NCIT
The National Center for Intermodal Transportation

ANALYZING CONGESTION AND CAPACITY IMPACTS FROM DISRUPTIONS TO CRITICAL INFRASTRUCTURES IN THE RAIL NETWORK

FINAL REPORT

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1.0 Abstract

As an energy-efficient transportation mode, railways play a vital role in U.S. freight transportation. During any natural or man-made disasters, it is essential to keep the freight flow by efficiently re-routing the disrupted traffic. This project develops a model for routing the trains to minimize the total travel time for the whole network and determines how significant disruptions to railway infrastructure impact regional and inter-regional freight movements. The routing problem is formulated as a minimum-cost network flow problem that has a nonlinear objective function of minimizing the total travel time on all links and considers Origin-Destination specific demand. To make the model computationally tractable, the nonlinear travel time function at each link is approximated with a piece-wise linear function so that the whole model can be directly solved by ILOG CPLEX 9.0. The criticality of a railway link is evaluated by the increased delay when the link is disrupted. A case study is conducted for the railway network in the State of Mississippi. The map showing criticalities of all links in the study area is provided. In addition, this article discusses about the literature and data availability of other two surface transportations modes – highway and waterway.

2.0 Introduction

2.1 Growth of US Railway Infrastructure and Its Significance

Railways play an important role in U.S. freight transportation as an energy-efficient transportation mode [1]. In 2006, the freight railroad industry produced over 1.77 trillion ton-miles and generated $54 billion revenue [2]. In 2006, total ton-miles of rail freight (one ton of freight moved one mile counts as one ton-mile) transported over the national rail system have doubled since 1980, and the density of train traffic—measured in ton-miles per mile of track—has tripled since 1980 [3]. Again, from 1990 to 2006 Class I railroads' traffic (ton-miles) increased by 93 percent while their network miles decreased by 42 percent. In other words, the railroads have significantly increased their traffic density. Among all four major freight modes, class I railroads had the highest fuel efficiency of 337 Btu per ton mile, compared to 514 Btu, 3,357 Btu, and 9,600 Btu per ton mile for domestic waterborne, heavy trucks, and air freight in 2005 [1]. Therefore, major railroads are now expanding their capacity in highest density corridors by adding more tracks [2].

Since railway freight security and resilience are critical to the U.S. economy and homeland security, the Freight Rail Division has been established under the Transportation Security Administration (TSA)'s Office of Transportation Sector Network Management (TSNM). The mission of the division is to “ensure the security of the nation’s freight rail network using a risk based approach.” To support this mission, it is necessary to develop models to identify rail areas of high consequence and vulnerability, from which railway stakeholders can better develop tactics to protect the increasingly stressed railway infrastructure. This paper presents a model to evaluate the criticality of the links of railway network and implements the model for the rail network in Mississippi and parts of its neighboring states.

2.2 US Waterway and Highway and their significance

Inland waterway transportation is quite important in the in the United States and other countries, especially for heavy or bulky commodities, since it is inexpensive, energy efficient, and safe. It contains 25,000 miles of navigable rivers and canals in the United States [4]. To serve such functions as aiding navigation, most U.S. waterways consist of stepped navigable pools formed by dams at intervals on most of these waterways. A tow, consisting of a towboat pushing a number of barges, traverses the dam by means of a lock. The lock structures used to raise or lower barges between adjacent pools constitute the major bottlenecks in the U.S. waterway network [5] and generate extensive queues. Some locks have only one chamber, while others may have two parallel chambers whose characteristics may differ. The most common chamber sizes are 110' x 1200' (i.e., 110 feet wide and 1200 feet long) and 110' x 600' [6]. Each chamber size can accommodate a limited number of barges at one time. For example, a 110' x 1200' chamber can accommodate at most 17 standard barges plus a towboat, while a 110' x 600' chamber can accommodate at most 8 standard barges plus a towboat. If a tow has more barges than the chamber can accommodate, it must be disassembled into several pieces (called "cuts") to move through the chamber and must later be reassembled. Therefore, the service time distributions depend on chamber size and tow-size distributions. Sometimes, chambers will be out of service (i.e., "stalled") for various reasons such as freezing, accidents, and mechanical failures. The tow typically moves at a speed of 5 to 10 miles per hour in the waterway, waits for its turn to enter a lock, is locked through and proceeds toward the next lock [4].

It is usually seen in a waterway that an occasional tow is steaming between locks and a number of tows queued at each lock waiting for service. If the number of tows were increased, the principal effect would be an increase in the number of tows queued at locks. Bottlenecks determine capacity, and it is the lock which determines the capacity of a waterway. Again, an increase in the utilization of a facility can result in longer waiting time or in a less appealing service. For example, an increased number of tows on a waterway can give rise to greater delays at locks. The resulting delays and variability of service times have very substantial economic implications.

Next, the largest percentage of US freight is carried by trucks (60%), followed by pipelines (18%), rail (10%), ship (8%), and air (0.01%) [7]. Also, in comparison to most of the Western world, the United States relies much more heavily on its roads both for commercial and personal transit. The ability to accommodate vehicular traffic is a primary consideration in the planning, design, and operation of streets and highways. Highway capacity is, very broadly, a measure of the effectiveness of various highways in accommodating traffic and its application requires both a general knowledge of traffic behavior and specific knowledge of traffic volumes that can be accommodated under a variety of roadway configurations and operating conditions [8]. Specifically, capacity is defined here as the maximum number of vehicles per unit of time that can be handled by a particular roadway component under the prevailing conditions.

It is of little value to know the quantitative measure alone, without knowing the prevailing conditions. Similarly, the overall traffic-carrying capabilities of a roadway cannot be treated without reference to other important considerations, such as the quality of service of level of service provided and the duration of the time period considered.

Usually, the performance of a highway can be measured in two ways. These are traffic efficiency and safety. Traffic efficiency involves the performance of networks in terms of their ability to handle volumes of moving traffic. Safety is a concern on all roads, and should include qualitative as well as quantitative aspects. Public transport operations and the efficient and safe movement of vulnerable road users are integral parts of traffic systems and have their own special needs.

2.3 Problem Description and Objective function

The problem of evaluating the criticality of links for a railway network can be stated as follows. For a given railway network, we first collect the physical and operating properties — length, number of tracks, signal type, etc., of all the links. Based on these properties, the capacities of the links are determined. It is to be noted that we only consider the capacities of the links not the stations. In other words, the stations are considered as nodes that have no capacity. The data regarding the volume of trains flowing within and through the test network are collected for routing in the network. The model considers the routing of trains as link-based routing in the network for different OD-specific demand. In the model, the objective function is to minimize the total routing time of the trains in the network. Each individual link is considered to be disrupted once at a time and we optimize the total routing time. The difference between the objective functions of undisrupted and disrupted situation is the amount of delay occurred by that disrupted link. We define the most critical link as the one whose disruption results in maximum delay.

The objective function of the model is considered to be exponential function based on [9]. We simplified the objective function by making it piece-wise linear. For further simplification and ease of computation, we consider two pieces of linear functions of the exponential function. However, it is suggested to make more pieces of linear functions for exact approximation of the exponential objective function.

3.0 Literature Review

This section describes the literature on railway capacity and delay measurement techniques and also for other surface transportation modes—highway and waterway. As this project mainly focuses on the criticality measurement of railway network, we present railway literature in detail; whereas the highway and waterway literature is provided in brief.

3.1 Literature on Railway

It is relatively straightforward to determine the capacity on roads: it is normally determined merely as vehicles per hour. Capacity on railways is, however, more difficult to determine because the capacity depends on the infrastructure, the timetable and the rolling stock [10].

The capacity of a railway is complicated because of the fact that the running characteristics and the length of the train affect how many trains it is possible to operate per hour, because slow trains and long trains occupy the block sections for a longer time and might have lower acceleration rates. Although railway capacity is complex to understand, it is essential for determining the amount of traffic that can be moved over a rail system and the degree of service and reliability that can be expected.

3.1.1 Definition of Railway Capacity

Although capacity seems to be a self-explanatory term in common language, its scientific use may lead to substantial difficulties when it is associated to objective and quantifiable measures. It is a complex term that has numerous meanings and for which numerous definitions have been given. When referring to a rail context, it can be described as follows:
''Capacity is 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'' [11].

3.1.2 Types of Railway Capacity

Different types of capacity are usually used in the railway environment [12]:

- Theoretical capacity: It is the number of trains that could run over a route, during a specific time interval, in a strictly perfect, mathematically generated environment, with the trains running permanently and ideally at minimum headway (i.e. temporal interval between two consecutive trains). It is an upper limit for line capacity. Frequently, it assumes that traffic is homogeneous, that all trains are identical, and that trains are evenly spaced throughout the day with no disruptions. It ignores the effects of variations in traffic and operations that occur in reality. It is not possible to actually run the number of trains that can be worked out mathematically.
- Practical capacity: It is the practical limit of ''representative'' traffic volume that can be moved on a line at a reasonable level of reliability. The ''representative'' traffic reflects the actual train mix, priorities, traffic bunching, etc. If the theoretical capacity represents the upper theoretical bound, the practical capacity represents a more realistic measure. Thus, practical capacity is calculated under more realistic assumptions, which are related to the level of expected operating quality and system reliability, as shown in Figure 1. It is usually around 60–75% of the theoretical capacity [13] Practical Capacity is the most significant measure of track capacity since it relates the ability of a specific combination of infrastructure, traffic, and operations to move the most volume within an expected service level.

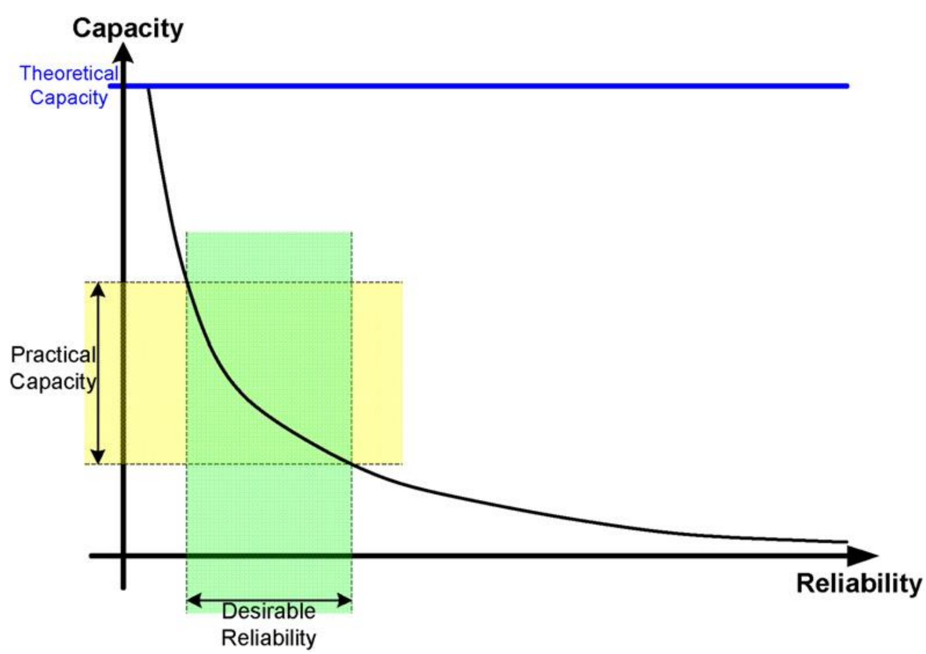


Figure 1. Practical capacity involves the desirable reliability level [12].

- Used capacity: It is the actual traffic volume occurring over the network. It reflects actual traffic and operations that occur on the line. It is usually lower than the practical capacity.

- Available capacity: It is the difference between the Used Capacity and the Practical Capacity. It is an indication of the additional traffic volume that could be handled in the route. If it allows new trains to be added, it is a useful capacity; otherwise, it is lost capacity.

3.1.3 Methods to Evaluate Railway Capacity

Numerous approaches have been developed to evaluate railway capacity. The most relevant methods can be classified in three levels: Analytical Methods, Optimization Methods, and Simulation Methods.

3.1.3.1 Analytical Methods

These methods are designed to model the railway environment by means of mathematical formulae or algebraic expressions. They usually obtain theoretical capacities and determine practical capacities either as a percentage of the theoretical capacity or by including regularity margins when they calculate the theoretical capacity.

For example, the International Union of Railways, more generally known as the UIC, proposed the UIC method [14]; it calculates capacity in line sections to identify bottlenecks. One of the most recent references about railway capacity is [15]. It develops several approaches to calculate theoretical capacity (called ‘‘absolute capacity’’) for railway lines and networks. These approaches take numerous railway aspects into account; for example, mix of trains, signal locations, or dwell times. Analytical methods for computing railway line capacity may be a good start for identifying bottlenecks and major constraints; however, analytical results vary from one method to another depending on what type of parameters they model. Furthermore, analytical models are very sensitive to parameter input and train mix variations.

3.1.3.2 Optimization Methods

They are designed to provide more strategic methods for solving the railway capacity problem and provide much better solutions than purely analytical formulae. Optimization methods for evaluating railway capacity are based on obtaining optimal saturated timetables. These optimal timetables are usually obtained by using mathematical programming techniques (Mixed Integer Linear Programming Formulations and Enumerative algorithms). A particular method of optimization is saturation. This method obtains line capacity by scheduling a maximum number of additional train services in a timetable (starting with either an empty timetable or with an initial base timetable).

Among many works on railway capacity evaluation by optimization method, the International Union of Railways proposes a new method that is included in the framework of the optimization a method [16], which is based on a timetable compaction method. By modifying the base timetable, existing train paths are scheduled as close as possible to each other. Modifying the travel times, the overtakings, the crossings, and the commercial stops is prohibited during the process of compaction. The remaining blank (empty, or unused) time left in the timetable represents the maximum spare time during which additional train services may theoretically be scheduled.

In practice, if too much of the unused capacity is taken to run more trains, this may cause serious reliability problems because it reduces the buffer times that allow minor incidents to be absorbed. An example of this method is shown in [17]

3.1.3.3 Simulation Methods

For train scheduling, simulation has often been used in combination with other methods, originating what could be defined as ‘‘hybrid models’’. A composite simulation and optimization method also appears in the work of [18]. A model called Strategic Capacity Analysis for Network (SCAN) was developed by [19], who defined factors at different levels of detail that together determine the capacity of a network. More information about these systems and other simulation environments can be found in [20].

In the following sections, we will only discuss capacity calculation procedures of optimization method.

3.1.4 Evaluating Capacity Using Optimization Method

This section describes the capacity calculation based on a timetable compaction method developed by [21] based on [16]. The subject “Railway capacity” is a combination of the capacity consumption and how the capacity is utilized. The capacity utilization of railways can be divided into 4 core elements: The number of trains, the average speed, the heterogeneity of the operation, and the stability, as shown in Figure 2.

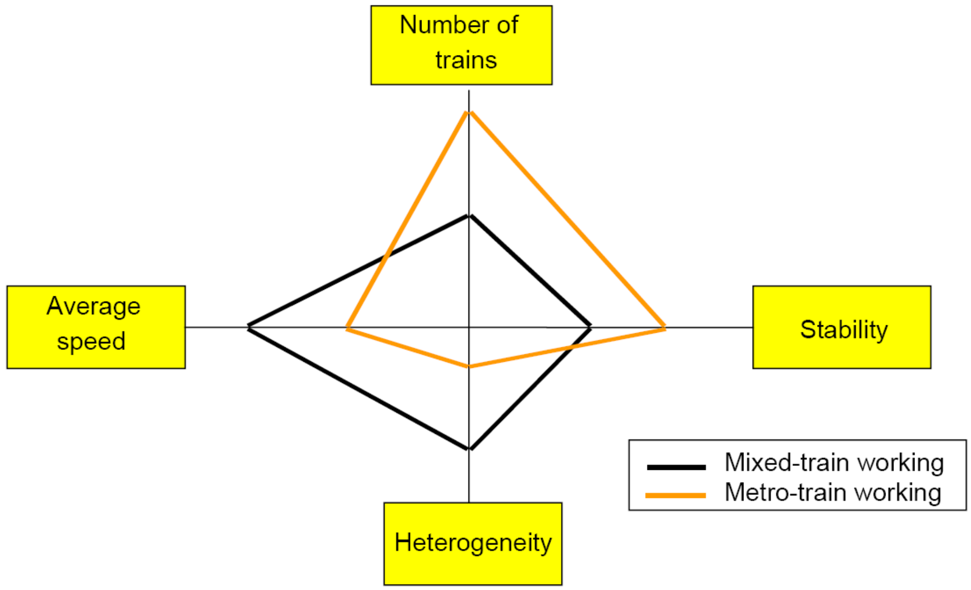


Figure 2. The balance of railway capacity [16].

In the following sections, we will present how to calculate capacity consumption and the core elements of capacity utilization of railways.

3.1.4.1 Calculating the Capacity Consumption

The UIC 406 [16] method describes an easy and effective way of calculating the capacity consumption on railway lines. However, it is also possible to expound the UIC 406 method in different ways which can lead to different capacity consumptions.

This method defines railway capacity as “the total number of possible paths in a defined time window, considering the actual path mix or known developments respectively…” [16]. To measure railway capacity consumption it is necessary to know the timetable graphs for the railway line(s) examined. By using the timetables graphs for the given infrastructure the dynamics of rolling stock is implicitly included as the rolling stock is determining the size of the blocking stairs. The capacity consumption of the railway infrastructure is then measured by compressing the timetable graphs so that the buffer times are equal to zero, as shown in Figure 3. This compression considers the minimum headway times, which depends on the interlocking system and train characteristics [22].

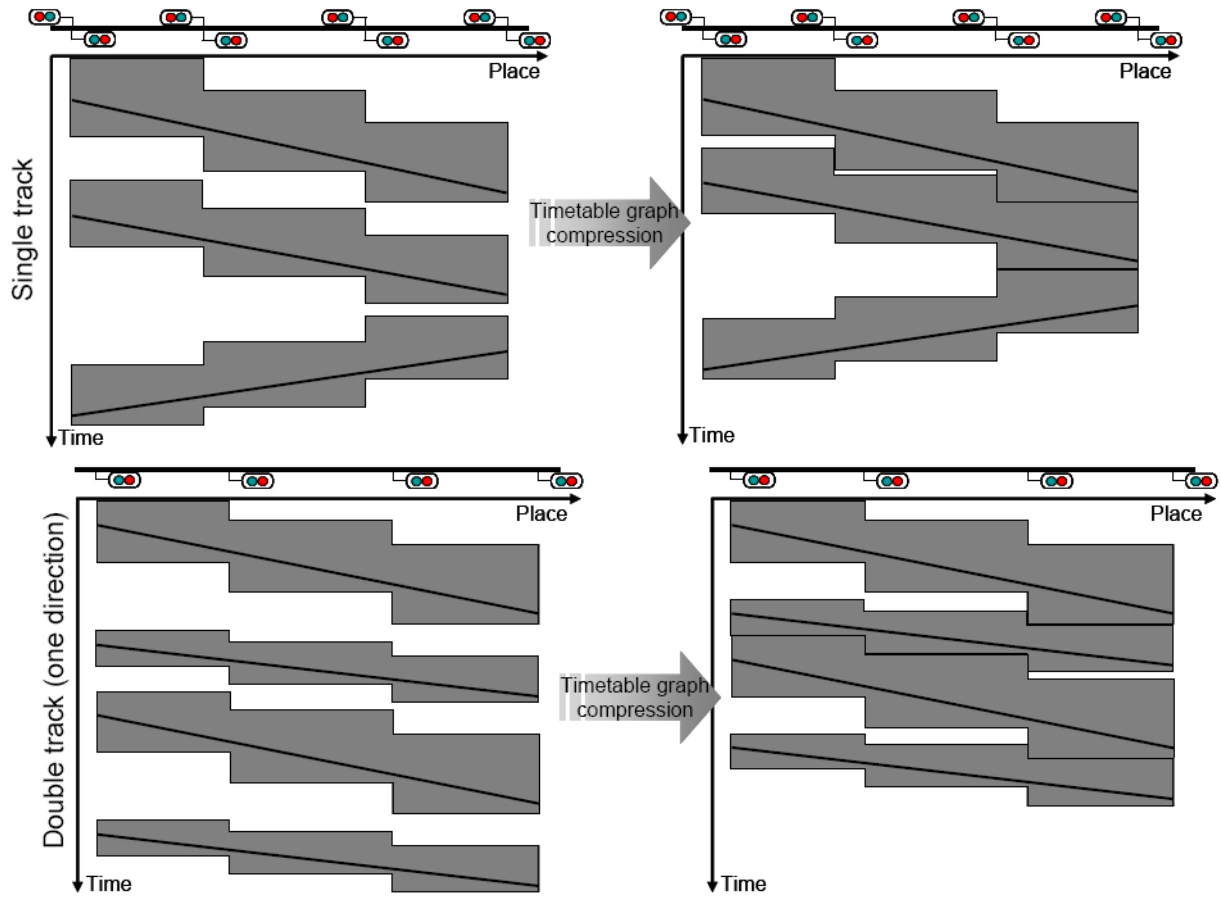


Figure 3. Compression of timetable graph according to the UIC406 capacity method. Partly based on [23]

As it is difficult or even impossible to compress the timetable graphs for an entire complex railway network, it is necessary to divide the network into smaller line sections which easily can be handled by the UIC 406 capacity method. Railway lines are divided into smaller line sections at junctions, overtaking stations, line end stations, transition between double track and single track (or any other number of tracks) and at crossing stations, as in Figure 4.

