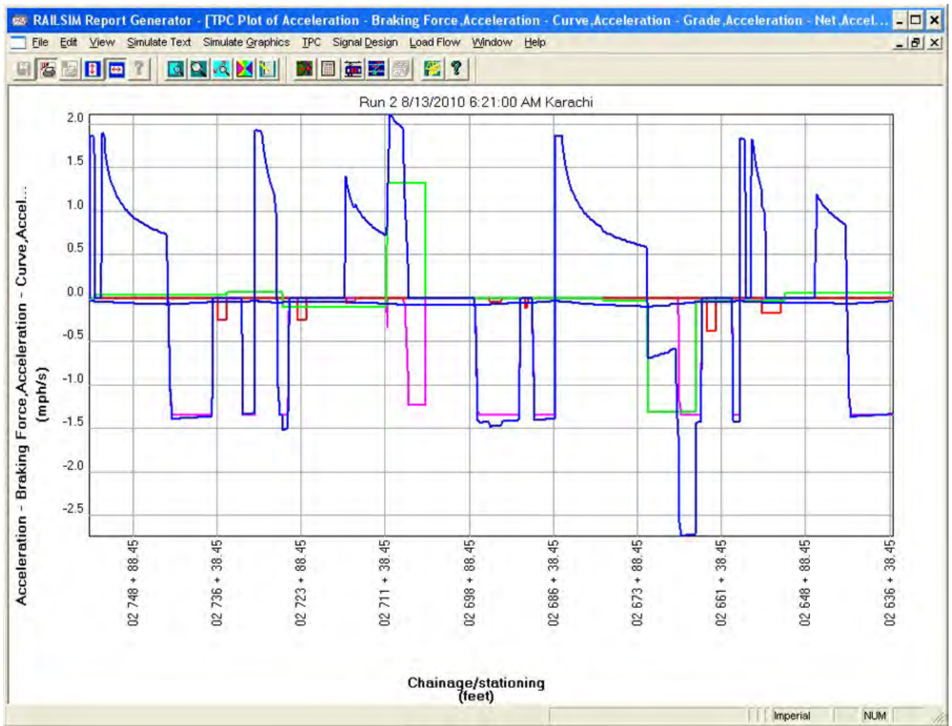
4.1.4 RailSim[14]

RailSim is a commercial suite of modules developed by SYSTRA for complete evaluation of railroad operations. Modules include Train Performance Calculator (TPC), RAILSIM Editor, Network Simulator, Load Flow Analyzer, Headway Calculator, Safe Braking Calculator, Control Line Generator, and supporting modules. According to SYSTRA's website, RailSim's TPC is capable of

- calculating curve speed limits where engineering calculations are not available,
- analyzing skip-stop operations, alternative stopping patterns, and the impacts of global or station-specific dwell time improvements,
- calculating peak power and energy consumption to evaluate energy savings from coasting strategies and more energy-efficient rolling stock,
- comparing the performance and trip times of different rolling stock models, including off-the-shelf and custom-built models,
- determining power to weight ratios under a variety of adhesion conditions where severe grades and curves are an issue, and
- evaluating trip time adjustments when low adhesion conditions prevail.

Figure 4.2 provides a screenshot of RailSim's TPC train plot of acceleration. RailSim is widely used and well recognized by the industry. Its main disadvantage is that it's proprietary and relatively expensive to acquire.

[13] http://www.aar.com/toes/downloads.asp
[14] RailSim, Systra RailSim, http://railsim.com/modules.html (accessed June 2012)



Source Railsim.com

Figure 4.2: RailSim's TPC Train Plot of Acceleration

4.1.5 CTRail

CTRail is a user-friendly mechanistic intermodal rail cost model developed by CTR that enables stakeholders to measure operational differences between trailers on flat car and double-stacked containers in intermodal service. It allows for the calculation of gallons of fuel consumed, greenhouse gas emissions produced, the effect of operational differences when using multiple locomotives or car types, and the influence of delay, and other route-specific characteristics such as grade changes and road curvature.

The initial intermodal model is mechanistic in nature and uses as inputs various factors such as cargo weight, energy consumption, and expert estimates of maintenance and crew labor costs. CTRail is divided into eight costing or analysis modules:

1. Cargo Weight, Number of Containers, and Rail Car Configuration,
2. Locomotive(s) Selection,
3. Train in Motion Calculations,
4. Fuel Consumption,
5. Locomotive Emissions,
6. Crew Labor Costs,
7. Maintenance Costs, and
8. Capital Cost and Investment Cost

These eight modules work together to provide cost estimates for line haul movement. An initial review of CTRail by William Huneke (Chief Economist) and Michael Smith (Economist) of STB, Dr. Carl Martland (Senior Research Associate [retired] at the Department of Civil and

Environmental Engineering, Massachusetts Institute of Technology), and James Blaze, a rail industry expert, has yielded positive comments and encouragement.

According to Seedah et al. (2011), CTRail is limited to line haul movement operation and therefore does not account for terminal operations such as arrival operations, inspection operations, classification operations, assembly and disassembly operations, and the labor involved in the above operations (Seedah et al., 2011). In addition, capital investments such as road construction, right-of-way acquisition, grading, signal and interlock installation, stations and office buildings, and all other infrastructural investment cost are not included (Seedah et al, 2011). Other operational limitations of CTRail include an assumption of average speed instead of varying speeds at different sections of the track, assumption of full throttle operations without consideration for acceleration and decelerations, and omission of resistances caused by changes in grade, curvature, and wind resistance which are route specific. Locomotive idling is also ignored in the model except when calculating fuel consumption when a train stops at a siding. The model also assumes all the locomotives are identical and of the same horsepower, which may not necessarily be the case as railroad companies may use different locomotives with different horsepower to optimize fuel consumption or enhance tractive effort (Seedah et al, 2011). Depending on the commodity type, railroad monopoly, and the route being used, railroad companies have additional charges such as switch charges, hazmat, and other charges not currently captured in the model. In addition, railroads install and maintain traffic signals, construct sidings, develop double tracks, and spend on other capital investments that cannot be captured by this model.

Based on these limitations, CTRail—in its current form—can be used for rail cost comparison purposes only and not for determining railroad rates. It is publicly available and thus provides an opportunity for future improvements by the research team.

4.1.6 Canadian National Parametric Model

In addition to CTRail, a publicly available rail capacity model developed by Canadian National (CN) offers a robust but simpler alternative to popular and expensive commercial model such as the Rail Traffic Controller. The CN parametric model provides a system-wide measure of subdivision capacity in a rail network and enables evaluation of the effect of improvements for various alternatives (Krueger, 1999). The resulting comparisons of capacity can be used to identify areas of limited (bottlenecks) or excess capacity.

The model measures the capacity of a subdivision by predicting its relationship between train delay (hours per trip) and traffic volume (trains per day). In general, the more trains that run on a subdivision in a given time period, the more delay each train experiences (Prokopy et al., 1975). The CN model calculates this relationship using several key parameters that affect the traffic handling capability of a subdivision. The CN model can be used in network capacity planning to monitor system track capacity and support short- and long-term planning. The biggest downside to this model is that it can handle only 75% of a double track. It is, however, publicly available.

4.2 Rail Model Recommendations

Based on the review of selected rail models, Table 4.1 was generated to indicate which models accounted for the rail cost variables discussed in the earlier sections. It can be inferred that CTRail, TEM, and RailSim meet most of the desired criteria. These models are able to capture changes in track design, fuel consumption, tonnage, and train speed. These variables are necessary when simulating specific routes for analysis. However, TEM and RailSim are proprietary and thus cannot be accessed by the research team. Therefore, a combination of CTRail and CN’s Parametric Model will form the core of the rail component of TRIT. CN’s Parametric Model captures the external parameters such as delay and track capacity and will be useful for determining bottlenecks and testing track improvements. Using the above selections as base models, further enhancements will be made to these models to ensure an accurate current model that can be used for freight rail planning purposes.

4.3 Chapter Summary

In summary, most available rail models are limited in their ability to be integrated into planning models because they are either proprietary software or built to be standalone applications. Publicly available models are also limited in scope, and need to be further developed to output accurate rail operating parameters. To address these limitations, TRIT is being developed to combine both intermodal truck and rail operation models. These models contain features that account for the effects of cargo weight, running speeds, network capacity, and route characteristics on both truck and rail operations.

In the next chapter, an intermodal rail costing model is introduced to provide researchers with a tool to assist in further studies of rail operations. This tool is designed to provide insight into the everyday operational costs and determine the comparative costs for different routes. In particular, the rail mode will be evaluated by analyzing specific corridors, which is a necessary component in planning.

Table 4.1: Review of Selected Rail Cost Models based on Influence Factors

Variable	**CTRail v. 1.0**	**URCS**	**TOES**	**TEM**	**RailSim**	**CN Parametric Model**
Track design (grade, curvature, rise and fall)	Yes	Distance Only	Yes	Yes	Yes	Distance Only
Fuel	Yes			Yes	Yes	
Labor	Yes					
Tonnage	Yes	Yes	Yes	Yes	Yes	
Train speed	Yes		Yes	Yes	Yes	
Length of train	Yes	Yes		Yes	Yes	
Commodity type		Yes				
Track capacity					Yes	Yes
Bottlenecks					Yes	Yes
Idling time at sidings				Yes	Yes	
Terminal dwell time						
Switching		Yes			Yes	
Total trip delay		Yes		Yes	Yes	Yes
Terminal operations cost	Yes	Yes				
Capital investment costs	Yes					
Overhead costs		Yes				
Cost of maintenance			Yes			
Freight car rental		Yes				
Empty car traffic		Yes				
Emissions	Yes					
Current status	2010	Model 1980s; Data 2009	2008, RR Members Only	RR Members Only	Commercial	1999
License	Public	Public	Proprietary	Proprietary	Proprietary	Public

Chapter 5. Development of the Rail Model

Focusing on CTRail's limitations suggested some improvements and adjustments for the model. As discussed earlier, CTRail is limited in its ability to determine rail operating variables. For example, it assumes the train is running at a user-specified average speed instead of variable speeds caused by changes in grade, curvature, wind resistance, and traffic delays. In addition, CTRail always operates its train at full throttle, without consideration for acceleration and deceleration. The model also assumes all locomotives are identical and run at the maximum horsepower, which is not always the case as railroad companies run locomotives at different horsepower to optimize fuel consumption or enhance tractive effort.

5.1 Rail Corridor Modeling

CTRail improvements were made to allow for the input of more detailed track and operating information regarding a specific route—essential elements for planners considering rail as an alternative to trucking. The improved model, called *TRIT*, can determine fuel consumption based on the specific characteristics of the rail track such as elevations, grades, and curvature. This new model is capable of estimating trip delays through the integration of the CN's parametric model developed by Kruger (1999) and enhanced by Lai et al. (2009). It also allows for almost any combination of train characteristics such as type of car, type of container, cargo weight, number of locomotives, and HPTT (horsepower per trailing ton) ratio. Operating variables such as train crew, maintenance, and loading/unloading costs are also considered. Following are the seven modules composing TRIT's rail model:

1. Track Data Acquisition (distance, elevation, speed, curvature),
2. Equipment and Cargo Selection,
3. Pre-Process Calculations,
4. Locomotive Selection,
5. Train-In-Motion Calculations,
6. Travel Time, Rail Capacity and Delay Calculations, and
7. An Output Module

These seven modules work together to provide cost estimates for line haul corridor movement. Further details for these modules are as follows.

5.1.1 Track Data

The user must first upload track data for the route of interest to begin rail analysis using TRIT. This data is extremely basic but is often difficult to acquire. The first input is the distance or milepost data—the incremental milepost data along the entire route. All rail routes in the US have this milepost data, but the data are easier to acquire on some routes than on others. The associated elevation data and speed limit data for each distance (milepost) is also required. Curvature information is also strongly recommended when running this model.

The track data is used by the model to simulate train movement along the route to determine the necessary resistance forces required to move the train. The integrity of the track characteristic data is necessary for the accuracy of this model. Milepost, elevation, and curvature data remain the same over time for any particular section unless actual changes are made to the track. However, speed limit data varies frequently due to construction work, track maintenance, or incidents along the track where speed must be regulated. This makes speed data difficult to accurately estimate on any given day. It is therefore recommended that users assume that the acquired speed data is a reflection of general conditions on the track. TRIT also enables users to segment routes using mileposts thus providing the ability to analyze specific segments of the route. The flexibility to segment tracks, allows users to not only capture the effect of freight rail movement on a corridor but by subdivision without compromising the integrity of the model as a whole.

5.2 Equipment and Cargo Selection

Intermodal trains carry five types of international containers, each having its own tare weight and maximum payload:

- 20 feet dry,
- 20 feet reefer,
- 40 feet dry,
- 40 feet reefer, and
- 45 feet H-Cube.

TRIT allows the user to select the desired container used for analysis based on these available options. In addition, there is a "no container" option that is useful in simulating piggy-back loads. Users can then specify the number of containers that will be transported as well as whether the containers are double-stacked on the rail car. Double-stacking the containers will simply increase the car weight but reduce the number of cars necessary for the trip. Each intermodal car type has unique characteristics such as tare weight, max payload, length, cost, and number of axles. TRIT allows the user to select what type of car will carry the load and apply the characteristics of that car to the train that will be simulated.

By specifying the weight of the cargo, the user consequently determines the weight of the commodity being shipped. For example, a grain train will have a much higher cargo weight per container than a train carrying electronic parts. The model considers both the container and car maximum payloads when the user inputs the cargo weight. The cargo weight cannot exceed either of these maximum payloads as specified above. TRIT also accounts for shipping empty containers, which is common for the re-positioning of equipment for the rail companies. This is done through a utilization ratio, which is a percentage of full containers. Although this model cannot account for the exact position on the train of these empty containers, the total weight is still considered.

Once the car, container, and cargo selection is complete, the train characteristics can be calculated. This includes the total number of cars, rolling stock weight, and rolling stock length.
Given a certain number of cars, Nc, the total rolling stock weight, Ws, is determined as shown in Equation 5.1:

$$W_s = \sum_{i=1}^{N_c} [c_i + d(x_i + k_i)] \tag{5.1}$$

where c_i is the tare weight of one rail car, x_i is the tare weight of one container, k_i is the cargo weight, N_c is the total number of cars, and d equals 2 for double-stacked containers or equals 1 for single-stacked containers and trailer of flat cars.

For an intermodal service, given a certain number of containers, N_{con}, the total number of cars will be

$$\mathrm{N_c} = \frac{\mathrm{N_{con}}}{\mathrm{d}} \tag{5.2}$$

where d is as previously defined. Given a certain number of cars, N_c, the total rolling stock length, L_s, will be

$$\mathrm{L_s} = \sum_{\mathrm{i=1}}^{\mathrm{N_c}} \mathrm{N_c l_s} \tag{5.3}$$

where l_s is the length of one rail car based on the selected car and its associated properties.

5.2.1 Pre-Process Calculations

The Pre-Process module performs calculations prior to simulating train movement along the route to determine the necessary constraints and number of locomotives required to move rail cars. The calculations involve determining the maximum (governing or ruling) grade, the maximum resistance encountered, and the minimum horsepower required for the train to traverse the track. According to Hay (1982), ruling grade is an important factor when considering a train's route because this factor can limit the tonnage and give insight to the necessary train size. Ruling grade can be defined as the maximum gradient over which a train of certain tonnage and a given speed can be navigated (1982).

The ruling grade, maximum resistance, and required horsepower are calculated at a specified incremental distance ("solution step") using the uploaded track data and the following algorithm.

Step 1. Get user-specified "solution step" in miles - for iteration purposes
Step 2. Looping through the track data in increments of the "solution step," determine the front and back elevations of the train by linear interpolation.
Step 3. Calculate grade using the change in elevations divided by the length of the train.
Step 4. Using the calculated grade, determine the resistance encountered at that section of the route. Train resistance (R_t) is modeled using the Basic Davis Equation (1982) defined as

$$R_t = \left(1.3 + \frac{29}{\left(\frac{w_c}{A_c}\right)} + bV + \frac{cAV^2}{\left(\frac{w_c}{A_c}\right) * n}\right) * W_c * K_{adj} + W_C * 20 * G + W_C * .8 * C_v \tag{5.4}$$

Here, R_t is the train resistance, w_c is weight of a single car, n is the number of cars, A_c is the number of car axles, V is train speed, A *is* car cross-sectional area, b is the coefficient of flange friction, and c is the drag coefficient of air. W_c is total weight of all cars, K_{adj} is an adjustment factor to modernize the Davis equation, G is the grade for that section, and C_v is the curvature for that section. These car properties were automatically used based on the car and container selection. Velocity (V) is assumed to be the maximum posted speed for that section which was obtained from the track data portion of the model.

Step 5. Determine the required train horsepower ($\mathrm{HP}_{required}$) using Equation 5.5 where e is the engine efficiency of the locomotive—the default is 82% (1982).

$$\mathrm{HP}_{required} = \frac{\mathrm{R_t} * \mathrm{V}}{375 * e} \tag{5.5}$$

Step 6. Store $\mathrm{HP}_{required}$ in a list, move to next increment of solution step and return to Step 3.

Step 7. Search through list of stored governing grades to determine the largest required horsepower required along the entire route.