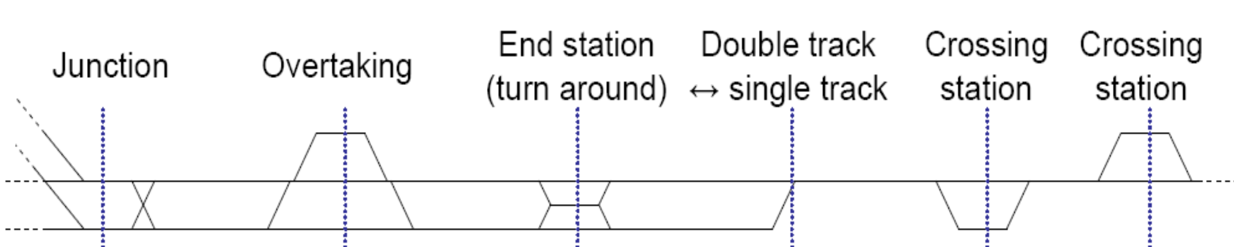


Figure 4. Division of railway line into line sections [24, 25]

To evaluate the capacity consumption, it is necessary to know both the infrastructure and the timetable. Therefore, the first step of evaluating the railway capacity is to build up the infrastructure and create/reproduce the timetable. To evaluate the railway capacity according to the UIC 406 method, the railway network has to be divided into line sections. For each line section the timetable has to be compressed so that the minimum headway time between the trains is achieved. When the timetable has been compressed it is possible to work out the capacity consumption of the timetable by comparing the cycle times (the compression ratio). The workflow of the capacity evaluation can be seen in Figure 5.

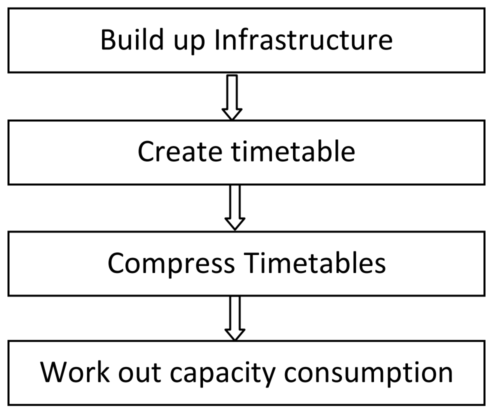


Figure 5. General workflow of the UIC 406 method [26]

The total capacity consumption (k) can also be calculated in a more analytical way by summing the infrastructure occupation time (t_A), the buffer time (t_B), the time supplement for single track lines (t_C) and maintenance (t_D) [27]:

$$k = t_A + t_B + t_C + t_D \quad (1)$$

The capacity consumption in per cent (K) can be worked out based on the total capacity consumption measured in time (k) and the chosen time window (t_U) [16]:

$$K = \frac{k}{t_u} 100\% \quad (2)$$

Equations (1) & (2) can be expressed differently to calculate the capacity consumption in one step [38]:

$$K = \frac{(t_A + t_B + t_C + t_D)}{t_u} 100\% \quad (3)$$

The infrastructure occupation time (t_A) and the time window (t_U) are the most important factors in Equation (3). This is because the infrastructure occupation time makes up most of the capacity consumption of the time window examined (t_U). The buffer time (t_B) is normally (in the Danish context) set equal to zero but can be set to a different value to improve the quality of the operation by ensuring fewer consecutive delays. It could be argued that the buffer time is a kind of quality factor.

The time supplement for single track operation (t_C) can be added at the crossing stations the same way to improve the quality of the operation by reducing the risk of consecutive delays. Alternatively, the time supplement for single track operation can be used in the completely analytically examination of the capacity consumption. This is done by considering the running time from the entrance of the station to the release of the train route before the train in the opposite direction can depart from the platform together with the extra time it might take if the crossing station cannot handle parallel movements. In the Danish context, the time supplement for single track operation is normally set to zero.

The time supplement for maintenance (t_D) can be used in cases of possession planning for maintenance and/or construction works. In Denmark, these supplements are not included in the UIC 406 capacity analysis.

The railway capacity consumption can be optimized, or minimized, by changing the parameters. Reducing the buffer time (or quality factor) will lead to less capacity consumption. However, it should be noted that the buffer time (together with time supplements) improves the stability of the timetable [28]. Additionally, the time supplements for single track operation and maintenance are time supplements that improve the stability of the timetable.

If the stability of the timetable is not to be reduced, only the infrastructure occupation time can be reduced. This can be done by bundling the trains so that trains with the same stopping pattern and train characteristics follow each other. Alternatively, the block occupation times should be reduced.

In Summary, the UIC 406 capacity method can be used in an analytical way determining the capacity consumption as the sum of the occupation time, buffer time, time supplements for single track operation and maintenance. This sum is then divided by the time window observed. In addition to the analytical way of determining capacity consumption, the capacity consumption can be measured by compressing the timetable graphs as much as possible in the line section and then using the compression ratio as a measurement of the capacity consumption.

3.1.4.2 Workflow of Capacity Consumption Analysis

The detailed workflow of railway lines capacity consumption analysis can be shown in Figure 6, based on the UIC 406 method:

First, the infrastructure to be analyzed must be built up to a detailed level in a timetabling system. Then the timetable to be analyzed must be established. Based on the infrastructure, the railway lines are divided into overall line sections (at the transition stations) of single track lines, double track lines, and lines with more tracks respectively. These overall line sections are then analyzed in different ways depending on the number of tracks.

Double track railway lines are the easiest to examine. In Denmark, the overall line sections are equal to the line sections whereupon the timetable graphs are compressed, according to the UIC 406 capacity method. When the timetable graphs have been compressed, the capacity consumption of the line section is worked out.

Single track railway lines are more complicated to examine as it is necessary to add as many trains as possible without changing the original timetable or infrastructure. Then the overall single track line section is divided into line sections for each time a crossing station is in use. When the railway line has been divided into line sections, the timetable graphs of the original timetable are compressed according to the UIC 406 capacity method and the capacity consumption of each line section is worked out (without the extra “dummy” trains).

For overall line sections containing three, four or more tracks another approach must be used. Tracks that are used only for traffic in one direction must be divided into line sections in the same way as double track lines, while tracks used for traffic in both directions must be divided into line sections in the same way as single track lines, and the intersection of division points is then used to find the final line sections. After the division into line sections, the timetable graphs are compressed and the capacity consumption for each line section is worked out. If it appears that there is a large difference in the capacity consumption between the tracks, one or more trains must change tracks and the compression is redone until the capacity consumption of the tracks is more or less equal.

When the capacity consumption for all line sections has been worked out, it is possible to determine the capacity consumption for the entire railway line equal to the line section with the highest capacity consumption.

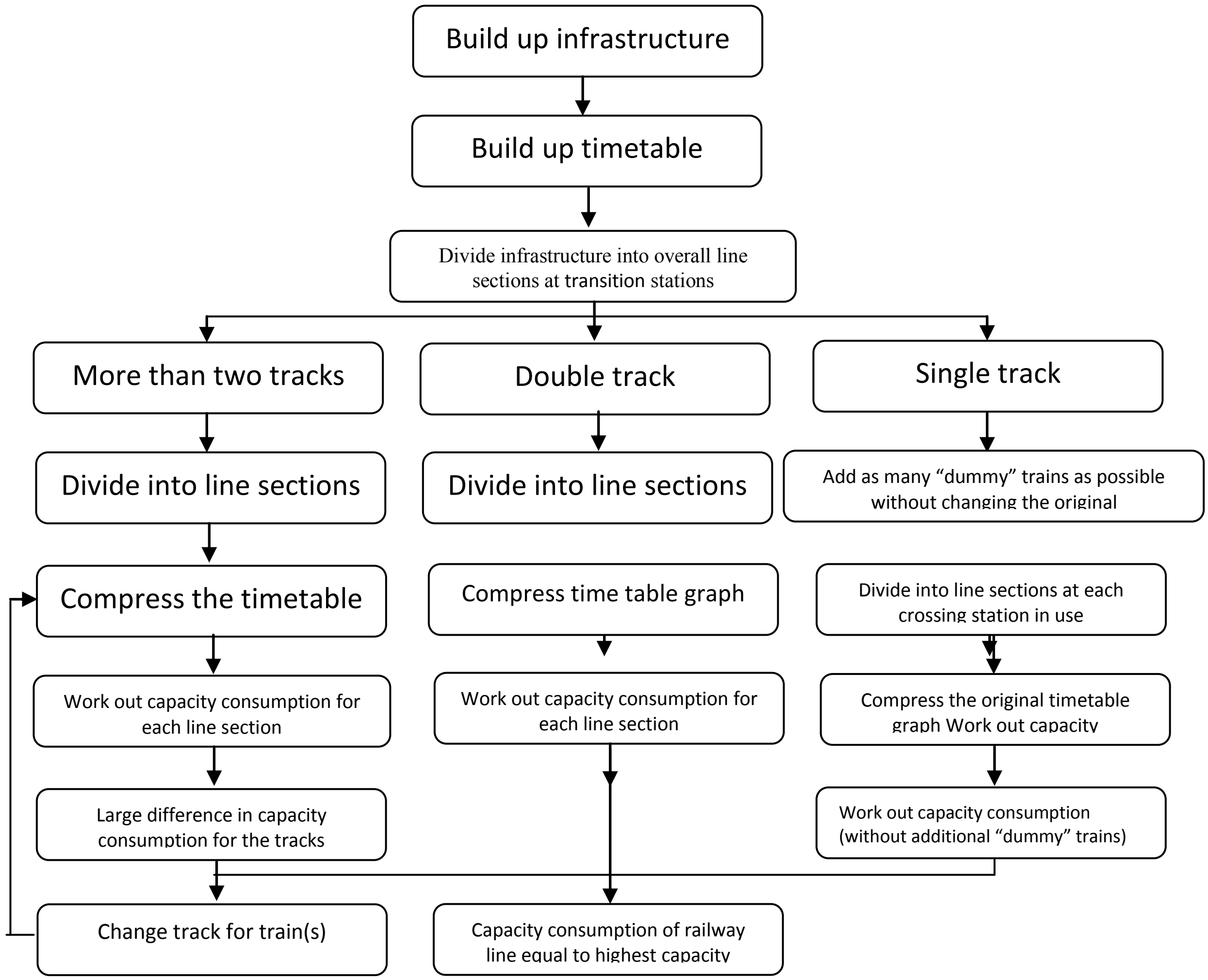


Figure 6: Workflow of measuring capacity consumption of railway lines [29].

The workflow described above (Figure 6) can also be used if the exact infrastructure and/or timetable are unknown.

3.1.5 Capacity Analyses on the European Rail Traffic Management System

To ensure the safe operation of the train and to enable the optimization of the line capacity, the specifications of European Rail Traffic Management System (ERTMS) include the calculation method of the Headway Time between consecutive trains [12]. ERTMS determines the Headway Time by summing up the following four times, shown in Equation (4) (Figure 7):

$$Headway\ Time = Travel\ Time + Braking\ Time + Release\ Time + OT \quad (4)$$

Here,

Travel Time is the time required to cover the distance between two consecutive virtual signals. It depends inversely on the train speed and directly on the distance between consecutive virtual signals.

$$Travel\,Time \;=\; F(Distance/Speed)$$

Braking Time is the time needed to cover the braking distance, that is, the distance required to stop a train before a virtual signal. It depends directly on the train speed and inversely on the maximum deceleration.

$$Braking\,Time \;=\; F'\,(Speed/Deceleration)$$

Release time is the time required for the entire length of a train to cross a virtual signal. It depends on the train speed and the train length.

$$Release\,Time \;=\; F''(Length/Speed)$$

Operating Time (OT) is a safety time. It is a constant, and it is set by the infrastructure managers.

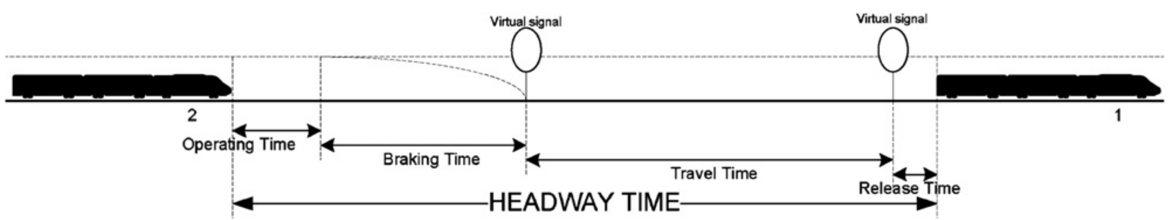


Figure 7: Headway Time diagram [12]

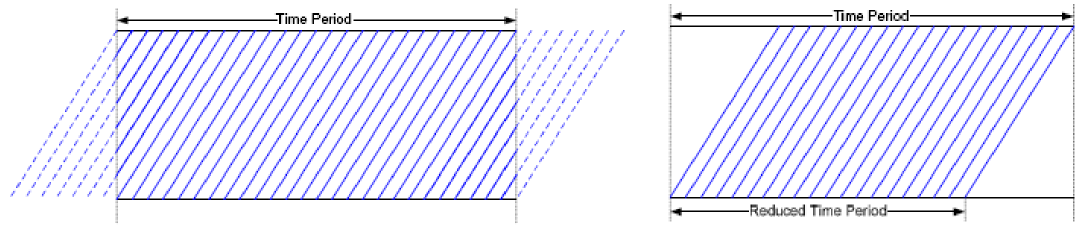
The capacity of a double-track line in a fixed *time period* depends on the *Headway Time* between consecutive trains. This *Headway Time* is the maximum of all *Headway Times* between consecutive virtual signals of the line. In each line section, capacity is,

$$Capacity = \frac{Time\ period}{Headway\ time}$$

Or,

$$Capacity = \frac{Time\ period}{F\left(\frac{Distance}{Speed}\right)+F'\left(\frac{Speed}{Deceleration}\right)+F''\left(\frac{Length}{Speed}\right)+OT} \tag{5}$$

We assume a continuous operating time without interruptions (Figure 8a). However, with discontinuous operating times, the time period decreases due to the journey time of the first train (Figure 8b).



(a) (b)

Figure 8: Difference between (a) continuous and (b) discontinuous time periods [12]

Equation (5) shows that capacity is strongly dependent on the train speed: It is directly proportional to speed due to the Travel and Release Times, but it is indirectly proportional to speed due to the Braking Time. When speed is constant, Equation (5) can be simplified as,

$$Capacity = \frac{Time\ period}{\frac{Distance}{Speed} + \frac{Speed^2}{Deceleration} + \frac{Length}{Speed} + OT} \quad (6)$$

3.1.6 Train Delays

Delays in railway operation can be divided into initial and consecutive delays [24]. Initial delays are the original delays caused by a delay for a single train, and the consecutive delays are delays caused by other (delayed) trains. The initial delays normally occur due to longer time for exchange of passengers, e.g., due to many passengers, or to passengers who require extra help to board/alight the train; errors on the infrastructure or the rolling stock; and weather conditions. The total amount of delays in the railway system ($\sum t_d$) is equal to the sum of consecutive delays ($\sum t_{d,x,c}$) and the initial delay ($\sum d, 1, i$) (Equation (7)):

$$\sum t_d = \sum d, 1, i + \sum_{x=2}^{X} t_{d,x,c} \quad (7)$$

3.1.6.1 Delay Propagation on a Double Track Line with Homogeneous Traffic

Delay propagation on a double track line with homogeneous one-way operation on each track (meaning that both the speed and the buffer time are constant) is the simplest case. The amount of delay propagation, or consecutive delay for the following train ($t_{d,2,i}$), for the idealized situation can be calculated as the initial delay ($t_{d,1,i}$) minus the buffer time to the following train (t_b), as in Equation (8):

$$t_{d,2,c} = \begin{cases} t_{d,1,i} - t_b; t_b < t_{d,1,i} \\ 0; else \end{cases} \quad (8)$$

Equation (8) can be generalized to calculate the consecutive delay for any of the following trains where there are no more initial delays:

$$t_{d,(j+1),c} = t_{d,1,i} - j\, t_b \tag{9}$$

In Equation (9), *j* is the number of trains receiving consecutive delays. The number of trains receiving consecutive delays (*j*) can be calculated based on Equation (9). By setting the consecutive delay ($t_{d,(j+1),c}$) in Equation (9) equal to zero (meaning that the last train will receive no consecutive delay), it is possible to calculate the number (*j*) of trains/buffer times (t_b) needed before the trains again run on time:

$$j = \frac{t_{d,1,i}}{t_b} \tag{10}$$

Calculating the number of trains receiving consecutive delays (*j*) simply by dividing $t_{d,1,i}$ with t_b (Equation (10)) does not necessarily result in an integer. A train is either delayed or on time, and a train will not receive consecutive delays except if all the buffer time (t_b) to the train in front has been used. Therefore, the decimal numbers in Equation (10) should be truncated:

$$j = \left\lfloor \frac{t_{d,1,i}}{t_b} \right\rfloor \tag{11}$$

Knowing the number of trains receiving consecutive delays (*j*), it is possible to calculate the total delay ($\sum t_d$) caused by the initial delay ($t_{d,1,i}$) by Equation (12) :

$$\sum t_d = t_{d,1,i} + \sum_{x=1}^{j+1} t_{d,x,c} \tag{12}$$

Combining Equation (9) and (12), the total delay ($\sum t_d$) caused by the initial delay ($t_{d,1,i}$) can be calculated as:

$$\sum t_d = (j+1)t_{d,1,i} - \frac{j}{2}(j+1)t_b \tag{13}$$

Combining Equation (10) and (13), the total delay ($\sum t_d$) can be calculated based on the initial delay ($t_{d,1,i}$) and the buffer time t_b (Equation (14)

$$\sum t_d = \left(\left\lfloor \frac{t_{d,1,i}}{t_b} \right\rfloor + 1\right) t_{d,1,i} - \frac{1}{2}\left\lfloor \frac{t_{d,1,i}}{t_b} \right\rfloor \left(\left\lfloor \frac{t_{d,1,i}}{t_b} \right\rfloor + 1\right) t_b \tag{14}$$

For initial delays much larger than the buffer time, Equation (14) can be simplified to Equation (15):

$$\sum t_d = \left(\frac{t_{d,1,i}}{t_b} + 1\right) \frac{t_{d,1,i}}{2} \tag{15}$$

The simplification in Equation (15) is not necessarily precise for either small initial delays or large buffer times between the trains. Therefore, the more precise Equation (14) is used instead.

To examine the influence of high capacity consumption on the delay propagation the buffer time (t_b) can be expressed based on the capacity consumption in percent (*K)* and the minimum headway time ($t_{h,min}$), as in Equation (16):

$$t_b = t_h - t_{h,min} = \frac{t_{h,min}}{k} - t_{h,min} = \left(\frac{1}{k} - 1\right) t_{h,min} \tag{16}$$

The sum of delays ($\sum t_d$) can then be expressed as in Equation (17):

$$\sum t_d = \left(\left\lfloor \frac{t_{d,1,i}}{\left(\frac{1}{k}-1\right) t_{h,min}} \right\rfloor + 1\right) t_{h,min} - \frac{\left(\frac{1}{k}-1\right) t_{h,min}}{2} \left\lfloor \frac{t_{d,1,i}}{\left(\frac{1}{k}-1\right) t_{h,min}} \right\rfloor \left(\left\lfloor \frac{t_{d,1,i}}{\left(\frac{1}{k}-1\right) t_{h,min}} \right\rfloor + 1\right) \tag{17}$$

For a railway line with a minimum headway time ($t_{h,min}$) of 3 minutes, the sum of delays ($\sum t_d$) can be calculated for various initial delays ($t_{d,1,i}$) and capacity consumptions (K) based on Equation (17).