5.2.2 Locomotive(s) Selection Module

The total number of locomotives required is dependent on the horsepower of each locomotive and the desired HPTT ratio. HPTT ratio is determined by railroads, and varies by route and service type (Seedah et al., 2011). It dictates the desired maximum speed of the train (Seedah et al., 2011). The typical ratios used by Class I railroads varies between 2.5 to 3.5 HPTT ratio for intermodal and less than for other heavier cargo such as coal (Seedah et al., 2011). TRIT enables the user to specify both the HPTT ratio and the size of locomotives. Properties associated with different sizes of locomotives such as the weight, length, and numbers of axles are incorporated into the model. The selected locomotives horsepower governs the total horsepower available to the train and thus the train's required horsepower for each solution step cannot exceed the available train horsepower (Equation 5.6).

$$HP_{required} \times HPTT_{ratio} \leq Available\ Train\ HP \tag{5.6}$$

Given the weight of a single locomotive (w_{l_i}), and the number of locomotives ($\mathrm{N_L}$), the total weight of all the locomotives is equal to W_L. The total weight of the train is then equal to W, which is the sum of the rolling stock weight and the locomotive weight.

$$\mathrm{W_L} = \sum_{\mathrm{i}=1}^{\mathrm{N_L}} \mathrm{w_{l_i}} \tag{5.7}$$

$$W = W_s + W_L \tag{5.8}$$

5.2.3 Train-in-Motion Calculations

The Train-In-Motion module simulates the train traveling over the route to determine the resistance encountered, horsepower needed, running speeds achieved, and fuel consumed at each solution step along the route. According to Hay (1982), train movement and speed are opposed by resistances that must be overcome by propulsive force (also called *tractive effort*) of the locomotive. Wind resistance, external axle loading resistance, curve resistance, grade resistance, acceleration resistance, and inertia (starting) resistance are only present intermittently but are also estimated through empirical relationships (1982).

Resistance and Power

TRIT aims to move the train by some specified incremental distance—a "solution step" similar to that specified in the Pre-Process module. The locomotive and car resistances are then calculated to find the total resistance for each incremental step using Equation 5.4. Current posted speed limits are used in determining the minimum required horsepower HP_{min}, via Equation 5.5. The train's actual running speed V_i is then solved iteratively using the Equation of Motion (Eqn 5) defined as $f(V_i)$ and Newton's method (see Equation 5.9 and 5.10):

$$f(V_i) = 308 * HP_{min} - \left[1.3W_L + 0.6K_{adj}W_C + (20g + 0.8c)W + 29A_L + 20K_{adj}A_C\right]V_i - \left[0.03W_L + 0.01K_{adj}\right]V_i^{\,2} - \left[0.3N_L + K_{adj}KN_C\right]V_i^{\,3} \tag{5.9}$$

$$V_{i+1} = V_i - \frac{f(V_i)}{f'(V_i)} \tag{5.10}$$

where W is the total gross weight of the train in tons, g is percentage gradient of terrain, and c is the degree of curvature, K_{adj} is an adjustment factor to modernize the Davis equation and K is the drag coefficient which varies based on the equipment selected by the user. N_L is the number of locomotives, and A_L and A_C are the total number of axles of all locomotives and railcars, respectively. $f'(V_i)$ is the derivative of $f(V_i)$. All other variables remain as earlier defined.

Throttle Controls

TRIT uses an algorithm similar to the General Automatic Train-controller (GAT) developed for TEM. According to Drish (2004), GAT uses a set of train-handling rules to form a "knowledge base" that directs the controller to operate the train and minimizes the speed error (difference between the current reference speed and the actual train speed). Using input information about acceleration, train speed, and track position, a set of "IF THEN" train-handling rules determine when a command is to be executed to obtain the desired operation of the train (Start, Accelerate, Maintain Reference Speed, Decelerate, and Stop) (Drish, 2004).

TRIT currently uses the simplest knowledge base in GAT, which "assumes that the throttle is the only control available to the controller" (Drish, 2004). The throttle controller uses the speed, V_i, as well as the posted speed to determine which throttle position the train should be operating at each incremental solution step. The knowledge base consists of only three action rules and assumes that the only available train control is the throttle. It therefore does not use the dynamic and air brake controls. It automatically "anchors" the train with a full air brake setting of 100% when the train comes to a stop (Drish, 2004). The knowledge base used in TRIT is as follows:

```
Rule 1
If  PRO_ERR is less than PRO_LOW,
And REC_THR is greater than THR_SET,
Then INC_THR.
Rule 2
If  SPD_ERR is less than SPD_LOW,
Then INC_THR.
Rule 3
If  PRO_ERR is greater than or equal to PRO_LOW,
And REC_THR is less than THR_SET
Then DEC_THR.
```

According to Drish (2004), “Rule 1 and Rule 3 each use a condition on the projected speed error, PRO_ERR, at the time of throttle/dynamic transition (9 seconds hence), and a condition on the current throttle setting, THR_SET, to increase and decrease the throttle setting, respectively. Rule 2 uses a condition on the current speed error, SPD_ERR, to increase the throttle setting. In Rules 1 and 3, PRO_ERR is compared to the long-term lower threshold for speed error, PRO_LOW (which has the value -1 MPH in this case), and THR_SET is compared to the recommended equilibrium throttle setting, REC_THR, which is determined by the current average grade under the train and the current reference speed. In Rule 2, SPD_ERR is compared to the short-term lower threshold for speed error, SPD_LOW (which has the value -4 MPH in this case).”

Fuel Consumption

For each “solution step” increment, fuel consumption is calculated using reported fuel consumption rates (FCR), similar to those shown in Table 5.1, at the train’s current throttle position (THR_SET) multiplied by the time the throttle stays at that position—which is determined by the “solution step” and running speed (Equation 5.11).

$$FC = FCR(Throttle\ Position) \times \frac{Step\ Distance}{V_i} \tag{5.11}$$

Table 5.1: Typical Fuel Consumption Rates (Drish, 2004; Horizon Rail, 2012)

3000 HP - EMD SD40			**3800 HP - EMD SD60**		
HP	**Throttle**	**FCR(Throttle) Gal/Hour**	**HP**	**Throttle**	**FCR(Throttle) Gal/Hour**
0	0	0.8	0	0	3.1
200	1	7	189	1	12.0
390	2	25	418	2	22.8
710	3	41	943	3	47.8
1,085	4	57	1,298	4	64.9
1,420	5	79	1,749	5	86.9
1,830	6	108.5	2,530	6	123.2
2,375	7	145.8	3,324	7	157.5
3,000	8	167.7	3,808	8	184.7

Travel Time, Rail Capacity, and Delay Calculations

Estimated travel time can be calculated by finding the travel time for each solution step based on the estimated running speed of step. TRIT then allows the user to input any idle time experience while making the trip. This can include any time spent waiting in sidings or in a terminal along the route. To account for delays, TRIT integrates the CN parametric model (Krueger, 1999; Lai and Barkan, 2009), which measures subdivision capacity and evaluates the effect of improvements on the system. The relationship between train delay (hour/train) and the traffic volume curve and key parameters were developed on the basis of a series of regression analyses and found to be as shown in Equation 5.12:

$$Train\ delay = A_o e^{B_o V} \tag{5.12}$$

where coefficient A_o represents the relationship between train delay and parametric values and is unique for each combination of parameters defined by the plant, traffic, and operating conditions of a subdivision; B_o is constant; and V is traffic volume (trains/day) (Krueger, 1999; Lai and Barkan, 2009).

The user can also specify if any refueling or crew changes are made as well as the time the stop would take. Once this information is entered, the total trip travel time (T_T) is calculated by summing the running time (T_s), train delay (T_d), idle time (T_i), and crew change or refueling time (T_{cr}) and N_{cr} is the number of stops (see Equation 5.13)

$$\mathrm{T_T} = \sum_{\mathrm{i=1}}^{N_s} T_s + T_d + T_i + (T_{cr} * N_{cr}) \tag{5.13}$$

Cost Output

Cost outputs from the model include crew labor cost, capital and investment costs, maintenance costs, fuel costs, and loading and unloading costs. These costs are then aggregated to find the total cost, costs per mile, costs per payload ton-mile, and costs per trailing ton-mile.

Crew Labor Cost Module

Although previous work indicates that crew costs can be estimated by distance, a more realistic and effective method of crew wages can be applied. Train crew costs, benefits and bonuses are calculated using methodology derived in the 2013 United Transportation Union's "Rate Tables—Standard Basic Daily and Mileage Rates of Pay" table. Schedule agreements, mileage, work hours, and overtime calculations were taken from the UTU GO-001 Agreements—Northern Pacific Territories Conductor's Schedule[15]. According to the schedule, Basic Day and Overtime rates shall be charged as follows:

ARTICLE II - Freight Service - Basic Day and overtime - Rule 32:

a) In all freight service 100 miles of less, 8 hours or less (straightaway or turnaround), shall constitute a day's work. Miles in excess of 100 will be paid for at the mileage rates provided.
b) On runs of 100 miles or less overtime will begin at the expiration of 8 hours; on runs of over 100 miles overtime will begin when the time on duty exceeds the

[15] http://www.utu1.com/agreements/NP/NP%20Conductors%20Schedule.pdf

miles run divided by 12 1/2. Overtime shall be paid for on the minute basis, at a rate per hour of three-sixteenths of the daily rate.

c) Conductors performing more than one class of road service in a day or trip will be paid for the entire service at the highest rate applicable to any class of service performed. The overtime basis for the rate paid will apply for the entire trip.

The rate table used in the current version of TRIT can be found in Figure 5.1. Crew wages can then be calculated using the following equations developed by DeSalvo (1969):

$$C_W = \begin{cases} r_1 d_T & if\ d_T \le D\ and\ T_T \le d_T/\bar{V} \\ Dr_1 + r_2(d_T - D), & if\ d_T > D\ and\ T_T \le d_T/\bar{V} \\ \bar{V} r_1 T, & if\ d_T \le D\ and\ T_T > d_T/\bar{V} \\ Dr_1 + r_2(\bar{V}T - D) & if\ d_T > D\ and\ T > d_T/\bar{V} \end{cases}$$

where

C_W = crew member's cost to the trip,
$\bar{V}$ = average freight train speed
D = maximum possible distance travelled during 8 hour period at average freight train speed, $\bar{V}$
r_1 = crew member's wage rate per mile for first D miles,
r_2 = crew member's wage rate per mile after first D miles,
d_T = actual trip distance in miles,
T_T = actual trip time in hours

TRIT allows the user to input crew information and determines labor cost on an hourly basis. Some of these inputs include the number of crew members, average freight train speed (default 12.5 MPH), maximum possible distance travelled during an 8-hour period at average freight train speed (default 100 miles), crew member's wage rate per mile for first D = 100 miles (taken from Figure 5.1), and crew member's wage rate per mile after first D = 100 miles (taken from Figure 5.1).

STANDARD DAILY AND MILEAGE RATES OF PAY
AS OF JULY 1, 2013

RESULTING FROM THE APPLICATION OF A
3.0 PERCENT INCREASE TO THE
STANDARD BASIC RATES OF PAY WHICH WERE IN EFFECT JUNE 30, 2013

UTU

LOCOMOTIVE ENGINEERS (MOTORMEN) -- THROUGH FREIGHT SERVICE

WEIGHT ON DRIVERS (POUNDS)	STANDARD BASIC DAILY AND MILEAGE RATES DAILY RATES	MILEAGE RATES
LESS THAN 140,000	$221.19	164.80 ¢
140,000 AND LESS THAN 200,000	$221.62	165.23 ¢
200,000 AND LESS THAN 250,000	$221.79	165.40 ¢
250,000 AND LESS THAN 300,000	$221.94	165.55 ¢
300,000 AND LESS THAN 350,000	$222.09	165.70 ¢
350,000 AND LESS THAN 400,000	$222.30	165.91 ¢
400,000 AND LESS THAN 450,000	$222.51	166.12 ¢
450,000 AND LESS THAN 500,000	$222.72	166.33 ¢
500,000 AND LESS THAN 550,000	$222.93	166.54 ¢
550,000 AND LESS THAN 600,000	$223.11	166.72 ¢
600,000 AND LESS THAN 650,000	$223.29	166.90 ¢
650,000 AND LESS THAN 700,000	$223.47	167.08 ¢
700,000 AND LESS THAN 750,000	$223.65	167.26 ¢
750,000 AND LESS THAN 800,000	$223.83	167.44 ¢
800,000 AND LESS THAN 850,000	$224.01	167.62 ¢
850,000 AND LESS THAN 900,000	$224.19	167.80 ¢
900,000 AND LESS THAN 950,000	$224.37	167.98 ¢
950,000 AND LESS THAN 1,000,000	$224.55	168.16 ¢
1,000,000 POUNDS AND OVER: FOR EACH ADDITIONAL 50,000 POUNDS OR FRACTION THEREOF - ADD:	$0.18	0.18 ¢

DAILY EARNINGS MINIMUM $222.70
ARTICLE III(B) OF AGREEMENT OF OCTOBER 14, 1955

DIFFERENTIAL FOR ENGINEERS WORKING WITHOUT FIREMEN:
ON LOCOMOTIVES ON WHICH UNDER THE FORMER NATIONAL DIESEL AGREEMENT OF 1950 FIREMEN WOULD HAVE BEEN REQUIRED, A UNIFORM DIFFERENTIAL OF $6.00 PER BASIC DAY AND 6¢ PER MILE FOR MILES IN EXCESS OF THE BASIC DAY WILL BE ADDED TO THE ABOVE RATES (IN ADDITION TO THE LOCAL FREIGHT DIFFERENTIAL IF APPLICABLE).

B-2 (UTU) NRLC

Figure 5.1: 2013 United Transportation Union Freight Rail Rate Table for Through Service Locomotive Engineers (UTU, 2013)

Capital Cost and Investment Cost Module

Capital and investment costs are the most difficult to model (Seedah et al., 2011). Investments by rail companies are extremely private and most capital costs vary by location and/or provider. Some of the capital costs include large investments in the construction of rail tracks, structures, rail yards, signals, cars, and locomotives. Because obtaining adequate data to model these costs would be nearly impossible, TRIT currently uses a straight-line depreciation equation where trip depreciation is determined for each car and locomotive by multiplying hourly depreciation by the total trip time as shown in Equation 5.14.

$$C_{cap} = \sum_i^N \frac{Cost\ of\ Asset_i - Scrap\ Value_i}{Life\ Span\ (years) \times 8760\frac{hrs}{years}} \times \mathrm{T_T} \tag{5.14}$$

Maintenance Cost Module

The maintenance cost module includes track, car, and locomotive maintenance. These costs are calculated using a per-mile system average rate (Seedah et al., 2011). TRIT allows the user to input the cost per mile for each of these maintenance categories but some default values are given based on rail expert recommendations. Total maintenance cost (C_M) is determined using Equation 5.15.

$$C_M = c_{m_T}(N_C + N_L) + \ c_{m_c}N_C + \ c_{m_l}N_L \tag{5.15}$$

where c_{m_T} is track maintenance cost per mile per car and locomotive, c_{m_c} is the car maintenance cost per mile, and c_{m_l} is the locomotive maintenance cost per mile. N_c is the number of cars in the train and N_L is the number of locomotives.

Fuel Cost Module

The fuel cost module in TRIT allows the user to change the price per gallon of fuel in order to estimate the total fuel cost for a haul. The estimated total gallons of fuel used come from the Train-In-Motion module. This is simply multiplied by the price per gallon to get the total fuel cost.

$$C_F = f_{pg} * FC_g \tag{5.16}$$

where C_F is the total fuel cost for the trip, f_{pg} is the specified fuel price per gallon, and FC_g is the total estimated fuel consumption for the trip in gallons.

Loading and Unloading Cost Module

This module tries to capture the cost of loading and unloading the train. Considering the challenges for shipments by rail to compete with trucking in this area, it is important to try and incorporate the loading and unloading costs associated with freight rail. TRIT allows the user to specify loading and unloading cost per container. These per-container costs are then multiplied by the number of containers being shipped, which comes from the Equipment and Cargo selection module.

$$C_{LU} = (L_c + U_c) * N_{con} \tag{5.17}$$

where C_{LU} is the total cost for loading and unloading the train, L_c is the specified loading cost per container, U_c is the specified unloading cost per container, and N_{con} is the number of containers being shipped.

Total Cost

The total cost of moving a single train over a user-specified route is determined as shown in Equation 5.18.

$$C_{Tot} = C_{Labor} + C_{Cap} + C_M + C_F + C_{LU} \tag{5.18}$$

5.3 Model Limitations

The input data requirements, as with many models, limit the easy utilization of this model. Detailed track data is complicated to derive and usually rail companies are hesitant to make such data available due to competitive concerns. The data needed to run this model for any scenario include milepost, elevation, posted speeds, and curvature data. Finding a method to easily access this data or develop it in another way would greatly improve the usability of this model for a planner seeking to evaluate mode-choice options on any route.

For most input variables, TRIT gives the option to use default values. Most of these values will change with each scenario and should be adjusted as necessary. Most of the default values are simply system averages or acquired from previous published data and research. A limitation that rail models encounter is the ability to model the train engineer's driving behavior. Although there is a posted maximum speed that cannot be exceeded, train engineers have almost complete control over how fast they will drive the route. This allows for a variance in speeds for different drivers based on the driver's behavior. More aggressive drivers can consume a substantially higher amount of fuel than someone less aggressive. Modeling an engineer's behavior is very complex and therefore TRIT assumes that on average the drivers operate similarly. In addition, future work should allocate track maintenance costs on a gross ton-mile basis rather than a car-mile basis as this is more reflective of current railroad operations. Furthermore, track maintenance renewal programs are known to be more cost effective and preferred to ordinary maintenance activities. Future work should incorporate elements of renewal capital expenditures in the calculation of maintenance cost. Dynamic and air braking behavior is also currently excluded from TRIT because of insufficient data. Future versions of the model should include these braking options.

In addition, TRIT does not individually prioritize one train over the other. In practice, some trains are given higher priority over others to ensure a timely delivery of service. This means that some trains will have to wait in sidings while others can travel freely. TRIT accounts only for delay time based on track capacity, and future versions of the model will provide users with the ability to assign a train's priority. Lastly, there are certain costs that cannot be captured by this model, such as traffic signals, switch charges, hazmat, and other leasing costs. Railroads also face decisions of double-tracking certain routes and making additional capital investments.