The total amount of delay ($\sum t_d$) can also be calculated based on the initial delay ($t_{d,1,i}$) and a delay propagation factor ($y_{t_{d,1,i}}$) as in Equation (18):

$$\sum t_d = t_{d,1,i} \, y_{t_{d,1,i}} \tag{18}$$

The delay propagation factor ($y_{t_{d,1,i}}$) expresses the growth of delay based on the initial delay. Knowing the total delay ($\sum t_d$) and the initial delay ($t_{d,1,i}$), the delay propagation factor ($y_{t_{d,1,i}}$) can be calculated based on Equation (18)

$$y_{t_{d,1,i}} = \frac{\sum t_d}{t_{d,1,i}} \tag{19}$$

By combining Equation (17), and (19), the delay propagation factor can be calculated for given initial delays ($t_{d,1,i}$) and capacity consumptions (K):

$$y_{t_{d,1,i}} = \left\lfloor \frac{t_{d,1,i}}{\left(\frac{1}{k}-1\right)t_{h,min}} \right\rfloor + 1 - \frac{\left(\frac{1}{k}-1\right)t_{h,min}}{2t_{d,1,i}} \left\lfloor \frac{t_{d,1,i}}{\left(\frac{1}{k}-1\right)t_{h,min}} \right\rfloor \left(\left\lfloor \frac{t_{d,1,i}}{\left(\frac{1}{k}-1\right)t_{h,min}} \right\rfloor + 1 \right) \quad (20)$$

To make the delay propagation more robust for variations in the initial delay, the delay propagation can be generalized so that the initial delay ($t_{d,1,i}$) is expressed as a multiple of the minimum headway time ($t_{h,min}$), where the factor is *n*.

$$t_{d,1,i} = nt_{h,min} \quad (21)$$

Equation (21) ensures that the delay propagation factor ($y_{t_{d,1,i}}$) in Equation (80) is dependent only on the capacity consumption (*K*) and the size of the minimum headway time ($t_{h,min}$) (compared with the minimum headway time ($t_{h,min}$)). In this way the delay propagation factor is independent of the minimum headway time ($t_{h,min}$) and can be used for all railway lines with homogeneous operation. The delay propagation factor ($y_{t_{d,1,i}}$) can then be calculated as in Equation (22):

$$y_{t_{d,1,i}} = \left\lfloor \frac{nt_{h,min}}{\left(\frac{1}{k}-1\right)t_{h,min}} \right\rfloor + 1 - \frac{\left(\frac{1}{k}-1\right)t_{h,min}}{2n\, t_{h,min}} \left\lfloor \frac{n\, t_{h,min}}{\left(\frac{1}{k}-1\right)t_{h,min}} \right\rfloor \left(\left\lfloor \frac{n\, t_{h,min}}{\left(\frac{1}{k}-1\right)t_{h,min}} \right\rfloor + 1 \right)$$

Or,

$$y_{t_{d,1,i}} = \left\lfloor \frac{n}{\left(\frac{1}{k}-1\right)} \right\rfloor + 1 - \frac{\left(\frac{1}{k}-1\right)}{2n} \left\lfloor \frac{n}{\left(\frac{1}{k}-1\right)} \right\rfloor \left(\left\lfloor \frac{n}{\left(\frac{1}{k}-1\right)} \right\rfloor + 1 \right) \quad (22)$$

3.1.6.2 Summary on Delays

Delays on railways can be divided into initial delays and consecutive delays. The amount of consecutive delays can be estimated based on the initial delay, the headway time, and the minimum headway time. The higher the capacity consumption on railway lines the higher the risk of consecutive delays.

Consecutive delays can be estimated mathematically for both double- and single-track railway lines. However, the estimated delays are often for idealized situations only, as delays can propagate from railway line to railway line and two initial delays occurring immediately after each other will most often result in less consecutive delays than if the initial delays occurred at longer time intervals.

3.2 Literature on Waterway

3.2.1 Waterway Capacity

The physical capacity of a waterway might be measured in terms of the number of barges that could be locked through in the course of a year, *C*. These barges arrive in tows, the rate at which tows can be served, $\mu(b)$, is inversely related to the number of barges in the tow, *b*. The relationship is assumed to have the shape shown in Figure 9.

Thus, the number of tows that could be served in a year, *K*, depends on the size of each tow. If all tows were of the same size, *K* could be calculated from Equation (23) [4].

$$K = \frac{8{,}760}{1/_{\mu(b)}} = 8{,}760\mu(b) \tag{23}$$

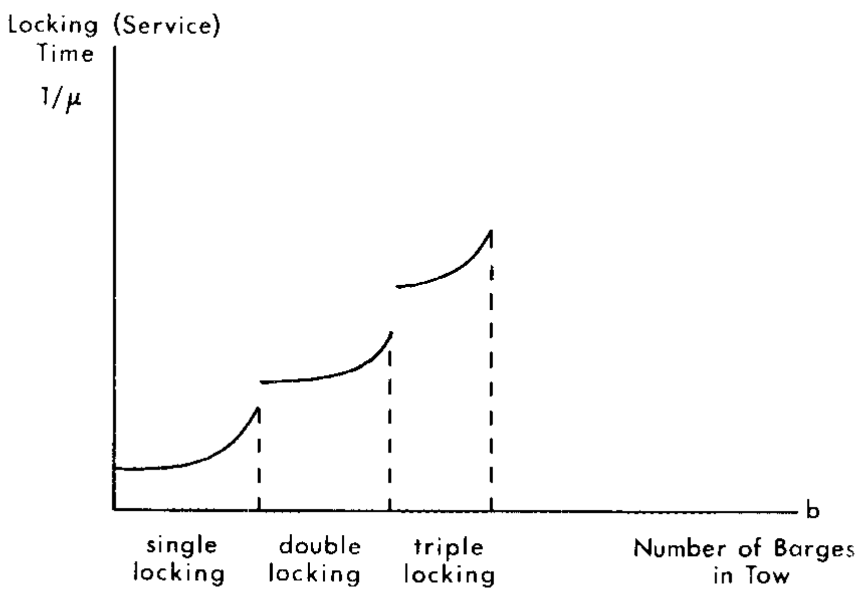


Figure 9. Service time as a function of the size of tow [30]

Here 8,760 is the number of hours in a year, and $1/\mu(b)$ is the service time for a tow of *b* barges (measured in hours). Assuming all tows have *b* barges, the number of barges that could be serviced in a year is given in equation (24) [4].

$$C = Kb \tag{24}$$

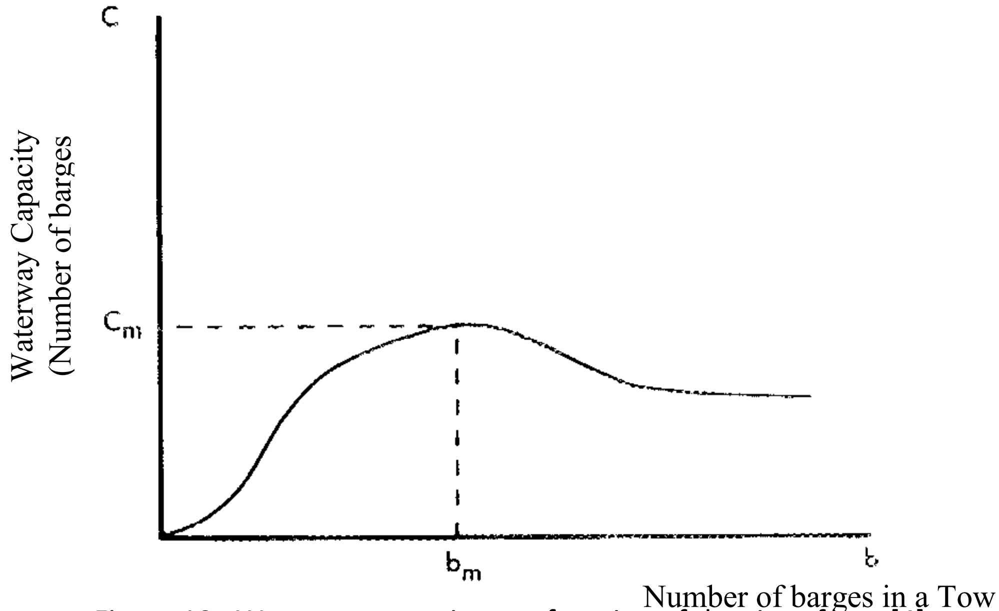


Figure 10. Waterway capacity as a function of the size of tow [4]

Capacity as a function of the number of barges in each tow is graphed in Figure 10. Equation (24) and Figure 10 characterize the physical measure of the capacity of a waterway. They imply that as many as C_m barges could be served. However, there are difficulties precluding a lock from attaining this rate of output. Equation (23) and (24) are based on the assumption that tows are of uniform size (and thus that service time is uniform). Since this assumption is not true in practice, one would never observe C_m. Moreover, even if the average tow consisted of b_m barges (the number required to produce C_m), this maximum would not be attained because of the variation about the size and the fact that service time is not proportional to b. A more important difficulty is associated with another assumption that is implicit in this analysis.

Equation (24) is based on the implicit assumption that there is always another tow ready for service at a lock when a tow is through the lock. Thus, tows must be scheduled to arrive at the proper time. Otherwise, extremely long delays would be encountered.

3.2.2 Waterway Delay

3.2.2.1 An analysis of Waiting Time (Delay) as M/M/1 queuing model

For a tow to traverse a lock, five operations are involved [4].

1. The tow arrives and awaits permission to approach the lock (previous tows must be serviced first).
2. When permission is received, the tow approaches the lock and maneuvers into the

chamber.

3. The lock goes into operation and is filled or emptied (depending on the direction of the movement).
4. After locking completed, the tow maneuvers out of the lock and into the channel.
5. If the tow is large, operations (2), (3) and (4) must be repeated to “double lock” the remainder of the tow.

Operations (1) and (3) will be independent of the number of barges in the tow; the other operations will be directly related to tow size. One might translate this description into graphic form as in Figure 1, which shows the time taken to service a tow as a function of tow size (waiting time is excluded).

We now model the locking process (operations (1-5)) in order to predict the average total locking time (waiting plus service time). An *M/M/*1 model has been estimated using data collected on the Illinois Waterway [4]. The number of tows arriving at a lock within an interval of duration t follows a Poisson distribution with parameter λt, where λ is the arrival rate (number of tows per time unit). In addition, the number of tows serviced in an interval of duration t is also assumed to be Poisson distributed with parameter μt, where μ is the service rate (number of tows per time unit). Given the assumption of Poisson arrivals and services, the mean delay, W and total locking time T_L for a tow are derived based on the queuing theory in Equations (25) and (26) [4].

$$W = \frac{\lambda}{\mu(\mu - \lambda)} \tag{25}$$

$$T_L = \frac{1}{\mu} + T_{Lq} = \frac{1}{\mu - \lambda} \tag{26}$$

Here, the total locking time is the sum of waiting time and service time. The analysis could be easily extended to a general case in which a waterway contains a series of locks rather than a single one. Under the assumptions of random arrivals of tows at each lock, independent operations across locks, and smaller arrival rate than service rates, the total locking time (for a tow) will merely be the sum of total locking times at each lock.

3.2.2.2 An analysis of Waiting Time (Delay) as M/G/1 queuing model

Khisty [31] analyzed the waterway traffic at Chicago River and the locks on the river. Detailed observations at the Chicago River locks revealed that the average service time of a lock varies from 11 to 13 minutes.

The following assumptions were made in Khisty's study [31].

- Vessels arrive at the lock randomly.
- The arrival of one vessel is independent of the arrival of the previous vessel of the same type or any other.
- Vessels are categorized into 3 groups: commercial barges, commercial passenger and government vessels, and recreational vessels.
- Lock operation analysis was done for one directional movement at a time.
- The queue discipline is FIFS.

The system has a single server (lock) and follows Poisson arrival pattern with a fixed mean arrival rate, λ. The service pattern is represented by the mean service rate, μ, and a variance, σ_s^2, for the service time. Under the above assumption, an $M/G/1$ model is developed as follows.

L = number of single servers (locks)

$\gamma = \left({}^{\sigma_s}/_{\mu}\right)L$= traffic intensity

So, the mean delay, W can be calculated by Equation (27) [31]:

$$W = \frac{\lambda}{2\mu^2(\mu^2\lambda^2 + 1)(1-\gamma)} \tag{27}$$

3.3 Literature on Highway

3.3.1 Important Traffic Parameters and Their Basic Relationships

The relationships can be shown graphically as follows:

- **Average speed and volume:** This relationship is shown in Figure 11.

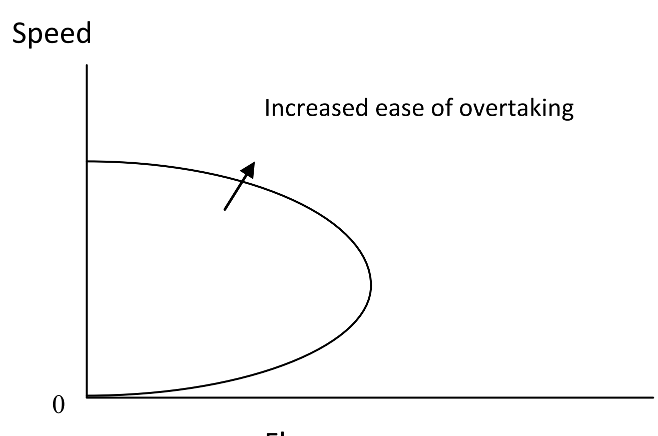


Figure 11. Speed-Flow envelope

When a road segment does not have many vehicles and is not congested, more vehicles usually mean lower speed but bigger volume (throughout) of the segment because of the higher density. When more and more vehicles are in the segment, the speed will be reduced a lot and start to hurt the volume of the segment. In the worst case, the segment is extremely crowded with vehicles so that the speed is reduced to zero and the volume becomes zero.

- **Average speed and density:** This relationship is shown in Figure 12. The straight line is the simplified case assuming the speed and density have a linear decreasing relationship. In a more sophisticated model, a curve rather than a straight line could be used to represent their relationship.

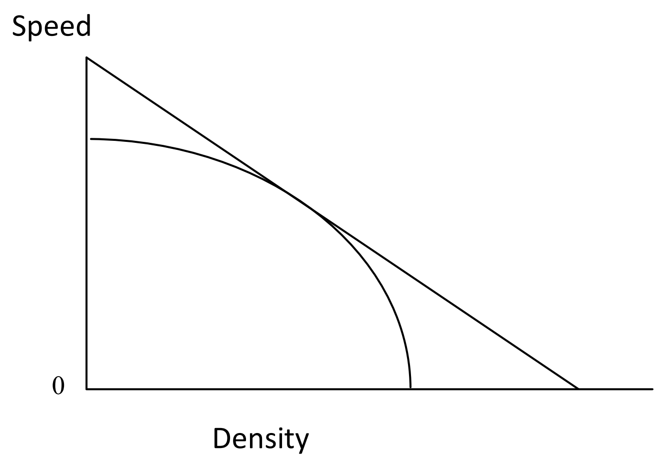


Figure 12. Typical Speed-Density relationship

- **Volume and density:** This relationship is shown in Figure 13.

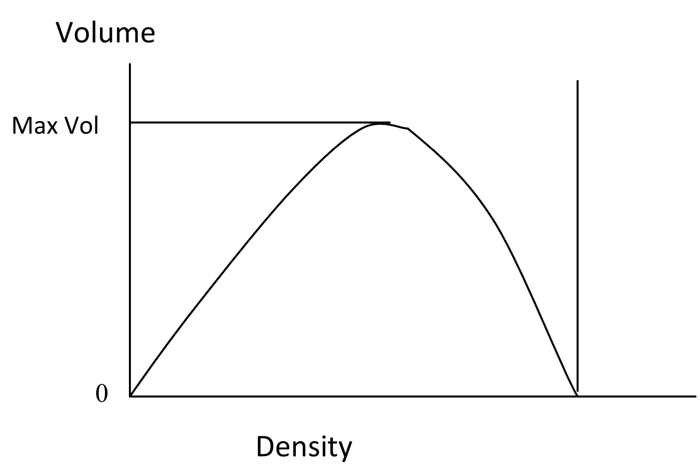


Figure 13: Typical Volume-Density relationship

In Figure 13, when density increases from a very small value, the speed is not significantly impacted so that the volume increases along with the density. Over the critical density, more vehicles in a segment can cause congestion (a big speed deduction) so that the volume decreases.

Among the three relationships, the speed-flow curves are widely used because it is easy to collect both the speed and flow (volume) data. Figure 14 is one example speed-flow curve provided by Hall (1992) [32].

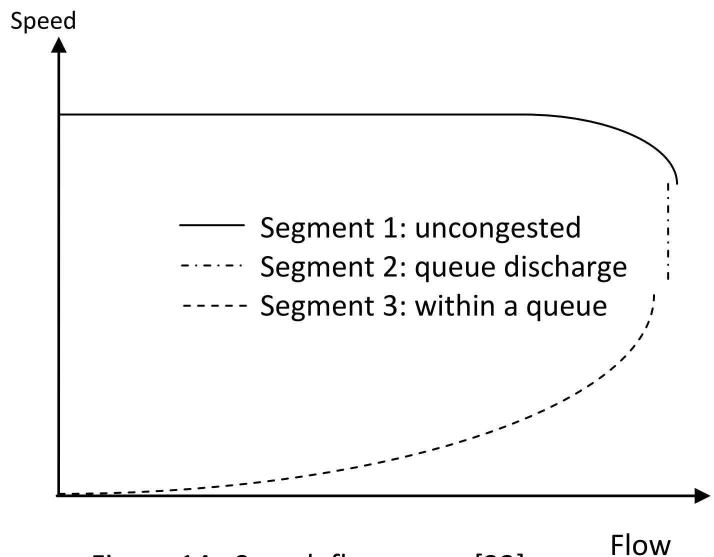


Figure 14. Speed–flow curve [33]

Mahmassani et al. proposed a simplified two-regime speed–density relationship in Equation (28) for the simulation purpose [33]:

$$S_{it} = \begin{cases} F_i & \text{if } 0 \le d_{it} \le \underline{d}_i \\ (\overline{F}_i - \underline{F_i})(1 - \frac{d_{it}}{d_i})^{\beta i} + \underline{F_i} & \text{if } \underline{d}_i \le d_{it} \le \overline{d}_i \end{cases} . \tag{28}$$

Here,

S_{it} = average speed of a vehicle on sub-segment *i* at time *t* (miles/h);
d_{it} = density on sub-segment *i* at time *t*;
$\overline{d}_i$ = jam density for sub-segment *i*;
$\underline{d}_i$ = critical density for sub-segment *i*;
F_i = free flow (or mean free) speed on sub-segment *i* for the first regime, i.e. when $0 \le d_{it} \le \underline{d}_i$;

$\overline{F}_i$ = free flow (or mean free) speed on sub-segment *i* for the second regime, i.e. when $\underline{d}_i \leq d_{it} \leq \overline{d}_i$ ($\overline{F}_i$ has no physical meaning as the second regime only applies for mid-range density values and hence will never be exhibited by vehicles);

$\underline{F_i}$ = minimum speed on sub-segment *i;*

βi = power term used to capture the sensitivity of speed to density.

Equation (28) is illustrated in Figure 15. Before the traffic density reaches critical density, vehicles are assumed to move under the free flow speed. Beyond the critical density, the speed drops with a curve until zero.

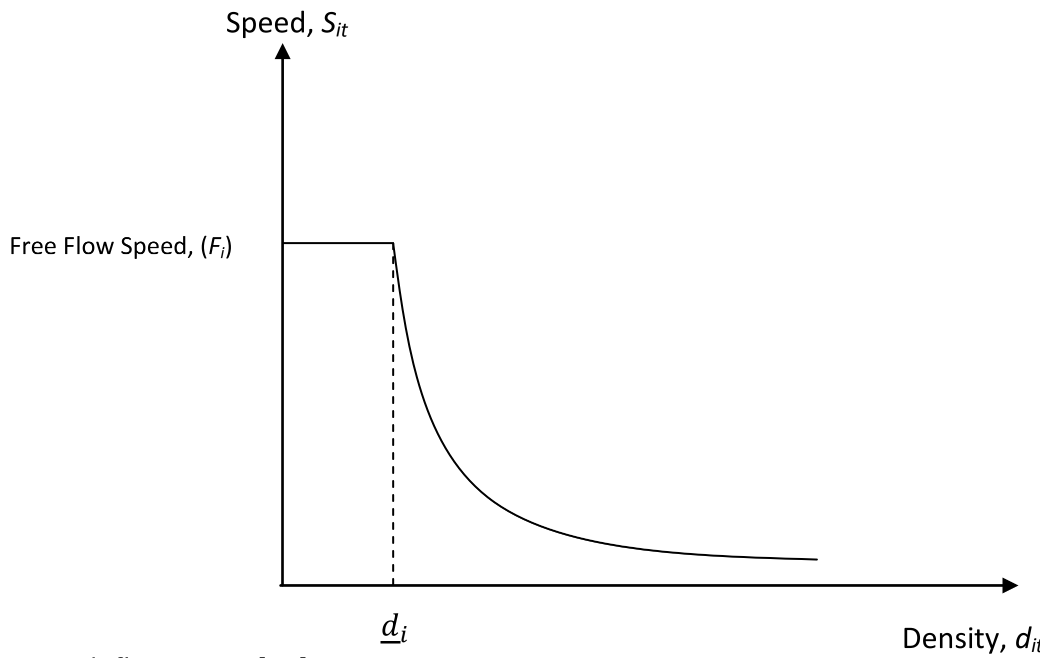


Figure 15: Speed–flow curve [33]

3.3.2 Highway Capacity Calculation

Capacity is the maximum number of vehicles which has a reasonable expectation of passing over There exist different methods for calculating the capacity of highways according to the specific characteristics (physical and flow) of the road segments. For deciding among the different methods we used the criteria provided by Highway Performance Monitoring System (HPMS 2000) [34].

3.3.2.1 Freeway Procedure

The main difference between freeways and multilane highways is that the roads in the case of freeways are separated from the rest of the traffic and can only be accessed by ramps.

Step 1: Calculate Free Flow Speed (FSS)

The first step in the procedure is to estimate free flow speed (FFS) of the segment. Equation (29) shows the relationship:

$$FFS = BFFS - f_{LW} - f_{LC} - f_N - f_{ID} \tag{29}$$

Here,

$BFFS$ = base free flow speed

f_{LW} = adjustment factor for lane width

f_{LC} = adjustment factor for right shoulder lateral clearance

f_N = adjustment factor for number of lanes

f_{ID} = adjustment factor for interchange density

Base Free Flow Speed: BFFS is set at 70 mph for urban facilities and 75 mph for rural facilities.