The limitations specified above do not impair the utility of the model as long as the average values for key variables are calibrated and users are encouraged to use the model to determine variable cost differentials, not full costs. The researchers recommend that TRIT should not be used to decide or predict pricing rates, but be used as a comparison tool between truck and rail routes.

5.4 Chapter Summary

This toolkit can estimate the comparative costs on any rail route if given the track input data and train information. The input data requirements, as with many models, limit the easy utilization of this model. Detailed track data is complicated to derive and usually rail companies are hesitant in making such data available due to competitive concerns. The data needed to run this model for any scenario include milepost, elevation, posted speeds, and curvature data.

The next chapter describes how to determine what combination of traffic, distance, curvature, rise and fall, and gradient gives the best economic outcome for railroad operations. It is also necessary to develop a method to obtain this data without depending on the rail companies. If the track input data can be easily acquired, this rail model can be extremely beneficial for corridor analysis. A brief description on how data can be acquired through the use of GIS technologies is presented in the next chapter.

Chapter 6. Rail Alignments, Hay's Location Process, and Acquiring Track Data

Rail infrastructure is most important for interstate trade because of its efficiency in long-haul movements. However, railroads in the US will face capacity constraints should freight traffic continue to increase (Cambridge Systematics, 2007). Rail demand is estimated to rise by at least 37% by tonnage and 86% by value (FAF 3, 2009) between now and 2040. The current infrastructure can only handle this demand if investments are made in double-tracking existing lines to remove various bottlenecks in the system, providing for new sidings, or constructing alternative routes (Cambridge Systematics, 2007).

Hay (1982) developed a route location process that determines what combination of traffic, distance, curvature, rise and fall, and gradient gives the best economic outcome for railroad operations. His route location process is one of the few efforts aimed at comparing route alternatives from a purely economically viable approach without the need to intrude on the privacy of railroad companies.

6.1 The Location Process by Hay

Hay's location process determines the rate of return for any given railroad route as a measure of its economic benefit (Hay, 1982). It was not intended to provide precise answers but can be used as a comparative tool for planning purposes, such as determining those traffic combinations and route characteristics that give the best economic outcome. Input data required by the location process include the following:

- Annual gross and net tonnage,
- Revenue per ton mile,
- Total distance of route,
- Total central angle,
- Class of total rise and fall,
- Ruling grade,
- Construction cost per mile,
- Motive power, and
- Equipment to be hauled

Once the necessary input data is determined, the location process calculations can be performed for each line being compared. The first calculation determines estimated route revenues using Equation 6.1 where R is the total revenue, T_g is the gross tonnage, D is the route distance, and R_{ptm} is the revenue per ton mile, which is either an estimate or a system-wide average.

$$R = T_g * D * R_{ptm} \tag{6.1}$$

Construction cost is then determined using Equation 6.2, where C_c is the total construction cost, and C_{cptm} is the construction cost per mile for the route. Note that construction costs can vary greatly depending on the routes chosen for comparison.

$$C_c = D^*C_{cptm} \tag{6.2}$$

The next calculation is the estimated operating costs for the distance of the route. This is done by assuming that the shorter of the two routes for comparison is the base case and the other is calculated off of that base case by introducing a distance cost factor (F_D) that is intended to correlate the non-base case operating cost to the base case operating cost. The calculation for the base case is performed using Equation 6.3 where OC_{Dbase} is the operating cost for the distance traveled on the base case route, Tg is the gross tonnage for both directions, D_{base} is the distance of the base case route, and C_{kgtm} is the system wide average cost per thousand ton miles.

$$OC_{Dbase} = \frac{T_g}{1000}{}^*D_{base}{}^*C_{kgtm} \tag{6.3}$$

To find the other route's costs, a distance factor (F_D) must be determined. Hay (1982) calculated this by summing published operating costs percentages from the American Railway Engineering Association (Hay, 1982). This was then multiplied by the base case cost as shown in Equation 6.4 where OC_D is the operating cost for the distance traveled on the non-base case route, and D is the distance of the non-base case route.

$$OC_D = OC_{Dbase} + \frac{T_g}{1000}{}^*\left(D\text{-}D_{base}\right)^*C_{kgtm}{}^*F_D \tag{6.4}$$

The operating cost for curvature is then determined using Equation 6.5 where OC_C is the operating cost for the curvature along the route, A_{TC} is the total central angle, and F_C is the curvature factor. Again, F_C was determined by published percentages from the American Railway Engineering Association (Hay, 1982).

$$OC_C = \frac{T_g}{1000} * \frac{A_{TC}}{528}{}^*C_{kgtm}{}^*F_C \tag{6.5}$$

The next operational costs the must be considered is the effect of rise and fall along the route. This is down by breaking down rise and fall in three classes: A, B, and C (Hay, 1982). Class A gradients are so small that no throttle changes or breaking is necessary. These grades usually don't affect the trains speed unless there are long successions of these classes of grades. Class A gradients are usually considered to be 30 feet or less (Hay, 1982). Class B gradients are those of which small throttle adjustments must be made but still no breaking required. These grades usually fall between more than 30 feet up to 0.06% (Hay, 1982). Class C gradients usually required considerable additional power by increasing the throttle and brake application when the train is descending (Hay, 1982).

Since Class A gradients are minimal, only the effect of Class B and C grades are considered for calculation. It is assumed that an average value of train resistance is 10 lbs/ton, meaning that would be the same power as a 0.50% gradient for 26.4 ft/mile (Hay, 1982). The Class B calculation can be found using Equation 6.6 where OC_{RFB} is the operating costs for rise and fall class B grades, RF_{TB} is the total rise and fall for the class B grades, and F_{RFB} is the rise and fall factor for class B grades.

$$OC_{RFB} = \frac{RF_{TB}}{26.4} * \frac{T_g}{1000} * C_{kgtm} * F_{RFB} \tag{6.6}$$

Class C grades have a similar calculation (Equation 6.7) but must also account for the ruling grade when necessary where OC_{RFC} is the operating costs for a rise and fall class C grades, RF_{TC} is the total rise and fall for the class C grades, and F_{RFC} is the rise and fall factor for class C grades.

$$OC_{RFC} = \frac{RF_{TC}}{26.4} * \frac{T_g}{1000} * C_{kgtm} * F_{RFC} + RG_F \tag{6.7}$$

RG_F is only added when the ruling grade is considered. The calculation of RG_F is shown in Equation 6.8.

$$RG_F = 0.03 * \left(\frac{RF_{TC}}{26.4} * \frac{T_g}{1000} * C_{kgtm} * F_{RFC}\right) \tag{6.8}$$

Next, the required drawbar pull of the train must be calculated by finding the resistance of the train for both routes in each direction (Equation 6.9). An arbitrary locomotive or car type can be selected as a representation of the equipment that will most likely be used on the route.

$$R_L = \left(1.3 + \frac{29}{\frac{w_L}{A_L}} + bV + \frac{cAV^2}{\left(\frac{w_L}{A_L}\right) * n}\right) * W_L * K_{adj} + W_L * 20 * G \tag{6.9}$$

Here, R_L is the locomotive resistance, w_L is weight of a single locomotive, n is the number of locomotives, A_L is the number of locomotive axles, V is train speed, A *is* locomotive cross-sectional area, b is the coefficient of flange friction, c is the drag coefficient of air, W_L is total weight of all locomotives, K_{adj} is an adjustment factor to modernize the Davis equation, and G is the grade for that section as a percent. For rail cars, Equation 6.9 can be used by simply changing the variables to their respective car properties.

Drawbar pull can then be calculated by subtracting the locomotive resistance from the motive power (tractive effort). Equation 6.10 shows the final drawbar pull calculation where DBP is the total drawbar pull for each route and direction, TE is the tractive effort supplied by the locomotives, and R_L is the locomotive resistance found from Equation 6.9.

$$DBP = TE - R_L \tag{6.10}$$

Train tonnages can then be calculated for each route and direction by simply dividing the drawbar pull by the car resistances shown in Equation 6.11.

$$TT = \frac{DBP}{R_c} \tag{6.11}$$

The total number of trains (N) can then be defined by dividing the gross tonnage by the train tonnage (TT) as shown in Equation 6.12. Obviously this can be converted into the number of trains per day by dividing by the number of operating days in the year, which is usually 365 days.

$$N = \frac{T_g}{TT} \tag{6.12}$$

Hay (1982) then finds an estimated cost of additional trains by using the difference in traffic densities of the routes. It assumes that any extra traffic on one line creates additional costs. Using a pre-defined cost per train mile value (E_{ptm}) and the percentage of change (F_{pnt}) in operating expenses affected by the number of trains, the cost of an additional train C_{AT} can be found as shown in Equation 6.13.

$$C_{AT} = (N_B\text{-}N_A)*D*E_{ptm}*F_{pnt} \tag{6.13}$$

where N_B number of trains for the route with more trains, and N_A is the number of trains for the route with lesser trains.

Total operating cost, OC_{Total}, is then determined by summing the individual costs for distance, curvature, rise and fall, and traffic density for each route (see Equation 6.14), where C_{AT} is only included for the route with the higher train traffic flows to account for any costs associated with the increased volumes.

$$OC_{Total} = OC_D + OC_C + OC_{RF} + C_{AT} \tag{6.14}$$

Finally, the rate of return for each route is determined to aid in the decision of which route is more cost effective and economical (see Equation 6.15). The route with the higher rate of return is the preferable route.

$$ROR = \frac{R\text{-}OC_{Total}}{C_c} \tag{6.15}$$

A limitation of Hay's location process is that the cost values used in the example calculations (Hay, 1982) were developed in the 1970s, which are much different than what currently exists. It is thus important that those values be replaced with more current data when performing analysis.

6.2 Route Data Acquisition Model

Acquiring the necessary route data for the location process seems to be a challenge for planners. A route data acquisition model was therefore developed to allow users to determine the elevation profile of any existing or planned rail route, thus providing information on grades. The route data acquisition model requires two GIS data sources: 1) railroad network data, and 2) the Digital Elevation Models (DEM), which are three-dimensional representations of a terrain's surface. DEM models for the US can be acquired from the US Geological Survey (USGS) National Elevation Dataset (NED). According to USGS (USDOI, 2006), "the NED is updated on a nominal two month cycle to integrate newly available, improved elevation source data. The data is derived from diverse source data that are processed to a common coordinate system and unit of vertical measure. NED data are distributed in geographic coordinates in units of decimal degrees, and in conformance with the North American Datum of 1983 (NAD 83).” Elevation data from the NED is available nationally at resolutions of 1 arc-second (about 30 meters) and 1/3 arc-second (about 10 meters), and in limited areas at 1/9 arc-second (about 3 meters), except in Alaska where much data is available only at 2 arc-second (about 60 meters) grid spacing (USDOI, 2006). For this model, a 1 arc-second resolution—30 meters, 100 feet, or 0.01 miles—is sufficient. When the rail network is overlaid on top of the DEM data file, it is possible to obtain the digital elevations of the network at 0.01-mile intervals. Using a GIS application, alternative routes can be drawn and elevation data obtained. The data can then be processed and used as a route’s distance and elevation profile.

In order to validate the route data acquisition model, the profile of an existing rail line from Houston to Fort Worth was obtained and the comparison presented in Figure 6.1. A visual assessment of the two datasets displays few differences in elevation changes. These changes correlate to track grade changes that are necessary for accurately determining a route’s ruling grade. A limitation of using the data acquisition model is its inability to accurately capture elevated structures such as overpasses and bridges. The GIS profile data follows the land’s topography and elevated structures may not be captured. This limitation can be mitigated by analyzing extreme changes in elevation with a map that shows riverbeds, low-lying spots, bridges, and overpasses, and adjusting the points accordingly using available data or linear interpolation where possible. For example, most rail lines are built with grades of less than 2%; for grades greater than 3%, it is recommended that modelers investigate discrepancies in the data, as this may be an error in the model’s output.

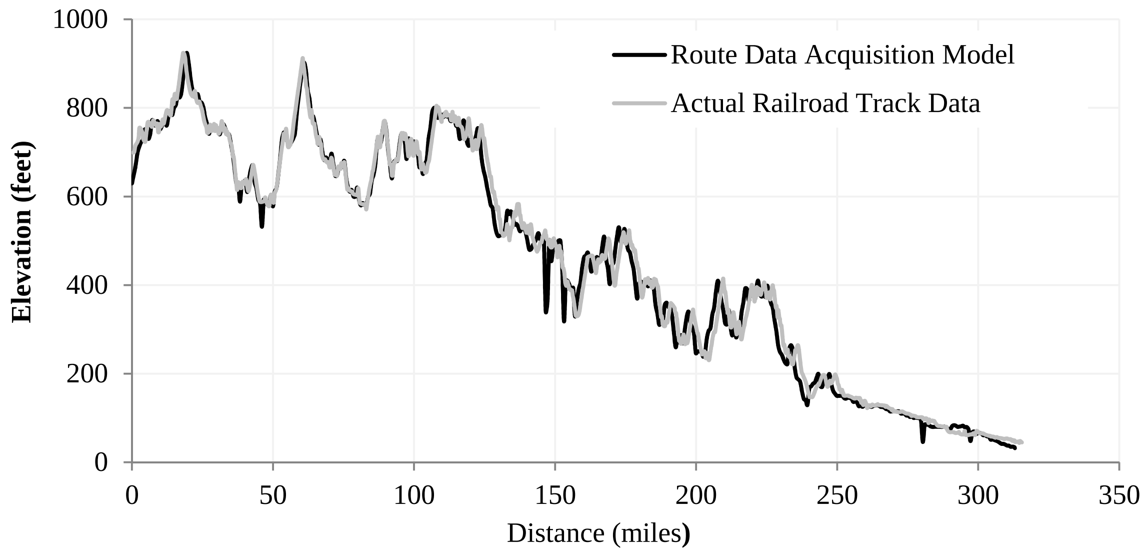


Figure 6.1: Elevation Profiles Comparing the Two Datasets – Model (darker color) and Actual Railroad Track Data (gray color)

6.3 Chapter Summary

Hay's location process model in combination with the route data acquisition model creates a solid method of analyzing and comparing rail routes. The use of the data acquisition model obviates the need to obtain track characteristics from the rail companies, making it easier to analyze corridors. This becomes especially important for corridors with multiple rail routes or when testing the feasibility of new routes. The next chapter describes a methodology used to account for rail capacity at the subdivision level.

Chapter 7. Rail Capacity

TRIT estimates travel time based on the estimated running speed of the train. To account for delays, users can input any estimated idle time in the model and this can include any time spent waiting in sidings or in a terminal along the route. To estimate delays caused by rail capacity constraints, TRIT integrates a model developed in an earlier study on *Parametric Analysis of Railway Line Capacity* (Prokopy and Rubin, 1975) which measures subdivision capacity and evaluates the effect of improvements on the system. The Federal Railroad Association (FRA) model forms the basis of more recent parametric models such as those developed by Krueger (1999) and Lai (2009).

7.1 Parametric Analysis of Rail Capacity

In Lai (2009), rail capacity is defined as "a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan." Furthermore, Lai (2009), Krueger (1999), and Vantuono (2005) determined that rail capacity is dependent on these variables:

- Length of subdivision
- Siding length, spacing, and uniformity
- Intermediate signal spacing
- Percentage of single, double, or multiple track
- Peak train counts
- Average and variability in operating speed
- Heterogeneity in train types (train length, power to weight ratios)
- Dispatching priorities, and
- Schedule

According to Abril (2007) and Martland (2005), there are no clearly identified rail capacity analysis tools as each model is designed for a specific purpose (Lai, 2009). A parametric approach which bridges "the gap between [the computationally intensive] simulation and [theoretically biased] simple formulae" is therefore the recommended approach for rail capacity analysis (Lai, 2009). Parametric models "account for the dynamic nature of line capacity, and provide system-wide capacity measurement of subdivisions in a rail network" (Lai, 2009).

According to Lai (2009), the CN parametric model developed by Krueger (1999) is currently the most useful parametric model as it can be calibrated for multiple scenarios and is capable of determining delay versus volume relationships of a rail track. Lai (2009) further developed the CN parametric model to be able to evaluate alternative planning schemes, "estimate the construction costs, and determine tradeoffs between capital investments, delay and operating costs."

A basic version of the CN parametric model is currently incorporated into TRIT. This version utilizes methodologies developed by Prokopy and Rubin (1975). The goal of the CN

Parametric Model is to determine the relationship between train delay (hour/train) and traffic volumes. A sample output from TRIT demonstrating this relationship is shown in Figure 7.1.