Step 2: Calculate Base Capacity (BaseCap)

The Base Capacity (passenger cars per hour per lane; pcphpl) of a freeway facility is based on information found in HCM Exhibit 23-3. The following relationships were developed based on this information, shown in Equation (30):

$$\begin{gathered} BaseCap = 1700 + 10FFS;\ for\ FFS \leq 70 \\ BaseCap = 2400;\ for\ FFS > 70 \end{gathered} \tag{30}$$

Step 3: Determine Peak Capacity (PeakCap)

The HCM 2000 [35] procedure does not make adjustments to the Base Capacity in order to calculate level of service and performance measures. Instead, adjustments are made to the hourly demand volume. However, for HPMS, the capacity of the segment, in terms of total vehicles per hour (vph), must be computed for a variety of analytic purposes. Therefore, the same factors used in the HCM 2000 to adjust volume are used to adjust base capacity instead. Essentially, these adjustments convert the units from passenger cars to vehicles and lower capacity to account for the effect of heavy vehicles. The procedure is based on Equation (31):

$$PeakCap = BaseCap * PHF * N * f_{HV} - f_P \tag{31}$$

Where,

PeakCap = HPMS Peak Capacity (Data Item 95), vehicles per hour (all lanes, one direction)

PHF = Peak Hour Factor

N = Number of lanes in one direction. Number of Peak Lanes (Data Item 87)
F_{HV} = adjustment factor for heavy vehicles
f_P = adjustment factor for driver population

3.3.2.2 Multilane Highway Procedure

In the case of the multilane highway, the roads have two or more lanes in each direction with a divided flow in both directions. The main difference from the freeway is that multilane highways have crossings and sometimes can be accessed by merging traffic without ramps.

Step 1: Calculate Free Flow Speed (FFS)
The first step in the procedure is to estimate free flow speed (FSS) on the facility. Equation (32) is applied for this step:

$$FFS = BFFS - f_{LW} - f_{LC} - f_M - f_A \tag{32}$$

Where,

$BFFS$ = base free flow speed
f_{LW} = adjustment factor for lane width
f_{LC} = adjustment factor for right shoulder lateral clearance
f_M = adjustment factor for median type
f_A = adjustment factor for access point

***Step 2: Calculate Base Capacity* (*BaseCap*)**
The Base Capacity (passenger cars per hour per lane; pcphpl) of a multilane facility is based on the information found in HCM Exhibit 21-3. The following Equation (33) shows the relationships:

$$BaseCap = 1000 + 20FFS; for\ FFS \leq 60 \tag{33}$$
$$BaseCap = 2200; for\ FFS > 60$$

***Step 3: Determine Peak Capacity* (*PeakCap*)**
The HCM 2000 procedure does not make adjustments to the base capacity in order to calculate level of service and performance measures. Instead, adjustments are made to the hourly demand volume. However, for HPSM, the capacity of the section, in terms of total vehicles per hour (vph), must be computed for a variety of analytic purposes. Therefore, the same factors used in the HCM 2000 to adjust volume are used to adjust base capacity. Essentially, these adjustments convert the units from passenger cars to vehicles and lower capacity to account for the effect of heavy vehicles. The procedure is based on Equation (34):

$$PeakCap = BaseCap * PHF * N * f_{HV} - f_P \quad (34)$$

Where,

PeakCap = HPMS Peak Capacity (Data Item 95), vehicles per hour (all lanes, one direction)
PHF = Peak Hour Factor
N = Number of lanes in one direction. Number of Peak Lanes (Data Item 87)
f_{HV} = adjustment factor for heavy vehicles
f_P = adjustment factor for driver population. 1.0 for HPMS

3.3.3 Delay Calculation

In this section, we are particularly interested in incident delay. Many models have been proposed to estimate incident delay. These models can be classified into three types based on the methods adopted: (1) methods based on queuing analysis [36]; (2) methods based on shock wave analysis [37-38] and (3) methods based on freeway traffic simulation [39-40]. These models can also be categorized into two types based on the scales: (1) models that focus on total incident delay caused by incidents [37-40]; and (2) models that focus on individual vehicle incident delay [41].

3.3.3.1 Basic Concept of Incident Delay

It is useful to describe the basic concepts and ideas that are involved in predicting non-recurrent delay. When an incident occurs, there is an increase in the congestion on top of the recurrent delay. Figure 16 shows the queuing diagram approach that is typically used to describe the general ideas of estimating incident delay.

- *Incident detection time* is the interval from the occurrence to the detection of the incident.
- *Incident response time* is the time between detection to the time the first response unit arrives.
- *Clearance time* is the time it takes for the incident to be removed from the road.
- *Recovery time* or residual delay is the time for the queue formed due to the incident to dissipate and the demand flow rate is restored after the incident has been cleared from the road.

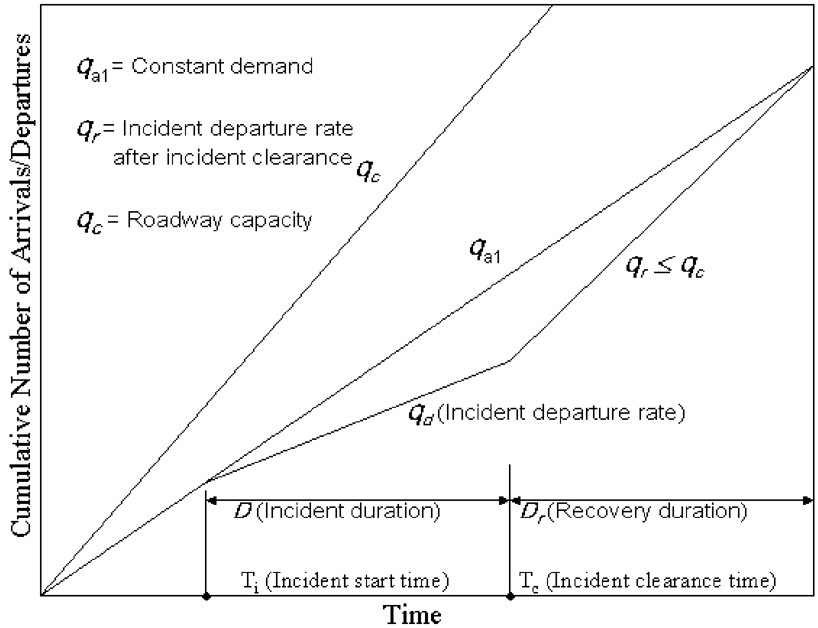


Figure 16. Incident Delay Diagram - Deterministic Model (one arrival rate) [42]

Incident detection, response, and clearance times constitute the incident duration, which is denoted by *D*. Most incident duration models are concerned with these three components. The last component, residual delay or recovery time (D_r) assesses the efficiency of the traffic control strategies used to recover from the event, such as traffic diversion and early traveler information systems. Not every incident involves all four components.

The delay equation that expresses the total incident delay based on the simple deterministic model shown in Figure 16 is as follows, Equation (35) [43]:

$$Delay = \frac{D^2(q_r - q_d)(q_{a1} - q_d)}{2(q_r - q_{a1})} \tag{35}$$

Here, *D* is the incident duration, q_{a1} is the rate of traffic flow just before the incident occurs, q_c is the saturation flow rate (prevailing roadway capacity) of the road segment where the incident occurs, q_d is the departure flow rate while the incident is present, and q_r is the departure flow rate once the incident has been cleared.

4.0 Data Availability Study

Though this project deals with freight transportation through railway network, we studied the data availability for all these three transportation modes-railway, highway and waterway.

4.1 Freight Flow Demand Data

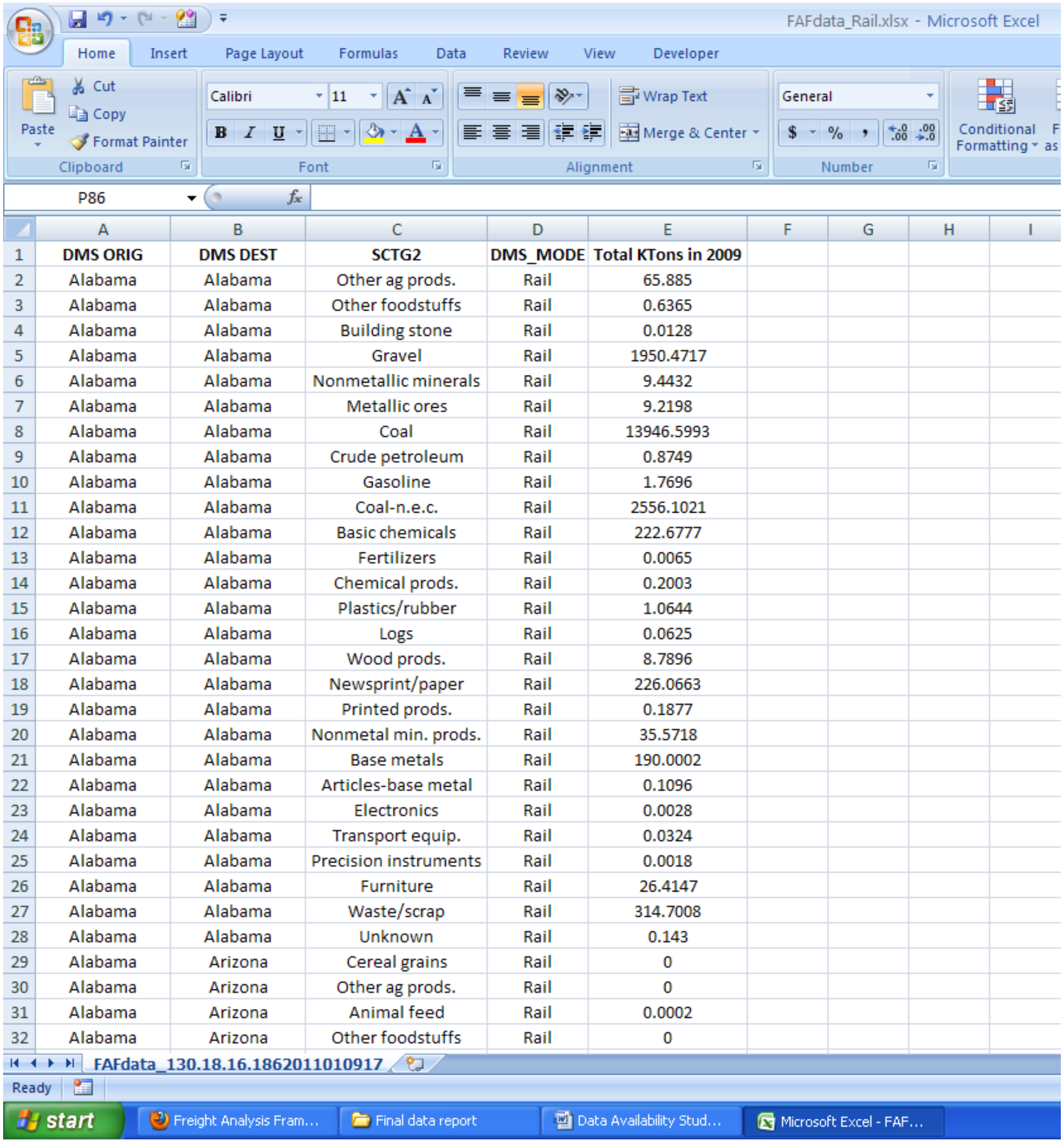
In this section, we will discuss various Origin-Destination-Commodity (ODC) flow data sources for surface transportation modes (*i.e.* railway, highway and waterway) in USA to understand freight demand. The datasets are maintained either by federal and state governments or private companies. The research team has collected the ODC flow data from two different sources. The sources are Freight Analysis Framework Version 3 (FAF^3) and PIERS [44]. The former source of data are maintained by the Office of Freight Management and Operations of Federal Highway Administration (FHWA), which is a branch of US department of transportation (USDOT) and funded by federal government for its overall management. So, this source of data is publicly available for free. On the other hand, the latter source of data provided by PIERS is privately owned. Therefore, this data source is commercially available to purchase. The research team has purchased six months export/import data from PIERS for study. The data collected from those two sources are described below:

4.1.1 Freight Analysis Framework Version 3 (FAF^3)

The Freight Analysis Framework (FAF) combines data from a variety of sources to create a comprehensive picture of freight movement among states and major metropolitan areas by all modes of transportation [44].

FAF^3 database provides the data for seven different transportation modes. For our project, we have collected the ODC flow data for the year 2009 for the three surface transportation modes --- railway, highway and waterway. The snapshots of sample data for the three modes of transportation are provided in Figures 17 through 19.

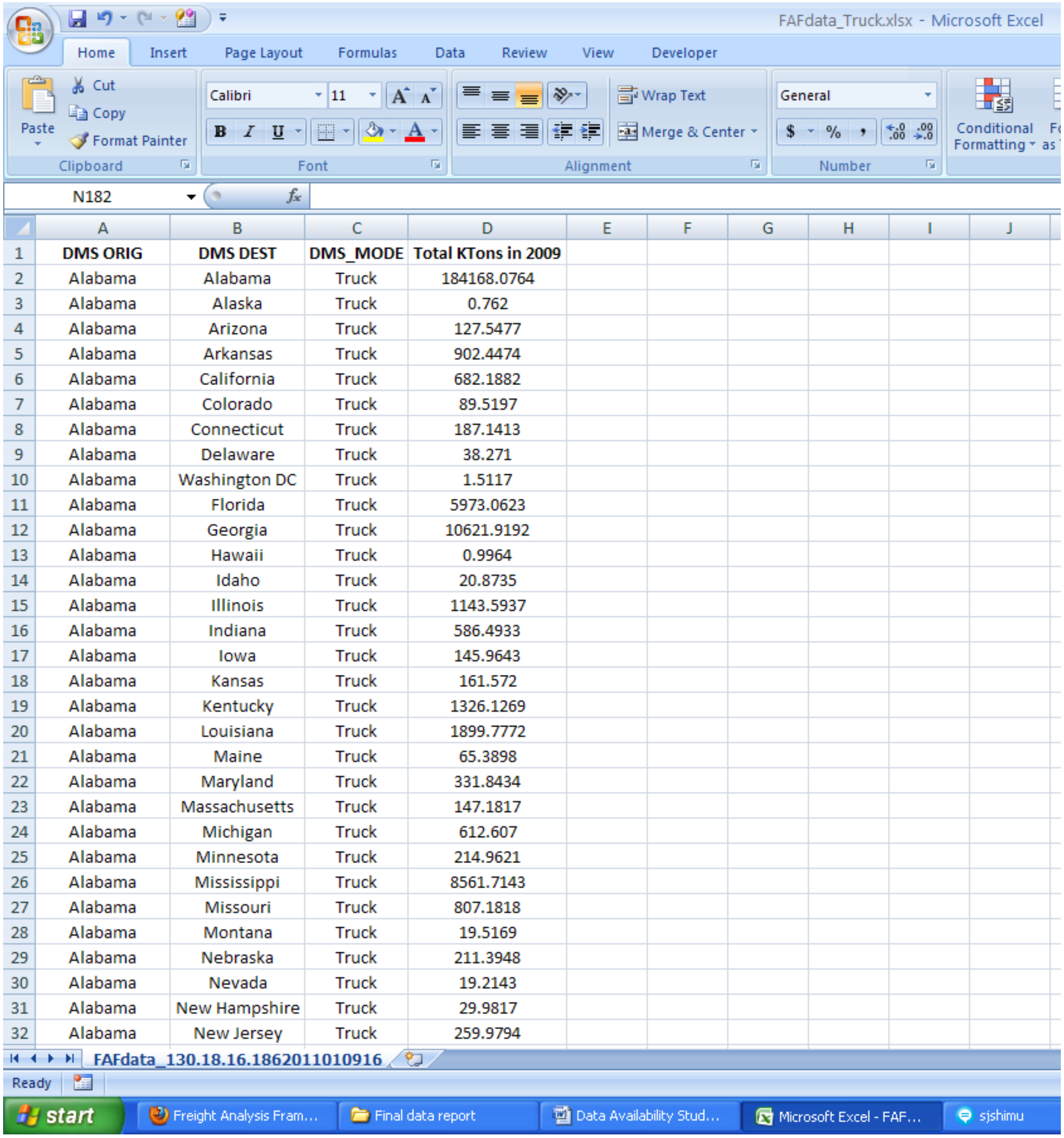
In Figure 17, column A corresponds to the domestic origin state; column B specifies domestic destination state; column C represents standard commodity group; column D represents the domestic transportation mode; and finally column E represents the annual amount (in Thousand Tons) of commodity transported from one state to another state in 2009. Here, the acronyms 'DMS ORIG' stands for Domestic Origin; 'DMS DEST' stands for Domestic Destination; 'SCTG2' stands for 2-digit Standard Classification of Transported Goods; 'DMS_MODE' stands for Domestic Mode of Transportation; and 'Total KTons in 2009' stands for Total Kilo Tons in 2009.



DMS ORIG	DMS DEST	SCTG2	DMS_MODE	Total KTons in 2009
Alabama	Alabama	Other ag prods.	Rail	65.885
Alabama	Alabama	Other foodstuffs	Rail	0.6365
Alabama	Alabama	Building stone	Rail	0.0128
Alabama	Alabama	Gravel	Rail	1950.4717
Alabama	Alabama	Nonmetallic minerals	Rail	9.4432
Alabama	Alabama	Metallic ores	Rail	9.2198
Alabama	Alabama	Coal	Rail	13946.5993
Alabama	Alabama	Crude petroleum	Rail	0.8749
Alabama	Alabama	Gasoline	Rail	1.7696
Alabama	Alabama	Coal-n.e.c.	Rail	2556.1021
Alabama	Alabama	Basic chemicals	Rail	222.6777
Alabama	Alabama	Fertilizers	Rail	0.0065
Alabama	Alabama	Chemical prods.	Rail	0.2003
Alabama	Alabama	Plastics/rubber	Rail	1.0644
Alabama	Alabama	Logs	Rail	0.0625
Alabama	Alabama	Wood prods.	Rail	8.7896
Alabama	Alabama	Newsprint/paper	Rail	226.0663
Alabama	Alabama	Printed prods.	Rail	0.1877
Alabama	Alabama	Nonmetal min. prods.	Rail	35.5718
Alabama	Alabama	Base metals	Rail	190.0002
Alabama	Alabama	Articles-base metal	Rail	0.1096
Alabama	Alabama	Electronics	Rail	0.0028
Alabama	Alabama	Transport equip.	Rail	0.0324
Alabama	Alabama	Precision instruments	Rail	0.0018
Alabama	Alabama	Furniture	Rail	26.4147
Alabama	Alabama	Waste/scrap	Rail	314.7008
Alabama	Alabama	Unknown	Rail	0.143
Alabama	Arizona	Cereal grains	Rail	0
Alabama	Arizona	Other ag prods.	Rail	0
Alabama	Arizona	Animal feed	Rail	0.0002
Alabama	Arizona	Other foodstuffs	Rail	0

Figure 17. A snapshot of Railway ODC data from FAF^3 database

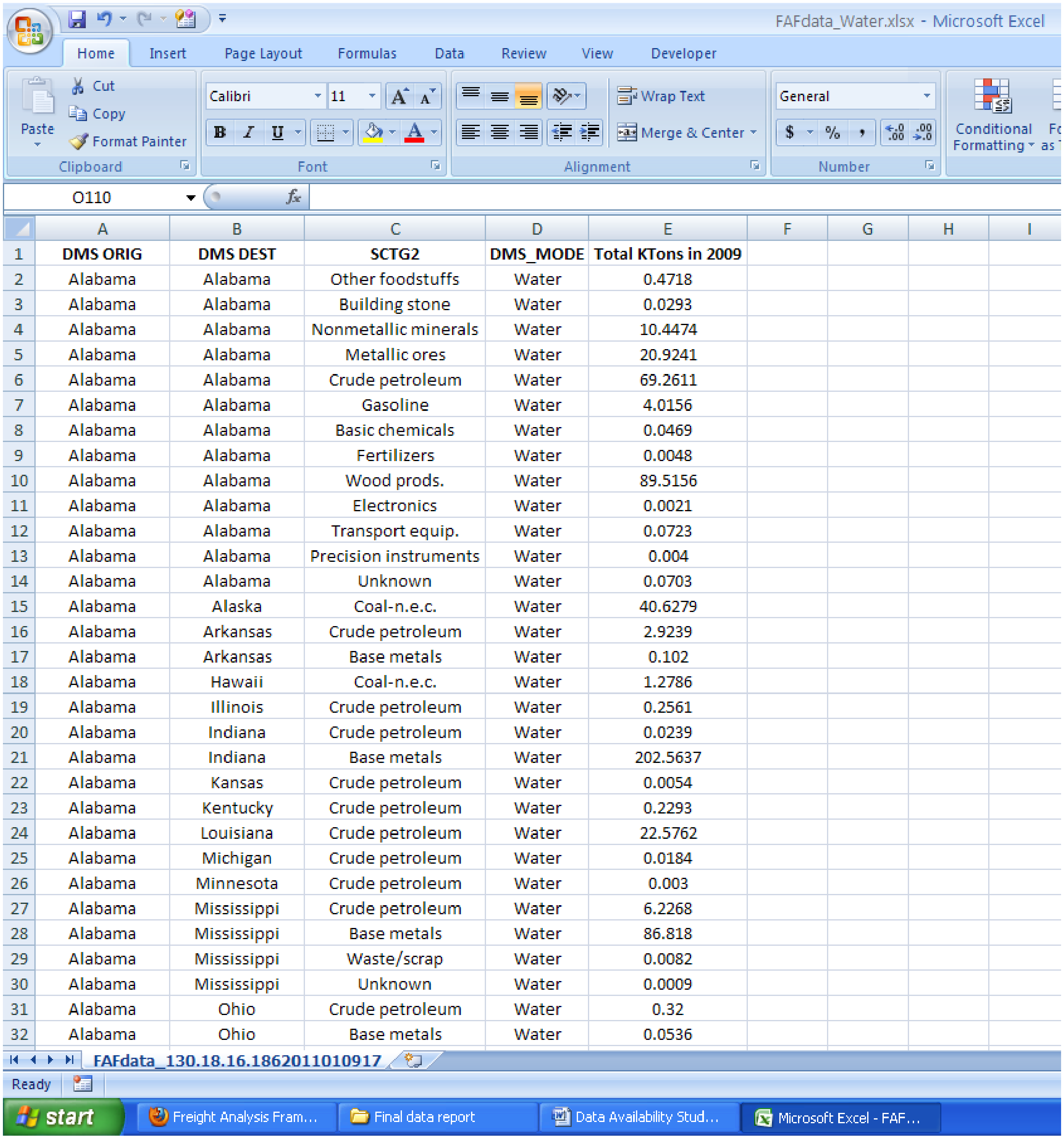
Figure 18 represents the ODC flow data from one state to another state through the highways of USA. The column definitions in Figure 18 are same as in Figure 17 with the following exceptions. In this figure, it is obvious that the amount of commodity transported from one state to other state is not commodity specific. Instead, they are accumulated together to represent the total amount of flow at the state-state level through highways. In fact, the commodity based flow for highways are not available in the FAF^3 database.