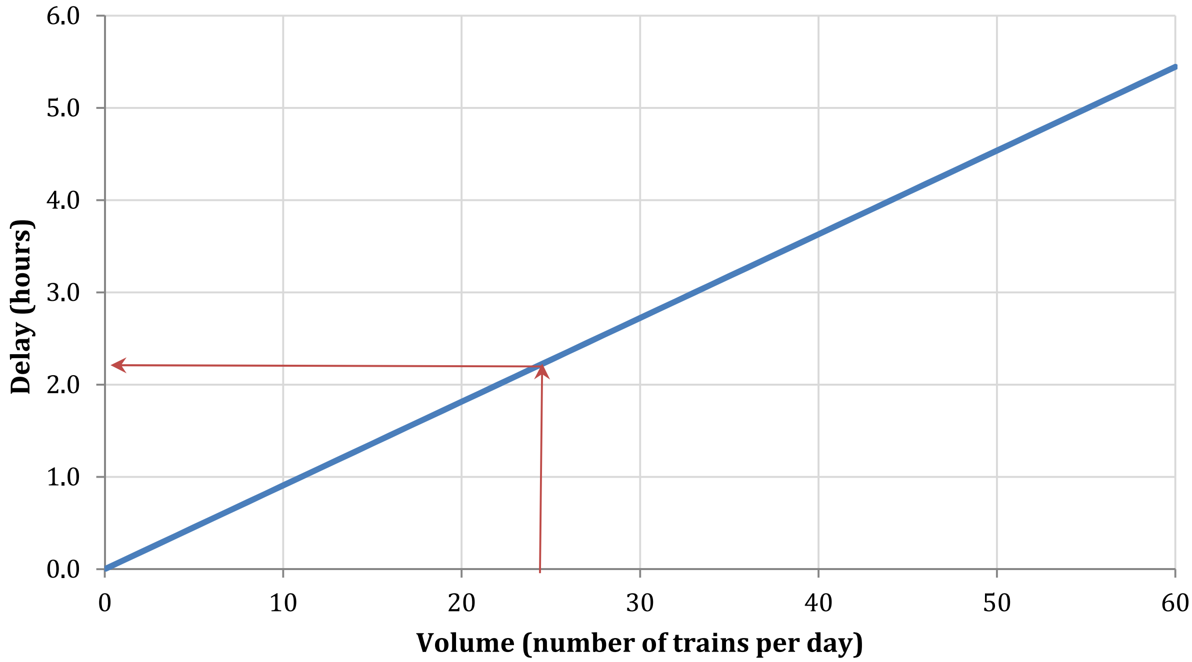


Figure 7.1: Sample TRIT Output for Relationship between Delay and Volume

TRIT users can currently input the following data into the model to evaluate rail capacity on a specific subdivision:

- Average Block Size (in miles): This is a section of track that may be occupied by only one train at a time. Blocks are used to control train separation, and occupancy is regulated either by the dispatcher, an operator at a station[16], or an automatic signal system.
- Train Priority: This is the preference given to a train based on its class[17]. A low-priority train gives way to a high-priority train when they meet. The options include
  - No priority: Priorities for all train classes in both directions of movement are the same.
  - Base priorities: Priorities are assigned by train class, e.g., intermodal trains have a higher priority than manifest or mixed trains.
- Average Segment Size (in miles): This is the section of track between two stations; may contain one or more parallel tracks and must contain at least one signal or train separation block.
- Train Speed Uniformity
  - Base speeds by class: Train speeds are assigned based on train class.

[16] Station: any point on a rail line where track configuration changes

[17] Class: This is the type of train as defined by its performance characteristics. Train classes include Intermodal, Manifest or mixed freight, Unit trains and Local or road switching

    - Uniform speeds: All trains are assigned the same speed irrespective of class.
        - Uniform Train Speed (in miles per hour): This is specified by user if the Uniform Train Speed option is selected.

- Average Train Speed (in miles per hour): This is the average train speed of all trains within the segment.

- Siding Capacity: A siding is a track at a station (or within a segment) used for trains to meet, overtake, or perform switching. Options include
    - Base capacity: the number of trains of a given length that could be held by sidings at a station.
    - Double capacity: an increase in the number of sidings so that the number of trains at the station can be doubled.

- Segment Uniformity: Segment uniformity is a measure of the segment lengths relative to one other.
    - Non-uniform segments have varying segment lengths
    - Uniform segment assumes all segments are of the same length

- Dispatch Peaking or Non-peaking (Fraction daily volume in peak/fraction of day in peak)

- Presence of Rare Events: Rare events simulate train and track failures and track maintenance interruptions. The options for users include
    - Consideration for rare events, and
    - No consideration for rare events

- Train Length as Fraction of Base Length of Siding: In the base case, all trains can fit into all sidings. By increasing this fraction, e.g., from 1.0 to 1.2, the user specifies that some of the trains cannot fit into a shorter siding.

- Change in Directional Imbalance (No. of trains in heavy direction/no. of trains in light direction): This measures the impact of dispatching more trains in one direction over the other during the course of the day.

- Base Block Configuration between Stations: This measures the impact of signal block spacing on rail capacity. The "Base Block Configuration" option assumes there are no additional signals between blocks and the "1 Block Between Station" option assumes there is one additional signal block between adjacent stations on a single track.

- General Double Track Crossover Flexibility: A crossover is a pair of switches that connects two parallel rail tracks, allowing a train on one track to cross over to the other. Options include full crossover and alternate crossover. Further review of this parameter is required as it exists only in double tracking. One limitation of the CN Parametric Model is its inability to accurately handle double track percentages greater than 75% in a given subdivision (Krueger, 1999; Lai, 2009).

- Fraction of Line Mileage with Double Track (Double, 1-in-3 Single, 1-in-2 Single, 2-in-3 Single, Single): This is a ratio of single track segments to the total number of segments.

7.2 Rail Capacity Calculation Methodology

The following describes the methodology used in the determination of rail capacity and train delay as outlined by the report *Parametric Analysis of Railway Line Capacity* (Prokopy and Rubin, 1975). More detailed discussions concerning the methodology can be found in that report.

The basic equation for capacity is

$$C = \frac{A_C}{K}\left(\frac{100}{L}\right) \qquad \text{(Eq. 7.1)}$$

C = capacity of the line in trains per day,
Ac = average delay per train (in hours, exclusive of scheduled delays),
K = delay slope (for a 100-mile line), and
L = length of the line in miles.

Ac is determined for single tracks using the quadratic formula:

$$A\_C = \ (-b + \ \surd(b\hat{}2 - 4ac))/2a \qquad \text{(Eq. 7.2)}$$

$$a = 0.04325(S)\left(\frac{150}{L}\right)^2 = \frac{973.125\ (S)}{L^2} \qquad \text{(Eq. 7.3)}$$

$$b = \left(\frac{150}{L}\right)(0.44851\ P + 1.01139\ D) = \frac{1}{L}(67.2765\ P + 151.7085\ D) \qquad \text{(Eq. 7.4)}$$

$$c = 1.41432 - M\left(\frac{150}{L}\right) + \frac{150}{S} + I \qquad \text{(Eq. 7.5)}$$

M = the maximum allowable total running time (12 hours less allowance for terminal time)
S = the speed of the slowest class of through freight trains (MPH)
P = the dispatch peaking factor:

$$\frac{trains\ peak\ hour\ during\ peak}{trains\ peak\ hour\ off\ peak} - 1 \qquad \text{(Eq. 7.6)}$$

D = the directionality factor:

$$\frac{trains\ in\ dominant\ direction}{trains\ in\ opposite\ direction} - 1 \qquad \text{(Eq. 7.7)}$$

I = the amount of imposed delays on regular freight trains (such as required stops, including the start and stop lost time)

For double tracks, the following formula is used:

$$A_c = 0.031274\ L\sqrt{\frac{1}{S}\left[\ M\ \left(\frac{150}{L}\right) - \ \frac{150}{S} - I - 1.84636\right]} \qquad \text{(Eq. 7.8)}$$

Upon determination of *Ac* using the appropriate formula for a given line and the maximum running time for a freight train, line capacity is calculated using Equation 7.1

The delay slope, *K*, is determined based on modifications of base scenarios shown in Table 7.1. A modification from the base case (V_o) can be represented as V_i, and the percent change in a parameter *i* is equivalent to:

$$P_i = \frac{(V_i - V_o)}{\frac{1}{2}(V_i + V_o)} \qquad \text{(Eq. 7.9)}$$

The delay slope adjustment factor (f_{oi}) is then determined from Table 7.1. The delay slope for the change in parameter *i*, which is K_i, is then solved using Equation 7.10, where K_o is the delay slope for the base case[18].

$$K_i = K_o(f_{oi})^{P_i} \qquad \text{(Eq. 7.10)}$$

For multiple observed modifications (*m*), a modification factor (f_{om}) is required in calculating the delay slope (K_m) as shown in Equation 7.11[19]

$$K_m = f_{om}K_o \qquad \text{(Eq. 7.11)}$$

where

$$f_{om} = C_I C_D^{-1} \qquad \text{(Eq. 7.12)}$$

[18] The default value of K_o for the base case is 0.04538

[19] For this study, f_{om} is assumed to be equivalent to $\hat{f}_{om}$ which is used by Prokopy and Rubin (1975) as the synthesized multiple modification factor.

Table 7.1: Policy Variable Units and Modifications from Base Case

POLICY VARIABLES UNITS							
Type	**Modification**	**Policy Variable**	**Unit (V1)**	**Base Value (V0)**	**Modification from Base (Case Number)**		**foi**
A	Change block size	Average block size	Miles	1.6	A-F1	1-mile Blocks, 4 Aspects	1.5379
					A-F2	3-mile Blocks	1.1475
B1	Change train priority	Train priority	No priority	0.5	B-F1	No Priority	0.6569
B2	Change train priority	Train priority	Base priority	1.5			
C	Change station spacing (siding spacing)	Average segment size	Miles	8.82	C-F1	5-mile Segments	1.7752
					C-F2	15-mile Segments	1.9486
					C-F3	21.4-mile Segments	2.8556
D1	Select uniform or non-uniform speed	Train speed uniformity	Base speeds by class	0.5	D-F1	8 mph Uniform Speed	0.1124
D2	Select uniform or non-uniform speed	Train speed uniformity	Uniform speeds	1.5	D-F2	25 mph Uniform Speed	0.2140
					D-F3	32.8 mph Uniform Speed	0.7062
					D-F4	50 mph Uniform Speed	0.1121
					D-F5	70 mph Uniform Speed	0.4799
E	Change uniform speed	Uniform train speed	mph	32.8	E-F1	8 mph Uniform Speed	0.1124
					E-F2	25 mph Uniform Speed	0.2140
					E-F3	32.8 mph Uniform Speed	0.7062
					E-F4	50 mph Uniform Speed	0.1121
					E-F5	70 mph Uniform Speed	0.4799
F	Change proportional speed	Average train speed	mph	32.8	F-F1	33% Decrease in Speeds	0.4154
					F-F2	40% Increase in Speeds	0.1395
G1	Change siding capacity	Siding capacity	Base capacity	0.5	G-F1	Double Siding Lengths	0.9170
G2	Change siding capacity	Siding capacity	Double capacity	1.5			
H1	Select uniform or non-uniform segments	Segment uniformity	Non-uniform	0.5			
H2	Select uniform or non-uniform segments	Segment uniformity	Uniform	1.5	H-F1	Uniform Segments	0.7897
I	Select dispatch peaking or non-peaking	Fraction daily volume in peak / Fraction of day in peak	Peaking fraction	1	I-F1	Coincident Peaks	0.9049
					I-F2	Separate Peaks	0.6866
J1	Select rare events or no rare events	Presence of rare events	Rare events	0.5			
J2	Select rare events or no rare events	Presence of rare events	No rare events	1.5	J-F1	No Rare Events	0.8219
K	Change train length	Train length as fraction of base length	Train length as fraction of base length	1	K-F1	1.5 Length Trains	1.0806
					K-F2	Double Train Lengths	1.8823
L	Change directional imbalance	No. of trains in heavy direction/No. of trains in light direction	Directional imbalance fraction	1	L-F1	1:2 Directional Imbalance, No Rare Events	0.7834
					L-F2	1:4 Directional Imbalance, No Rare Events	0.7273
M1	Select base blocks or 1 block between stations	Same as Modification	Base block configuratio n	0.5			
M2	Select base blocks or 1 block between stations	Same as Modification	1 block between stations	1.5	M-F1	1 Block Between Stations	2.8890
N1	Select full crossovers or alternate directional crossovers	General double track crossover flexibility	Full	0.5			
N2	Select full crossovers or alternate directional crossovers	General double track crossover flexibility	Alternate	1.5	N-F1	Alternate Direction Crossovers	1.2520
P1	Change fraction of double track	Fraction of line mileage with double track	Double	1	P-F1	Double Track, Double Run Base	0.6029
P2	Change fraction of double track	Fraction of line mileage with double track	1-in-3 single	0.7	P-F2	1 in 3 Segments Single	0.0677
P3	Change fraction of double track	Fraction of line mileage with double track	1-in-2 single	0.533	P-F3	1 in 2 Segments Single	0.3438
P4	Change fraction of double track	Fraction of line mileage with double track	2-in-3 single	0.3467	P-F4	2 in 3 Segments Single	0.7436
P5	Change fraction of double track	Fraction of line mileage with double track	Single	0	P-F5	Single Track Base Case	0.9450

Derived from Prokopy and Rubin (1975)

C_I is the component for factors which increase the delay slope and $C_D$is for factors which decrease the slope. C_I and C_D are defined as Equations 7.13 and 7.14 where N_I and N_D are the respective number of slope-increasing or slope-decreasing modifications.

$$C_I = \left(\sum_{f_{oi} \geq 1} f_{oi}^{P_i}\right) - (N_I - 1) \qquad \text{(Eq. 7.13)}$$

$$C_D = \left(\sum_{f_{oi} < 1} f_{oi}^{-P_i}\right) - (N_D - 1) \qquad \text{(Eq. 7.14)}$$

The delay slope (K_m) is thus equivalent to Equation 7.15 and is the hours of delay per train per 100 miles of line. Once K_m is determined, the capacity of the rail line can be calculated using Equation 7.15.

$$K_m = \left[\left(\sum_{f_{oi}\geq 1} f_{oi}{}^{P_i}\right) - (N_I - 1)\right]\left[\left(\sum_{f_{oi}< 1} f_{oi}{}^{-P_i}\right) - (N_D - 1)\right]^{-1} K_o \qquad \text{(Eq. 7.15)}$$

7.3 Sensitivity and Significance of Parameters

According to Prokopy and Rubin (1975), rail line capacity "is not so much a function of the capability to move trains over a line…as it is the ability to move trains over a line without undue delay." When delays generally exceed acceptable limits, lines lock up. Therefore, rail lines are limited by their ability to "absorb considerable increases in traffic without major changes in line or operating characteristics."

One parameter found to be sensitive to capacity is the number of available tracks. However, "theoretical capacities for both single and double track can only be approached as trains are run at moderately high uniform speeds." Trains speeds are generally a function of train priority as intermodal trains which carry high value commodities tend to travel at faster speeds than low value commodity trains such as coal trains. Train priority is thus considered to having the greatest effect on train delays (Dingler 2009). It was found that the greater the distribution of train speeds on any line, the more the interactions occur among trains and the greater the delay (Prokopy and Rubin 1975, Dingler 2009).

Line capacity was also found to be generally less sensitive to siding spacing, except for larger siding spacing, which resulted in greater sensitivity. Other parameters found to be sensitive to line capacity include signal block length, crossover spacing, siding, and train lengths. Further review of these parameters can be found in the report, *Parametric Analysis of Railway Line Capacity* (Prokopy and Rubin, 1975).

7.4 Chapter Summary

This chapter demonstrated how rail capacity can be integrated into the development of the TRIT model. To estimate delays caused by rail capacity constraints, TRIT integrates a model developed in an earlier study on *Parametric Analysis of Railway Line Capacity* (Prokopy and Rubin, 1975), which measures subdivision capacity and evaluates the effect of improvements on the system. It was found that heterogeneous trains speed is the most sensitive parameter to line capacity as trains running at different speeds are most likely to interact and cause delays. The next chapter is dedicated to examining the sensitivity of key variables found in the toolkit and how they affect rail operations.

Chapter 8. Rail Model Sensitivity Analysis

Sensitivity analysis of the model considered only an intercity line-haul movement and excluded short branch line movements and yard switching, as the goal was to test the model's sensitivity to variables such as horsepower per trailing ton (HPTT) ratio, fuel price changes, and cargo weight. The research team acquired rail track data for a route stretching from Houston to Dallas/Fort Worth. The total distance of the track is 318 miles with the highest elevation at 913 feet, the lowest elevation at 45 feet, and a ruling grade of 1.28%. Due to insufficient data, calculation of track curvature resistance was excluded from the analysis, which may result in an underestimation of total train resistance and fuel consumption. The train is assumed to be a high priority train with no stops along the route. Labor cost, maintenance cost, and the price of fuel were taken from a previous study and adjusted for inflation. Fixed cost for intermodal terminal operations for loading and unloading containers was also set at $75 a container (Resor et al. 2007). A summary of the inputs are as follows:

- Distance of route: 318 miles
- Tare weight of one 40-ft container: 4.2 tons
- Tare weight of one container carrier car: 17.60 tons
- Utilization ratio: 100%
- Engine efficiency: 85%
- Locomotive horsepower: 4,000 HP
- Number of crew members: 2
- Average crew wages: $1.53 per mile (UTU, 2013)
- Fuel price: $3.00/gal
- Track maintenance: $0.0021 per gross ton-mile—calculated using reported repair and maintenance operating expenses and gross ton-miles by five Class I Railroads in 2011 (STB, 2012)
- Car maintenance: $0.13 per mile (Resor et al. 2007, Seedah et al., 2011)
- Locomotive maintenance: $2.21 per mile (Resor et al. 2007, Seedah et al., 2011)
- Loading cost: $75, unloading cost: $75

8.1 Effect of HPTT Ratio

A two-locomotive train running at different HPTT ratios was tested. The scenario involved a 110 double-stacked container train with a cargo weight of 25 tons, with the assumption that all the train was 100% fully loaded. HPTT ratio was varied from 1.0 to 2.0 at 0.25-intervals as presented in Table 8.1. As HPTT ratio increased, train speeds increased and so did fuel consumption and cost per payload ton-mile. Fuel consumption for all five scenarios ranged between 1979.8 to 2022.4 gallons; average travel speeds ranged between 23.7 MPH and 26.9 MPH, and travel times decreased from 13.9 hours to 12.4 hours. The results show that at higher HPTT ratios, trains run at faster a speed but in turn consume more fuel. Cost savings achieved through shorter travel times may be offset by an increase in fuel cost. On an average, payload cost per ton-mile for all five scenarios was determined as 3.559¢ per ton-mile.

A key observation in this analysis is the comparison of the model's ton-mile moved per gallon of fuel consumed. From all five scenarios, the payload ton-mile per gallon of fuel ranged from 442.3 to 433.0 ton-miles per gallon. The published national average for Class I railroads is estimated at 480 ton-miles per gallon of fuel by the Association of American Railroads (*AAR, 2012*). A recent FRA study (*ICF Consulting, 2009*) also determined that for intermodal movements involving 2 locomotives, fuel consumption ranged from 226 and 512 for payload ton-mile per gallon, and 588 and 849 for trailing ton-mile per gallon. Trailing ton-mile per gallon for the five scenarios ranged from 736.7 and 721.2 ton-mile per gallon as shown in Table 8.1. A percentage cost breakdown of the various output variables also shows that the most dominant variable is the loading and unloading cost, followed by maintenance, fuel, labor, and equipment depreciation. Cost outputs determined to be influenced by HPTT ratio are fuel and the time-dependent variables: labor and equipment depreciation.

Table 8.1: Effect of HPTT Ratio on Rail Operations

Variables	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**
HPTT Ratio	1.00	1.25	1.50	1.75	2.00
Model Output					
Trailing weight (in tons)	4180	4180	4180	4180	4180
Fuel consumed (in gallons)	1979.8	2000.1	2010.6	2011.1	2022.4
Cost per payload ton-mile (in cents)	3.564¢	3.562¢	3.556¢	3.554¢	3.554¢
Cost per trailing ton-mile (in cents)	2.345¢	2.343¢	2.341¢	2.334¢	2.334¢
Trailing ton-mile moved per gallon	736.7	729.2	725.4	725.2	721.2
Payload ton-mile moved per gallon	442.3	437.9	435.6	435.5	433.0
Estimated average speed (MPH)	23.69	24.74	25.65	26.32	26.87
Estimated travel time (hours)	13.9	13.3	12.9	12.6	12.4
Percentage Cost Breakdown					
Fuel cost	19.03 %	19.23 %	19.36 %	19.39 %	19.49 %
Maintenance cost	21.15 %	21.16 %`	21.18 %	21.21 %	21.21 %
Loading/unloading cost	52.86 %	52.89 %	52.95 %	53.02 %	53.02 %
Equipment depreciation cost	1.00 %	0.97 %	0.94 %	0.92 %	0.90 %
Labor cost	5.96 %	5.75 %	5.58 %	5.46 %	5.37 %

8.2 Effects of Fuel Price Changes

The effect of fuel price changes on payload cost per ton-mile was also evaluated using the two-locomotive train configuration and an HPTT ratio of 1.5. For changes in fuel price from $2.50 a gallon to $6.00, payload cost per ton-mile increased 23% from 3.444¢ to 4.247¢. For every 50 cent increase in fuel price, payload cost per ton-mile increased on an average of 3.04%.

8.3 Effect of Cargo Weight

Figure 8.1 shows how cargo weight affects the total costs per ton-mile for this train along this corridor using a similar train configuration as earlier. This sensitivity was conducted with an HPTT ratio of 1.50 and fuel price of $3.00. As cargo weight increased by 5 tons per container to 25 tons per container the payload cost per ton-mile decreased from 15.72¢ for 5-ton containers to 3.22¢ for 25-ton containers. The trend here seems to suggest that as the cargo weight increases, rail becomes more cost effective.

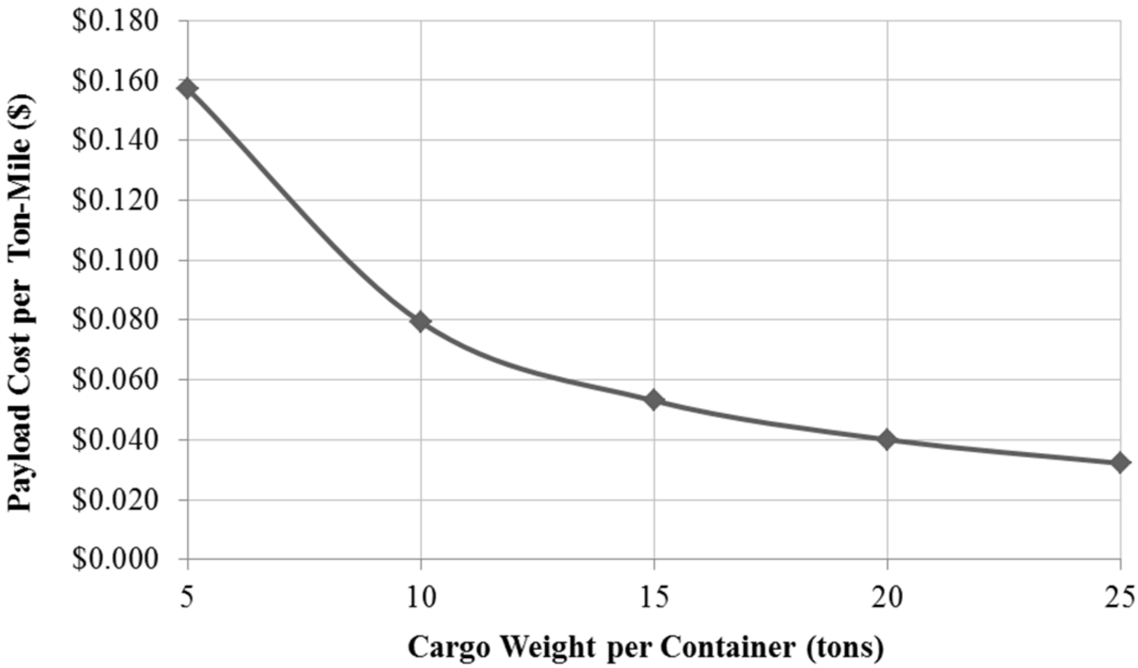


Figure 8.1: Effects of Cargo Weight on Total Costs per Ton-Mile

8.4 Chapter Summary

A sensitivity analysis of the model using the Houston-to-Dallas corridor indicated that HPTT ratio influence fuel costs, travel speeds, travel time, and the time-dependent variables such as labor and equipment depreciation. In addition, it was determined that for every 50¢ increase in fuel price, payload cost per ton-mile increased on an average of 3.0%. Increasing cargo weight was also seen to influence payload cost per ton-mile as the analysis showed that as the cargo weight increases, rail becomes more cost effective. Additional analysis that may be done by planners include testing how changes in distance, delays, labor costs, and grades can influence payload cost per ton-mile and other factors.

This chapter is followed by an example case study of the Houston-to-Dallas/Fort Worth Interstate 45 freight corridor using freight data reported by the 2007 Freight Analysis Framework.

Chapter 9. Corridor Case Study

Here we report the findings from a series of scenarios tested with the most recent version of TRIT. The scenarios were developed for freight flows along Interstate 45 (I-45) corridor, which was selected by members of the PMC during the completion of Task 6. The I-45 corridor directly connects Houston and Dallas/Fort Worth and facilitates freight movements for both truck and rail. The corridor is served by two Class I railroads (BNSF and UP), and was appropriate for multimodal corridor analysis because of the provision of rail track data along the corridor by one of the railroad companies.

The following scenarios of the I-45 corridor were developed to demonstrate how TRIT can be used in performing multimodal corridor analysis. Four types of analysis were performed to compare truck and rail movement scenarios along the corridor using freight flow data from the Freight Analysis Framework (FAF). The analyses examined the following questions:

1. What will be the most cost-effective train configuration to enable railroads to consider a daily service along the corridor?
2. What will be the impact of an increase in rail share along the corridor on overall fuel consumption, CO2 emissions, and the number of truck trips along the corridor?
3. Can trucks compete with rail at greater fuel efficiencies than what currently exists?
4. What are the effects of drayage distance on overall rail movement?

This chapter begins with a general description of the characteristics of the corridor, states the assumptions made for the analyses, describes the methodologies used, and reports on the findings from the above proposed research questions.

9.1 Corridor Characteristics

I-45 is a 285-mile roadway connecting the cities of Dallas and Houston, terminating in Galveston, on the coast of the Gulf of Mexico (see Figure 9.1). Average annual daily traffic along the corridor varied between 43,000 vehicles per day in Navarro County (near Dallas) to 57,000 in Montgomery County near the city of Houston in 2010. Truck traffic at those locations was reported at 8,351 (i.e., 19.4% of total traffic) and 9,787 (i.e., 17.2% of total traffic) respectively. The 2010 daily truck traffic showed a decrease of 33.3% for Navarro County and 5.2% for Montgomery County compared to the 2009 figures (12,512 in Navarro County and 10,328 in Montgomery County).

The corridor is served by seven rail terminal facilities—three located in Dallas/Fort Worth and four in Houston. In Dallas/Fort Worth, BNSF operates from the Alliance Intermodal Facility, and UP operates from the Mesquite and Dallas Intermodal Terminal facilities in Dallas. In Houston, BNSF operates the Houston (Pearland) Intermodal Facility and UP operates the Settegast, Englewood, and Barbours Cut facilities (see Figure 9.2).

According to the FHWA, 23,765,000 tons of cargo was moved between the Houston and Dallas/Fort Worth Combined Statistical Areas (CSA) in 2007 (see Table 9.1). This number is projected to increase by 137% by 2040. Cargo moved from Dallas/Fort Worth to Houston alone accounts for 46.8% of goods moved between the two cities in 2007, and this number is projected to increase to 65.5% by 2040. By value, $32.4 billion of goods were transported between the two cities in 2007, which is projected to increase by 218% to $102.9 billion by 2040.

Table 9.1: 2007 and 2040 Freight Flows between Dallas/Fort Worth and Houston CSAs (FHWA, 2010)

Origin	**Destination**	**KTons in 2007**	**KTons in 2040**	***Percent Change***	**M$ in 2007**	**M$ in 2040**	***Percent Change***
Dallas/Fort Worth CSA	Houston CSA	11,127	36,885	*231%*	14,587	37,383	*156%*
Houston CSA	Dallas/Fort Worth CSA	12,639	19,383	*53%*	17,776	65,477	*268%*
	Total	**23,765**	**56,269**	***137%***	**32,363**	**102,860**	***218%***

The top five commodities transported by all modes from Dallas/Fort Worth to Houston in 2007, by weight and classified using a two-digit SCTG (Standard Classification Transportable Goods) code, were non-metallic mineral products, waste/scrap, other foodstuffs, basic chemicals, and coal. By value, the top five commodities moved include mixed freight, electronics, motorized vehicles, machinery, and miscellaneous manufactured products. The top five commodities, by weight, transported from Houston to Dallas/Fort Worth by all modes include waste/scrap, coal, basic chemicals, base metals, and fuel oils. By value, the top five commodities transported by all modes include motorized vehicles, machinery, plastics/rubber, electronics, and coal.

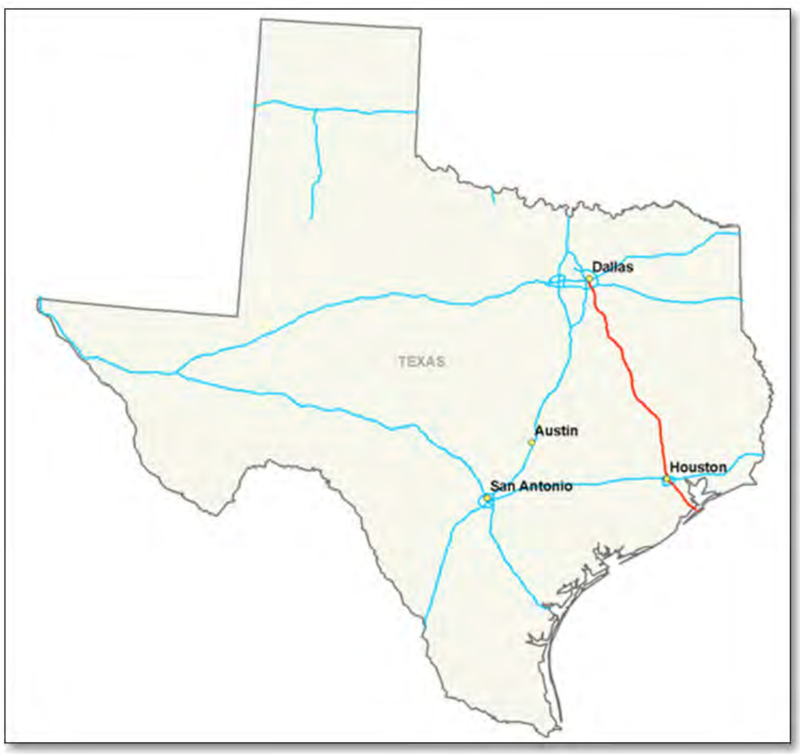


Figure 9.1: Interstate 45 Corridor Connecting Houston to Dallas/Fort Worth

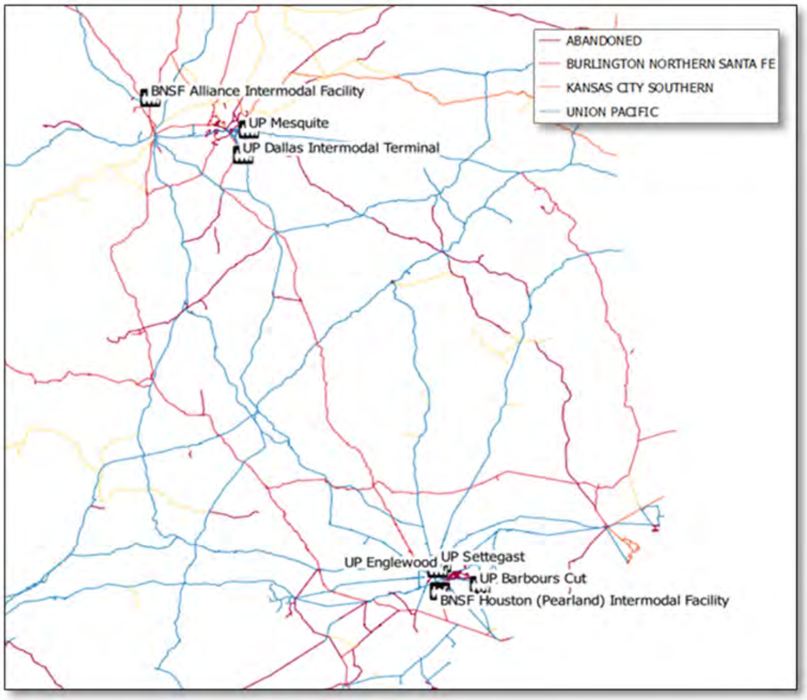


Figure 9.2: Rail Lines and Terminals Serving Houston and Dallas/Fort Worth

9.2 Case Study Inputs and Assumptions

The research team acquired rail track data for a route stretching from Houston to Dallas/Fort Worth as illustrated in Figure 9.3. The total distance of the track is 318 miles with the highest elevation at 913 feet and the lowest elevation at 45 feet (see Figure 9.3). Posted speeds ranged between 20 MPH and 55 MPH, with a weighted average of 41 MPH (see Figure 9.4). Due to insufficient data, track curvature and its associated resistances were excluded in the calculation of train resistances. Labor cost, maintenance cost, and loading/unloading costs were taken from previous studies and adjusted for inflation. A summary of the inputs are as follows:

- Distance of route: 318 miles,
- Tare weight of one 40-ft container: 4.2 tons,
- Tare weight of one container carrier car: 17.60 tons,
- Utilization ratio: 100%
- Engine Efficiency: 85%
- Locomotive horsepower: 4,000 HP
- Number of crew members: two,
- Average Crew wages: $63.50 per hour per crew member,
- Fuel price: $3.00/gal,

- Track maintenance: $0.0020 per gross ton-mile – calculated using reported repair and maintenance operating expenses and gross ton-miles by five Class I Railroads in 2011,
- Car maintenance: $0.13 per mile,
- Locomotive maintenance: $2.21 per mile, and
- Loading Cost: $75, Unloading Cost: $75 (Resor, Blaze and Morlok, 2004)