DMS ORIG	DMS DEST	DMS_MODE	Total KTons in 2009
Alabama	Alabama	Truck	184168.0764
Alabama	Alaska	Truck	0.762
Alabama	Arizona	Truck	127.5477
Alabama	Arkansas	Truck	902.4474
Alabama	California	Truck	682.1882
Alabama	Colorado	Truck	89.5197
Alabama	Connecticut	Truck	187.1413
Alabama	Delaware	Truck	38.271
Alabama	Washington DC	Truck	1.5117
Alabama	Florida	Truck	5973.0623
Alabama	Georgia	Truck	10621.9192
Alabama	Hawaii	Truck	0.9964
Alabama	Idaho	Truck	20.8735
Alabama	Illinois	Truck	1143.5937
Alabama	Indiana	Truck	586.4933
Alabama	Iowa	Truck	145.9643
Alabama	Kansas	Truck	161.572
Alabama	Kentucky	Truck	1326.1269
Alabama	Louisiana	Truck	1899.7772
Alabama	Maine	Truck	65.3898
Alabama	Maryland	Truck	331.8434
Alabama	Massachusetts	Truck	147.1817
Alabama	Michigan	Truck	612.607
Alabama	Minnesota	Truck	214.9621
Alabama	Mississippi	Truck	8561.7143
Alabama	Missouri	Truck	807.1818
Alabama	Montana	Truck	19.5169
Alabama	Nebraska	Truck	211.3948
Alabama	Nevada	Truck	19.2143
Alabama	New Hampshire	Truck	29.9817
Alabama	New Jersey	Truck	259.9794

Figure 18. A snapshot of Highway ODC data from FAF^3 database

Figure 19 represents the ODC flow data through the US waterways. As in Figure 17, the column definitions in Figure 19 correspond to exactly the same meaning. The only exception is column 4 tells about the mode of transportation is waterway. The amount of each commodity transported is also in thousand tons from one state to other state, same as in Figure 17 & 18.



DMS ORIG	DMS DEST	SCTG2	DMS_MODE	Total KTons in 2009
Alabama	Alabama	Other foodstuffs	Water	0.4718
Alabama	Alabama	Building stone	Water	0.0293
Alabama	Alabama	Nonmetallic minerals	Water	10.4474
Alabama	Alabama	Metallic ores	Water	20.9241
Alabama	Alabama	Crude petroleum	Water	69.2611
Alabama	Alabama	Gasoline	Water	4.0156
Alabama	Alabama	Basic chemicals	Water	0.0469
Alabama	Alabama	Fertilizers	Water	0.0048
Alabama	Alabama	Wood prods.	Water	89.5156
Alabama	Alabama	Electronics	Water	0.0021
Alabama	Alabama	Transport equip.	Water	0.0723
Alabama	Alabama	Precision instruments	Water	0.004
Alabama	Alabama	Unknown	Water	0.0703
Alabama	Alaska	Coal-n.e.c.	Water	40.6279
Alabama	Arkansas	Crude petroleum	Water	2.9239
Alabama	Arkansas	Base metals	Water	0.102
Alabama	Hawaii	Coal-n.e.c.	Water	1.2786
Alabama	Illinois	Crude petroleum	Water	0.2561
Alabama	Indiana	Crude petroleum	Water	0.0239
Alabama	Indiana	Base metals	Water	202.5637
Alabama	Kansas	Crude petroleum	Water	0.0054
Alabama	Kentucky	Crude petroleum	Water	0.2293
Alabama	Louisiana	Crude petroleum	Water	22.5762
Alabama	Michigan	Crude petroleum	Water	0.0184
Alabama	Minnesota	Crude petroleum	Water	0.003
Alabama	Mississippi	Crude petroleum	Water	6.2268
Alabama	Mississippi	Base metals	Water	86.818
Alabama	Mississippi	Waste/scrap	Water	0.0082
Alabama	Mississippi	Unknown	Water	0.0009
Alabama	Ohio	Crude petroleum	Water	0.32
Alabama	Ohio	Base metals	Water	0.0536

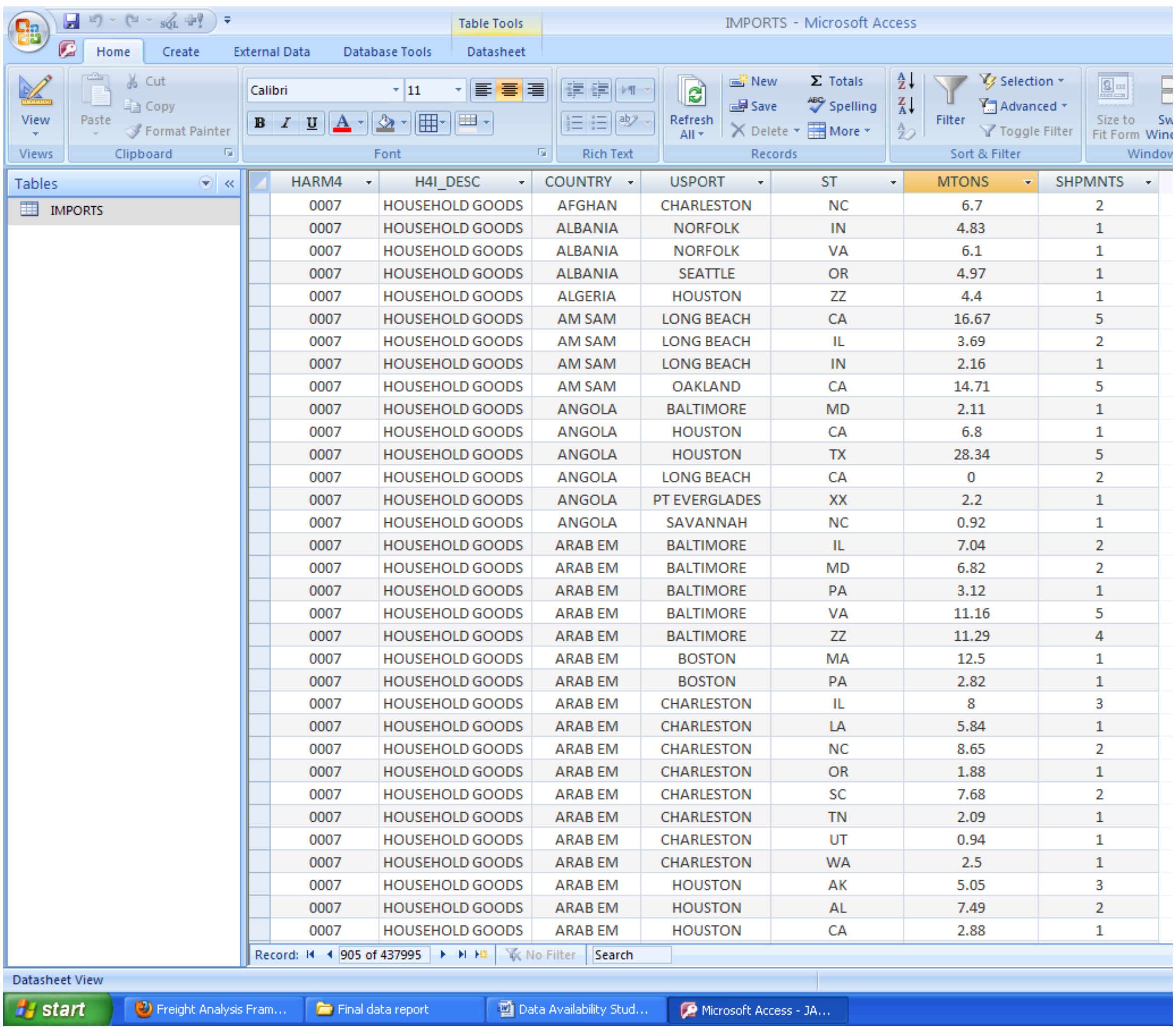
Figure 19. A snapshot of Waterway ODC data from FAF^3 database

4.1.2 PIERS Data

PIERS, a division of UBM Global Trade, provides trade information since 1950. It maintains the most comprehensive service of complete, accurate and reliable import and export information on cargoes moving through ports in the United States, Latin America and Asia. PIERS collects data from more than 15,000,000 bills of lading per year, which translates into greater than

20,000,000 shipments annually. PIERS processes the raw data into cleansed, standardized, enhanced and validated facts and figures that provide companies the trusted intelligence to make profitable decisions.

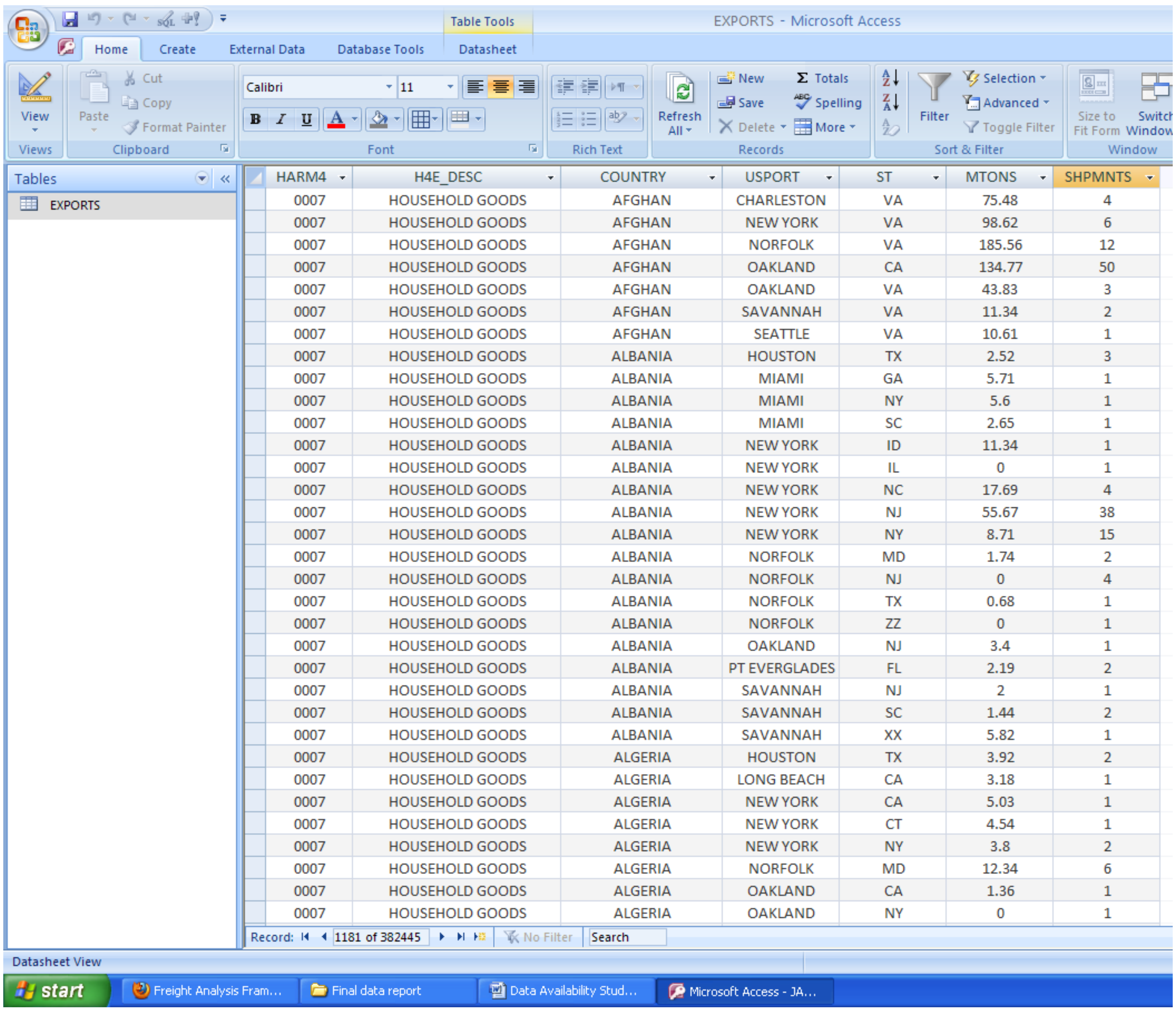
With 35 years of experience, PIERS is the only provider of export data and sets the standard for accuracy, reliability and insight. As mentioned earlier, PIERS is a privately owned company. Due to the budget constraint, we have purchased six months, January to June 2010, export and import ODC data of USA. Some sample data are presented in Figures 20 and 21.



HARM4	H4I_DESC	COUNTRY	USPORT	ST	MTONS	SHPMNTS
0007	HOUSEHOLD GOODS	AFGHAN	CHARLESTON	NC	6.7	2
0007	HOUSEHOLD GOODS	ALBANIA	NORFOLK	IN	4.83	1
0007	HOUSEHOLD GOODS	ALBANIA	NORFOLK	VA	6.1	1
0007	HOUSEHOLD GOODS	ALBANIA	SEATTLE	OR	4.97	1
0007	HOUSEHOLD GOODS	ALGERIA	HOUSTON	ZZ	4.4	1
0007	HOUSEHOLD GOODS	AM SAM	LONG BEACH	CA	16.67	5
0007	HOUSEHOLD GOODS	AM SAM	LONG BEACH	IL	3.69	2
0007	HOUSEHOLD GOODS	AM SAM	LONG BEACH	IN	2.16	1
0007	HOUSEHOLD GOODS	AM SAM	OAKLAND	CA	14.71	5
0007	HOUSEHOLD GOODS	ANGOLA	BALTIMORE	MD	2.11	1
0007	HOUSEHOLD GOODS	ANGOLA	HOUSTON	CA	6.8	1
0007	HOUSEHOLD GOODS	ANGOLA	HOUSTON	TX	28.34	5
0007	HOUSEHOLD GOODS	ANGOLA	LONG BEACH	CA	0	2
0007	HOUSEHOLD GOODS	ANGOLA	PT EVERGLADES	XX	2.2	1
0007	HOUSEHOLD GOODS	ANGOLA	SAVANNAH	NC	0.92	1
0007	HOUSEHOLD GOODS	ARAB EM	BALTIMORE	IL	7.04	2
0007	HOUSEHOLD GOODS	ARAB EM	BALTIMORE	MD	6.82	2
0007	HOUSEHOLD GOODS	ARAB EM	BALTIMORE	PA	3.12	1
0007	HOUSEHOLD GOODS	ARAB EM	BALTIMORE	VA	11.16	5
0007	HOUSEHOLD GOODS	ARAB EM	BALTIMORE	ZZ	11.29	4
0007	HOUSEHOLD GOODS	ARAB EM	BOSTON	MA	12.5	1
0007	HOUSEHOLD GOODS	ARAB EM	BOSTON	PA	2.82	1
0007	HOUSEHOLD GOODS	ARAB EM	CHARLESTON	IL	8	3
0007	HOUSEHOLD GOODS	ARAB EM	CHARLESTON	LA	5.84	1
0007	HOUSEHOLD GOODS	ARAB EM	CHARLESTON	NC	8.65	2
0007	HOUSEHOLD GOODS	ARAB EM	CHARLESTON	OR	1.88	1
0007	HOUSEHOLD GOODS	ARAB EM	CHARLESTON	SC	7.68	2
0007	HOUSEHOLD GOODS	ARAB EM	CHARLESTON	TN	2.09	1
0007	HOUSEHOLD GOODS	ARAB EM	CHARLESTON	UT	0.94	1
0007	HOUSEHOLD GOODS	ARAB EM	CHARLESTON	WA	2.5	1
0007	HOUSEHOLD GOODS	ARAB EM	HOUSTON	AK	5.05	3
0007	HOUSEHOLD GOODS	ARAB EM	HOUSTON	AL	7.49	2
0007	HOUSEHOLD GOODS	ARAB EM	HOUSTON	CA	2.88	1

Figure 20. A snapshot of Import ODC data from PIERS

Figure 20 contains import data through US ports. In Figure 20, the first column represents 4-digit Harmonized Tariff codes for different products and commodities; the second column describes the product/commodity categories; the third column specifies the foreign countries of origin; fourth column specifies the entry ports of USA; fifth column represents the destination states in USA for the shipment; sixth column represents the amount of commodity (in Million Tons) imported within first six months of 2010; and finally seventh column represents the number of shipments entered into USA within the specified time period. It is to be noted that the six-month data will be doubled to estimate the approximate annual amount of imports by USA from foreign countries.



HARM4	H4E_DESC	COUNTRY	USPORT	ST	MTONS	SHPMNTS
0007	HOUSEHOLD GOODS	AFGHAN	CHARLESTON	VA	75.48	4
0007	HOUSEHOLD GOODS	AFGHAN	NEW YORK	VA	98.62	6
0007	HOUSEHOLD GOODS	AFGHAN	NORFOLK	VA	185.56	12
0007	HOUSEHOLD GOODS	AFGHAN	OAKLAND	CA	134.77	50
0007	HOUSEHOLD GOODS	AFGHAN	OAKLAND	VA	43.83	3
0007	HOUSEHOLD GOODS	AFGHAN	SAVANNAH	VA	11.34	2
0007	HOUSEHOLD GOODS	AFGHAN	SEATTLE	VA	10.61	1
0007	HOUSEHOLD GOODS	ALBANIA	HOUSTON	TX	2.52	3
0007	HOUSEHOLD GOODS	ALBANIA	MIAMI	GA	5.71	1
0007	HOUSEHOLD GOODS	ALBANIA	MIAMI	NY	5.6	1
0007	HOUSEHOLD GOODS	ALBANIA	MIAMI	SC	2.65	1
0007	HOUSEHOLD GOODS	ALBANIA	NEW YORK	ID	11.34	1
0007	HOUSEHOLD GOODS	ALBANIA	NEW YORK	IL	0	1
0007	HOUSEHOLD GOODS	ALBANIA	NEW YORK	NC	17.69	4
0007	HOUSEHOLD GOODS	ALBANIA	NEW YORK	NJ	55.67	38
0007	HOUSEHOLD GOODS	ALBANIA	NEW YORK	NY	8.71	15
0007	HOUSEHOLD GOODS	ALBANIA	NORFOLK	MD	1.74	2
0007	HOUSEHOLD GOODS	ALBANIA	NORFOLK	NJ	0	4
0007	HOUSEHOLD GOODS	ALBANIA	NORFOLK	TX	0.68	1
0007	HOUSEHOLD GOODS	ALBANIA	NORFOLK	ZZ	0	1
0007	HOUSEHOLD GOODS	ALBANIA	OAKLAND	NJ	3.4	1
0007	HOUSEHOLD GOODS	ALBANIA	PT EVERGLADES	FL	2.19	2
0007	HOUSEHOLD GOODS	ALBANIA	SAVANNAH	NJ	2	1
0007	HOUSEHOLD GOODS	ALBANIA	SAVANNAH	SC	1.44	2
0007	HOUSEHOLD GOODS	ALBANIA	SAVANNAH	XX	5.82	1
0007	HOUSEHOLD GOODS	ALGERIA	HOUSTON	TX	3.92	2
0007	HOUSEHOLD GOODS	ALGERIA	LONG BEACH	CA	3.18	1
0007	HOUSEHOLD GOODS	ALGERIA	NEW YORK	CA	5.03	1
0007	HOUSEHOLD GOODS	ALGERIA	NEW YORK	CT	4.54	1
0007	HOUSEHOLD GOODS	ALGERIA	NEW YORK	NY	3.8	2
0007	HOUSEHOLD GOODS	ALGERIA	NORFOLK	MD	12.34	6
0007	HOUSEHOLD GOODS	ALGERIA	OAKLAND	CA	1.36	1
0007	HOUSEHOLD GOODS	ALGERIA	OAKLAND	NY	0	1

Figure 21. A snapshot of Export ODC data from PIERS

Figure 21 is a snapshot of export data through US ports. In Figure 21, the column definitions are same as in Figure 20 with the following exceptions. In column 3, the foreign countries are the countries of destination instead of countries of origin as in Figure 20. Next, in column 4, the US ports are the ports of exit from USA and in column 5, the US states are the origin states is USA for the shipment.

4.2 Surface Transportation Network Data

This section deals with the surface transportation network data, including railway, highway and waterway networks. In additional to geographic information of the infrastructure in the networks, the data also provide the capacity of each link and node of the freight network. Capacity of a network is measured in terms of network throughput, which is the number of tons or vehicles passing through the system, or specific components of it, during a specific time interval. Also the other physical properties of the network, for example – length, width, number of tracks of the links, are provided in the network data.

The research team has collected the surface transportation network data from the Oak Ridge National Laboratory (ORNL). They provided the network data in two formats – SHP format and DBF format. These data contain the intermodal network data of 2008. There are some other formats of network data were also collected from them. The details of those data are described based on Figures 22 through 27.

Figure 22 contains the link data of intermodal network of USA. The first column is the link ID. The second column contains the link identities in alpha-numeric form that describes the links identification in details, such as the transportation mode, the operator, etc. The third and fourth columns are the tail and head nodes comprising the links. The fifth and sixth columns represent the length of links in miles and the number of access points to a particular link, respectively. The seventh and eighth columns specify whether it is a one-way or two-way link and in which direction the link is heading, respectively. The ninth and tenth columns indicate the mode of transportation and specific type of cargo used in that particular transportation mode, respectively. The eleventh column defines the name of the links. The twelfth and thirteenth columns specify the two different types of FIP (Federal Information Processing Standards) numbers for the links. The last two columns correspond to the capacity and volume of vehicles transported though the links, respectively.

Figure 23 contains the nodal data of intermodal network of USA. The column definitions in Figure 23 are the same meaning as in Figure 22, except that they are for nodes rather than for links. Please note 'j' in Figure 23 stands for "juncture".

Figure 24 is a snapshot of intermodal network data of links of USA of 2008. This figure presents the same kind of information about intermodal links but with different file format. On the other hand, Figure 25 also shows the snapshot of intermodal link data. It provides the data related to the location of the links in terms of longitudes and latitudes.

Figure 26 is similar to Figure 24, but it conveys the information about nodes of intermodal network of USA in 2008. In contrast, Figure 27 conveys the similar information like Figure 25, but it conveys the location information about the nodes of intermodal network of USA in 2008.

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Lid	Lident	Ja	Jb	Miles	Access	Oneway	Heading	Mode	Cargo	Lname	Fips	Fip2	Capacity	Volume
1202	vr01053001AGR 1	8	55200	0.0	1	1	_	vr	DF	Frank Cu	1053	1053	1500.	0.0
1203	vr01069002NS 1	10	55202	0.0	1	1	_	vr	DF	AL St Do	1069	1069	1500.	0.0
1204	vr01073001BNSF 1	15	55203	0.0	1	1	_	vr	C	BNSF Bir	1073	1073	2000.	0.0
1205	vr01073002NS 1	16	55204	0.0	1	1	_	vr	C	NS Irond	1073	1073	2000.	0.0
1206	vr01073004CSXT 1	17	55205	0.0	1	1	_	vr	LK	Penn Tan	1073	1073	3000.	0.0
1207	vr01073004CSXT 2	17	55205	0.0	1	1	_	vr	LF	Penn Tan	1073	1073	3000.	0.0
1208	vr01073005CSXT 1	18	55206	0.0	1	1	_	vr	DK	CSXT Bir	1073	1073	1500.	0.0
1209	vr01073005CSXT 2	18	55206	0.0	1	1	_	vr	DF	CSXT Bir	1073	1073	1500.	0.0
1210	vr01073005CSXT 3	18	55206	0.0	1	1	_	vr	DO	CSXT Bir	1073	1073	1500.	0.0
1211	vr01073005CSXT 4	18	55206	0.0	1	1	_	vr	LK	CSXT Bir	1073	1073	3000.	0.0
1212	vr01073005CSXT 5	18	55206	0.0	1	1	_	vr	LF	CSXT Bir	1073	1073	3000.	0.0
1213	vr01073006JEFW 1	19	55207	0.0	1	1	_	vr	DO	JEFW Bir	1073	1073	1500.	0.0
1214	vr01073007NS 1	20	55208	0.0	1	1	_	vr	DK	ERS Rail	1073	1073	1500.	0.0
1215	vr01073007NS 2	20	55208	0.0	1	1	_	vr	DF	ERS Rail	1073	1073	1500.	0.0
1216	vr01073007NS 3	20	55208	0.0	1	1	_	vr	DO	ERS Rail	1073	1073	1500.	0.0
1217	vr01073007NS 4	20	55208	0.0	1	1	_	vr	LK	ERS Rail	1073	1073	3000.	0.0
1218	vr01073007NS 5	20	55208	0.0	1	1	_	vr	LF	ERS Rail	1073	1073	3000.	0.0
1219	vr01073008CSXT 1	21	55209	0.0	1	1	_	vr	LF	Nutritiv	1073	1073	3000.	0.0
1220	vr01073009BNSF 1	22	55210	0.0	1	1	_	vr	DK	Material	1073	1073	1500.	0.0
1221	vr01077001TSRR 1	25	55211	0.0	1	1	_	vr	DF	Lauderda	1077	1077	1500.	0.0
1222	vr01089001NS 1	30	55215	0.0	1	1	_	vr	C	Huntsvil	1089	1089	2000.	0.0
1223	vr01091001NS 3	31	55216	0.0	1	1	_	vr	DF	AL State	1091	1091	1500.	0.0
1224	vr01095003CSXT 1	34	55218	0.0	1	1	_	vr	DF	Cargill	1095	1095	1500.	0.0
1225	vr01095006CSXT 1	35	55221	0.0	1	1	_	vr	DF	Cargill	1095	1095	1500.	0.0
1226	vr01095007CSXT 1	36	55222	0.0	1	1	_	vr	DF	Great Co	1095	1095	1500.	0.0
1227	vr01097002CSXT 1	38	55223	0.0	1	1	_	vr	C	CSXI Mob	1097	1097	2000.	0.0
1228	vr01097005TASD 1	39	55224	0.0	1	1	_	vr	LK	PM Ag Pr	1097	1097	3000.	0.0
1229	vr01097005TASD 4	39	55224	0.0	1	1	_	vr	LF	PM Ag Pr	1097	1097	3000.	0.0
1230	vr01097009TASD 1	41	55227	0.0	1	1	_	vr	DF	AL St Do	1097	1097	1500.	0.0
1231	vr01097023CN 1	44	55230	0.0	1	1	_	vr	C	IC Mobil	1097	1097	2000.	0.0
1232	vr01097024CSXT 1	45	55231	0.0	1	1	_	vr	DK	McKenzie	1097	1097	1500.	0.0
1233	vr01097024CSXT 2	45	55231	0.0	1	1	_	vr	LD	McKenzie	1097	1097	3000.	0.0
1234	vr01097024CSXT 3	45	55231	0.0	1	1	_	vr	LK	McKenzie	1097	1097	3000.	0.0
1235	vr01101002CSXT 2	48	55233	0.0	1	1	_	vr	DF	AL State	1101	1101	1500.	0.0
1236	vr01103003NS 1	50	55236	0.0	1	1	_	vr	DK	NS Decat	1103	1103	1500.	0.0
1237	vr01103003NS 2	50	55236	0.0	1	1	_	vr	DF	NS Decat	1103	1103	1500.	0.0
1238	vr01103003NS 3	50	55236	0.0	1	1	_	vr	DO	NS Decat	1103	1103	1500.	0.0
1239	vr01103003NS 4	50	55236	0.0	1	1	_	vr	LD	NS Decat	1103	1103	3000.	0.0
1240	vr01103003NS 5	50	55236	0.0	1	1	_	vr	LK	NS Decat	1103	1103	3000.	0.0
1241	vr01103003NS 6	50	55236	0.0	1	1	_	vr	LF	NS Decat	1103	1103	3000.	0.0
1242	vr01103006CSXT 1	52	55238	0.0	1	1	_	vr	DF	AL Farme	1103	1103	1500.	0.0
1243	vr01103006NS 2	52	55239	0.0	1	1	_	vr	DF	AL Farme	1103	1103	1500.	0.0
1244	vr01103009CSXT 1	54	55241	0.0	1	1	_	vr	DF	Con-Agra	1103	1103	1500.	0.0
1245	vr01107001BNSF 3	55	55242	0.0	1	1	_	vr	DF	Pickens	1107	1107	1500.	0.0
1246	vr01113003NS 1	58	55244	0.0	1	1	_	vr	DF	AL St Do	1113	1113	1500.	0.0
1247	vr01121001NS 1	60	55245	0.0	1	1	_	vr	DK	Material	1121	1121	1500.	0.0
1248	vr01121001NS 2	60	55245	0.0	1	1	_	vr	DF	Material	1121	1121	1500.	0.0
1249	vr01121001NS 3	60	55245	0.0	1	1	_	vr	LK	Material	1121	1121	3000.	0.0

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Figure 22. A snapshot of intermodal network data of links from ORNL

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Jid	Jident	Access	Domestic	Mode	Cargo	Jname	Fips
2	vf01003001	1	1	vf	BL	Intl Pap	1003
3	vf01003002	1	1	vf	BL	Scott Pa	1003
4	vf01005001	1	1	vf	B%	AL State	1005
5	vf01025001	1	1	vf	BL	Intl Pap	1025
6	vf01025002	1	1	vf	BL	Po Jacks	1025
7	vf01047001	1	1	vf	B%	AL State	1047
8	vf01053001	1	1	vf	DF	Frank Cu	1053
9	vf01069001	1	1	vf	B%	AL St Do	1069
10	vf01069002	1	1	vf	DF	AL St Do	1069
11	vf01071001	1	1	vf	BL	Bowater	1071
12	vf01071003	1	1	vf	DE	N AL Shi	1071
13	vf01071004	1	1	vf	BM	Inman En	1071
14	vf01071005	1	1	vf	BL	AL St Do	1071
15	vf01073001	1	1	vf	C	BNSF Bir	1073
16	vf01073002	1	1	vf	C	NS Irond	1073
17	vf01073004	1	1	vf	LK	Penn Tan	1073
18	vf01073005	1	1	vf	DK	CSXT Bir	1073
19	vf01073006	1	1	vf	DO	JEFW Bir	1073
20	vf01073007	1	1	vf	DK	ERS Rail	1073
21	vf01073008	1	1	vf	LF	Nutritiv	1073
22	vf01073009	1	1	vf	DK	Material	1073
23	vf01073010	1	1	vf	LD	Ergon In	1073
24	vf01073011	1	1	vf	BL	Port Wes	1073
25	vf01077001	1	1	vf	DF	Lauderda	1077
26	vf01077002	1	1	vf	BM	Florence	1077
27	vf01077003	1	1	vf	DE	Methvin	1077
28	vf01077005	1	1	vf	BM	Hill's M	1077
29	vf01083001	1	1	vf	DF	Wheeler	1083
30	vf01089001	1	1	vf	C	Huntsvil	1089
31	vf01091001	1	1	vf	B%	AL State	1091
32	vf01095001	1	1	vf	DE	Po Gunte	1095
33	vf01095002	1	1	vf	DE	Po Gunte	1095
34	vf01095003	1	1	vf	DF	Cargill	1095
35	vf01095006	1	1	vf	DF	Cargill	1095
36	vf01095007	1	1	vf	DF	Great Co	1095
37	vf01095009	1	1	vf	BM	Guntersv	1095
38	vf01097002	1	1	vf	C	CSXI Mob	1097
39	vf01097005	1	1	vf	LK	PM Ag Pr	1097
40	vf01097008	1	1	vf	C	Alabama	1097
41	vf01097009	1	1	vf	DF	AL St Do	1097
42	vf01097013	1	1	vf	BL	Po Mobil	1097
43	vf01097015	1	1	vf	C	Mobile-C	1097
44	vf01097023	1	1	vf	C	IC Mobil	1097
45	vf01097024	1	1	vf	DK	McKenzie	1097
46	vf01097025	1	1	vf	LC	Ergon Oi	1097
47	vf01099001	1	1	vf	DF	AL State	1099
48	vf01101002	1	1	vf	B%	AL State	1101
49	vf01103002	1	1	vf	DO	Tenn Val	1103

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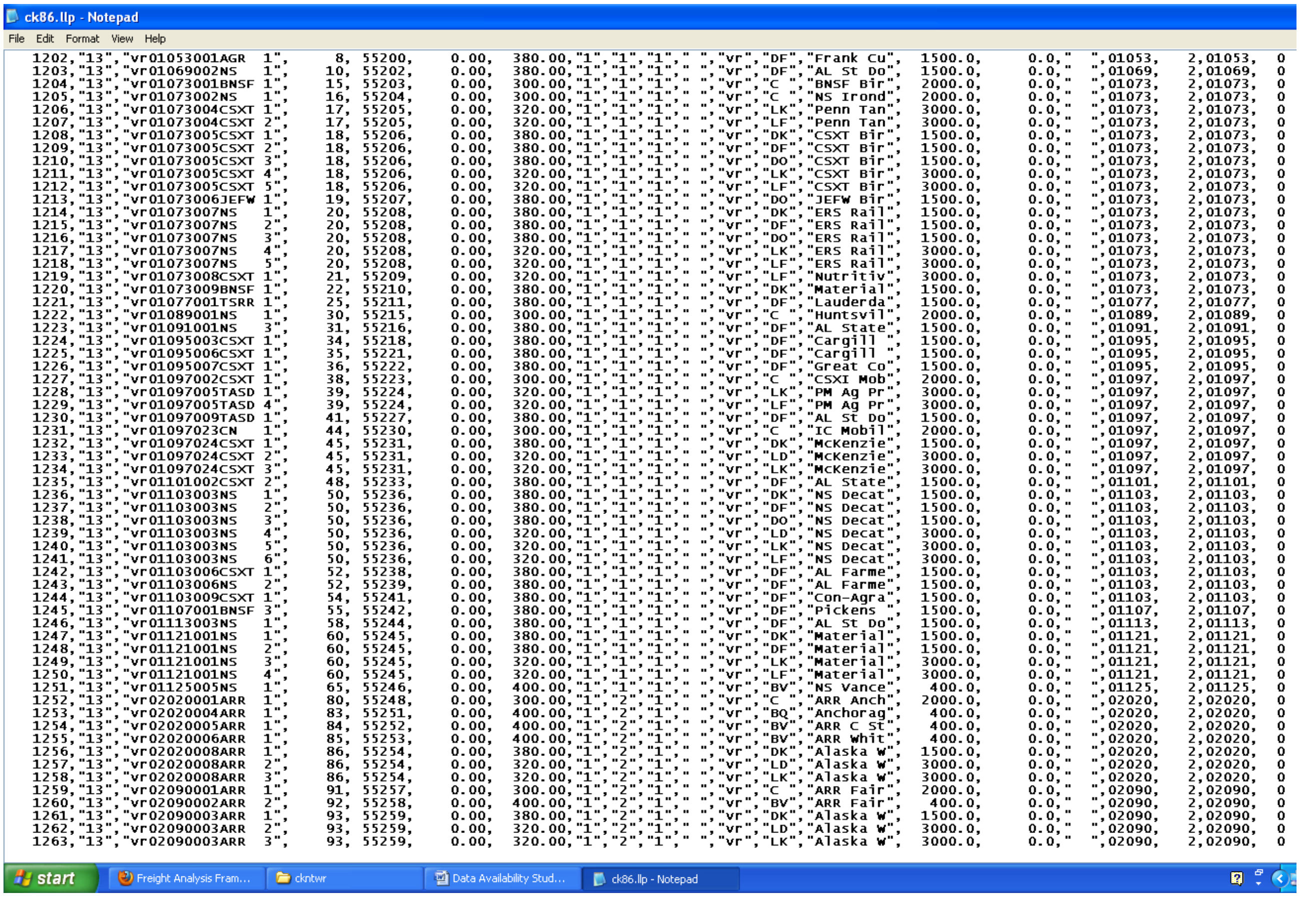
Figure 23. A snapshot of intermodal network data of nodes from ORNL