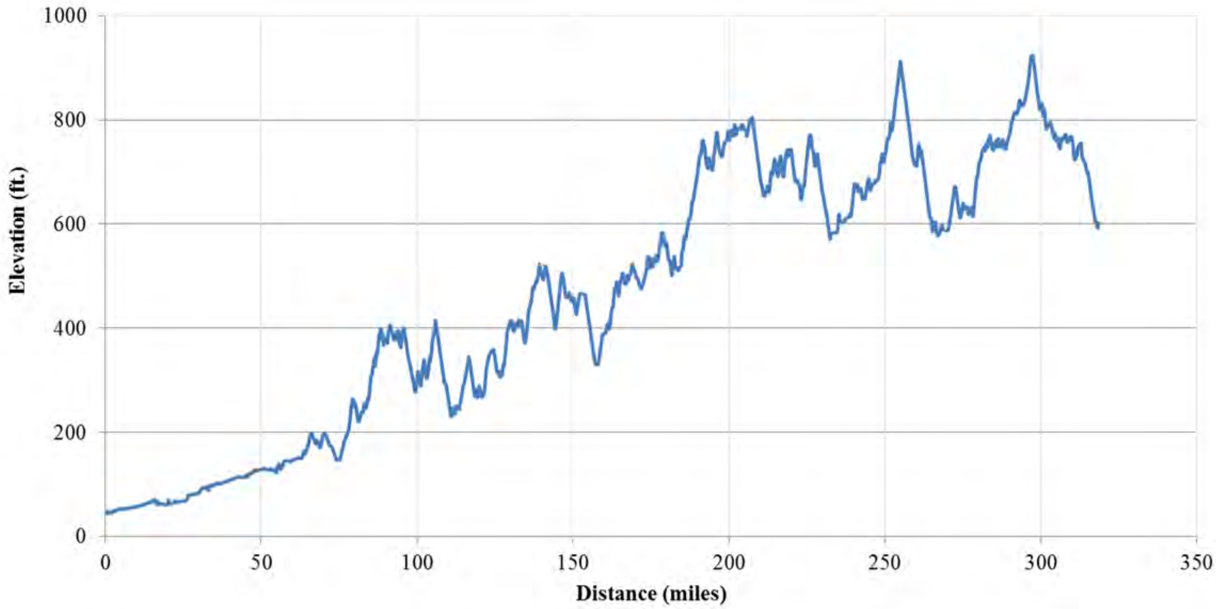


Figure 9.3: Sample Rail Track Elevations from Houston-Fort Worth

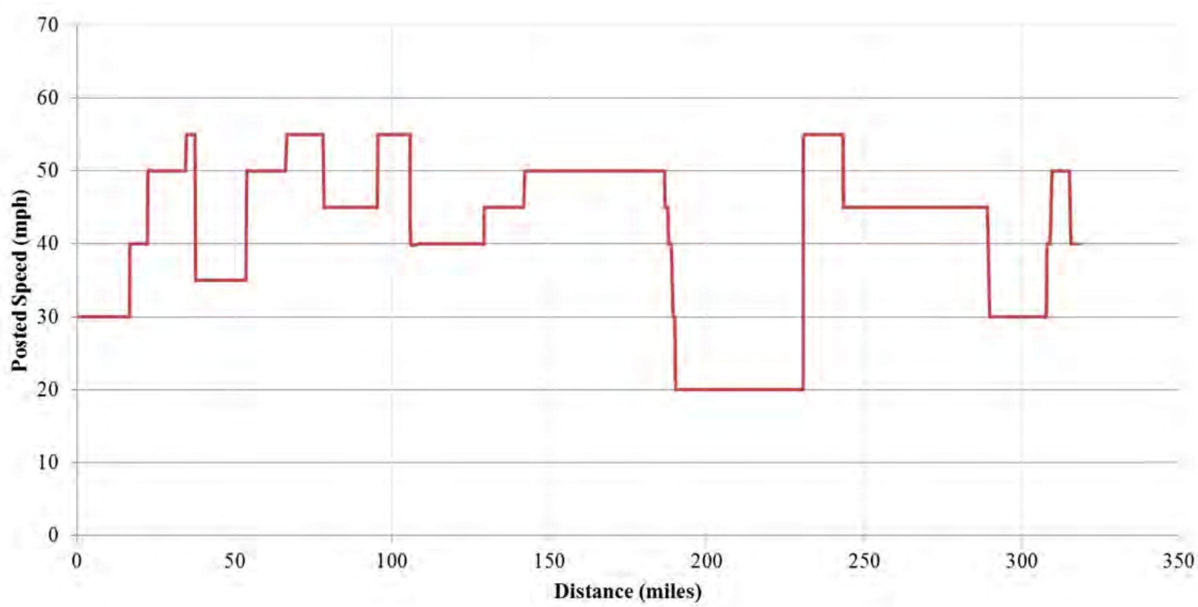


Figure 9.4: Sample Rail Track Posted Speeds from Houston-Fort Worth

The following assumptions were made in the scenarios:

- Only truck and rail movements tonnage values as defined by the FAF are used;
- Cargo weight is 25 tons for both truck and rail modes;
- Diesel fuel price is $3.00 a gallon for both truck and rail;
- There are no stops between the two cities;
- Except for the last scenario analysis, assume a 315-mile trip for both truck and rail movements;
- Rail can move most of the commodities currently being transported by trucks;
- Average truck fuel consumption was taken as 6.35 MPG to account for recent technological improvements in trucking;
- Average truck speed is assumed to be 60 MPH and railroad speeds are governed by posted speeds;
- Only intermodal trains were considered and an HPTT ratio of 3.0 is selected;
- Number of locomotives was adjusted to reflect required horsepower; and
- Containers carried by rail are assumed to be double-stacked for efficiency purposes.

9.2.1 Scenario 1: Most cost-effective train configuration for daily service

In order for rail to compete with trucks, the first consideration made in this case study is that there should be at least one train trip between each city every day of the year. Based on current projected shares from FAF, for trips between Houston and Dallas, 436 kilotons of cargo was transported by rail in 2007 and 614 kilotons in 2011 (see Table 9.2). This number is expected to continue to grow to 761 kilotons by 2040. To calculate the minimum number of annual trips required to meet demand, reported annual tonnage was divided by the total number of containers the daily service train carries, and assuming each container weighed 25 tons. By dividing the calculated number of trips by 365 days, the average daily utilization (in percentages) per train is determined. The equation for calculating daily utilization ratio was therefore determined using the following:

$$Daily\ Train\ Utilization = \frac{Annual\ Tonnage}{Total\ no.of\ containers\ carried \times 25\ tons\ a\ container\ \times 365\ days}$$

For the 50-container train, 96% of the daily train was calculated to be full for each trip in 2007 and this number increased to 135% by 2011,which means that at least two trains are required to move the cargo with one train being 100% full and the other train being 35% full. For the 100-container train, 175 trips were required in 2007, with each train carrying 48% loaded containers and 52% empties. The number of full containers, however, increases to 83% by 2040 if rail had a 4.8% share of total goods moved. It can also be observed that for a 200-container train with 25 tons of cargo, 87 trips are required to meet the annual demand in 2007. This number is expected to increase to 152 trips by 2040. However, the daily load per train (or the utilization ratio) of the train per trip is 24%, i.e., 76% of the train will be carrying empties.

Utilization ratio increases to 42% in 2040, which means 58% of the load being carried will be empties.

Table 9.2: Number of Trips and Daily Loads per Train

Year	Rail (KTons)	50-container train		100-container train		200-container train	
		Min. No. of Trips	Daily Load per Train	Min. No. of Trips	Daily Load per Train	Min. No. of Trips	Daily Load per Train
2007	436	349	96 %	175	48 %	87	24 %
2011	614	491	135 %	246	67 %	123	34 %
2015	635	508	139 %	254	70 %	127	35 %
2020	676	541	148 %	270	74 %	135	37 %
2025	687	550	151 %	275	75 %	137	38 %
2030	706	565	155 %	282	77 %	141	39 %
2035	724	579	159 %	290	79 %	145	40 %
2040	761	609	167 %	304	83 %	152	42 %

Using TRIT, the ton-mile costs and fuel consumptions associated with moving the different types of trains at different utilization ratios were tested from totally empty (0%), 20% full, 40% full, 60% full, 80% full, and 100% full. Based on the analysis of the three train options as presented in Table 9.2, the 100-container train was selected as the most competitive for comparison with trucking along the corridor. Its payload per ton-mile was competitive to that of the 200-container train (see Figure 9.5), and from an energy use and emissions perspective, the 100-container train consumes up to 50% less fuel than the 200-container train (see Figure 9.6). In addition, it can be inferred from the model's output in Table 9.2 that the 200-container train will mostly be moving empties. The complete output data for the three train types is presented in Table 9.3 and shows the average travel speeds and number of locomotives required to meet the horsepower demands of the train.

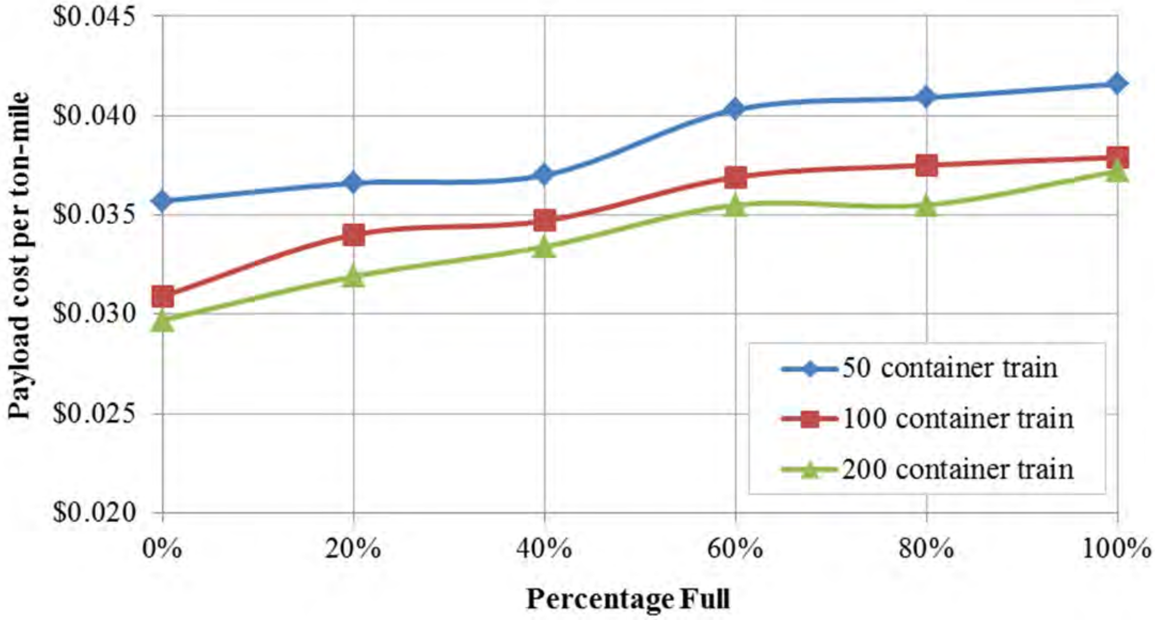


Figure 9.5: Operating Payload Cost per Ton-Mile

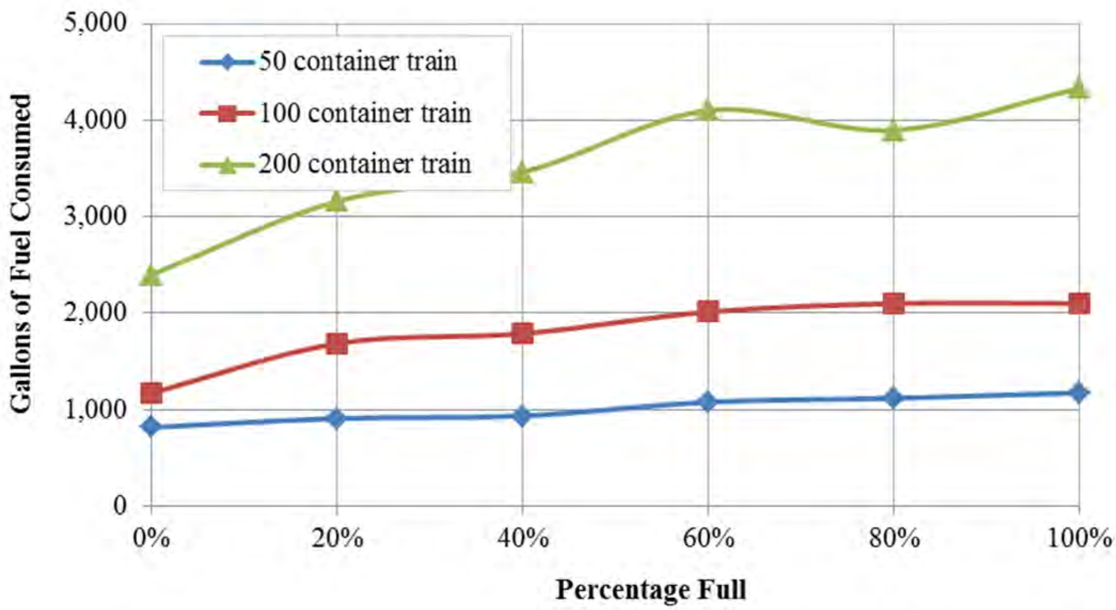


Figure 9.6: Fuel Consumption (in gallons)

Table 9.3: Trip Characteristics at Different Utilization Ratios

50-container train						
Utilization Ratio	*0%*	*20%*	*40%*	*60%*	*80%*	*100%*
Required No. of Locos	1 loco	1 loco	1 loco	2 locos	2 locos	2 locos
Rolling stock (in tons)	816.55	900	1150	1400	1650	1900
Average travel speed	27.3	28.2	28.8	32	32.5	32.9
Payload cost per ton-mile	0.0357	0.0366	0.037	0.0403	0.0409	0.0416
Gallons used	816.55	908.46	935.16	1077.84	1118	1175
100-container train						
Utilization Ratio	*0%*	*20%*	*40%*	*60%*	*80%*	*100%*
Required No. of Locos	1 loco	2 locos	2 locos	3 locos	3 locos	3 locos
Rolling stock (in tons)	1300	1800	2300	2800	3300	3800
Average travel speed	24	27.3	28	30	30.5	31
Payload cost per ton-mile	0.0309	0.034	0.0347	0.0369	0.0375	0.0379
Gallons used	1174	1685	1788	2013	2100	2100.06
200-container train						
Utilization Ratio	*0%*	*20%*	*40%*	*60%*	*80%*	*100%*
Required No. of Locos	1 loco	2 locos	2 locos	5 locos	5 locos	6 locos
Rolling stock (in tons)	2600	3600	4600	5600	6600	7600
Average travel speed	23.6	25.6	27.3	28.5	29.1	30.1
Payload cost per ton-mile	0.0297	0.0319	0.0334	0.0355	0.0355	0.0372
Gallons used	2400	3160	3463	4101	3897	4330

9.2.2 Scenario 2: Measuring the Effect of an Increase in Rail Share

The second part of the I-45 corridor case study involved examining the effect of rail share along the corridor using fuel consumption, emissions used, and number of truck trips. This scenario compared FAF projections with a hypothetical scenario based solely on changes in rail share from 2007 to 2011. Only trips from Houston to Dallas/Fort Worth were considered.

According to FAF projections, freight rail share is projected to linger between 4.8% and 5.6% from 2015 to 2040 as shown in Table 9.4. Daily train utilization ratio (calculated using the equation from Section 9.2.2) for a 100-container train will increase from 48% in 2007 to 83% by 2040, i.e., the number of empty containers moved per trip will decrease from 52% in 2007 to 17% in 2040. Assuming each truck carried 25 tons of cargo, annual truck trips will grow by 60% from 2011 to 2040 (i.e., from 374,029 trips to 598,065 trips).

Table 9.4: Current FAF Projections

Year	Truck Tonnage (in Ktons)	Rail Tonnage (in Ktons)	FAF Projected Rail Share	Daily Train Utilization	Annual Truck Trips
2007	9,436	436	4.4%	48%	377,447
2011	9,351	614	6.2%	67%	374,029
2015	10,702	635	5.6%	70%	428,070
2020	11,361	676	5.6%	74%	454,453
2025	11,995	687	5.4%	75%	479,807
2030	12,667	706	5.3%	77%	506,666
2035	13,606	724	5.1%	79%	544,256
2040	14,952	761	4.8%	83%	598,065

Using 2007 to 2011 rail tonnage growth (i.e., 436 kilotons and 614 kilotons respectively), an annual rail cargo growth rate of 8.93% was calculated. Using this growth rate as an hypothetical growth rate, future rail traffic share along the corridor for trips from Houston to Dallas/Fort Worth increased from 4.4% in 2011 to 31.8% by 2040 (see Table 9.5).

Table 9.5: Current FAF Projections vs. Hypothetical Projections

Year	Current FAF Projections	Hypothetical Projections*
2007	4.40%	4.40%
2011	6.20%	6.20%
2015	5.60%	7.10%
2020	5.60%	9.90%
2025	5.40%	13.80%
2030	5.30%	18.90%
2035	5.10%	25.00%
2040	4.80%	31.80%

*Hypothetical projections based on 2007 to 2011 flows

Using a similar distance of 315 miles travelled by both rail and truck, the average fuel consumption for a single truck trip from Houston to Dallas/Fort Worth was determined to be approximately 50 gallons at a fuel consumption rate of 6.35 MPG. One gallon of fuel is also estimated to produce 2.66 E-5 metric tons of CO_2. The hypothetical projections resulted in the following observations:

1. Annual truck traffic decreases by 2% in 2015, and 44% in 2040 (see Table 9.5).
2. Fuel consumed by truck trips decreased by a similar percentage as change in truck trips, i.e., a reduction of 460,435 gallons in 2015 and 13,157,209 gallons in 2040 (see Table 9.6). Should fuel consumption rates be assumed to increase to 20.0 MPG (by 2040), reduction in truck fuel consumption based on the number of trips can be estimated at 3,639,284 gallons.
3. Decrease in truck fuel consumption will result in subsequent decrease in $C0_2$ emissions by 12 metric tons in 2015 and 350 metric tons in 2040 (see Table 9.6).

4. Daily train utilization, which measures the number of fully-loaded trains, will increase for the 100-container train from a 70% loaded train to a 95% loaded train in 2015 should rail share increase from 5.6% to 7.1%. By 2040, utilization of the 100-container train will increase from an 83% loaded train to eight 100% fully-loaded trains a day (see Table 9.7).
5. Increase in train utilization as a result of the increased rail shares, resulted in 716,495 extra gallons of fuel being consumed by rail in 2020, and 5,364,770 extra gallons of fuel being consumed by 2040, a 94% and 700% increase, respectively, in comparison to current projections. Rail CO_2 emissions increase by 704% in 2040 as well (see Table 9.8).
6. Combined truck and rail fuel consumption decreased by 2% (454,960 gallons) for the hypothetical scenario compared to the FAF projections in 2015, and by 25% (7,792,439 gallons) in 2040 (see Figure 9.7). CO_2 emissions also decreased by similar percentages at a reduction of 12 metric tons in 2015 and 196 metric tons in 2040 (Table 9.9).
7. If truck fuel consumption rates were to increase to say 20.0 MPG in 2040, total fuel consumption would have increased by 1,680,752 gallons as the trucks will have used less fuel than rail.