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1202,"13","vr01053001AGR  1",   8, 55200,   0.00,  380.00,"1","1","1"," ","vr","DF","Frank Cu",  1500.0,    0.0,"  ",01053,  2,01053,  0
1203,"13","vr01069002NS   1",  10, 55202,   0.00,  380.00,"1","1","1"," ","vr","DF","AL St Do",  1500.0,    0.0,"  ",01069,  2,01069,  0
1204,"13","vr01073001BNSF 1",  15, 55203,   0.00,  300.00,"1","1","1"," ","vr","C ","BNSF Bir",  2000.0,    0.0,"  ",01073,  2,01073,  0
1205,"13","vr01073002NS   1",  16, 55204,   0.00,  300.00,"1","1","1"," ","vr","C ","NS Irond",  2000.0,    0.0,"  ",01073,  2,01073,  0
1206,"13","vr01073004CSXT 1",  17, 55205,   0.00,  320.00,"1","1","1"," ","vr","LK","Penn Tan",  3000.0,    0.0,"  ",01073,  2,01073,  0
1207,"13","vr01073004CSXT 2",  17, 55205,   0.00,  320.00,"1","1","1"," ","vr","LF","Penn Tan",  3000.0,    0.0,"  ",01073,  2,01073,  0
1208,"13","vr01073005CSXT 1",  18, 55206,   0.00,  380.00,"1","1","1"," ","vr","DK","CSXT Bir",  1500.0,    0.0,"  ",01073,  2,01073,  0
1209,"13","vr01073005CSXT 2",  18, 55206,   0.00,  380.00,"1","1","1"," ","vr","DF","CSXT Bir",  1500.0,    0.0,"  ",01073,  2,01073,  0
1210,"13","vr01073005CSXT 3",  18, 55206,   0.00,  380.00,"1","1","1"," ","vr","DO","CSXT Bir",  1500.0,    0.0,"  ",01073,  2,01073,  0
1211,"13","vr01073005CSXT 4",  18, 55206,   0.00,  320.00,"1","1","1"," ","vr","LK","CSXT Bir",  3000.0,    0.0,"  ",01073,  2,01073,  0
1212,"13","vr01073005CSXT 5",  18, 55206,   0.00,  320.00,"1","1","1"," ","vr","LF","CSXT Bir",  3000.0,    0.0,"  ",01073,  2,01073,  0
1213,"13","vr01073006JEFW 1",  19, 55207,   0.00,  380.00,"1","1","1"," ","vr","DO","JEFW Bir",  1500.0,    0.0,"  ",01073,  2,01073,  0
1214,"13","vr01073007NS   1",  20, 55208,   0.00,  380.00,"1","1","1"," ","vr","DK","ERS Rail",  1500.0,    0.0,"  ",01073,  2,01073,  0
1215,"13","vr01073007NS   2",  20, 55208,   0.00,  380.00,"1","1","1"," ","vr","DF","ERS Rail",  1500.0,    0.0,"  ",01073,  2,01073,  0
1216,"13","vr01073007NS   3",  20, 55208,   0.00,  380.00,"1","1","1"," ","vr","DO","ERS Rail",  1500.0,    0.0,"  ",01073,  2,01073,  0
1217,"13","vr01073007NS   4",  20, 55208,   0.00,  320.00,"1","1","1"," ","vr","LK","ERS Rail",  3000.0,    0.0,"  ",01073,  2,01073,  0
1218,"13","vr01073007NS   5",  20, 55208,   0.00,  320.00,"1","1","1"," ","vr","LF","ERS Rail",  3000.0,    0.0,"  ",01073,  2,01073,  0
1219,"13","vr01073008CSXT 1",  21, 55209,   0.00,  320.00,"1","1","1"," ","vr","LF","Nutritiv",  3000.0,    0.0,"  ",01073,  2,01073,  0
1220,"13","vr01073009BNSF 1",  22, 55210,   0.00,  380.00,"1","1","1"," ","vr","DK","Material",  1500.0,    0.0,"  ",01073,  2,01073,  0
1221,"13","vr01077001TSRR 1",  25, 55211,   0.00,  380.00,"1","1","1"," ","vr","DF","Lauderda",  1500.0,    0.0,"  ",01077,  2,01077,  0
1222,"13","vr01089001NS   1",  30, 55215,   0.00,  300.00,"1","1","1"," ","vr","C ","Huntsvil",  2000.0,    0.0,"  ",01089,  2,01089,  0
1223,"13","vr01091001NS   3",  31, 55216,   0.00,  380.00,"1","1","1"," ","vr","DF","AL State",  1500.0,    0.0,"  ",01091,  2,01091,  0
1224,"13","vr01095003CSXT 1",  34, 55218,   0.00,  380.00,"1","1","1"," ","vr","DF","Cargill ",  1500.0,    0.0,"  ",01095,  2,01095,  0
1225,"13","vr01095006CSXT 1",  35, 55221,   0.00,  380.00,"1","1","1"," ","vr","DF","Cargill ",  1500.0,    0.0,"  ",01095,  2,01095,  0
1226,"13","vr01095007CSXT 1",  36, 55222,   0.00,  380.00,"1","1","1"," ","vr","DF","Great Co",  1500.0,    0.0,"  ",01095,  2,01095,  0
1227,"13","vr01097002CSXT 1",  38, 55223,   0.00,  300.00,"1","1","1"," ","vr","C ","CSXI Mob",  2000.0,    0.0,"  ",01097,  2,01097,  0
1228,"13","vr01097005TASD 1",  39, 55224,   0.00,  320.00,"1","1","1"," ","vr","LK","PM Ag Pr",  3000.0,    0.0,"  ",01097,  2,01097,  0
1229,"13","vr01097005TASD 4",  39, 55224,   0.00,  320.00,"1","1","1"," ","vr","LF","PM Ag Pr",  3000.0,    0.0,"  ",01097,  2,01097,  0
1230,"13","vr01097009TASD 1",  41, 55227,   0.00,  380.00,"1","1","1"," ","vr","DF","AL St Do",  1500.0,    0.0,"  ",01097,  2,01097,  0
1231,"13","vr01097023CN   1",  44, 55230,   0.00,  300.00,"1","1","1"," ","vr","C ","IC Mobil",  2000.0,    0.0,"  ",01097,  2,01097,  0
1232,"13","vr01097024CSXT 1",  45, 55231,   0.00,  380.00,"1","1","1"," ","vr","DK","McKenzie",  1500.0,    0.0,"  ",01097,  2,01097,  0
1233,"13","vr01097024CSXT 2",  45, 55231,   0.00,  320.00,"1","1","1"," ","vr","LD","McKenzie",  3000.0,    0.0,"  ",01097,  2,01097,  0
1234,"13","vr01097024CSXT 3",  45, 55231,   0.00,  320.00,"1","1","1"," ","vr","LK","McKenzie",  3000.0,    0.0,"  ",01097,  2,01097,  0
1235,"13","vr01101002CSXT 2",  48, 55233,   0.00,  380.00,"1","1","1"," ","vr","DF","AL State",  1500.0,    0.0,"  ",01101,  2,01101,  0
1236,"13","vr01103003NS   1",  50, 55236,   0.00,  380.00,"1","1","1"," ","vr","DK","NS Decat",  1500.0,    0.0,"  ",01103,  2,01103,  0
1237,"13","vr01103003NS   2",  50, 55236,   0.00,  380.00,"1","1","1"," ","vr","DF","NS Decat",  1500.0,    0.0,"  ",01103,  2,01103,  0
1238,"13","vr01103003NS   3",  50, 55236,   0.00,  380.00,"1","1","1"," ","vr","DO","NS Decat",  1500.0,    0.0,"  ",01103,  2,01103,  0
1239,"13","vr01103003NS   4",  50, 55236,   0.00,  320.00,"1","1","1"," ","vr","LD","NS Decat",  3000.0,    0.0,"  ",01103,  2,01103,  0
1240,"13","vr01103003NS   5",  50, 55236,   0.00,  320.00,"1","1","1"," ","vr","LK","NS Decat",  3000.0,    0.0,"  ",01103,  2,01103,  0
1241,"13","vr01103003NS   6",  50, 55236,   0.00,  320.00,"1","1","1"," ","vr","LF","NS Decat",  3000.0,    0.0,"  ",01103,  2,01103,  0
1242,"13","vr01103006CSXT 1",  52, 55238,   0.00,  380.00,"1","1","1"," ","vr","DF","AL Farme",  1500.0,    0.0,"  ",01103,  2,01103,  0
1243,"13","vr01103006NS   2",  52, 55239,   0.00,  380.00,"1","1","1"," ","vr","DF","AL Farme",  1500.0,    0.0,"  ",01103,  2,01103,  0
1244,"13","vr01103009CSXT 1",  54, 55241,   0.00,  380.00,"1","1","1"," ","vr","DF","Con-Agra",  1500.0,    0.0,"  ",01103,  2,01103,  0
1245,"13","vr01107001BNSF 3",  55, 55242,   0.00,  380.00,"1","1","1"," ","vr","DF","Pickens ",  1500.0,    0.0,"  ",01107,  2,01107,  0
1246,"13","vr01113003NS   1",  58, 55244,   0.00,  380.00,"1","1","1"," ","vr","DF","AL St Do",  1500.0,    0.0,"  ",01113,  2,01113,  0
1247,"13","vr01121001NS   1",  60, 55245,   0.00,  380.00,"1","1","1"," ","vr","DK","Material",  1500.0,    0.0,"  ",01121,  2,01121,  0
1248,"13","vr01121001NS   2",  60, 55245,   0.00,  380.00,"1","1","1"," ","vr","DF","Material",  1500.0,    0.0,"  ",01121,  2,01121,  0
1249,"13","vr01121001NS   3",  60, 55245,   0.00,  320.00,"1","1","1"," ","vr","LK","Material",  3000.0,    0.0,"  ",01121,  2,01121,  0
1250,"13","vr01121001NS   4",  60, 55245,   0.00,  320.00,"1","1","1"," ","vr","LF","Material",  3000.0,    0.0,"  ",01121,  2,01121,  0
1251,"13","vr01125005NS   1",  65, 55246,   0.00,  400.00,"1","1","1"," ","vr","BV","NS Vance",   400.0,    0.0,"  ",01125,  2,01125,  0
1252,"13","vr02020001ARR  1",  80, 55248,   0.00,  300.00,"1","2","1"," ","vr","C ","ARR Anch",  2000.0,    0.0,"  ",02020,  2,02020,  0
1253,"13","vr02020004ARR  1",  83, 55251,   0.00,  400.00,"1","2","1"," ","vr","BQ","Anchorag",   400.0,    0.0,"  ",02020,  2,02020,  0
1254,"13","vr02020005ARR  1",  84, 55252,   0.00,  400.00,"1","2","1"," ","vr","BV","ARR C St",   400.0,    0.0,"  ",02020,  2,02020,  0
1255,"13","vr02020006ARR  1",  85, 55253,   0.00,  400.00,"1","2","1"," ","vr","BV","ARR Whit",   400.0,    0.0,"  ",02020,  2,02020,  0
1256,"13","vr02020008ARR  1",  86, 55254,   0.00,  380.00,"1","2","1"," ","vr","DK","Alaska W",  1500.0,    0.0,"  ",02020,  2,02020,  0
1257,"13","vr02020008ARR  2",  86, 55254,   0.00,  320.00,"1","2","1"," ","vr","LD","Alaska W",  3000.0,    0.0,"  ",02020,  2,02020,  0
1258,"13","vr02020008ARR  3",  86, 55254,   0.00,  320.00,"1","2","1"," ","vr","LK","Alaska W",  3000.0,    0.0,"  ",02020,  2,02020,  0
1259,"13","vr02090001ARR  1",  91, 55257,   0.00,  300.00,"1","2","1"," ","vr","C ","ARR Fair",  2000.0,    0.0,"  ",02090,  2,02090,  0
1260,"13","vr02090002ARR  2",  92, 55258,   0.00,  400.00,"1","2","1"," ","vr","BV","ARR Fair",   400.0,    0.0,"  ",02090,  2,02090,  0
1261,"13","vr02090003ARR  1",  93, 55259,   0.00,  380.00,"1","2","1"," ","vr","DK","Alaska W",  1500.0,    0.0,"  ",02090,  2,02090,  0
1262,"13","vr02090003ARR  2",  93, 55259,   0.00,  320.00,"1","2","1"," ","vr","LD","Alaska W",  3000.0,    0.0,"  ",02090,  2,02090,  0
1263,"13","vr02090003ARR  3",  93, 55259,   0.00,  320.00,"1","2","1"," ","vr","LK","Alaska W",  3000.0,    0.0,"  ",02090,  2,02090,  0
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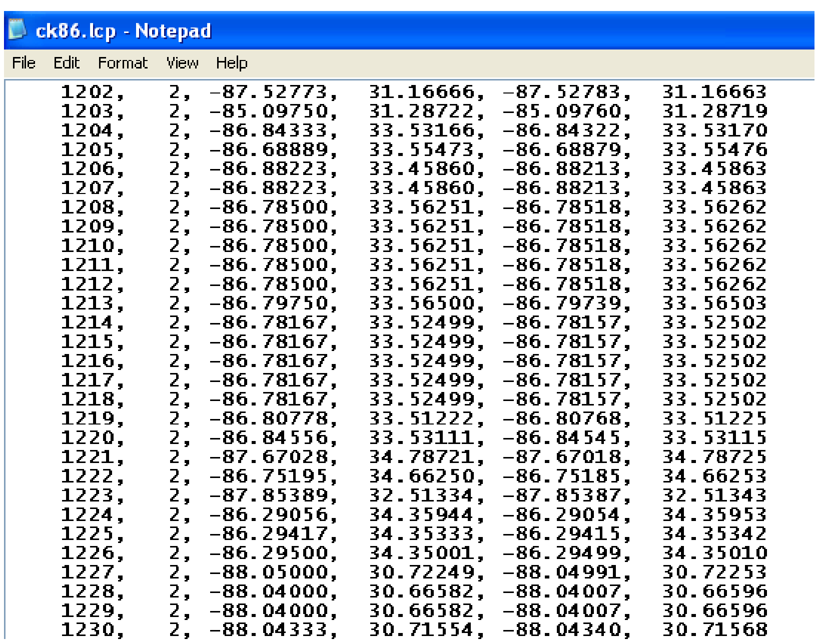
Figure 24. A snapshot of intermodal link data from ORNL in .llp



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File  Edit  Format  View  Help
1202,  2, -87.52773,  31.16666, -87.52783,  31.16663
1203,  2, -85.09750,  31.28722, -85.09760,  31.28719
1204,  2, -86.84333,  33.53166, -86.84322,  33.53170
1205,  2, -86.68889,  33.55473, -86.68879,  33.55476
1206,  2, -86.88223,  33.45860, -86.88213,  33.45863
1207,  2, -86.88223,  33.45860, -86.88213,  33.45863
1208,  2, -86.78500,  33.56251, -86.78518,  33.56262
1209,  2, -86.78500,  33.56251, -86.78518,  33.56262
1210,  2, -86.78500,  33.56251, -86.78518,  33.56262
1211,  2, -86.78500,  33.56251, -86.78518,  33.56262
1212,  2, -86.78500,  33.56251, -86.78518,  33.56262
1213,  2, -86.79750,  33.56500, -86.79739,  33.56503
1214,  2, -86.78167,  33.52499, -86.78157,  33.52502
1215,  2, -86.78167,  33.52499, -86.78157,  33.52502
1216,  2, -86.78167,  33.52499, -86.78157,  33.52502
1217,  2, -86.78167,  33.52499, -86.78157,  33.52502
1218,  2, -86.78167,  33.52499, -86.78157,  33.52502
1219,  2, -86.80778,  33.51222, -86.80768,  33.51225
1220,  2, -86.84556,  33.53111, -86.84545,  33.53115
1221,  2, -87.67028,  34.78721, -87.67018,  34.78725
1222,  2, -86.75195,  34.66250, -86.75185,  34.66253
1223,  2, -87.85389,  32.51334, -87.85387,  32.51343
1224,  2, -86.29056,  34.35944, -86.29054,  34.35953
1225,  2, -86.29417,  34.35333, -86.29415,  34.35342
1226,  2, -86.29500,  34.35001, -86.29499,  34.35010
1227,  2, -88.05000,  30.72249, -88.04991,  30.72253
1228,  2, -88.04000,  30.66582, -88.04007,  30.66596
1229,  2, -88.04000,  30.66582, -88.04007,  30.66596
1230,  2, -88.04333,  30.71554, -88.04340,  30.71568
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Figure 25. A snapshot of intermodal link data from ORNL in .lcp

ck86.ndp - Notepad

File Edit Format View Help

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  2, -87.76667,  31.29305,"1A","vf01003001        ","1","1"," "," ","vf","BL","Intl Pap","   ",01003, 2,    0,  0.000
  3, -87.76417,  31.29502,"1A","vf01003002        ","1","1"," "," ","vf","BL","Scott Pa","   ",01003, 2,    0,  0.000
  4, -85.15250,  31.84917,"1A","vf01005001        ","1","1"," "," ","vf","B%","AL State","   ",01005, 3,    0,  0.000
  5, -88.14750,  31.85750,"1A","vf01025001        ","1","1"," "," ","vf","BL","Intl Pap","   ",01025, 2,    0,  0.000
  6, -87.90500,  31.49249,"1A","vf01025002        ","1","1"," "," ","vf","BL","Po Jacks","   ",01025, 3,    0,  0.000
  7, -86.87000,  32.41499,"1A","vf01047001        ","1","1"," "," ","vf","B%","AL State","   ",01047, 4,    0,  0.000
  8, -87.52773,  31.16666,"1A","vf01053001        ","1","1"," "," ","vf","DF","Frank Cu","   ",01053, 2,    0,  0.000
  9, -85.09805,  31.28638,"1A","vf01069001        ","1","1"," "," ","vf","B%","AL St Do","   ",01069, 2,    0,  0.000
 10, -85.09750,  31.28722,"1A","vf01069002        ","1","1"," "," ","vf","DF","AL St Do","   ",01069, 3,    0,  0.000
 11, -85.98055,  34.64278,"1A","vf01071001        ","1","1"," "," ","vf","BL","Bowater ","   ",01071, 2,    0,  0.000
 12, -85.80417,  34.83417,"1A","vf01071003        ","1","1"," "," ","vf","DE","N AL Shi","   ",01071, 3,    0,  0.000
 13, -85.80250,  34.83750,"1A","vf01071004        ","1","1"," "," ","vf","BM","Inman En","   ",01071, 4,    0,  0.000
 14, -85.70000,  34.94417,"1A","vf01071005        ","1","1"," "," ","vf","BL","AL St Do","   ",01071, 4,    0,  0.000
 15, -86.84333,  33.53166,"1A","vf01073001        ","1","1"," "," ","vf","C ","BNSF Bir","   ",01073, 2,    0,  0.000
 16, -86.68889,  33.55473,"1A","vf01073002        ","1","1"," "," ","vf","C ","NS Irond","   ",01073, 2,    0,  0.000
 17, -86.88223,  33.45860,"1A","vf01073004        ","1","1"," "," ","vf","LK","Penn Tan","   ",01073, 3,    0,  0.000
 18, -86.78500,  33.56251,"1A","vf01073005        ","1","1"," "," ","vf","DK","CSXT Bir","   ",01073, 6,    0,  0.000
 19, -86.79750,  33.56500,"1A","vf01073006        ","1","1"," "," ","vf","DO","JEFW Bir","   ",01073, 2,    0,  0.000
 20, -86.78167,  33.52499,"1A","vf01073007        ","1","1"," "," ","vf","DK","ERS Rail","   ",01073, 6,    0,  0.000
 21, -86.80778,  33.51222,"1A","vf01073008        ","1","1"," "," ","vf","LF","Nutritiv","   ",01073, 2,    0,  0.000
 22, -86.84556,  33.53111,"1A","vf01073009        ","1","1"," "," ","vf","DK","Material","   ",01073, 2,    0,  0.000
 23, -87.10750,  33.56002,"1A","vf01073010        ","1","1"," "," ","vf","LD","Ergon In","   ",01073, 2,    0,  0.000
 24, -87.11250,  33.58833,"1A","vf01073011        ","1","1"," "," ","vf","BL","Port Wes","   ",01073, 4,    0,  0.000
 25, -87.67028,  34.78721,"1A","vf01077001        ","1","1"," "," ","vf","DF","Lauderda","   ",01077, 3,    0,  0.000
 26, -87.66972,  34.78943,"1A","vf01077002        ","1","1"," "," ","vf","BM","Florence","   ",01077, 7,    0,  0.000
 27, -87.66666,  34.78971,"1A","vf01077003        ","1","1"," "," ","vf","DE","Methvin ","   ",01077, 4,    0,  0.000
 28, -87.66861,  34.79111,"1A","vf01077005        ","1","1"," "," ","vf","BM","Hill's M","   ",01077, 2,    0,  0.000
 29, -87.22417,  34.80611,"1A","vf01083001        ","1","1"," "," ","vf","DF","Wheeler ","   ",01083, 2,    0,  0.000
 30, -86.75195,  34.66250,"1A","vf01089001        ","1","1"," "," ","vf","C ","Huntsvil","   ",01089, 2,    0,  0.000
 31, -87.85389,  32.51334,"1A","vf01091001        ","1","1"," "," ","vf","B%","AL State","   ",01091, 4,    0,  0.000
 32, -86.29000,  34.36084,"1A","vf01095001        ","1","1"," "," ","vf","DE","Po Gunte","   ",01095, 4,    0,  0.000
 33, -86.28972,  34.36000,"1A","vf01095002        ","1","1"," "," ","vf","DE","Po Gunte","   ",01095, 4,    0,  0.000
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 35, -86.29417,  34.35333,"1A","vf01095006        ","1","1"," "," ","vf","DF","Cargill ","   ",01095, 3,    0,  0.000
 36, -86.29500,  34.35001,"1A","vf01095007        ","1","1"," "," ","vf","DF","Great Co","   ",01095, 3,    0,  0.000
 37, -86.28083,  34.34832,"1A","vf01095009        ","1","1"," "," ","vf","BM","Guntersv","   ",01095, 5,    0,  0.000
 38, -88.05000,  30.72249,"1A","vf01097002        ","1","1"," "," ","vf","C ","CSXI Mob","   ",01097, 2,    0,  0.000
 39, -88.04000,  30.66582,"1A","vf01097005        ","1","1"," "," ","vf","LK","PM Ag Pr","   ",01097, 7,    0,  0.000
 40, -88.04250,  30.70500,"1A","vf01097008        ","1","1"," "," ","vf","C ","Alabama ","   ",01097,11,    0,  0.000
 41, -88.04333,  30.71554,"1A","vf01097009        ","1","1"," "," ","vf","DF","AL St Do","   ",01097, 4,    0,  0.000
 42, -88.04000,  30.72584,"1A","vf01097013        ","1","1"," "," ","vf","BL","Po Mobil","   ",01097, 5,    0,  0.000
 43, -88.06000,  30.76861,"1A","vf01097015        ","1","1"," "," ","vf","C ","Mobile-C","   ",01097, 7,    0,  0.000
 44, -88.04333,  30.70167,"1A","vf01097023        ","1","1"," "," ","vf","C ","IC Mobil","   ",01097, 2,    0,  0.000
 45, -88.04250,  30.66750,"1A","vf01097024        ","1","1"," "," ","vf","DK","McKenzie","   ",01097, 4,    0,  0.000
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 48, -86.32584,  32.40001,"1A","vf01101002        ","1","1"," "," ","vf","B%","AL State","   ",01101, 5,    0,  0.000
 49, -87.00611,  34.62250,"1A","vf01103002        ","1","1"," "," ","vf","DO","Tenn Val","   ",01103, 2,    0,  0.000
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 51, -86.98556,  34.61805,"1A","vf01103004        ","1","1"," "," ","vf","DK","Decatur ","   ",01103, 4,    0,  0.000
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 53, -87.06750,  34.65250,"1A","vf01103007        ","1","1"," "," ","vf","DO","Hill's M","   ",01103, 2,    0,  0.000
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 55, -88.27500,  33.22665,"1A","vf01107001        ","1","1"," "," ","vf","BL","Pickens ","   ",01107, 6,    0,  0.000
 56, -88.23556,  33.07860,"1A","vf01107002        ","1","1"," "," ","vf","DF","Tom Soya","   ",01107, 2,    0,  0.000
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 58, -84.96833,  32.43501,"1A","vf01113003        ","1","1"," "," ","vf","DF","AL St Do","   ",01113, 3,    0,  0.000
 59, -88.09583,  32.68334,"1A","vf01119001        ","1","1"," "," ","vf","DO","Po Epes ","   ",01119, 2,    0,  0.000
 60, -86.18056,  33.61055,"1A","vf01121001        ","1","1"," "," ","vf","DK","Material","   ",01121, 5,    0,  0.000
 61, -87.58250,  33.21332,"1A","vf01125001        ","1","1"," "," ","vf","BL","AL St Do","   ",01125, 6,    0,  0.000
 62, -87.41750,  33.26751,"1A","vf01125002        ","1","1"," "," ","vf","DE","Abston C","   ",01125, 2,    0,  0.000
 63, -87.41750,  33.28499,"1A","vf01125003        ","1","1"," "," ","vf","DE","Mitchell","   ",01125, 2,    0,  0.000
```

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Figure 26. A snapshot of intermodal node data from ORNL in .ndp

ck86.ncp - Notepad

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  2, -87.76667,  31.29305
  3, -87.76417,  31.29502
  4, -85.15250,  31.84917
  5, -88.14750,  31.85750
  6, -87.90500,  31.49249
  7, -86.87000,  32.41499
  8, -87.52773,  31.16666
  9, -85.09805,  31.28638
 10, -85.09750,  31.28722
 11, -85.98055,  34.64278
 12, -85.80417,  34.83417
 13, -85.80250,  34.83750
 14, -85.70000,  34.94417
 15, -86.84333,  33.53166
 16, -86.68889,  33.55473
 17, -86.88223,  33.45860
 18, -86.78500,  33.56251
 19, -86.79750,  33.56500
 20, -86.78167,  33.52499
```

Figure 27. A snapshot of intermodal node data from ORNL in .ncp

5.0 Model Formulation

Consider a graph *G* = (*V*, *E*), where *V* is the vertex set and *E* is the bi-directed link set. In other words, $(k, l) \in E$ implies$(l, k) \in E$. Other notations are defined as follows:

Parameters:

D_i^j	the demand for an OD pair (i, j), where $i \in V, j \in V$, and $D_i^i = 0$;
$C_{k,l}^1$	the marginal time required for unit flow on link $(k, l) \in E$ for the part of the flow that is below $u_{k,l}$;
$C_{k,l}^2$	the marginal time required for unit flow on link $(k, l) \in E$ for the part of the flow beyond $u_{k,l}$, where $C_{k,l}^1 \leq C_{k,l}^2$;
$u_{k,l}$	the capacity of a link $(k, l) \in E$;
$A(k)$	the adjacent node list of node k, where $A(k) = \{l \in V: (k, l) \in E\}$;
a_i^k	$\begin{cases} 1, & i = k \\ 0, & i \neq k \end{cases}$ for $\forall i \in V, \forall k \in V$.