Table 9.6: Annual Truck Traffic

Year	Current FAF Projections	Hypothetical Projection	% Decrease
2007	377,447	377,447	
2011	374,029	374,029	
2015	428,070	418,861	-2%
2020	454,453	428,424	-6%
2025	479,807	425,908	-11%
2030	506,666	410,091	-19%
2035	544,256	381,804	-30%
2040	598,065	334,921	-44%

Table 9.7: Truck Fuel Consumption and CO_2 Emissions

Year	Truck Fuel Consumption			Truck CO_2 Emissions		
	Current FAF Projections	Hypothetical Projection	Change in Gallons	Current FAF Projections	Hypothetical Projection	Change in Metric Tons
2007	18,872,375	18,872,375		502	502	
2011	18,701,438	18,701,438		497	497	
2015	21,403,505	20,943,070	-460,435	569	557	-12
2020	22,722,627	21,421,178	-1,301,448	604	570	-35
2025	23,990,342	21,295,419	-2,694,923	638	566	-72
2030	25,333,288	20,504,545	-4,828,744	674	545	-128
2035	27,212,782	19,090,182	-8,122,600	724	508	-216
2040	29,903,263	16,746,054	-13,157,209	795	445	-350

Table 9.8: Daily Train Utilization

Year	Current Projections	Hypothetical Projection
2007	48%	48%
2011	67%	67%
2015	70%	95%
2020	74%	145%
2025	75%	223%
2030	77%	342%
2035	79%	524%
2040	83%	804%

Table 9.9: Rail Fuel Consumption and CO_2 Emissions

	Rail Fuel Consumption			Rail CO_2 Emissions		
Year	Current FAF Projections	Hypothetical Projection	Change in Gallons	Current FAF Projections	Hypothetical Projection	Change in Metric Tons
2007	666,125.00	666,125		18	18	
2011	759,200.00	759,200		22	22	
2015	761,025.00	766,500	-5,475	22	22	0
2020	765,040.00	1,481,535	-716,495	22	32	10
2025	766,500.00	2,149,120	-1,382,620	22	49	27
2030	766,500.00	2,955,405	-2,188,905	22	75	53
2035	766,500.00	4,450,080	-3,683,580	22	115	93
2040	767,230.00	6,132,000	-5,364,770	22	176	154

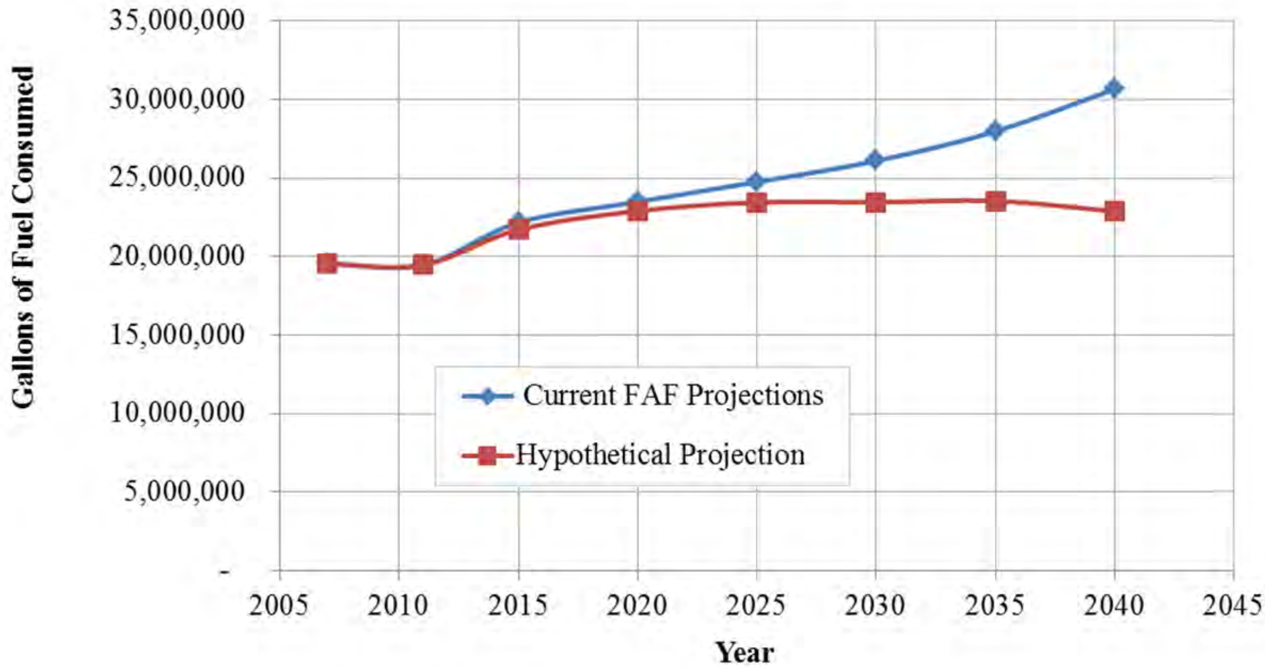


Figure 9.7: Combined Truck and Rail Fuel Consumption

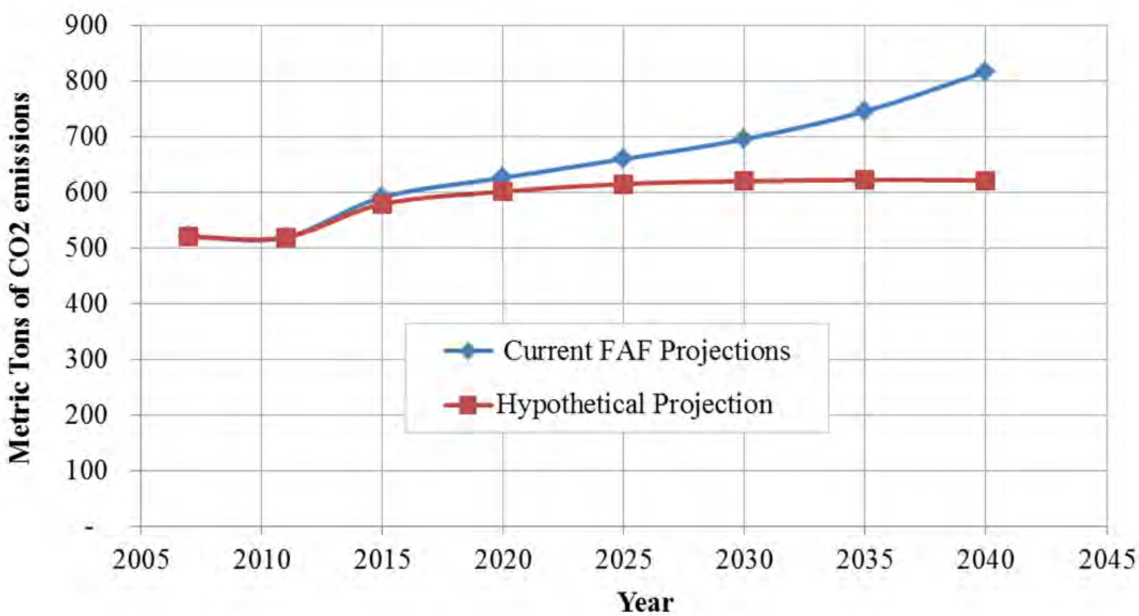


Figure 9.8: Combined Truck and Rail CO2 emissions

9.2.3 Scenario 3: Can trucks compete with rail at greater fuel efficiencies than what currently exists?

Based on the observations of the previous scenario, it was determined that in 2040, overall fuel consumption reduced when average truck fuel economy increased to 20 MPG.

Scenario 3 seeks to further examine if the trucking industry can be competitive to rail along the corridor from a fuel consumption perspective should truck fuel economy increase. This experiment was designed by determining the number of trucks and train trips required to move an increasing amount of cargo annually. For example, for a 2,000 kiloton annual demand, 80,000 fully loaded truck trips will be required, and 2.2 100-container train trips will be required daily (i.e., two trips of 100% fully loaded containers and a single trip at 20% fully loaded containers) as presented in Table 9.10 and Figure 9.9.

Table 9.10: Gallons of Fuel Consumed for Varying Truck Fuel Economy

Kilotons of	Number of	Number of	Fuel Consumption (in gallons)						
Cargo	Truck Trips	Rail Trips	5 mpg	10 mpg	15 mpg	20 mpg	25 mpg	30 mpg	Rail
500	20,000	0.5	1,272,000	636,000	300,000	318,000	254,400	212,000	1,821
1,000	40,000	1.1	2,544,000	1,272,000	600,000	636,000	508,800	424,000	3,498
1,500	60,000	1.6	3,816,000	1,908,000	900,000	954,000	763,200	636,000	3,698
2,000	80,000	2.2	5,088,000	2,544,000	1,200,000	1,272,000	1,017,600	848,000	5,404
2,500	100,000	2.7	6,360,000	3,180,000	1,500,000	1,590,000	1,272,000	1,060,000	5,556
3,000	120,000	3.3	7,632,000	3,816,000	1,800,000	1,908,000	1,526,400	1,272,000	7,348
3,500	140,000	3.8	8,904,000	4,452,000	2,100,000	2,226,000	1,780,800	1,484,000	7,414
4,000	160,000	4.4	10,176,000	5,088,000	2,400,000	2,544,000	2,035,200	1,696,000	9,224
4,500	180,000	4.9	11,448,000	5,724,000	2,700,000	2,862,000	2,289,600	1,908,000	9,290
5,000	200,000	5.5	12,720,000	6,360,000	3,000,000	3,180,000	2,544,000	2,120,000	11,088
5,500	220,000	6.0	13,992,000	6,996,000	3,300,000	3,498,000	2,798,400	2,332,000	11,148
6,000	240,000	6.6	15,264,000	7,632,000	3,600,000	3,816,000	3,052,800	2,544,000	12,988
6,500	260,000	7.1	16,536,000	8,268,000	3,900,000	4,134,000	3,307,200	2,756,000	14,646
7,000	280,000	7.7	17,808,000	8,904,000	4,200,000	4,452,000	3,561,600	2,968,000	14,846
7,500	300,000	8.2	19,080,000	9,540,000	4,500,000	4,770,000	3,816,000	3,180,000	16,552
8,000	320,000	8.8	20,352,000	10,176,000	4,800,000	5,088,000	4,070,400	3,392,000	16,704
8,500	340,000	9.3	21,624,000	10,812,000	5,100,000	5,406,000	4,324,800	3,604,000	18,496
9,000	360,000	9.9	22,896,000	11,448,000	5,400,000	5,724,000	4,579,200	3,816,000	18,562
9,500	380,000	10.4	24,168,000	12,084,000	5,700,000	6,042,000	4,833,600	4,028,000	20,372
10,000	400,000	11.0	25,440,000	12,720,000	6,000,000	6,360,000	5,088,000	4,240,000	20,438

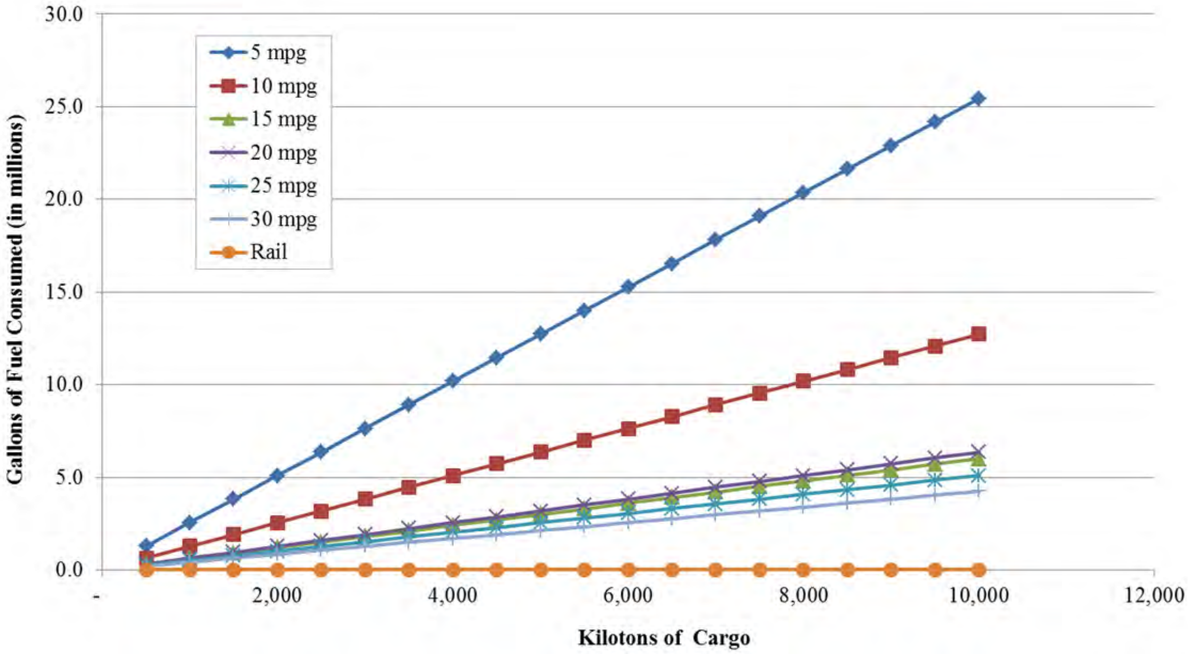


Figure 9.9: Gallons of Fuel Consumed for Increasing Cargo Demand and Varying Truck Fuel Economy

As illustrated, when the amount of cargo increases, so does the number of truck and rail trips. This leads to an increased use of fuel by both modes. However, trucking requires more fuel per ton-mile because of the limited amount of cargo moved for each trip. At higher MPGs, fuel use for trucks can reduce by up to 83% (i.e., at 30 MPG). This shows significant gains in trucking; however, compared to rail, truck fuel economy lags behind significantly. Even at 30 MPG, rail remains very competitive because of its ability to move large amounts of goods on a single trip.

9.2.4 Scenario 4: Effects of drayage distance on overall rail movement?

The last scenario examines the effect of drayage on overall rail movements. This analysis simulated cargo movements from a depot in Houston to the rail terminal then to another depot in Dallas/Fort Worth. The goal is to determine if trucking will be competitive with rail at various distances away from the terminal facility. Distances examined are 10, 20, 30, 40, and 50 miles from the BNSF rail terminal as illustrated in Figure 9.10.

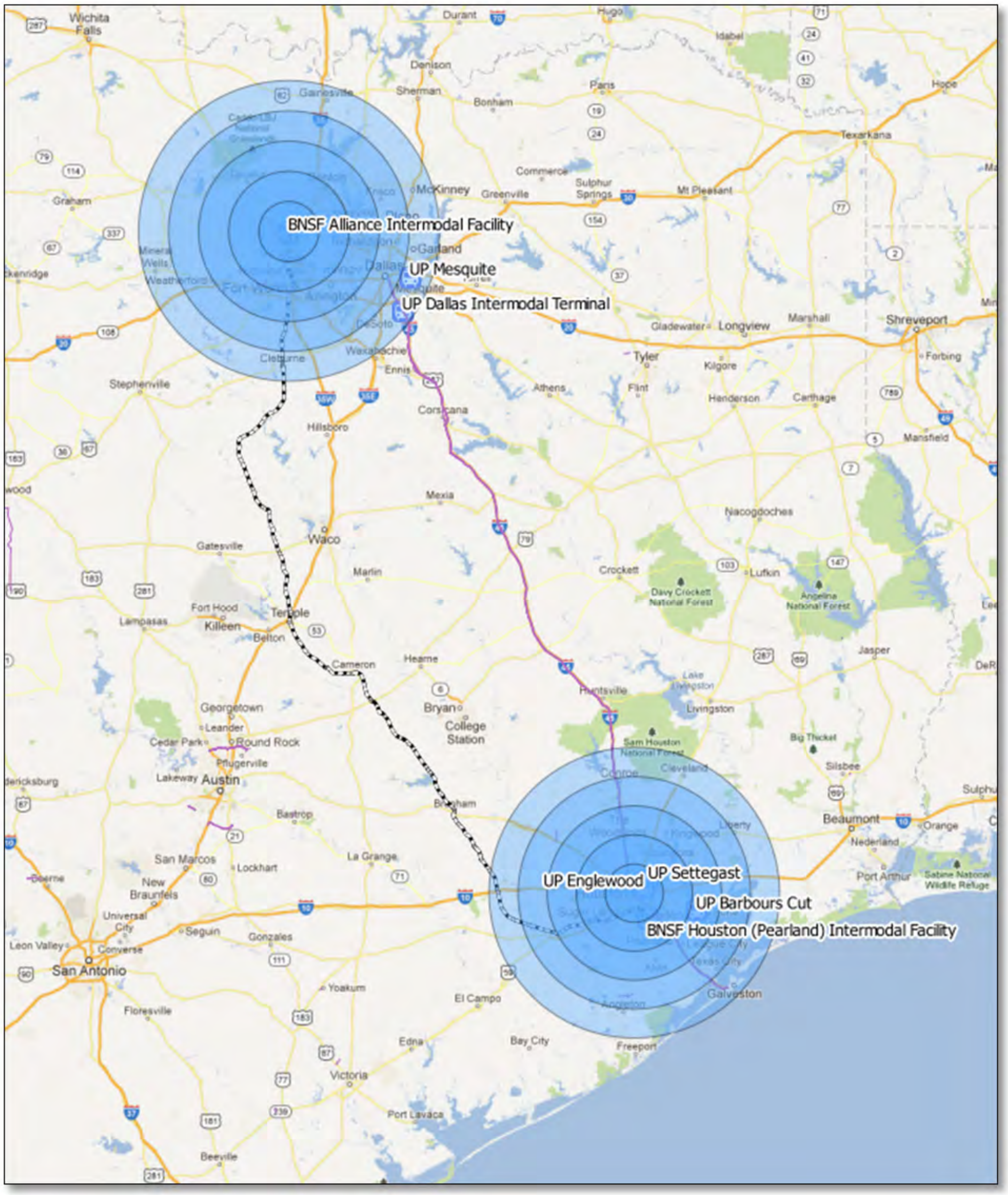


Figure 9.10: Rail Service Ranges

Preliminary results for full container movements from the analysis determined that rail operating cost per ton-mile remained competitive even at distances 50 miles away from the terminal facility (5.3¢ a ton-mile). Trucking operating cost per ton-mile was determined at 10.2¢. For movements including empty trips, rail operating cost per ton-mile increased to 10.2¢ and trucking doubled to 20.5¢. Tables 9.11 and 9.12 present the rail operating costs per ton-mile.