Variables:

$X_{k,l}^{i,j}$	the flow on link (k, l) for demand characterized by OD pair (i, j);
$y_{k,l}^1$	the part of flow on link (k, l) with marginal travel time of $C_{k,l}^1$, which is up to $u_{k,l}$; and
$y_{k,l}^2$	the additional flow on link (k, l) with marginal travel time of $C_{k,l}^2$ beyond $u_{k,l}$.

The model can be formulated as follows:

Minimize $$\sum_{(k,l) \in E} (C_{k,l}^1 y_{k,l}^1 + C_{k,l}^2 y_{k,l}^2) \tag{36}$$

Subject to: $$a_i^k D_i^j + \sum_{l \in A(k)} X_{l,k}^{i,j} = \sum_{l \in A(k)} X_{k,l}^{i,j} + a_j^k D_i^j \qquad i \in V, j \in V, k \in V, i \neq j \tag{37}$$

$$y_{k,l}^1 + y_{k,l}^2 = \sum_{i \in V} \sum_{j \in v, j \neq i} X_{k,l}^{i,j} \qquad \forall (k, l) \in E \tag{38}$$

$$y_{k,l}^1 \leq u_{k,l} \qquad \forall (k, l) \in E \tag{39}$$

$$X_{k,l}^{i,j}, y_{k,l}^1, y_{k,l}^2 \geq 0 \tag{40}$$

The objective function (36) minimizes the total travel time for the whole system/network. For each link there are two components of travel time $C_{k,l}^1$ and $C_{k,l}^2$ for flows $y_{k,l}^1$ and $y_{k,l}^2$ respectively. Constraint set (37) enforces the usual flow conservation requirements. Constraint set (38) states that the sum of two different piece-wise linear flows in a link should be equal to the total flow in that link. Constraint set (39) makes sure the flow volume on link (k, l) with marginal unit travel time $C_{k,l}^1$ cannot exceed its capacity $u_{k,l}$. Since $C_{k,l}^1 \leq C_{k,l}^2$, $y_{k,l}^2$ will be greater than zero only when $y_{k,l}^1 = u_{k,l}$. All variables are non-negative as shown by (40). The relationship among $C_{k,l}^1, C_{k,l}^2$, and $u_{k,l}$ can be shown in Figure 28, in which $TC_{k,l}$ is the total travel time of all traffic on link (k, l) and $y_{k,l}$ is the total flow on link (k, l) and equal to $y_{k,l}^1 + y_{k,l}^2$.

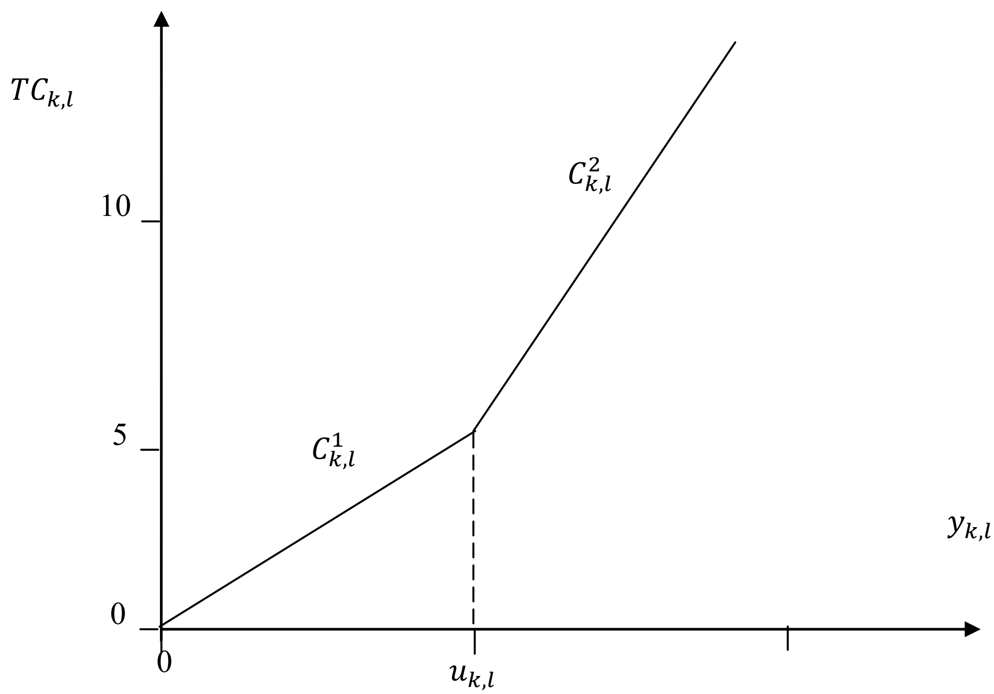

Figure 28. Piecewise linear approximation of the cost-flow function

6.0 Case Study

In this section we report the case study conducted on the railway network of Mississippi and its surrounding states (Alabama, Arkansas, Tennessee and Louisiana). The following subsections deal with the data collection, calculation and representing the criticality of the links in graphical format.

6.1 Data Collection

We require three types of data in order to evaluate the criticality of different links of the test network. They are railway network data, freight flow data and freight network capacity data.

6.1.1 Railway Network Data

The railway network considered in this study is shown in Figure 29. This network is collected from the North American Railroad Map, Railway Station Productions, LLC, software.

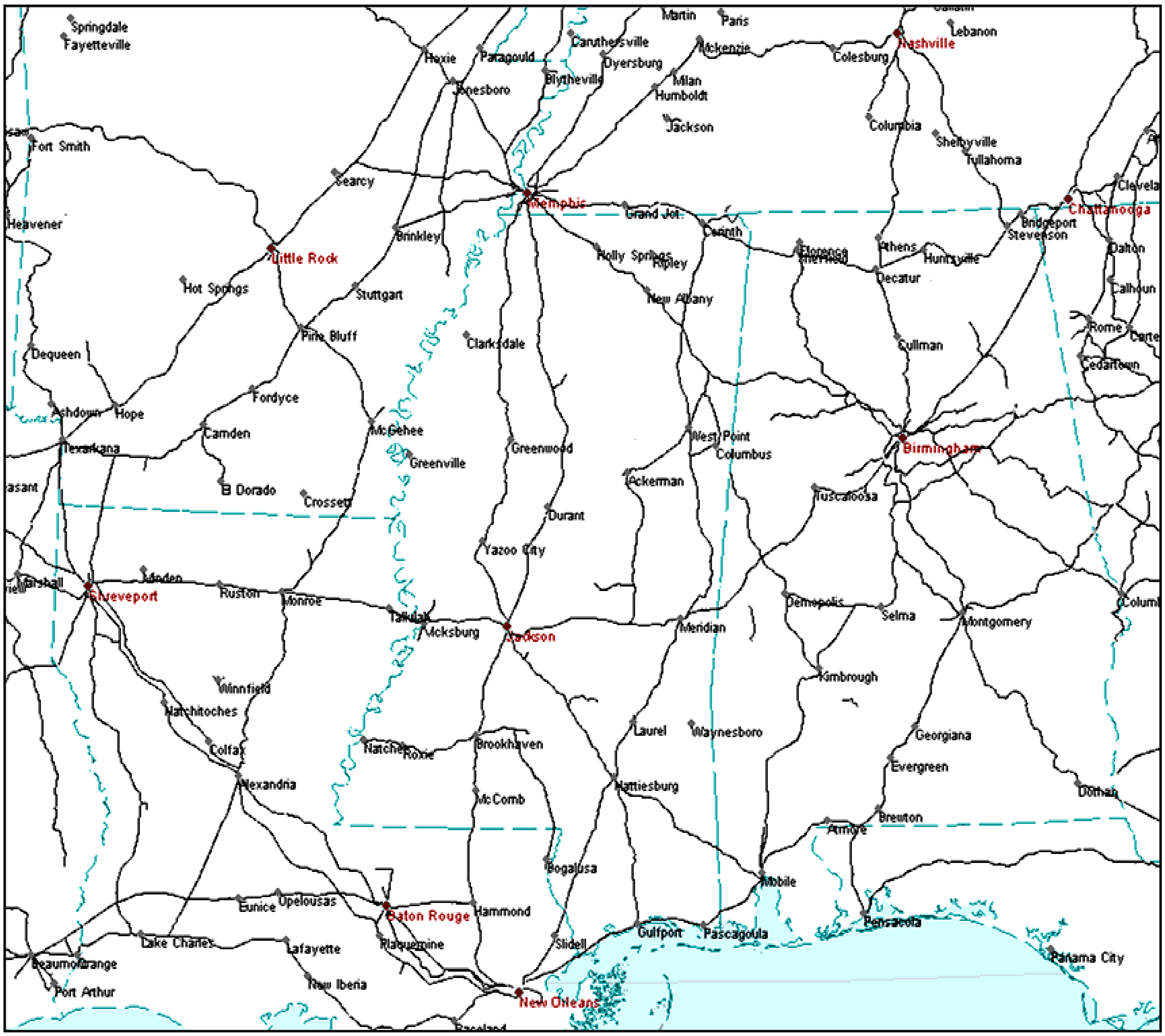

Figure 29. Railway Network Considered in the Study

6.1.2 The freight flow data

The freight flow data for the test railway network are collected from the Freight Analysis Framework (FAF) database. This paper considers 2009 rail freight flow data for different OD pairs to perform the case study and trains per day is calculated based on [45], given in Table 1.

Table 1. Freight flow data

OD-pairs	KTON 2009	Trains per day	OD-pairs	KTON 2009	Trains per day
Birmingham- Little Rock	866.7976	1	Nashville-Baton Rouge	173.92035	1
Birmingham-Shreveport	2710.7119	2	Nashville-New Orleans	173.92035	1
Montgomery-New Orleans	1919.89245	2	Jackson-Birmingham	432.5629	1
Montgomery-Baton Rouge	127.3409	1	Jackson-Decatur	171.2572	1
Mobile-Shreveport	68.79995	1	Gulf Port-Montgomery	628.7555	1
Mobile-Little Rock	73.6787	1	Jackson-Little Rock	685.2111	1
Birmingham-New Orleans	487.36275	1	Gulf Port-Little Rock	299.811	1
Birmingham-Memphis	51.0329	1	Jackson-Shreveport	344.1742	1
Memphis-New Orleans	178.07145	1	Gulf Port-Shreveport	109.2898	1
Memphis-Baton Rouge	178.07145	1	Jackson-Nashville	677.6764	1
Memphis-Shreveport	284.4188	1	Jackson-Mobile	686.0649	1
Little Rock-Birmingham	824.7493	1	Gulf Port-Memphis	994.12225	1
New Orleans-Nashville	3770.8709	3	Jackson-Baton Rouge	83.74435	1
Baton Rouge-Nashville	624.1593	1	Gulf Port-New Orleans	391.87785	1
Baton Rouge-Memphis	273.8304	1	Birmingham-Jackson	744.1761	1
New Orleans-Memphis	1998.918	2	Birmingham-West Point	744.1761	1
New Orleans-Birmingham	5922.9006	4	Montgomery-Hattiesburg	679.34313	1
New Orleans-Decatur	144.6022	1	Little Rock-Jackson	1320.2924	1
New Orleans-Tuscaloosa	144.6022	1	Little Rock-West Point	1293.025	1
New Orleans-Montgomery	909.8079	1	Little Rock-Hattiesburg	1297.48395	1
Shreveport-Decatur	245.15	1	Mobile-Jackson	39.0938	1
Baton Rouge-Montgomery	736.801	1	Memphis-West Point	1865.11717	2
Shreveport-Mobile	777.4838	1	Memphis-Hattiesburg	1988.93804	2
Shreveport-Birmingham	2103.8464	2	Memphis-Jackson	2066.46912	2
Baton Rouge-Birmingham	2024.2187	2	New Orleans-Hattiesburg	530.1709	1
Texarkana-Nashville	423.3888	1	Shreveport-Jackson	530.1709	1
Little Rock-Decatur	427.597	1	Shreveport-West Point	530.1709	1
Little Rock-Montgomery	1053.964	1	Jackson-Meridian	212.8324	1
Shreveport-Montgomery	22.193	1	Gulf Port-Jackson	212.8324	1
Birmingham-Baton Rouge	234.28655	1	Gulf Port-Hattiesburg	212.8324	1
Nashville-Little Rock	58.5693	1	Gulf Port-West Point	212.8324	1
Decatur-Shreveport	397.3265	1	Jackson-West Point	212.8324	1

Table 2. Freight network capacity data

Link	Capacity (trains/day)	Time[1]	Time[2]	Link	Capacity (trains/day)	Time[1]	Time[2]
Nashville-McKenzie	30	10.1	20.2	Decatur-Sheffield	18	3.8	7.6
Memphis-McKenzie	16	10.3	20.6	Birmingham-Sheffield	30	11.2	22.4
Memphis-Greenwood	30	11	22	West Point-Amory	16	2.8	5.6
Memphis-Jackson	18	18.8	37.6	Columbus-Amory	16	3.7	7.4
Greenwood-Jackson	30	10	20	West Point-Meridian	18	11	22
Memphis-Brinkley	18	6.8	13.6	Tuscaloosa-Meridian	30	8.6	17.2
Pine Bluff-Pine Bluff	30	7.7	15.4	Columbus-Demopolis	16	8.4	16.8
Little Rock-Pine Bluff	30	4	8	Tuscaloosa-Birmingham	30	4.8	9.6
Memphis-Bald Knob	30	9.5	19	Montgomery-Birmingham	46	11.8	23.6
Little Rock-Bald Knob	75	7	14	Selma-Birmingham	16	12	24
Little Rock-Texarkana	30	14.5	29	Montgomery-Mobile	30	19.2	38.4
Camden-Pine Bluff	30	8	16	Selma-Demopolis	16	5	10
Camden-B Dorado	16	4.6	9.2	Selma-Kimbrough	16	4.8	9.6
Camden-Texarkana	30	5	10	Demopolis-Kimbrough	16	3.8	7.6
Shreveport-Texarkana	30	6	12	Mobile-Kimbrough	16	12.2	24.4
Shreveport-Monroe	18	9	18	Jackson-Hattiesburg	16	9.5	19
Jackson-Monroe	18	10.6	21.2	Meridian-Hattiesburg	18	8	16
Pine Bluff-Monroe	30	13.9	27.8	Mobile-Hattiesburg	16	9.2	18.4
Memphis-Corinth	18	8.7	17.4	Gulf Port-Hattiesburg	18	6.6	13.2
Memphis-Tupelo	30	11.5	23	Gulf Port-Mobile	30	8.4	16.8
Corinth-Tupelo	30	4.2	8.4	New Orleans-Hattiesburg	18	12.8	25.6
Corinth-West Point	30	3.3	6.6	New Orleans-Gulf Port	30	7	14
Newton-West Point	18	12.9	25.8	Jackson-Brookhaven	30	5.6	11.2
Newton-Meridian	18	3	6	Mc Comb-Brookhaven	53	2.8	5.6
Newton-Jackson	18	6.2	12.4	Mc Comb-Hammond	30	5.8	11.6
Nashville-Columbia	16	3.5	7	New Orleans-Hammond	30	4.8	9.6
Nashville-Decatur	30	10.1	20.2	Baton Rouge-Hammond	18	4.2	8.4
Nashville-Stevenson	30	11.1	22.2	Baton Rouge-New Orleans	36	7.8	15.6
Decatur-Stevenson	18	8.4	16.8	Baton Rouge-Alexandria	16	10.5	21
Decatur-Chattanooga	30	4.5	9	Shreveport-Alexandria	18	11	22
Birmingham-Chattanooga	18	13	26	Monroe-Alexandria	30	8.5	17
Birmingham-Decatur	30	8.6	17.2	Bogalusa-Brookhaven	16	8.5	17
Tupelo-Amory	30	2.8	5.6	Plaquemine-Alexandria	30	8	16
Birmingham-Amory	30	11	22	Plaquemine-New Orleans	16	6	12
Corinth-Sheffield	18	4.2	8.4				

6.1.3 Freight Network Capacity Data

The capacity of each link of the network is determined by throughput. In this paper, the throughput of each link is measured in terms of the number of trains passing through the links during a specific time interval (e.g. per day). As traffic volume increases the amount of traffic delay due to congestion typically increases non-linearly as a function of a route's volume/capacity ratio. The capacities and two different travel time components of each link of the proposed network are shown in Table 2. The capacities are measured based on [3]. Again, the first time component ($Time^1$) is measured by considering the regular freight train speed of 10 mph [46] and the second time component ($Time^2$) is arbitrarily taken as twice the first time component.

6.2 Result

Using the data in section 6.1, we program the LP model in C according to the model formulated in Section 3 and using ILOG CPLEX 9.0 to solve it. All the links are considered to be disrupted individually to measure the criticality of each individual link of the test network. As mentioned earlier, criticality of a link is measured by the amount of increased delay from the base (undisrupted) network when the link is disrupted. The most critical link is the one that causes maximum delay when that particular link is disrupted. The results obtained from CPLEX for the problem instance are presented in Table 3.

The criticalities of all the links are demonstrated in Figure 30. The relative criticalities are represented by the width of the links. The most critical link has the maximum width, which means disruption to this link will cause the maximum delay on the total travel time for the whole network. The links with the minimum width are the least critical links of the test rail network. Disruptions to these links will have the least impact on the overall delay. For example, for the rail network of the state of Mississippi and its adjacent states, the top five critical links are Jackson-Monroe, Birmingham-Tuscaloosa, Meridian-Tuscaloosa, Jackson-Newton and New Orleans-Gulfport, sequentially.

7.0 Conclusions and Future Work

This article presents a piece-wise linear approximation of the non-linear programming problem for vehicle routing through the railway network to determine the criticality of the railway links. The modeling is based on link-based rather than path-based routing of the trains that also considers different OD-specific demand. Our simple translation of the non-linear programming problem into a piece-wise linear program is very effective. Its performance is satisfactory. We can solve the problem within reasonable amount of time with CPLEX and the criticality of all the links is measured easily with negligible amount of modifications to the code.

Future work includes incorporation of intermodal issues in the current model. In this work, we just considered the routing of trains in the disrupted network. We want to extend this model by incorporating highway and waterway capacities and routing algorithm through all these three modes of transportation so that total travel time delay is minimized.

Table 3. Results of the optimization model

Disrupted Link	Objective Value (Hrs.)	Disrupted Link	Objective Value (Hrs.)
Undisrupted	2578.2	Corinth-Sheffield	2598
Nashville-McKenzie	2595.2	Decatur-Sheffield	2593.2
Memphis-McKenzie	2647.3	Birmingham-Sheffield	2583
Memphis-Greenwood	2578.2	West Point-Amory	2583
Memphis-Jackson	2604.4	Columbus-Amory	2579.7
Greenwood-Jackson	2593.1	West Point-Meridian	2584.6
Memphis-Brinkley	2582.9	Tuscaloosa-Meridian	2737.8
Pine Bluff-Pine Bluff	2582.9	Columbus-Demopolis	2578.2
Little Rock-Pine Bluff	2605.4	Tuscaloosa-Birmingham	2737.8
Memphis-Bald Knob	2590.2	Montgomery-Birmingham	2595.7
Little Rock-Bald Knob	2590.2	Selma-Birmingham	2578.2
Little Rock-Texarkana	2578.2	Montgomery-Mobile	2616.2
Camden-Pine Bluff	2582.9	Selma-Demopolis	2578.2
Camden-B Dorado	2578.2	Selma-Kimbrough	2578.2
Camden-Texarkana	2590.6	Demopolis-Kimbrough	2590.2
Shreveport-Texarkana	2587.1	Mobile-Kimbrough	2653.3
Shreveport-Monroe	2671.1	Jackson-Hattiesburg	2641.1
Jackson-Monroe	2744.7	Meridian-Hattiesburg	2640.5
Pine Bluff-Monroe	2614.2	Mobile-Hattiesburg	2604.6
Memphis-Corinth	2591.2	Gulf Port-Hattiesburg	2611.2
Memphis-Tupelo	2582.4	Gulf Port-Mobile	2625.2
Corinth-Tupelo	2578.2	New Orleans-Hattiesburg	2584.6
Corinth-West Point	2587.4	New Orleans-Gulf Port	2671.1
Newton-West Point	2580.4	Jackson-Brookhaven	2625.8
Newton-Meridian	2652.2	Mc Comb-Brookhaven	2625.8
Newton-Jackson	2679	Mc Comb-Hammond	2625.8
Nashville-Columbia	2578.2	New Orleans-Hammond	2602.5
Nashville-Decatur	2588.8	Baton Rouge-Hammond	2609.5
Nashville-Stevenson	2578.2	Baton Rouge-New Orleans	2580.6
Decatur-Stevenson	2578.2	Baton Rouge-Alexandria	2578.2
Decatur-Chattanooga	2578.2	Shreveport-Alexandria	2581.9
Birmingham-Chattanooga	2629.2	Monroe-Alexandria	2578.2
Birmingham-Decatur	2590.6	Bogalusa-Brookhaven	2578.2
Tupelo-Amory	2578.2	Plaquemine-Alexandria	2581.9
Birmingham-Amory	2587.3	Plaquemine-New Orleans	2654.7

Figure 30. Railway network showing the criticality of the links

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