Table 9.11: Rail Operating Cost per Ton-Mile (Full Movements Only Including Terminal Costs)

Distance From Facility	10	20	30	40	50
10	$0.042	$0.044	$0.045	$0.047	$0.048
20	$0.044	$0.045	$0.047	$0.048	$0.050
30	$0.045	$0.047	$0.048	$0.050	$0.051
40	$0.047	$0.048	$0.050	$0.051	$0.052
50	$0.048	$0.050	$0.051	$0.052	$0.053

Table 9.12: Rail Operating Cost per Ton-Mile (Full and Empty Movement Including Terminal Costs)

Distance From Facility	10	20	30	40	50
10	$0.077	$0.081	$0.084	$0.087	$0.091
20	$0.081	$0.084	$0.087	$0.091	$0.094
30	$0.084	$0.087	$0.091	$0.094	$0.096
40	$0.087	$0.091	$0.094	$0.096	$0.099
50	$0.091	$0.094	$0.096	$0.099	$0.102

9.3 Chapter Summary

Multiple scenarios of truck and rail movements along the I-45 corridor were developed to demonstrate the various capabilities of TRIT. Specifically, four research questions were examined using freight flow data from the Freight Analysis Framework (FAF).

Based on the analysis of the three train options, the 100-container train was selected as the most competitive for comparison with trucking along the corridor. Its payload per ton-mile was competitive to that of the 200-container train, but consumes up to 50% less fuel. An increase in rail share can also result in as much as a 25% decrease in combined fuel consumption for both truck and rail modes, 196 metric tons fewer CO_2 emissions, and 44% fewer truck traffic by 2040.

Unfortunately for truckers, a significant increase in fuel economy is required to be able to compete with rail. Even with truck fuel economy at 30 MPG, rail remains very competitive because of its ability to move large amounts of goods on a single trip.

Drayage distance did not also radically influence rail efficiency even at distances 50 miles away from the rail terminal. Preliminary results for full and empty container movements from the analysis determined that rail operating cost per ton-mile remained competitive even at distances 50 miles away from the terminal facility—rail operating cost per ton-mile was 10.2¢ and trucking was 20.5¢.

The analysis seems to indicate that rail has a competitive edge over trucking from the perspectives of fuel consumption, emissions, and line-haul operating cost. However, rail's main disadvantage is its travel time and limited accessibility. Despite the benefits it has over trucking, it is limited by how quickly the train can be filled and its travel time. For example, in congested areas like Houston, adherence to much slower posted speeds due to encroachment around the rail line is critical for the safety of the surrounding populace. The slower speeds unfortunately result in substantial delays in line haul movements, and subsequently, may influence terminal operations.

In order for rail to be successful, there needs to be substantial investment in rail corridors currently influenced by encroachment. Faster speeds and reliability are necessary, in addition to an increased freight demand—more so than what currently exists. Should these occur, huge gains in fuel consumption and emissions, as illustrated in the scenarios, can be realized and benefit a statewide transportation plan.

Chapter 10. Findings and Recommendations

10.1 Key Findings

Freight moves across a variety of routes, modes, and transfer points while meeting shipper-specified needs such as speed, security, reliability, safety, and cost. Moreover, much of the system is dynamic, not static, thus complicating any analysis. Transportation planners at highway departments and metropolitan planning organizations who need to understand freight flows can only capture a cross section of the dynamic system that now drives freight logistics. They also have difficulty deriving good data that will allow them to determine effective multimodal policies and determine strategic thinking in highway agencies. This study derived data and models from previous work—much of it supported by TxDOT—in an attempt to build a basic, transparent model that could be used to evaluate multimodal corridors scenarios. The model described in the study compared truck and rail modes, though it was also structured to add waterways (river and canals) and pipelines, together with air, if necessary. This report shows that TRIT was able to be built using state and federal secondary data and models, was tested on a key segment of the TxDOT freight highway system, and provides plausible results. These results allow planners to screen scenarios, refine choices, and negotiate with users (rail and truckers) via an approach they can further refine using proprietary data. The belief is that the planning model captures the key elements that users will then employ to determine operational decisions.

TRIT was developed to help planners equally compare truck and rail freight movements for specific corridors and to give insight into some of the associated variables needed when dealing with each mode. The rail component of the model (CT-Rail) is designed to help planners and policy makers understand rail corridor operations and examine the opportunities and challenges for modal shifts from truck to rail. CT-Rail uses a mechanistic approach that adequately captures the effects of cargo weight, running speeds, network capacity, and route characteristics—key factors that are essential in any logistical analysis. The truck component of TRIT, CT-Vcost, developed from an earlier TxDOT study (Matthews et al., 2011), allows planners to simulate truck movements over a specified corridor given factors such as truck speed, equipment depreciation, financing, insurance, maintenance costs, fuel cost, driver costs, road use fees (e.g., tolls), and other fixed costs—factors that influence truck operating costs and delivery time. Comparative variables used in both models include incorporating roadway and track characteristic (elevations and grades), travel speeds, changes in fuel prices, maintenance cost, labor cost, and tonnage. The truck corridor model also accounts for toll rates and vehicle insurance cost whiles drayage cost is only included in the rail corridor model. Outputs from both models include fuel consumption and cost, travel time, and payload cost per ton-mile.

Succinctly, it was hoped that this type of modeling would provide planners with a basic Rosetta Stone that would enable acceleration of multimodal planning, particularly over key freight corridors, because the modal providers would find that their sophisticated proprietary models would confirm the cost differentials derived from TRIT. The study team found ways of estimating inputs that previously had to be supplied by railroad and trucking companies, thus accelerating the estimates during scenario evaluations. The model, originally built in a spreadsheet environment, would be better positioned as a web-based model, easing access to a range of data sources and becoming simpler to use. It would also be capable of accessing the new and established “big” data sources, which would refine modeling and capture the latest inputs, rather than relying on default values that might become obsolete. The team now believes that the beta version of the model is ready for implementation, perhaps linked to the current program of freight mobility, statewide transportation planning, and corridor analysis underway at TxDOT.

10.2 Recommendations for Project Implementation and Future Work

Successful and continued use of TRIT is dependent on the availability of recent and updatable data. The current design of TRIT enables users to calibrate the model based on available information, with default values included as a fallback option. Further enhancements of the model provide the opportunity for integration into current and existing freight planning models and databases. Figure 10.1 presents an example of a web-based version of the toolkit . The web-based version of the toolkit addresses some of the current limitations of the Microsoft® Excel™ version.

10.2.1 Accessibility

A key advantage to web-based software is that TRIT can be easily accessed by modelers and planners across the state without the need for software distribution. The application is accessible to users through any web browser and it is this form (not the spreadsheet product required by the research contract) that the study team recommends for implementation.

10.2.2 No Installation Required

The web-based application does not require users to install the application on their systems. Model updates, bug fixing, and new feature requests can be easily conveyed without the need for users to download and install new versions of the application. Management of the application is simplified, ensuring that the model is always kept up to date.

10.2.3 Integration into Other Planning Models or Databases

A web-based version of the application also enables the integration of TRIT with other existing applications and databases. An example of this is shown in Figures 10.1 and 10.2 where TRIT is integrated with Google Maps and the National Corridors Analysis and Speed Tool (N-CAST) traffic database. Future work can include the integration of the model into Houston's Transtar traffic reporting system (see Figure 10.3) and other traffic reporting systems. This enables the model modelers to evaluate corridors using both up-to-date and historical traffic data.

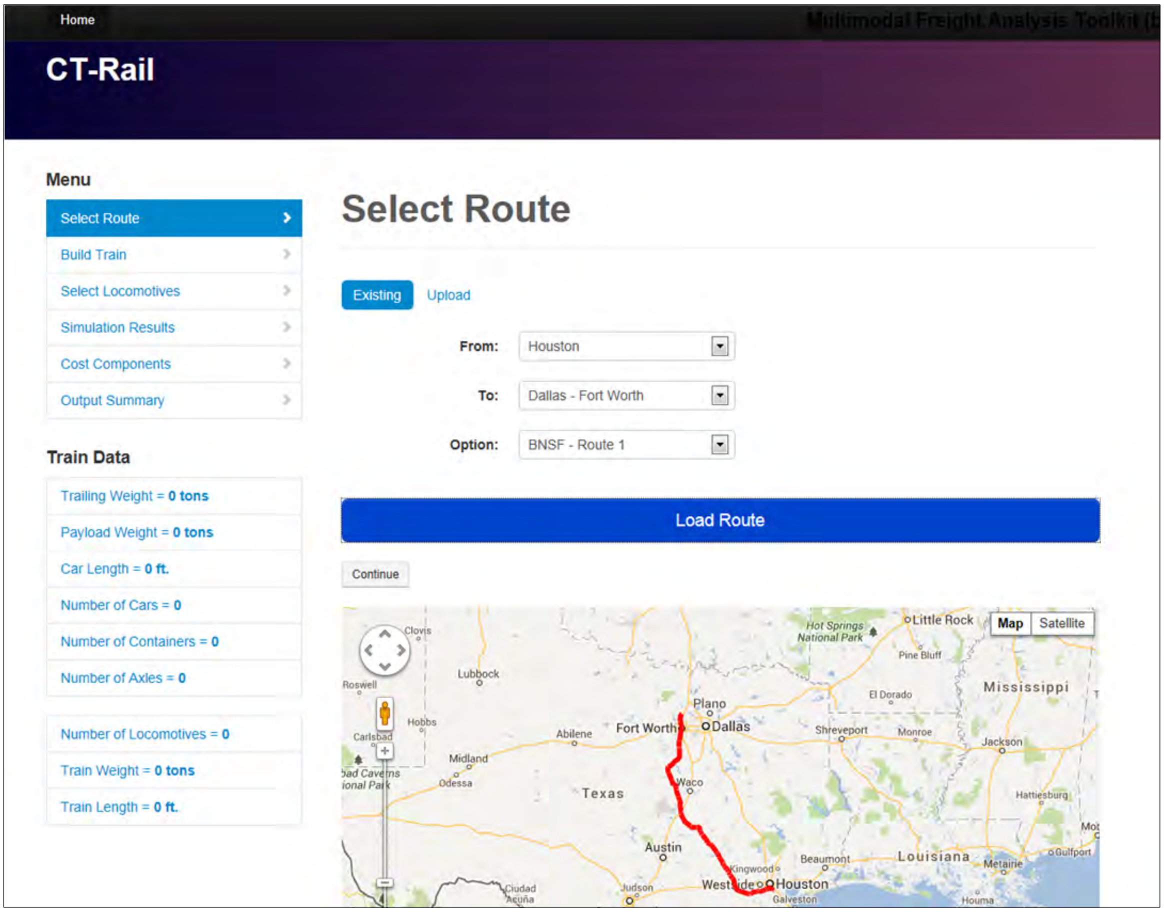


Figure 10.1: Screenshot of Beta Version of Web-Based Version of CT-Rail

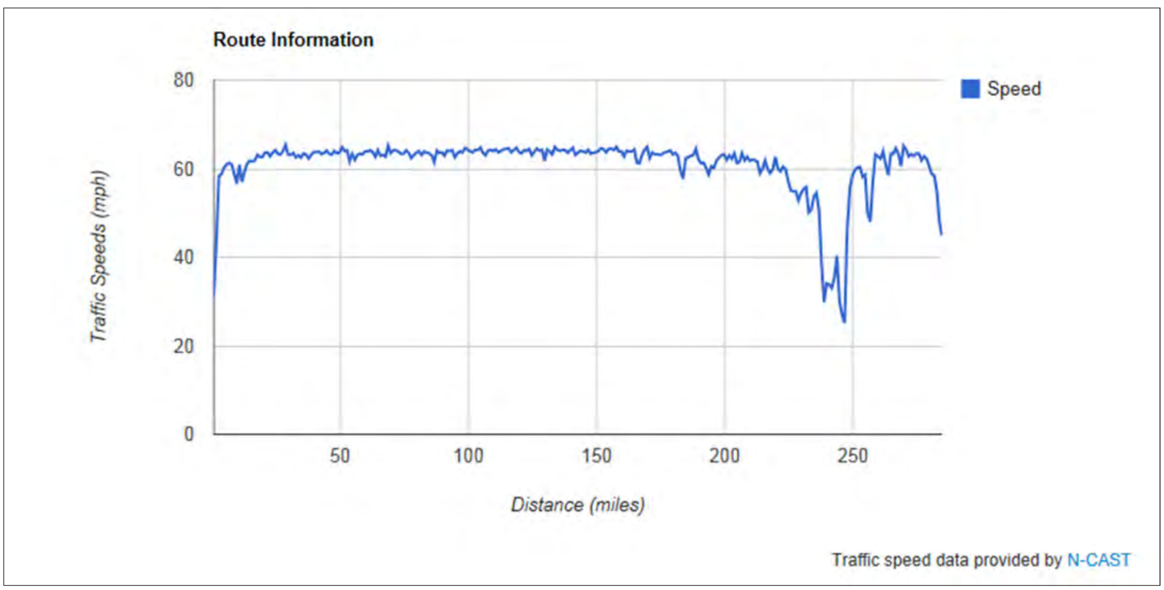


Figure 10.2: Screenshot of Data Integration with N-CAST Traffic Database

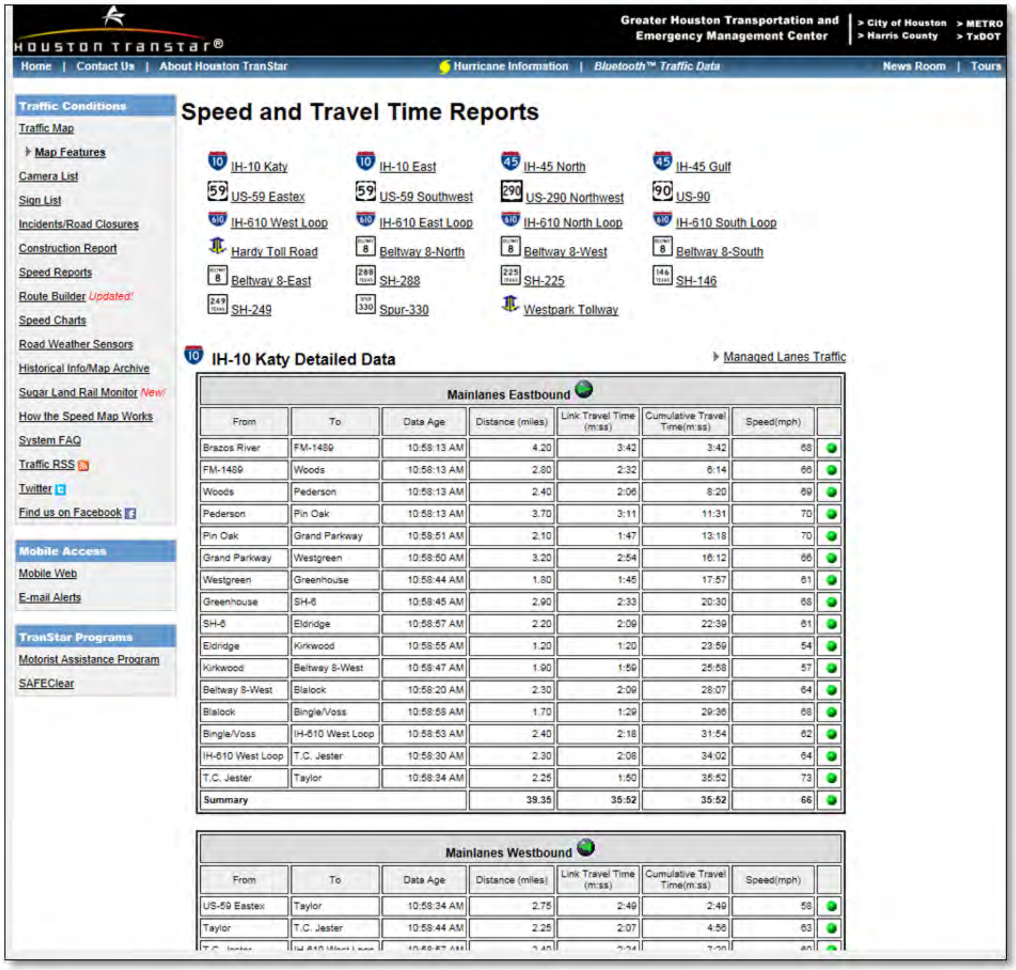


Figure 10.3: Screenshot of Houston's Transtar Traffic Reporting System

The timing for the implementation of TRIT coincides with a number of ITS initiatives and freight data sources that will support state and federal freight planning, such as TxDOT's freight user focus. It also shows why corridors are important to economic strength. State and federal research has, at regular intervals, examined corridors but hasn't demonstrated how the removal of system constraints in one state actually improves overall system efficiency and user benefits. An exception to this was the 2008 Cambridge Systematics Rail Freight study,[20] which identified key "bottlenecks" on rail corridors and showed how their mitigation raised overall capacity. The TRIT model could be used to evaluate freight in megaregional areas, such as Texas-Louisiana, and barge costs could be modeled as an additional mode to reflect the use of that mode by the petrochemical sectors. The research team has already begun to move the sub-models into a web-based structure in anticipation of easier and more powerful implementation by TxDOT planners.

[20] http://www.camsys.com/pressreleases/pr_jun08_rail_studies.htm

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